SUSTAINABILITY IN THE AERONAUTICAL SECTOR: A HIGHLY COMMITTED SECTOR

COIAE

Report of the Colegio Oficial de Ingenieros Aeronáuticos de España

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Introduction

The Colegio Oficial de Ingenieros Aeronáuticos de España has a strong commitment to the Spanish aeronautical sector.

This commitment has been transformed into concrete actions.

These actions include the creation of a sustainability committee since 2019, which has held several conferences on sustainability in the sector and has promoted all the measures that the sector is taking to be "greener". This commitment to sustainability is not only a commitment of this College, but it is a commitment of the entire aviation industry. This goal bonds us.

This report is one of these actions to raise awareness of the industry's efforts to be more sustainable, and to ensure that passengers around the world continue to rely on aviation as a very sustainable and safest environment known on this planet.

The aeronautical industry connects people, ties them together with sustainability and in solidarity with the planet.

Receive a cordial greeting,
Estefanía Matesanz
Dean of the Colegio Oficial de Ingenieros Aeronáuticos de España

Executive summary.

- The main aim of this report is to underline the great commitment of the aeronautical sector to the environment, being one of the sectors with more initiatives in progress to minimize the environmental impact.
- The mitigation of noise and the reduction of pollutant emissions, at the local level and inducing the greenhouse effect, are the main challenges to achieve an environmentally sustainable aeronautical industry. The main objective in this effort is to minimize the emission of carbon dioxide (CO_2), although it is also necessary to consider other elements, among them nitrogen oxides (NOX) or the formation of condensation trails and induced cloudiness.
- Despite its lower overall emissions compared to other transport sectors, commercial aviation led the way by launching in 2008 a coordinated and clearly established milestone plan to tackle climate change: improvements in energy efficiency of 1.5% per annum until 2020, CO_2-neutral growth from the same year, and reduction of total net emissions to 50% by 2050[1].
- In order to meet these ambitious targets, the aviation sector is investing substantial resources in multiple actions, covering emissions compensation, improving operations or research and development of new technologies that reduce noise and emissions. In the last four decades, the improvement in the energy efficiency of commercial aircraft has been over 60%. A state-of-the-art aircraft consumes an average of 3 liters of fuel per 100 passenger-km. This value, and therefore the associated CO_2 emissions, is equivalent to an efficient compact car.
- The European Emissions Compensation System (EU ETS) certified the reduction of 193 million tons of carbon dioxide emissions related to air traffic between 2013 and 2020. Globally, the first phase of the regulatory framework for carbon offsetting CORSIA will be operational by 2021. This, including almost all international civil aviation, means a determined and immediate effort to mitigate CO2 emissions from commercial aviation.
- The renewal of infrastructures and control systems, both in flight and at airports, allows a more efficient coordination and management of air traffic, and the consequent reduction of emissions and noise. In Europe, for example the implementation of the Single European Sky (SES), and the new integrated air management system SESAR.
- Continuous technological development in aeronautical construction, with gradual improvements in propulsion systems (e. g. by increasing the bypass ratio), new structural materials (advanced composites) and aerodynamic innovations (e. g. the use of laminar flow) make it possible to design ever more efficient and less polluting aircraft. In the longer term, disruptive designs that include, for example, open counter-rotator motors, braced wings or flying wings allow for even more significant future improvements.

1 Taking global CO_2 emissions due to aviation in 2005 as a reference.

- Sustainable fuels, both biologically and synthetically sourced from renewable energy sources, are already a reality and present themselves as a viable option, soon, to effectively reduce the environmental impact of aviation, particularly in terms of CO_2 emissions. Their great advantage is that they improve the sustainability of current aircraft (the "drop-in" concept), including those operating high capacity and long-haul flights. Their full life cycle, including the direct and indirect impacts of their production, should be considered when calculating their environmental performance.
- Electrically powered commercial aviation, which is expected to arrive this decade for small aircraft, is now the only way to be able to fly with zero environmental impact, assuming that renewable supplies are used and in the absence of an evaluation of the life cycle of the equipment used.
- The configurations that include electric motors are very varied and flexible, with multiple possibilities of hybridization with other propulsion systems to optimize their capacities. Electricity may come from batteries or fuel cells. The characteristics of electric motors open new possibilities and advantages in aircraft design (reduction of induced resistance, limit layer intake, distributed propulsion). The main technological hurdles to be overcome are the increase in specific energy from batteries and high-power distribution systems, where 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 passenger transport sector: aircraft with more than 100 passengers over distances around 2,000 km. Its industrial development and implantation are strongly promoted by the government in Japan and Europe, as it is an enormously versatile element in decarbonization strategies. In aviation, it is an essential part of the production of sustainable synthetic fuels, it drives electric propulsion through fuel cells, and allows direct combustion in turbojets. Projects are currently under way for commercial aeronautical applications in all these variants.
- Hydrogen solves the autonomy problem of electric propulsion, surpassing kerosene in specific energy by a factor of three, which lightens the weight of fuel required. On the other hand, its energy density is at least four times lower than conventional fuel, which makes it difficult to design the aircraft by requiring much more space to accommodate the pressurized or cryogenic tanks (liquid H_2). Although its combustion only theoretically produces water, more research is needed on its environmental effects since it releases H_2O in height (condensation trails and induced cloudiness), as well as continuing technological development to minimize the associated NOX emissions.
- Noise reduction due to air operations continues uninterrupted, the new aircraft registered a noise footprint 30-50% lower than the generation it replaces. Today's airplanes are 75% quieter than 50 years ago.
- Sustainable commercial aviation is an ambitious goal, within our reach, and it will require the involvement and effort of the entire aviation industry, governments, and international organizations, as well as the passengers. There is a wide range of measures, strategies, and technologies to achieve this, and the most likely path is to combine them all according to their optimal capabilities in different time frames. Within 10 to 20 years, it is possible to achieve, for example, a civil aviation dominated by electric and hybrid propulsion for regional and short-range transport, hydrogen combustion engines for intermediate and high-capacity routes, and long-haul flights using sustainable fuels.

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1 Introduction And purpose

The global challenge of this century is to achieve worldwide development that balances social, economic, and environmental considerations, as stated by the European Environment Agency[1].

This report provides an overview of the civil aviation sector in order to understand its current state of environmental sustainability, the actions and projects that have been carried out to improve it, as well as the proposed initiatives that will contribute to a more sustainable future in aviation.

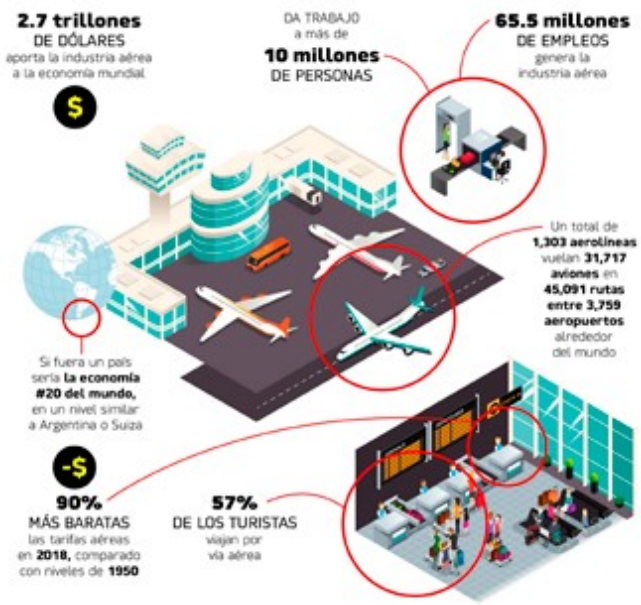


Figure 1. The airline industry in numbers.

The aeronautical sector comprises aircraft's manufacturers, engines and equipment, air lines, navigation and air traffic control organizations, airports, certification entities, research, and technology centers, and in general all the people who work for the aeronautics industry, contributing in many ways to economic growth, social well-being and, in particular, forging links between people at the national and international levels.

Civil aviation is a global engine that makes a decisive contribution to the improvement of our lives creating jobs and speeding up transport and distribution, promoting competitiveness, territorial cohesion, and the connectivity of our societies. In addition, aeronautics generates universally applicable technological developments, as well as significant scientific and cultural exchange, while maintaining the highest level of safety for all modes of transport and working to minimize their environmental impact.

IATA, the International Air Transport Association, sums up saying that "today's aviation industry brings loved ones together, connects cultures, expands minds, opens markets, and fosters development. "[2].

Figure 1 shows the airline industry data for 2018. More than 4 billion passengers and 62 million tons of cargo were transported safely through the global network[3]. In Spain, in 2019, 275,2 million passengers were transported by air, and a total of 1.069 million tons of cargo[4].

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

1 https://www.miteco.gob.es/es/calidad-y-evaluacion-ambiental/temas/agencia-europea-medio-ambiente-informacion-ambiental/soer2020esfinal_tcm30-504999.pdf

2 https://www.iata.org/en/pressroom/pr/2013-12-30-01?utm_source=&utm_medium=&utm_campaign=

3 IATA and ATAG https://a21.com.mx/aerolineas/2018/10/08/beneficios-de-la-aviacion-infografia

4 Aena's statistics. http://estadisticas.Aena.es/csee/ccurl/787/753/Anual2019_prov.pdf

According to the European Research Area (ERA), the aviation sector contributes $823 billion to Europe's economic activity, accounting for 3.3 per cent of all employment (12.2 million jobs) and 4.1 per cent of Europe's GDP. Globally, their contribution to GDP is $2.7 trillion, and 65.5 million jobs [1].

All these benefits have a cost in terms of environmental impact due to air transport, which can be classified, depending on their scope, into local and global effects.

Within the local effect, centered around airports, noise, local air pollution and space/landscape impact can be distinguished. Global impacts include consumption of non-renewable materials and, above all, emissions, and their contribution to climate change.

Since the beginning, the aircraft has undergone major transformations, although comparing a 70's airplane with a new generation aircrfat, the exterior appearance has hardly changed. Actually, most of the changes have been taken place inside, improving structural configurations of design, materials, and especially in electronics and engine efficiency.

This path of aviation towards the mitigation and elimination of emissions and other negative effects, which is the focus of this report, does not exhaust the analysis of the sustainability of the aviation industry. The life cycle study of all elements required to fly, must consider many other aspects, such as the complete aircrafts' production processes, infrastructure, and fuel; or the consideration of side effects or "rebound" effects to the introduction of new measures and more sustainable technologies. In this sense, and even if it goes beyond our objective, it is worth highlighting, for example, the recycling actions and projects in the aeronautics sector, the manufacturing level and the end of their operational life: the Sentry[5] and PAMELA[6] projects (developed within the European Union's Clean Sky and LIFE programmes respectively), or the work of companies dedicated to these fundamental tasks for sustainability of civil aviation[7].

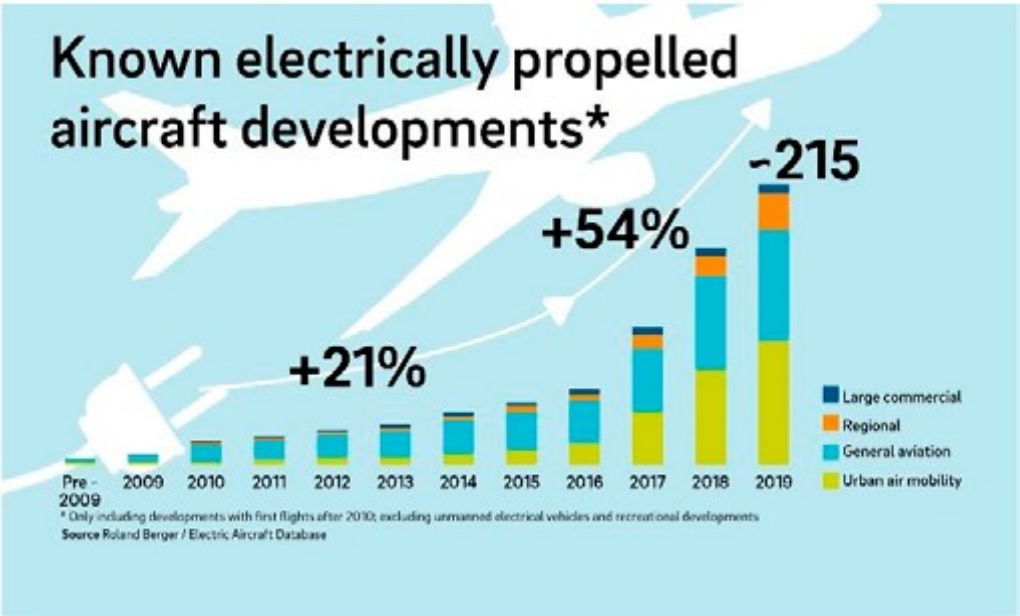


Figure 2. Evolution of the number of electrically powered aviation projects per year.

5 https://cordis.europa.eu/project/id/632487/reporting/es
6 LIFE05 ENV/F/000059
7 AELS, TARMAC Aerosave, etc.

In this context, it is unavoidable to mention the current crisis of COVID-19, which has hit society hard on a global scale, both in terms of health and economics, slowing down many key activities, including air transport. The impact on the airline industry, beyond the operations of airlines, also affects the research activities of manufacturers. The cancellation of R&D programmes, as a first rapid response to the crisis, has also affected some projects geared towards sustainable aviation, such as E-FanX[8].

On the other hand, the enormous challenge of the current pandemic is also an opportunity to highlight the need to move towards even more sustainable and environmentally friendly aviation. This is recognized by the European Union, making special aid conditional on economic recovery on projects compatible with the "European Green Deal" [2], and the objective of achieving a decarbonized continent by 2050. Other countries have also linked their extraordinary economic aid to sustainable development, such as France and its commitment to a carbon-neutral aircraft by 2035[9].

The aeronautics industry, which is always in the process of technological improvement, is ready to face this challenge successfully. For example, the evolution of the number of active electric aviation projects (Figure 2) to exceed 200 by the end of 2019[10].

This path to sustainable aviation is sustained in the short term by operational improvements, emissions mitigation and offsets, and incremental developments of established technologies; but also by disruptive innovations, revolutionary changes and new technologies in the long term.

The aviation industry has already made successfully changes in the past, and in collaboration with public and private entities, passengers, and society, it is prepared to do it again.

Given the importance and visibility of environmental impacts in the field of sustainability, and particular in everything related to climate change, this report will place particular emphasis on the effects of aircraft operations: emissions of gases and particulates, and noise. First, aviation will be contextualized in relation to other transport systems and then it will be shown the efforts, progress, and results that the aviation sector is making to control and minimize its impact.

8 https://www.airbus.com/newsroom/stories/our-decarbonisation-journey-continues.html

9 https://www.euractiv.com/section/aerospace/news/france-unveils-e15bn-in-aerospace-aid-sets-green-goals/

10 Roland Berger: https://www.rolandberger.com/en/Point-of-View/Electric-propulsion-is-finally-on-the-map.html

2 Contextualized environmental impact of aviation

The environmental impact of aviation, both in terms of emissions and noise generation, has been a subject of study and improvement by the aviation industry for decades. However, it was from the ONU climate change task force (IPCC), particularly in its 1999 report [3], that it achieved great public relevance, in parallel with growing environmental awareness.

The study of this global phenomenon has, as one of its main tasks, the evaluation of all the greenhouse gas emissions due to human activities, identified, almost with all certainty, as the main cause of this phenomenon [4]. In order to compare the intensity and impact of different types of emissions and effects, the concept of Radioactive Forcing (RF) is commonly used, which is a measure of the influence of any factor on the alteration of the energy balance of the earth-atmosphere system: the balance between incoming solar radiation and outgoing infrared radiation, compared to the pre-industrial era (1750).

For example, the release of gases such as CO_2 into the atmosphere helps to capture this outgoing thermal radiation and produces a positive RF that therefore increases the greenhouse effect. The albedo effect of clouds during the day, reflecting sunlight and consequently cooling the planet, produces a negative RF.

The overall impact of an activity on climate change can be assessed as that resulting from all the radioactive forcing that it generates, both positive and negative. For aviation, the available studies agree on its net contributor status, with figures of around 3,5% of the human contribution to climate change [5]. This assessment only considers confirmed factors, although it is estimated that it could be higher due to effects still under study such as induced cloudiness.

The main factors behind this impact of aviation are:

- Emissions of greenhouse gases, mainly CO_2, but also NOX, soot, water vapour and others.
- The formation of condensation trails (contrails) and the induction of cirrus (AIC). This latter effect, which is still difficult to assess, is estimated to account for between 34% and 70% of the total impact [5].

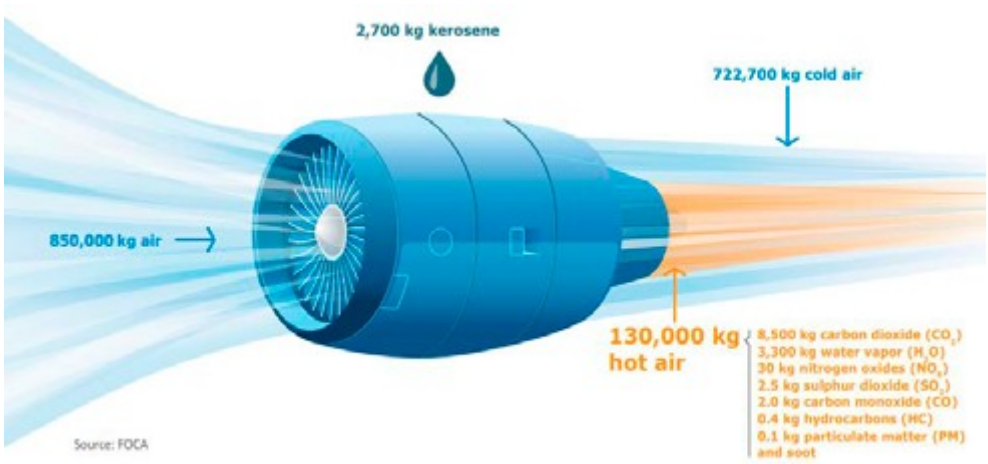
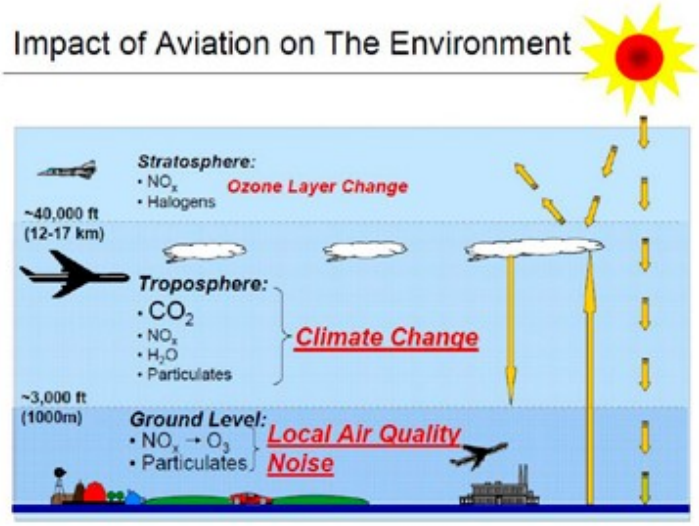


Figure 3. Consumption and typical emissions of an aircraft with 2 turbofans in a flight of 1 hour and 150 pax.

The interactions of these emissions in the high layers of the atmosphere are very complex, and are the subject of continuous research. For example, nitrogen oxides (NOX) have a double effect on the greenhouse effect: on the one hand it is terribly negative because it acts as a precursor to ozone (O3), but on the other hand it removes methane (CH4) from the atmosphere, another greenhouse gas. In any case, the global effect of NOX emissions is clearly favorable to climate change. Emissions of sulfur dioxide help to cool the atmosphere [5].

The increasing knowledge of the different mechanisms, which commercial aviation influence climate change, highlights the long road ahead to fully sustainable aviation. On the other hand, this knowledge, of the different phenomena involved, allows guiding the efforts of the industry to mitigate their impact.



Focusing on emissions, the main and best-known component is carbon dioxide (CO2), which is used to compare environmental impacts between different industries and sectors. One of the most comprehensive assessments concluded that commercial aviation accounted for 2,5% of global emissions in 2005 [5], similar to other more recent estimates (2,4% in 2018 [7]). This impact of aviation is slightly higher in studies limited to Europe (3,6% in 2016 [8]). Considering CO2 emissions by country, according to the origin of the flights, the United States (24%) and China (13%) stand out as the two largest contributors by far [7].

Figure 4. Scheme of aviation environmental impact.

To put these figures in context, it is useful to compare them with the environmental impact of road transport, which is responsible for 17% of global CO2 emissions, as Figure 5 shows, or maritime transport, which accounts for 3% of the total. According to the IPCC, the global contribution of the entire transport sector is about a quarter of the total CO2 emitted by human activities in 2010, and its contribution has grown rapidly, more than double that of 1970. 80% of this worrying increase is due to road transport [4].

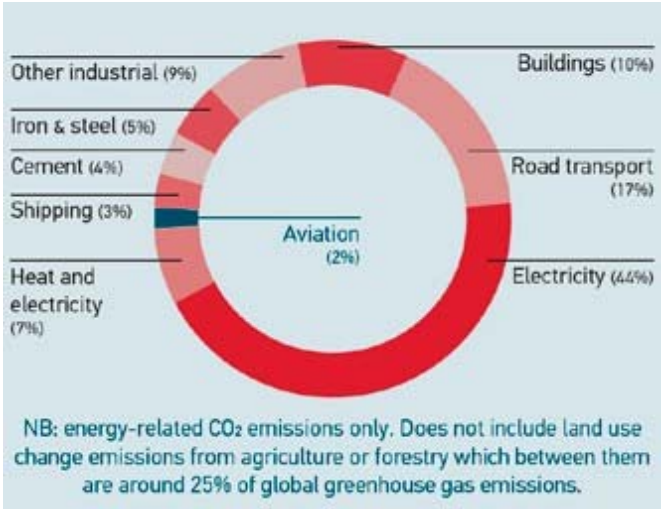


Figure5. Contribution of CO_2 due to aviation compared to global emitters in 2014.

The European Environment Agency (EEA), in its studies on CO_2 emissions at European level, corroborates this distribution of impacts in the transport sector (Figure 6).

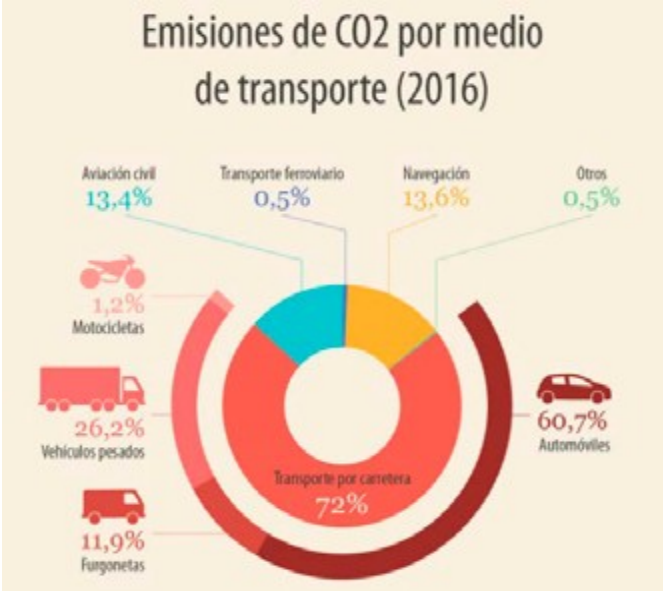


Figure 6. Proportional contribution to CO_2 emissions from transport in the EU.

On the other hand, Figure 7 details the importance of the different segments of aviation according to their CO_2 emissions. As it can be seen, the largest contribution of carbon dioxide is concentrated in aircraft with 100 and 200 passengers on and flights up to 2,000 km.

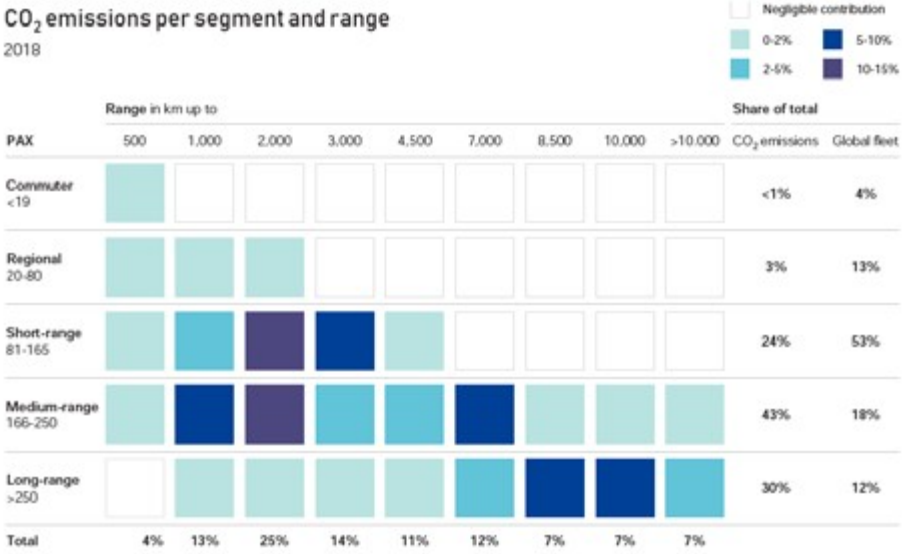


Figure 7. Contributions to CO2 emissions in aviation by distance and capacity of flights. (EU H2 2020).

Commercial passenger aircraft have constantly evolved over decades towards better efficiency in their energy consumption per kilometer and passenger. Over a period of 40 years this improvement has been estimated by more than 60% [5]. Despite this, net emissions associated with commercial aviation have grown steadily in recent years, mainly due to the huge increase in air traffic. This growth in emissions, estimated at 5,7% per annum between 2013 and 2018 [7], has occurred despite considerable mitigation by technological advances in the aviation industry, as shown in Figure 8. The amount of fuel needed per basic transport unit ("fuel intensity") has been steadily decreasing over the past decades. For example, a state-of-the-art aircraft, such as the A350 or 737Max, consumes on average 3 liters of fuel per 100 passenger-km. Despite the big difference in speed and range, this value is equivalent to that of any compact car[1].

Another comparison is based on the intensity of carbon emissions, which collects the CO2 emitted per passenger per kilometer travelled.

According to 2018 data [7], the average air passenger transport is 88 gCO_2/pax•km, which includes the oldest aircraft still in service. As a reference, newly registered cars in Europe in 2019 emit an average of 122 gCO2/km [2]. Using the usual reference occupancy (1,5 persons per vehicle), the average carbon intensity value for the most modern private road transport is 82 gCO_2/pax•km.

Efficiency improvements in commercial aircraft, without radical changes in technology or configuration, are estimated to be around 1-2% per annum [4]. The current uncertainty complicates the estimation of future growth of air traffic, which has suffered a profound stands-off in 2020 due to the COVID-19 pandemic but it will almost certainly outstrip improvements in fuel consumption in the medium term.

This meant that in order to reverse the trend and reduce net emissions, new strategies will be essential. Next, we will see how the civil aviation sector responds to this formidable challenge.

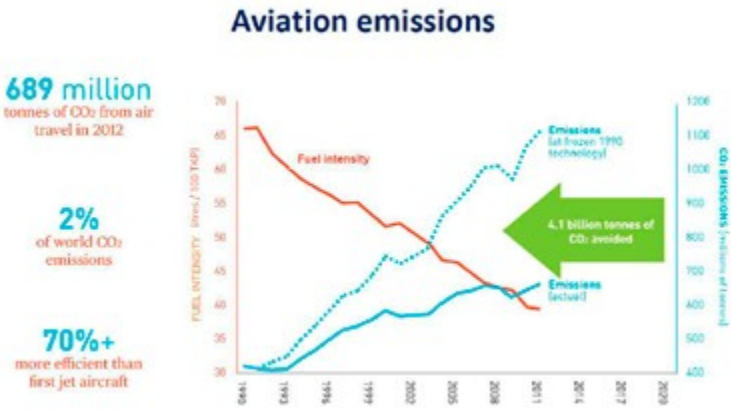


Figure 8. Aviation CO_2 emissions avoided due to efficiency gains between 1990 and 2012.

1 ATAG. https://aviationbenefits.org/environmental-efficiency/climate-action/efficient-technology

2 https://www.eea.europa.eu/highlights/average-co2-emissions-from-new-cars-vans-2019

Photographic archive

Figure 3. Source FOCA.
Figure 5. https://aviationbenefits.org/environmental-efficiency/aviations-impact-on-the-environment/
Figure 6. European Environment Agency. https://www.europarl.europa.eu/news/es/headlines/society/20190313STO31218/emisiones-de-co2-de-los-coches-hechos-y-cifras-infografia

3 Towards a more sustainable aviation

The aeronautical industry, including manufacturers, airports and airlines, is fully aware of this environmental challenge, and has been working for years to find solutions.
In 2008, the ATAG[1] association, which brings together the main players in the sector, signed a commitment to action against climate change[2]. As a result, three ambitious objectives were set:

1. An improvement in air transport efficiency of 1,5% per year, measured in CO_2 emitted by tonne-km transported (RTK) between 2009 and 2020.
2. Set as a cap on net CO_2 emissions at the level reached in 2020, committing to CO_2-neutral growth.
3. The reduction of net CO_2 emissions from aviation by 50% in 2050 and compared to 2005 levels.

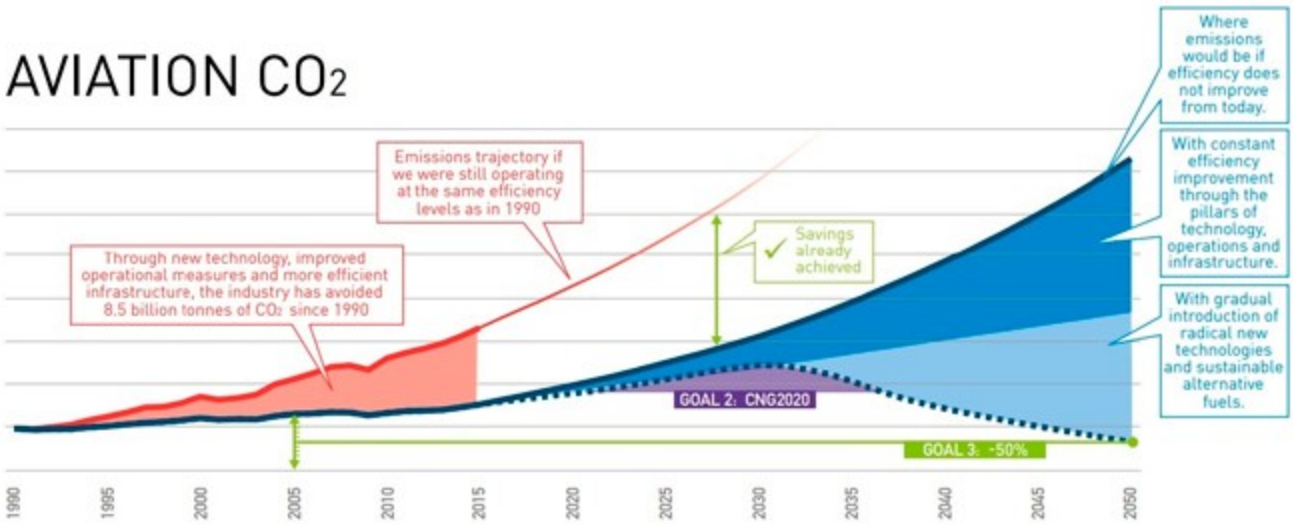


Figure 9. Evolution of CO_2 emissions from aviation and their projected mitigation.

A variety of actions are needed to achieve these objectives. According to the consensus reached across the sector, they can be grouped into four pillars [8]:

- Emissions offsetting through market-based systems.
- Modernization of infrastructure, including air traffic control.
- Improvements in the efficiency of aviation operations.
- Development of new technologies in aircraft, including Sustainable Aviation Fuels (SAF).

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

Firstly, the intention is to contain, and then reduce, as quickly as possible, the net contribution of commercial aviation to greenhouse gas emissions.

The ICAO, the ONU's specialized agency for the management of international civil aviation, plays a key role in the implementation of this strategy. On the one hand, it has completed a series of mandatory regulations for the certification of aircraft and engines in relation to noise, local air quality (NOX, hydrocarbon residues, CO, particulate matter) and climate change (CO_2), which implies a mandatory global environmental certification for civil aviation.

On the other hand, in 2016 ICAO launched the Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA), which is fundamental to the short-term mitigation strategy, and which has been accepted by the IATA industry association. Its first phase will enter into force on 1st January 2021. Later, we will discuss this initiative in more detail.

The European Union is also a key player in the drive towards sustainable air transport. In 2011 it set out its vision for the commercial aviation of the future: FlightPath 2050 [9], with targets similar to ATAG, but extending them to include NOX emissions, noise and aircraft recycling. To achieve such ambitious objectives, the CleanSky 2 programme was launched, a continuation of a successful public-private partnership to finance innovative projects in the field of sustainability. In the United States, the CLEEN I and II programmes, managed by the Federal Aviation Administration (FAA), have developed in a similar way.

The circular economy is the logical extension of sustainability initiatives within the aviation industry. In addition to the implementation of measures aligned with the original 3Rs (Reduce, Reuse, Recycle), redesign and repair are now added. To cite a few examples, TARMAC AEROSAVE has recycled more than 135 aircraft since 2007, approximately recovering materials that cover up to 92% of the total weight of an aircraft [10]. Other initiatives by the airlines include the circular economy strategy of Air France-KLM Group, with a redesign and sustainable management of all on-board catering and equipment. Biofuels produced from waste, whether urban, industrial or agricultural (see section 4. 4. 1) are another good example of these strategies. Finally, airports have also joined in this effort, such as Gatwick, which achieved the certificate of eradication of non-recyclable waste [10].

Figura 10. Programas de la UE CLEAN SKY 1 y 2, ACARE y FlighPath 2050. Evolución de objetivos medioambientales.

The society, in which we live, is moving unequivocally towards a sustainable and environmentally friendly world. The initiatives, programmes and tangible realities described in this section show that civil aviation is not only not falling behind in this endeavour, but is committed to going further with very ambitious objectives. Then, we will see what tools and technologies use to achieve them.

4 Actions Innovation Technology

4.1. Emissions Offsets

The aeronautical industry has always stood out for its capacity for technological development. The environmental challenge, requires a new effort of technical innovation which, as we shall see below, is already underway in many directions and, most importantly, is starting to flourish.

However, the development time required for the design, manufacture, and entry into service of a new aircraft, apart from basic technological research, is considerable. In addition, the large commercial fleet will continue operating for the most part over the next few years, even if the renewal of the fleet is started immediately. For all these reasons, it was essential to find a short-term solution to mitigate emissions from commercial flights. Emissions offsets are the missing bridging piece on aviation's road to sustainability.

The possibility that the emissions of gaseous pollutants produced during a commercial flight, usually focusing on CO_2 as a benchmark, can be offset by investing money in projects that reduce the same amount of emissions has been tested for a long time. In fact, nowadays airlines claim to offset 100% of their carbon dioxide emissions, such as Easyjet. The main challenge in these proposals is the verification of such compensation projects, ensuring their additionality and permanence [11], as well as the need to combine coordinated efforts if the benefit is to be global.

The EU Emissions Trading Scheme (EU ETS2) has included the aviation sector since 2012, setting the total emissions cap based on the average of the years 2004 – 2006. This scheme operates under the "cap-and-trade" principle, which limits the maximum total emissions by allocating the corresponding allowances to airlines, and obliges them to negotiate with them or buy credits from outside aviation, if they exceed their emission allowances. Although this mandatory regulation initially covered all domestic and international flights to and from countries of the European Economic Area (EEA), international pressure managed to suspend its effects on flights outside the EEA, pending ICAO's global proposal (known as "stop-the-clock" decision). The low prices of external credits, which have allowed airlines to continue increasing their emissions, prompted a series of changes to the system in 2017, that managed to reverse the situation.

Between 2013 and 2020 this scheme has certified a reduction of 193 million tons of CO_2 emissions related to air traffic [8]. With the advent of a global emissions control, trading, and offsetting scheme after 2021; the necessary integration or coordination with the EU-ETS poses a top-level political, regulatory, and operational challenge.

1 https://www.easyjet.com/en/sustainability
2 https://ec.europa.eu/clima/policies/ets_es

In 2016, ICAO approved to launch CORSIA3, a CO2 offsetting scheme for commercial aviation. This mechanism is designed to enable airlines of ICAO member countries, which cover many commercial flights, to meet their commitment to

Figura 11. Iniciativa CORSIA de la OACI.

offset carbon dioxide emissions above the 2020 level. The system will account the CO_2 emitted by each airline, allowing them to participate in an emissions trading market to take advantage of the capacity of other sectors, where reducing emissions is simpler and more efficient. As we know, this proposal materializes one of the pillars of environmental action proposed by ATAG in 2008.

In this vein, in 2019 the ICAO issued a standard with criteria for defining the eligibility of compensation projects (EUC) [12] and set up a technical committee for their evaluation (TAB). CORSIA will become operational on 1 January 2021 and is expected to mitigate around 2.5 billion tons of CO2 by 2035 [1].

The programme will be developed in three phases, and although participation in the first two phases is voluntary, the international response has been positive, as shown in Figure 12. At least 77% of the world's air traffic will be inside CORSIA by 2021. In addition, participation in this scheme will be mandatory for all ICAO member countries from 2027[4], with some marginal exceptions for small or less developed countries. Each state will be responsible for monitoring the emissions of airlines flying within its territory and to international destinations. The calculation of the amount of CO_2 to be offset by each airline, shall be based on

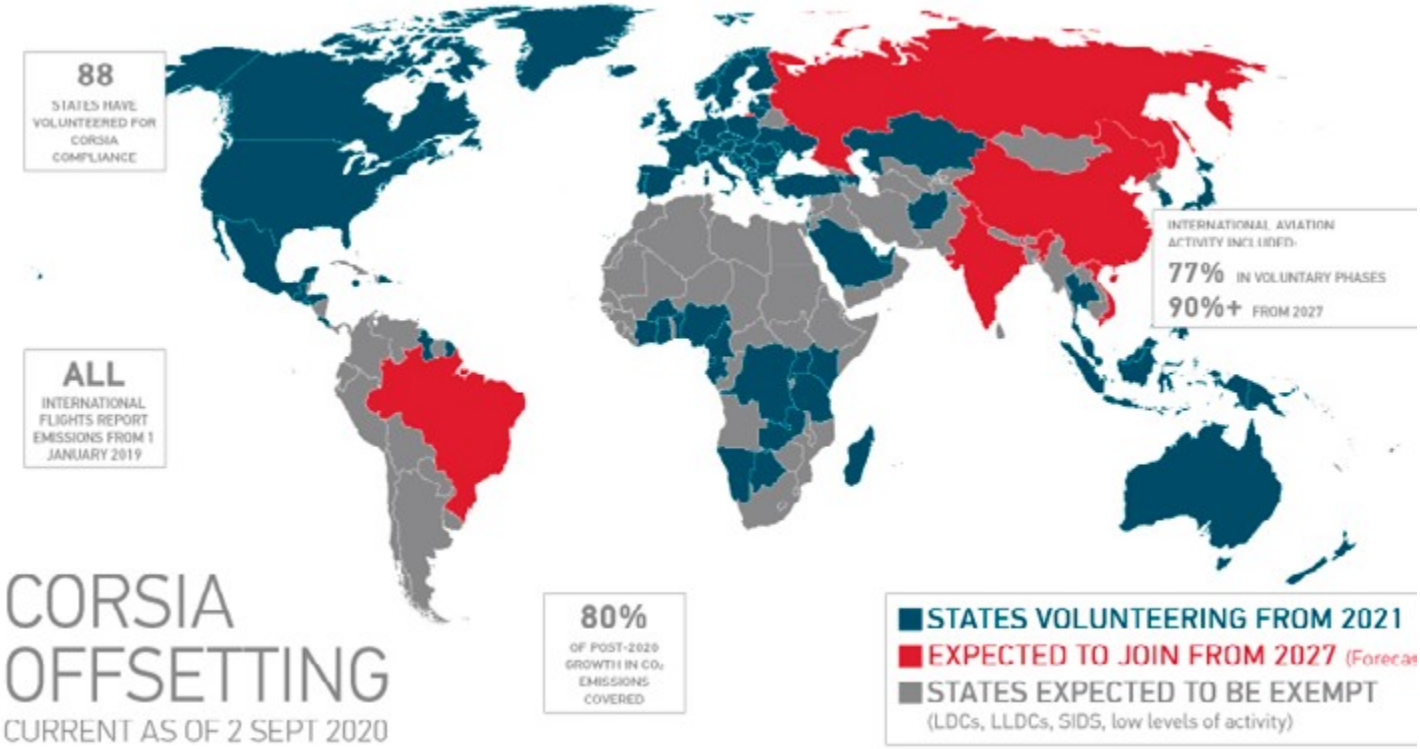


Figure 12. Countries joining CORSIA by stages.

The key to the success of this initiative will undoubtedly be the robustness of its control system, and the ability to ensure that these decarbonization actions are effective. For example, it must be ensured that such reductions would not have occurred if the compensation mechanism had not been mediated.

traffic growth factors, and actual emissions of that airline. This is important because it will encourage the modernization of fleets to avoid such compensation.

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

4 CORSIA has normative status as part of Annex 16 of the Convention on International Civil Aviation (Chicago Convention).

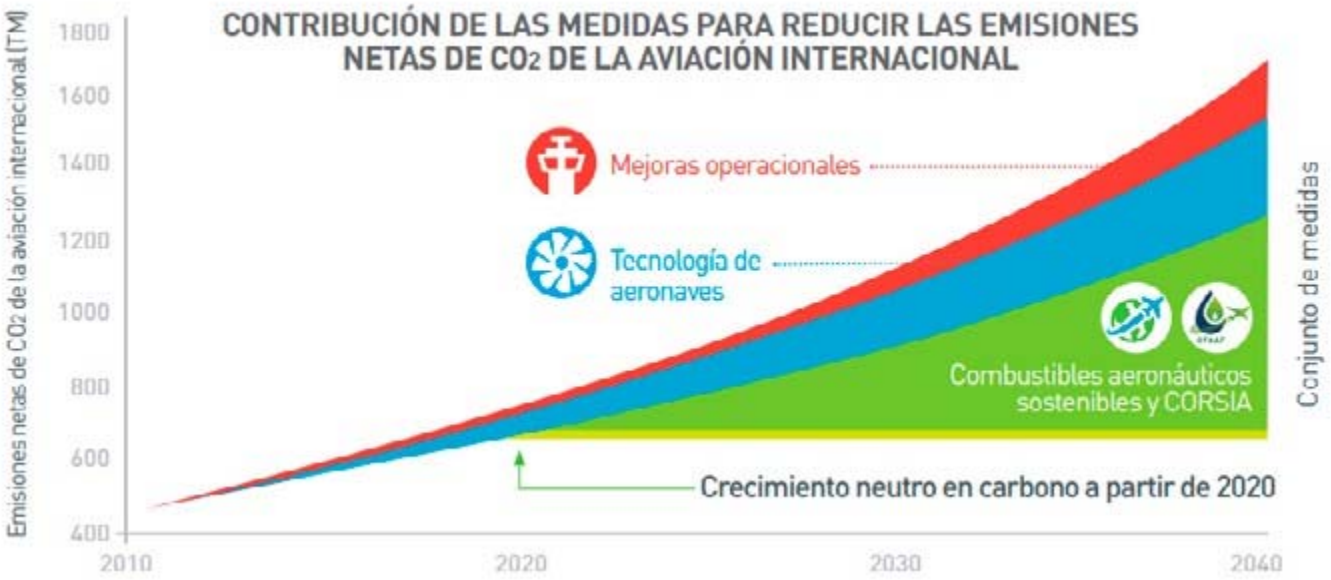


Figure 13. Forecast for CO2-neutral aviation growth from 2020.

Airlines will be required to settle their emissions accounts every three years, participating in the emissions offset market if they exceed their allotted ceilings. In addition, liabilities can be discounted using sustainable fuels which, as we will see below, reduce net CO_2 emissions.

In 2020, and following a process with relevant debate[5], ICAO decided to change the maximum emissions scale from using the average of the years 2019-2020 to considering only the data for 2019. This was justified by the impact of the COVID-19 pandemic on air traffic in 2020, which would distort the calculation of emissions in the face of the anomalous decrease in flights[6].

The main criticisms of this compensation scheme are that it is unlikely to be able to curb the gross increase in CO_2 emissions from aviation, or that it does not include other gases and negative environmental effects.

Alternatively, for example, direct carbon charges could be introduced to effectively reduce the environmental impact of air traffic, and to promote the energy efficiency of aircraft. The experience of the EU ETS, in different sectors, confirms that direct emission reductions can be achieved with these tools, although they need precise design and constant review to ensure their effectiveness.

Finally, it should be remarked that this system is a concrete expression of the airline industry's commitment to curb its net CO2 emissions immediately. CORSIA is the result of cross-cutting public-private partnership within the global commercial aviation sector. This scheme can certainly be improved, but it is a necessary first step, immediately applicable and whose success will be key to the future of civil aviation and the environmental sustainability of the planet.

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

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

Photographic archive

Figure 12.. https://aviationbenefits.org/environmental-efficiency/ climate-action/offsetting-emissions-corsia/corsia/who-volunteers-for-corsia/

Figure 13. https://www.icao.int/environmental-protection/CORSIA/Documents/CORSIA%20Brochure/CorsiaBrochure_SPA-Mar2019_Web.pdf

4.2. Navigation and ground operation

Operations in the context of the aviation sector include:

- Air operations: scheduling process, actual flight, and aircraft maintenance.
- Airport operations: activities at the aerodrome, such as airfield assistance ground, the use of ground-based systems and ground motion management.
- Air Traffic Management (ATM) operations: activities that have a direct impact on aircraft's flight, the traffic flow and the way in which airspace is used.

Operational improvements are a major opportunity to improve the environmental footprint of air transport, and include a wide range of measures aimed at improving the efficiency of aircraft operations, airport operations and air navigation procedures.

Across the world, both airlines and airports, are working hard to reduce their emissions, with major advances such as investments in carbon offsets, the replacement of diesel and gasoline land vehicles with electric alternatives, and even the development of their own renewable fuel sources. Some airports have already reduced their CO_2 emissions from fixed infrastructure by more than 50% since 1990 [8]. Advances in air traffic control are playing a key role in making flights cleaner and greener, because they have the potential to make travel 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 journeys and fewer delays) and consequently, flight costs and aircraft emissions are reduced. The objective of the SES, once completed around 2030-2035, is to triple airspace capacity, reduce ATM costs by 50%, improve safety and reduce the environmental impact of aviation by 10% compared to 2004[1].

In 2014, a Joint Undertaking (SJU) was set up to develop the next generation Single European Sky ATM Research, SESAR, with an extension to 2024, which the EU will contribute €1.5 billion [8].

As a result of these SES and FRA actions, more than 2.6 million tons of CO_2 have been saved since 2014 (approximately 0,5% of total CO_2 emissions from aviation) [8] and CO_2 emissions have remained stable in recent years despite the increase in air traffic, and despite the impossibility of taking optimal or unhindered routes due to adverse weather conditions, avoidance of hazardous areas and other operational constraints. According to an analysis carried out in 2017, the target of not flying more than 2,6% additional distance, which consequently leads to a reduction in flight time, is on track to be achieved due to better planning and a reduction in unnecessary route restrictions, such as military areas.

There is an increasing implementation of FRA (Free Route Airspace), where users are free to plan a route depending on the availability of airspace, encouraging the use of shorter routes and more efficient use of airspace. The proportion of flight time in clear-route airspace during 2017 was 20%, compared to 8,5% in 2014. At the end of 2019, 55 Area Control Centers (ACCs) had already implemented, fully or partially, operations in free-route airspace; and full operations across Europe are expected by 2023/2024 as shown in the figure below.

[1] https://www.europarl.europa.eu/factsheets/en/sheet/133/air-trans-port-single-european-sky

OPERATIONAL IMPROVEMENTS IN AIRPORTS

The airport's operational efficiency influences the average additional time for sequencing and measurement of arrivals (ASMA zone) or the average additional running time per departure.

To improve this efficiency, they have implemented arrival and departure management systems (AMAN) that, 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.

In this sense, there are several operational measures that can be used to reduce emissions around an airport.

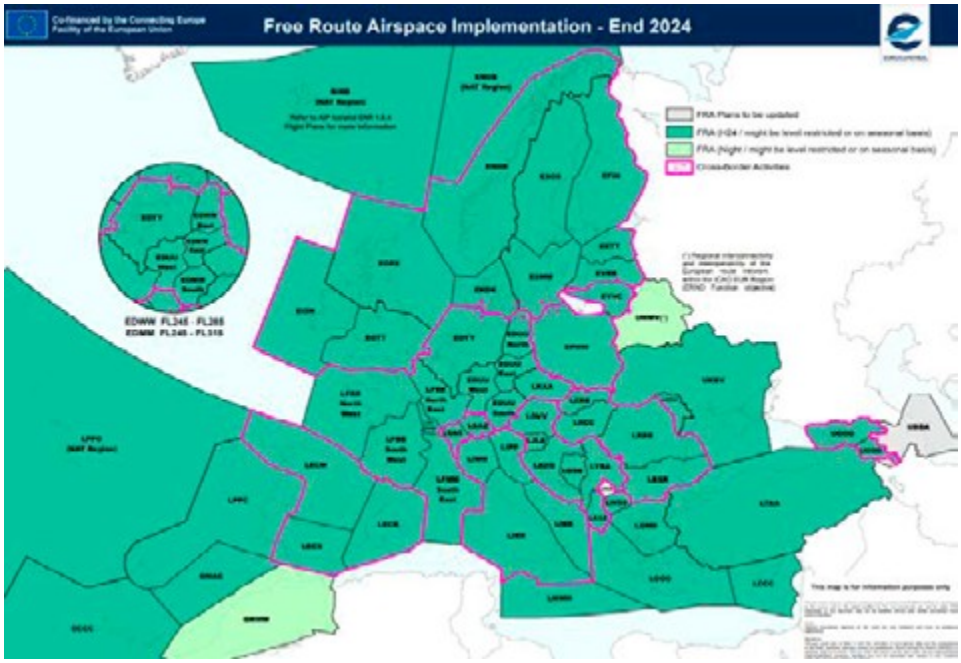


Figure 14. Implementation of FRA operations in Europe.

Table 1 describes some of those concerning, the airport design and facilities.

Action	Description	Result
Airport design	• Provide efficient track, taxiway, and platform design.	• Minimizes overload and congestion. • Facilitates more efficient earth movements through improved infrastructure. • (Design of the runway, location, and design of the fast-start runway, etc.).
Airport facilities	• Provide 400 Hz fixed ground power and, if required, pre-conditioning air at doors/maintenance areas. • Improve low visibility take-off and landing capabilities, supported by surface guidance and motion control systems, when required.	• Reduce or eliminate the use of APU, GPU and air conditioning equipment. • Reduce congestion and delay in bad weather, and may reduce the need for diversions to other aerodromes.

Table 1. Airport characteristics that minimize fuel consumption and emissions. [13]

There are many operational measures to reduce aircraft emissions in the environment of an airport, but on the other hand, there are operational noise abatement measures implemented at some airports which may lead to an increase in fuel consumption and therefore in emissions, such as:

- Noise abatement procedures and shared noise regimes, that increase distances travelled.
- Preferential runways that require additional flight time or ground movement (taxi).
- Noise fires that cause changes in operational procedures, reducing efficiency.
- Time restrictions that cause congestion on arrivals or departures, and lead to additional flight time, delays and restrictions, etc.
- To achieve the 2035 goals, several operational initiatives are under way.

OPERATIONAL IMPROVEMENTS IN AIR TRANSIT MANAGEMENT (ATM)

In 2015, harmonized definitions, metrics, and parameters for measuring continuous ascent operations (CCO) and descent operations (CDO) were agreed by an ATM group, including definitions of "CCO/CDO noise" and "CCO/CDO fuel." In 2017, a European-wide study of the actual implementation of CCO/CDO was carried out, in which fuel consumption, CO_2 and financial impact were measured and estimated. The results obtained indicate [8]:

- More potential to reduce noise and fuel in the CDO compared to the CCO, and the improvements achieved in noise will be smaller than in fuel, and therefore, in emissions.
- This ability to perform CCO / CDO operations is also linked to the complexity of the airspace, rather than to the capacity of the airport.
- A typical flight with levelled segments could benefit on average CO_2 savings of up to 48 kg for a CCO, and 145 kg for a CDO. The potential CO_2 benefits of CDO optimization across Europe were estimated to be ten times greater than those of CCO optimization.
- Much lower potential to optimize CCO/CDO noise compared to CCO/CDO fuel. Recognizing that the optimization of environmental benefits depends on local conditions.
- The implementation of CDO should be focused on optimizing the flight profile from the top of the descent.

With these operations, the total potential savings in Europe are up to 350,000 tons of fuel, equivalent to 1.1 million tons 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 a variety of reasons, such as safety (i. e. separation of time or distance), weather, or capacity [12].

Airport Collaborative Decision Making, A-CDM, is another ATM operational measure that aims to improve, both air traffic management and capacity management 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 timeliness 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 the resources.
- Airport: improved punctuality, and more efficient use of stationary resources.
- Air Traffic Control: optimization the use of the air side, reduction of congestion.
- CFMU: greater compliance with slots, optimization the use of airspace capacity.

The implementation of A-CDM allows a reduced shooting time, on average, of 1 to 3 minutes per departure. A further 17 airports have implemented A-CDM since 2016, representing more than 40,9% of European departures operating from an A-CDM airport.

The 2016 A-CDM impact assessment report, identified the savings generated from 13 of the 17 A-CDM airports, demonstrating tangible improvements in taxi time performance that translates into some 108,072 tons of CO_2 emissions.

The table below describes procedures that reduce the environmental impact, as well as the results obtained according to the operation.

Action	Operation	Result
Aircraft procedure.	• Continuous Descent Operations (CDOs). • Continuous Climb Operations (CCOs).	• Descending with low-power engines, reduces fuel consumption and noise below the flight path, but may be dependent on airspace management and capacity restrictions. • Continuous climb to avoid the need for levelled flights at low altitudes reduces fuel consumption and noise below the flight path but may be dependent on airspace management and capacity issues.
Pilot's discretionary actions.	• Minimizing the use of reverse thrust on landing. • Rolling without motor.	• The pilot must retain full authority over the safe operation of the aircraft.
Other procedures.	• Reduce engines period running at idle regime. • Aircraft towing.	• HC and CO emissions are higher during idling. Reducing this phase may also result in a decrease in engine operation. • Aircraft towing can significantly reduce the use of aircraft engines. Logistical problems may occur at airports with limited maneuvering areas.

Table 2. Operational opportunities to minimize fuel consumption and aircraft emissions at airports (3)

Other operational initiatives, which environmental benefits are expected, are shown in the table below [15]:

SESAR solutions	Environmental benefits
AMAN extended (E-AMAN). E-AMAN enables the sequencing of incoming traffic much earlier than is currently done by extending the AMAN horizon, and thus allowing a smoother traffic management	Reduced fuel consumption due to reduced vectorization to lower levels, reduced holding time, and the maintenance of more efficient flight levels for longer periods.
Improve terminal airspace using RNP operations. This allows that the aircraft follow precise flight paths, to reduce the distance travelled, and avoid noise-sensitive areas.	It reduces fuel consumption and noise.
Departure management synchronized with the previous departure sequence. Pre-departure management provides optimal traffic flow to the track, considering accurate taxi time forecasts, and data-driven route planning.	It reduces waiting times, saves fuel, and enables efficient air navigation service.
Departure management by integrating surface management restrictions. The solution integrates surface and route planning functions, to build a highly accurate departure sequence, considering tactical changes.	Reduced fuel consumption and emissions.
Time-based separation for final approach. Current distance separations replaced by time intervals, to adapt to climatic conditions, and maintain the ability to approach the runway.	Reduced fuel consumption due to reduced waiting time in the air.
Automatic Controller Assistance for planning surface movements and routes. Route planning functionality allows controllers to edit routes graphically, and automatically calculate estimated run-in times, contributing to more predictable surface operations.	Improved running-in times, resulting in lower fuel consumption.
Development of new GPS receiver and Data transmitter, known as ADS-88. Currently, air traffic controllers use radar data to help planes land or take off, GPS helps to create more efficient flight patterns.	It saves fuel and improves on-time arrivals, reduces unnecessary emissions when an aircraft is waiting to operate on the runway.

Table 2. Operational opportunities to minimize fuel consumption and aircraft emissions at airports (3)

In Spain, ENAIRE and Aena have a sustainability strategy as part of their corporate social commitment; the former as the main provider of air navigation and aeronautical information services, and the latter as the first airport operator to manage Spanish public airports and helipads.

ENAIRE is pioneering the integration and exchange of data in the "Network Manager", contributing to the improvement of the efficiency, capacity and safety of airspace through the use of new technologies, and continuous innovation through the development of its own tools that exchange information with EUROCONTROL, and other suppliers: "Flow tools", a multidisciplinary set of applications for problem solving; Perseo-Emissions, which allows the calculation of the numerous emissions (CO2, NOX, SOX, etc.) produced by air traffic in Spain; or the application to monitor points on an airway, where air traffic controllers offer pilots the possibility of more direct routes, identifying the points where such direct routes are provided, and calculating the distance savings achieved, compared to the route planned in the original flight. During 2018, this tool has allowed airlines to save 7 million nautical miles, thanks to the direct flights authorized in Spanish airspace, thus avoiding the issuance of 243,000 tons of CO_2 to the atmosphere, and fuel saving to airlines[2].

In addition, ENAIRE has facilitated the implementation of continuous slope-down operations at Spanish airports, has designed more precise procedures to minimize noise, and has implemented an integrated management system, that helps ensure the protection and conservation of biodiversity, with all energy consumed by ENAIRE, coming from renewable sources in 2015[3].

On the one hand, Aena has implemented energy efficiency measures in its facilities that reduce electricity consumption, while increasing self-sufficiency in energy from renewable sources. On the other hand, it has set up actions to reduce fuel emissions and collaborate with others, carrying out the characterization, control, monitoring, and correction of air emissions generated and monitoring noise as a cause of its activity by including some of its airports in the ACA program[4]. Examples of these measures are the implementation of A-CDM, the replacement of APUs by 400 Hz power supply on the runway and ground support vehicles (GSE) with alternative or eco-clean technology, the promotion of the use of sustainable fuels and the installation of solar power systems, cogeneration plants and wind turbines in their facilities, etc. Currently, 100% of gateway parking lots are already equipped with these systems and new sockets are planned, as well as old equipment replacement. In 2030, airports will have 470.400 Hz power supply points for aircraft, and the target is to have 152 electric vehicle charging points at airports, in public areas on the Aena network [16].

In addition, Aena carries out the environmental assessment of its projects (EIA) in accordance with the Environmental Assessment Act 21/2013, of 9 December, considering the environmental variable in decision making for the implementation of projects, and carrying out Acoustic Isolation Plans (PAA).

All these actions are in line with the commitment made in 2019 to join the NetZero2050 initiative of IAC Europe (International Airports Council), which is to achieve zero net carbon emissions at airports by 2050, and without including offsetting mechanisms.

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

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

4 The Airport Carbon Accreditation (ACA) program is a certification awarded by the International Airports Council (IAC 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 CO_2 emissions, with the goal of achieving carbon neutrality.

Photographic Archive

Figure 14.https://www.eurocontrol.int/sites/default/files/202004/eurocontrol-fra-implementation-end-2024-v7-30042020.pdf

4.3. Gradual and design efficiency improvements

4.3.1. Technology development programmes

In pursuit of this technological progress towards sustainability, the aeronautical industry has made high investments in R & D (15% of turnover in 1999[1], €19 billion in Europe and 4 times more in the USA[2]), with private initiatives and public support, mainly NASA, the aeronautical industry in the USA and Europe, with aeronautical activities carried out under the R & D Framework Programmes of the European Union.

R & D PROGRAMMES IN EUROPE CONCERNING THE ENVIRONMENTAL IMPACT OF AERONAUTICAL - CLEAN SKY

In Europe, a public-private EU-industry Joint Technology Initiative (JTI), Clean Sky, part of the European Union's 7th Framework Program for Research, Technological Development and Demonstration (2007-2013) was developed and funded with €1.6 billion, 50% of which, is provided by European industry. As a priority objective, which is based on the ACARE Strategic Research Agenda, the introduction of new technologies for the achievement of more environmentally friendly aircraft has been set, and all necessary steps have been taken to significantly reduce the impact of air transport on the environment. Through this program, six technological demonstrators were carried out, from which various developments will be obtained and will be monitored in an integrated manner within the Technology Evaluator, which will analyze the viability of the technologies developed.

Technology Evaluator

ITD	Smart Fixed Wing Aircraft	Green Regional	Green Rotorcraft	Sustainable & Green Engines	Systems for Green Operations	Eco Design
Activities	Active Wing New Aircraft Configurations	Advanced Aerodynamics (Low Drag & Noise) Low Weight Structures	New Powerplants Innovative Blades & Rotors New Aircraft Configurations	Advanced LP & HP System Technology New Engine Concepts (i.e. Open Rotor)	Mission & Trajectory Management Aircraft Energy Management	Whole Life Cycle Environmental Impact Analysis
Targets	CO_2 ~12 to 20% Noise ~10dB	CO_2 ~10 to 20% Noise ~10dB	CO_2 ~26 to 40% NO_x ~53 to 65% Noise ~10dB	CO_2 ~15 to 20% NO_x ~15 to 40% Noise ~15dB	CO_2 ~10 to 15% Noise ~17dB	CO_2 ~10% Noise ~10dB
Products	Widebody 2020 CO_2 -30% NOx -30% Noise -20dB	Narrowbody 2015 CO_2 -20% NOx -20% Noise -15dB	Regional 2020 CO_2 -40% NOx -40% Noise -20dB	Corporate 2020 CO_2 -30% NOx -30% Noise -10dB	Rotorcraft 2020 CO_2 -30% NOx -60% Noise -10dB	

Figure 15. Activities and Objectives of Technology Demonstrators in Clean Sky. [17]

[1] https://www.aero.upm.es/departamentos/economia/investiga/informe/consolidacion%20europea.pdf
[2] https://www.asd-europe.org/sites/default/files/atoms/files/ASD%202019%20Facts%20and%20Figures.pdf

The technological demonstrators were: Green Regional Aircraft (GRA), ECO design (ECO), Sustainable And Green Engines (SAGE), System Fixed Wing Intelligent Aircraft (SFWA), Systems for Green Operations (SGO) and Green RotorCraft (GRC).

Example of demonstrators[3]: replace the aluminum part of the fuselage with composite material, replace hydraulic or pneumatic power with electric power, test different vehicles with 1-axis, open rotor, or gear configurations, integrate passive, active or load control technologies into SFWconcepts, etc.

Figure 15 shows the details of the environmental objectives set in the different Integrated Technology Demonstrators.

In May 2014, the Council of the European Union agreed to extend the Clean Sky JTI (Clean Sky 2[4]), which would build on the achievements of Clean Sky 1, and its mission was to develop breakthrough technologies that would significantly reduce the environmental impact of aircraft and, more generally, air transport, resulting in lower noise and more fuel-efficient aircraft. Its funding was 4 billion euros.

Technological innovations in this program were grouped into large passenger aircraft, regional aircraft, fast IADP rotorcraft, aircraft structure, engines, systems, small air transport and eco-design, such as technology to integrate open rotor designs, boundary layer ingestion technologies, advanced aircraft rear design, Ultra Flight Test Demonstration Fan, active flow control for UHBR motor integration, natural and hybrid laminar flow control, etc.

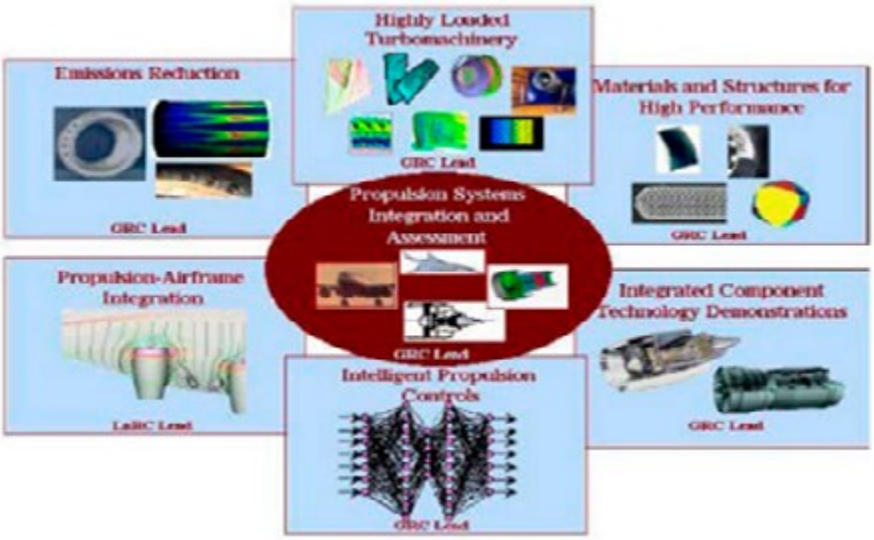
Clean Sky is working on several projects in tackling the environmental challenges related to engines and aerodynamics, one of the integrated technology demonstrators was Sustainable And Green Engines (SAGE), whose activities focused on advanced high-pressure and low-pressure systems technology, and on new engine concepts such as Sage2 Counter-Rotating Open Rotor (CROR), Ultrafan, and the BLADE aerodynamic demonstrator, among others.

In reference [18] you can find the progress of the program to date (last report of 2019), and Figure 10 shows the objectives of the Clean Sky together with the objectives of ACARE 2020 and Flightpath 2050.

US R & D PROGRAMMES RELATING TO THE ENVIRONMENTAL IMPACT OF AERONAUTICS

In the period between the 1990s and the first half of the 2000s, NASA developed in collaboration with other organizations the AST (Advanced Subsonic Technology)[5] and UEET (Ultra-Efficient Engine Technology Program) programs [19]. AST, with the aim of developing technologies of great impetus to ensure the competitiveness of US civil transport aircraft, and the search for new ways to improve the safety, productivity, and environmental acceptability of the national air transport system. UEET was divided into six major projects dedicated to the development and transmission of

Figura 16. Esquema del programa UEET. [17]



revolutionary propulsion technologies, that would enable future generation of vehicles at a wide range of flight speeds.

At AST, progress was made such as: a combustion chamber that reduced NOX by 50% in the testing of the PW4000 engine followed by P&W certification and product implementation. Another camera concept, the TAPS (Twin Annular Premixing Swirler), demonstrated a 62% NOX reduction in GE-Snecma's CFM56 engine.

Other Rolls-Royce combustion components also demonstrated the potential to achieve a 50% NOX

3 https://www.cleansky.eu/node/45
4 https://www.cleansky.eu/

5 https://er.jsc.nasa.gov/seh/pg36s95.html#:~:text=Therefore%2C%20NASA%2C%20other%20government%20agencies,ways%20to%20enhance%20the%20safety%2C

reduction without adverse effects on CO and UHC. UEET, specifically for engine technologies, was divided into six major projects, together with potential CO2 and NOX emission reductions, the latter for the LTO cycle [20].

In 2006, NASA, based on the technology it had developed at AST and UEET, established the Fundamental Aeronautics Program (FAP) to develop advanced propulsion technologies within five to fifteen years, also known as Generation N+1 to N+2 and for Generation N+3, or beyond 2025. Four different projects were created, subsonic rotary (SRW), supersonic, hypersonic, and fixed wing Subsonic (SFW) [21]. Subsequently, NASA established the Integrated Systems Research Program (ISRP) to carry out large-scale system demonstrations of technologies developed under SFW. The Environmentally Responsible Aviation project (ERA) [22] was also created in 2009 to develop such demonstrations of integrated systems in the period 2020-2025, or N+2 generation of aircraft systems.

The ERA project ended in 2015 and focused on exploring and documenting the viability, benefits, and technical risk of 8 major structural, aerodynamic and engine technologies:

- Small integrated nozzles that blow air over the surface of an aircraft's vertical stabilizer, showed that the aircraft of the future could be safely designed with smaller tails, reducing weight and strength.
- New process to join large sections of composite materials to create damage-tolerant structures to create aircraft structures 20% lighter.
- New and radical wing technology that allows the extension of the flaps without leaving spaces that increase noise and induce resistance.
- With GE, redesign of the compressor stage of a turbine engine to improve its aerodynamic efficiency, which could result in a 2,5 percent savings in fuel consumption.
- With Pratt & Whitney, an advanced fan design to improve propulsion efficiency and reduce noise, reducing fuel consumption by 15 percent and significantly improving noise.
- With Pratt & Whitney, on an improved design for the combustion chamber of a jet engine to reduce NOX, and it was possible to reduce emissions by about 80%.
- New design tools were developed to help engineers, reducing the noise of deployed wing, 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 seamless line, and jet engines are mounted on top of the aircraft at the rear, fuel consumption is minimized, and noise is reduced.

In addition, 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 FAA's main environmental effort to accelerate the development of new aircraft and engine technologies, advance the use of alternative fuels and achieve the modernization of the United States air transportation system to make flying even safer, more efficient, and more predictable and at the same time, make up the Next Generation Air Transportation System or Nextgen. In this program, the technologies addressed were related to revolutionary engine designs, wing technologies, flight management system improvements, improved combustion chambers and fuselage redesign.

The design of the Nextgen aircraft is based on previous projects such as ERA or the N+3 designs mentioned above, and on new projects such as: electric and hybrid propulsion, small-core gas turbine, Truss Transonic Wing Braced (TTWB) and increased use of composite materials, which will be discussed in more detail below, although electric and hybrid propulsion will be dealt with in Chapter 4.5.

As it has been said throughout the report, to make aviation more sustainable, it is necessary to reduce its environmental impact and, above all, its impact on climate change. To achieve this, greenhouse emissions must be reduced (CO_2 is the most important contributor), and for this, the amount of fuel burned, or sustainable fuels must be used. To reduce this amount of fuel burned, aircraft must be moved more easily and with the lowest possible energy, i. e. aircraft must be more efficient, lighter, and more aerodynamic. Therefore, to make aircraft more sustainable, technologies focused on propulsion, aerodynamics, and weight must be developed.

CLEEN Phase I Benefits:

Demonstrated technologies that reduce noise, emissions and fuel burn

Boeing

Adaptive Trailing Edge
~ 2% fuel burn reduction
~ 1.7 EPNdB cum in some single and twin aisles

CMC Acoustic Nozzle
~ 1% fuel burn reduction
~2.3 EPNdB cumulative noise margin to Stage 4

Honeywell

Fuel Burn Technologies
CLEEN technologies contributed to ~5% fuel burn reduction as part of a 15.7% fuel burn reduction engine package

Pratt & Whitney

Geared Turbofan Technologies
CLEEN techs expand design space for engine with ~ 20% fuel burn reduction, > 20 EPNdB cumulative noise margin to Stage 4

For more information: http://www.faa.gov/go/cleen

General Electric

TAPS II Combustor (entered fleet in 2016)
> 60% margin to CAEP/6 LTO NOx was achieved

FMS/Engine and FMS/ATM Integration (Entered into service - LEAP engine on B737MAX, Airbus A320 Neo aircraft, and GE9X engine on 777X)
0.7-1.0% fuel burn reduction

Open Rotor
~26% reduction in fuel burn (re: 737-800)
~15-17EPNdB cumulative noise margin to Stage 4

Rolls Royce

Ceramic Matrix Composite Turbine Blade Track
CMC blade tracks offer > 50% reduction in cooling flow and component weight.

Rolls-Royce – Dual Wall Turbine Airfoil
Dual Wall turbine airfoils provide > 20% reduction in cooling flow and increased operating temperature capability.

CLEEN tech will provide ~1% fuel burn reduction

Figure 17. Demonstrated fuel, emissions, and noise abatement technologies. [23]

Technology & Emissions Reduction

- Visible smoke emissions have been eliminated

DC-8, 1958

Boeing 787, 2012

- 50% reduction in CAEP Nitrogen Oxides (NOx) emissions standard since 1995
- CLEEN Program - Low NO_X Combustors
  - GE TAPS II Combustor,
    LTO Nox: 55% below most recent CAEP std
    PM: 90% below CAEP visibility smoke limit
  - CLEEN II combustor development ongoing with GE, Honeywell, RR

Figure 18. Evolution of Emission Reduction Technology. [23]

4.3.2. Propulsion

REDUCTION OF SPECIFIC FUEL CONSUMPTION (SFC).

Reducing SFC requires increasing the thermal and/or propulsive performance values for a given flight speed and fuel type.

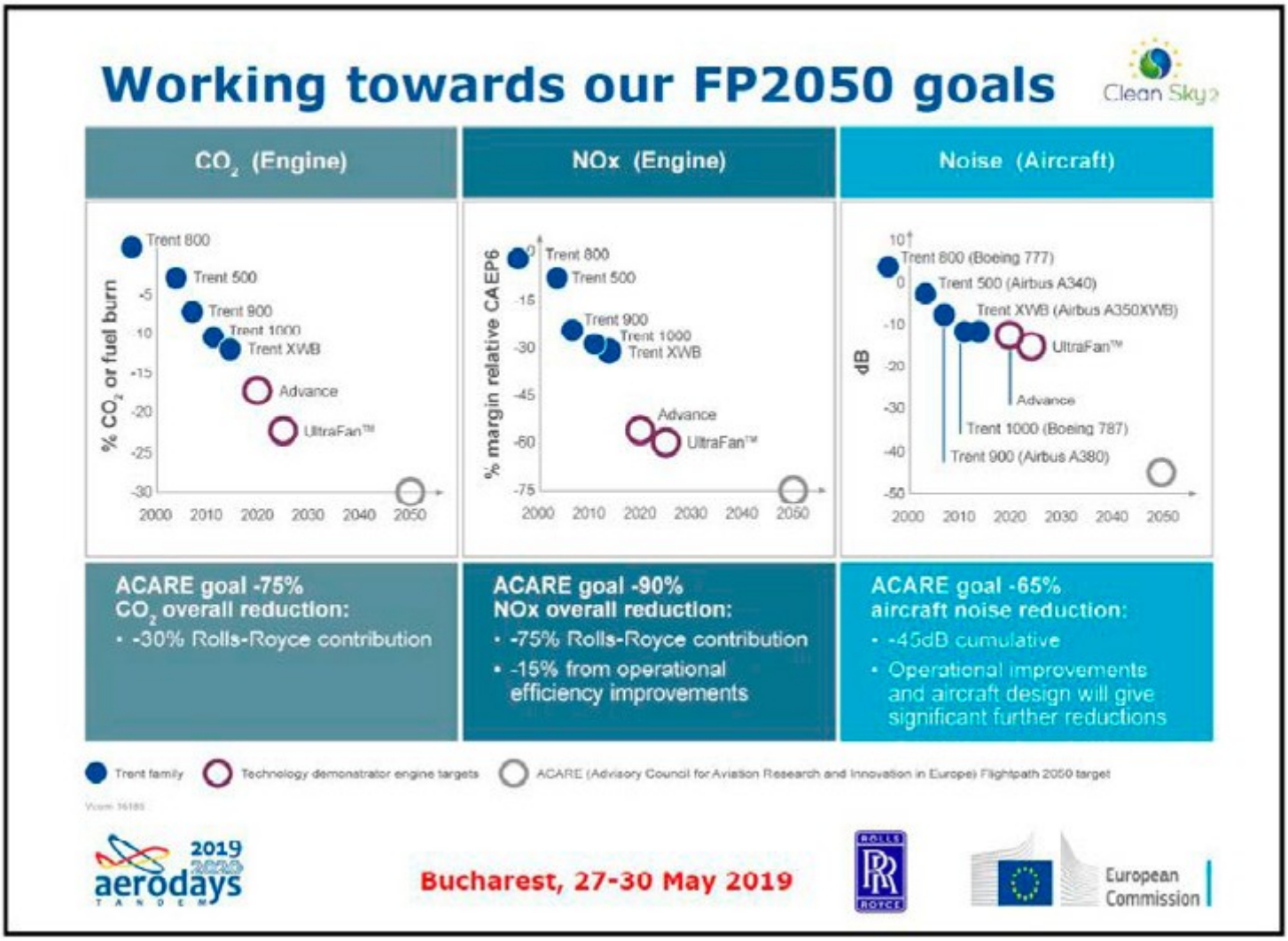


Figure 19. Evolution of an engine family vis-a-vis the objectives of ACARE 2050.

In the case of a turbofan, the thermal performance is largely determined by the overall pressure ratio (OPR), the turbine entrance temperature (TET) and the performance of the individual components (compressors, turbines and combustion chambers). Component efficiency levels have a direct impact on fuel consumption, and significant progress has been made over the past 30 years, with almost all turbofan components achieving polytropic efficiency levels of more than 90%, thanks to the development of accurate design CFD codes. Control of secondary flows through the mechanical will provide increases in component performance, but performance improvements occur when TET and OPR are increased together.

Currently, in order to reduce specific fuel consumption, three engine configurations are considered: direct drive engines (Direct Drive Turbofan, DDTF), engines with reducer gearbox (Geared Turbofan, GTF) and open rotor engines (Open Rotor):

DIRECT DRIVE MOTORS (DIRECT DRIVE TURBOFAN, DDTF).

They constitute the conventional approach, where the compressor and core components rotate on the same axis and operate at the same rotational speed; therefore, the system is constrained by the component with the lowest speed, which is the compressor, so that the core must operate at slower and less efficient speeds. High performance and low weight technologies have been developed that offer an optimization between fan and turbine requirements, reaching high performance. In the figure below, the evolution of the environmental performance of the Trent engine family (Trent XWB models - eXtra Wide Body - that equips the A350 and with the new Advance and Ultra-Fan developments, the latter within Clean Sky 2) in relation to ACARE's 2050 targets is shown.

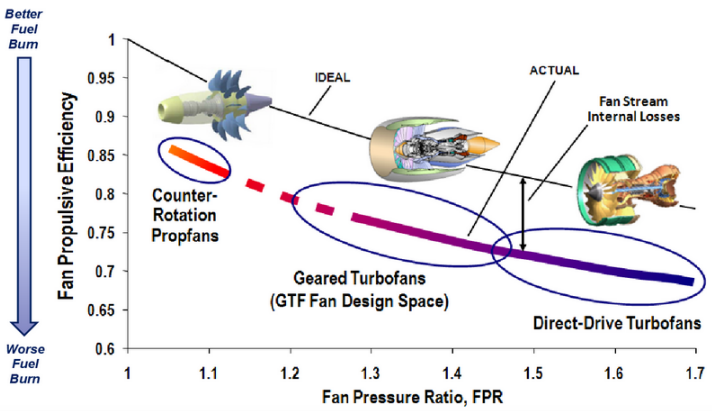


Figure 20. Tendency in fan propulsion efficiency vs. its pressure ratio. [25]

The first generation of GTF in the US, was developed by Pratt & Whitney (P&W) in collaboration with NASA, and is considered an N+1 technology. Technology areas investigated included low-speed, low-pressure ratio fan, fan gear system, low-emission combustion chamber; and low-pressure, high-speed, compact axle. These technologies allowed the engine's BPR (bypass ratio) to reach the Ultra High Bypass (UHB) ratio range of 12 or more, while reducing FPR[6] between 1. 3 and 1. 4 to achieve greater fan efficiency.

Once a maximum profit point is reached for this level of technology, as design BPR continues to increase and RPF declines, a second technology paradigm shift will be needed to extend the beneficial fuel consumption trend line. NASA and P&W are researching, a second generation of GTF propellant technologies, to help achieve these goals, reaching a BPR of up to 18 and an FPR of 1,25-1,3. The figure below shows the projection of the fuel economy benefit that the second generation of GTF will provide, a reduction of 25-30% compared to the current one, achieved by combining the DDTF V2500 with the A320.

In Europe, engine manufacturers set up a plan during the 5th, 6th, and 7th Framework Programmes with various projects, and subsequently in the Clean Sky program, for the development of technologies to facilitate the design and manufacture of new engines that are more efficient and have less environmental impact:

Project VITAL (enVIronmenTALly friendly aero engines, 2009) has investigated several new technologies for the low engine pressure system, to facilitate the development of lightweight 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; GTF, by MTU; and CRTF, by Snecma. The DDTF architecture offers an optimized compromise between fan and turbine requirements considering the low-weight technologies introduced by the program.

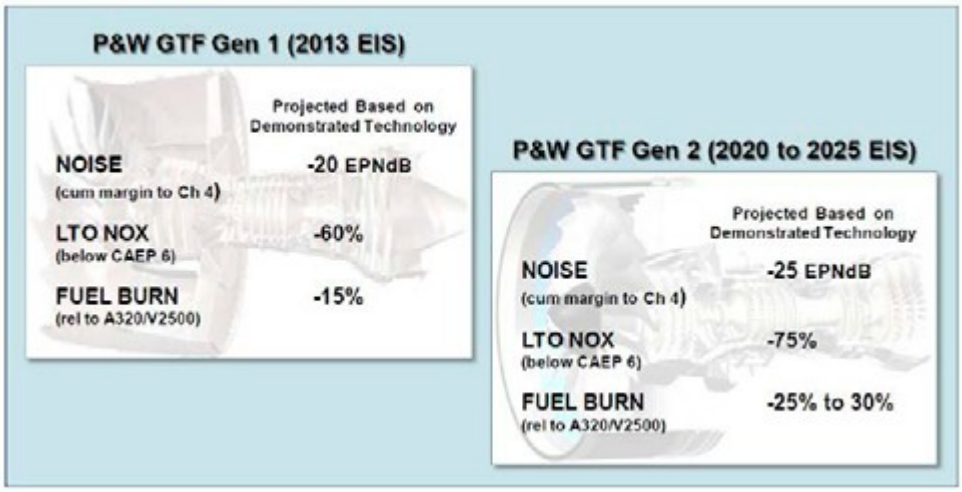


Figure21. Projections of fuel consumption reductions and other environmental impacts with the P&W, GTF engine cycle. [24]

6 Fan Pressure Ratio.

The GTF combines a compressor with a gear reducer train, to allow different rotation speeds for the fan on one side, and the booster and turbine on the other. The CRTF offers a configuration with two fans rotating in opposite directions, allowing lower rotation speeds, since the two fans split the loads involved.

Technologies being incorporated into these engines include, but are not limited to:

- New fan concepts with emphasis on counter-rotators and lightweight.
- Polymeric composites and advances in metallic materials.
- Saving weight of the low-pressure turbine through the design of ultra-high support, ultra-high step load, and lightweight materials.
- Technologies for light and low-strength installation of HBR motors related to nozzle, gondola and thrust inverter (reverse).

OPEN ROTOR MOTORS.

The design is intended to offer the speed and performance of a turbofan, with the fuel economy of a turbo propeller. In the mid-1980s, NASA, in partnership with several US engine industries, researched this new radical propulsion technology and re-emerged under the 7th Framework Program in the DREAM (valiDation of Radical Engine Architecture systeMs, 2011) and Clean Sky.

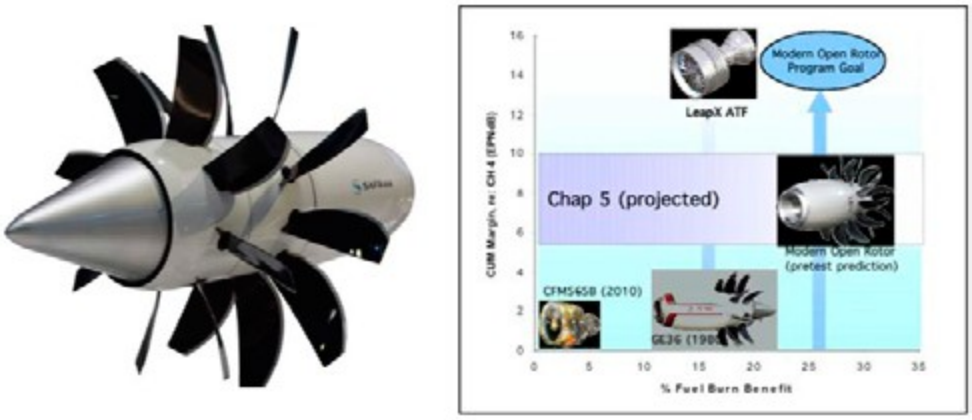


Figure 22. Benefits of the performance of Open Rotor Technology compared to current turbofans.

SAGE2 COUNTER-ROTATING OPEN ROTOR (CROR).

In 2017, the Sage2 CROR successfully demonstrated new technologies including composite propeller blades, pass control system, reverse-rotation reduction gearbox and aeroacoustics optimization at SAFRAN's test facilities, confirming the technical feasibility of a CROR, with an expectation of improved fuel consumption (-30% compared to 2000) and capacity to meet the current noise requirements of ICAO[7] Chapter 14.

ULTRAFAN.

It is being developed by Rolls-Royce and allows the compressor and turbine to be optimized independently by introducing a power transmission capable of operating up to 100.1 HP to provide much better propulsion efficiency. It will achieve a 25% improvement in fuel efficiency compared to the first Trent engine, and is being designed to meet the stringent potential noise and emissions levels for aircraft entering service before 2030.

ENGINE CORE TECHNOLOGIES.

In the area of the turbo core mechanical the emphasis, within NASA's projects to reduce fuel consumption, is on increasing the power density of the engine core, resulting in smaller units for a given thrust requirement. Increasing the overall pressure ratio of the core compression system (OPR), while maintaining or improving aerodynamic efficiency, is one of the areas of focus. Another area is, increasing the turbine entrance temperature (TET) to allow greater thermal performance.

Figure 23.

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

Higher OPR and TET pose difficult challenges that require a combination of advanced aerodynamic component design, higher-temperature, higher-strength materials, and advanced computational techniques.

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.

Figures 24 and 25 show the main technologies under development in these two strategy areas.

The introduction of Ceramic Matrix Composite materials (CMCs) has opened up opportunities for revolutionary changes in the design and operation of the propulsion system, due to its lower density and higher temperature capacity, compared to metallic components. They offer multiple benefits, such as weight savings, better efficiency and thrust, and lower specific fuel consumption. Figure 26 shows areas within a typical engine core where CMC technology can be applied, as well as design characteristics and potential benefits for the engine.

New core configurations have been developed through heat management (intercooler, cooling air cooler, recuperator), enhanced combustion, active systems, and others to significantly reduce CO_2 and NOX emissions: NEWAC (New Aero Engine Core Concepts, 2006-2011) project of the 6th Framework Program. NEWAC complemented other projects in this field, e. g. EEFAE in FP5 and VITAL in FP6.

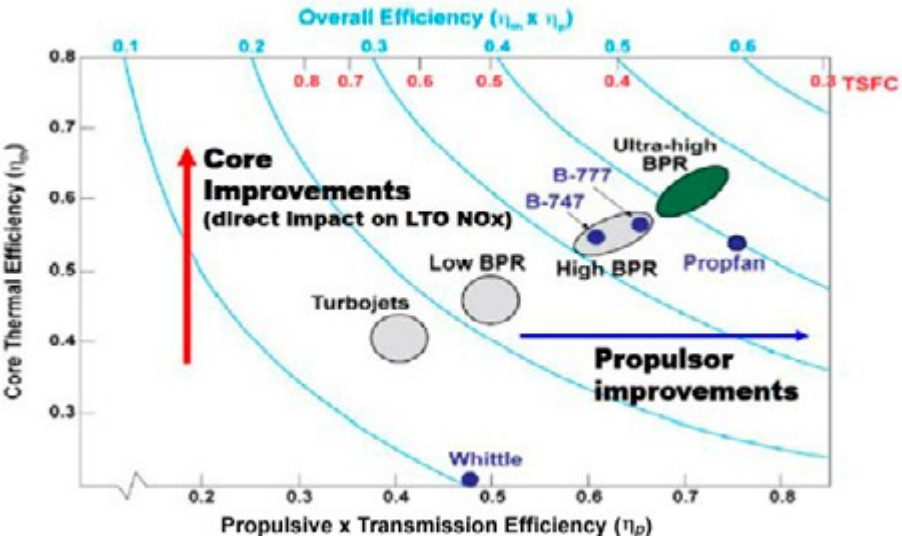


Figure 24. Performance trends with propellant and core improvements. [25]

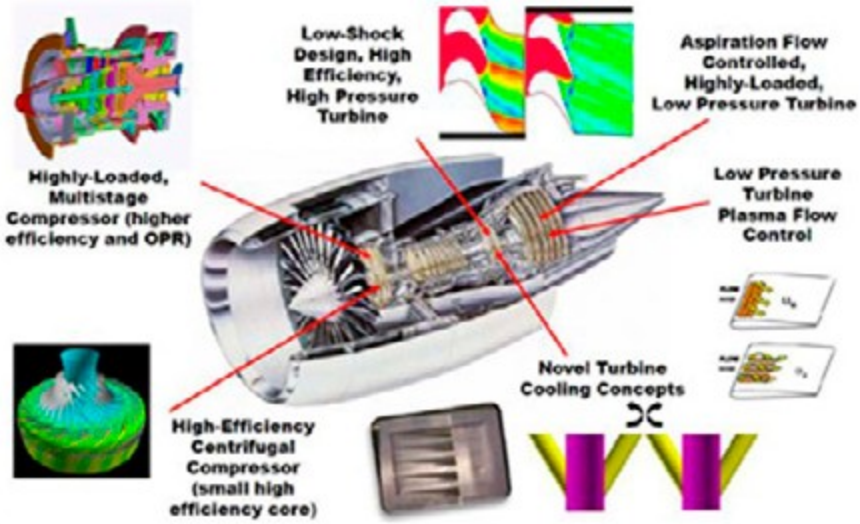


Figure 25. Technologies based on aerodynamic core design for advanced engines [25].

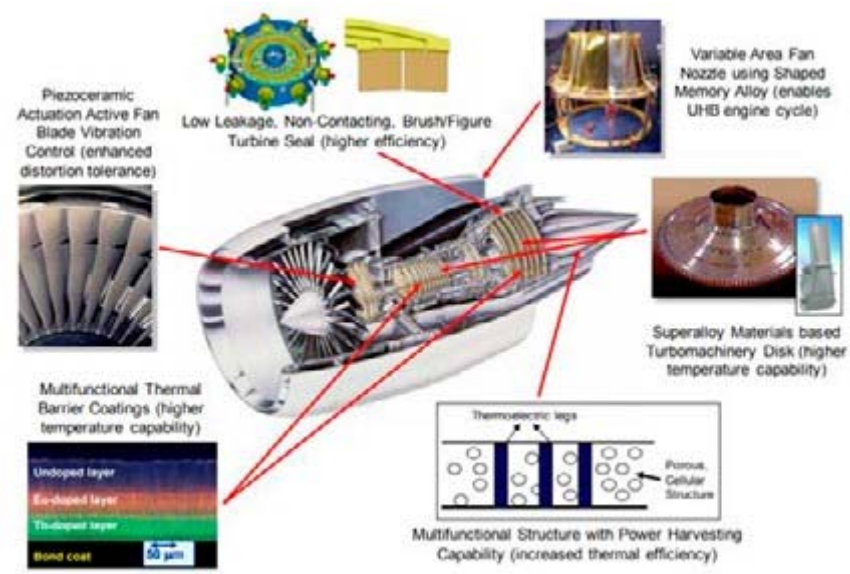
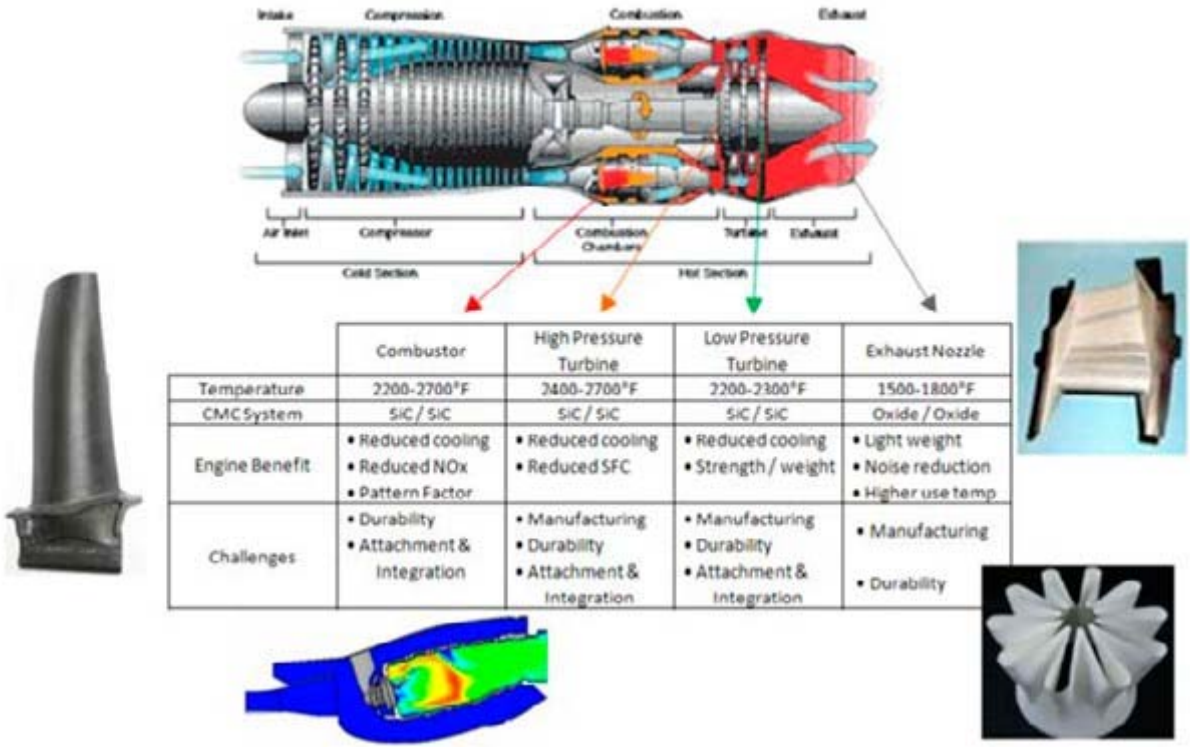


Figure 26. Technologies based on core materials for advanced engines [24].

The new core configuration proposals, dealt with in NEWAC, are four, each for a different type of turbofan:



	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 27. Applications for CMC materials in engine components and potential benefits. [20]

- Intercooled recuperative core for the Intercooled Recuperative Aeroengine (IRA), concept operated at low OPR, and using a Low Pre-mixed Pre-Vaporized (LPP) combustion chamber concept.
- Intercooled core for a high OPR engine concept based on a 3-axis DDTF with a Low Direct Injection (LDI) combustion chamber.
- Active core with active systems applicable to a GTF with average OPR, using a Partial Evaporation and Rapid Mixing (PERM) chamber.
- Controlled flow core for the Counter-Rotating TurboFan (CRTF) at average OPR, using a PERM or LDI camera.

These configurations are shown schematically in the Figure below:

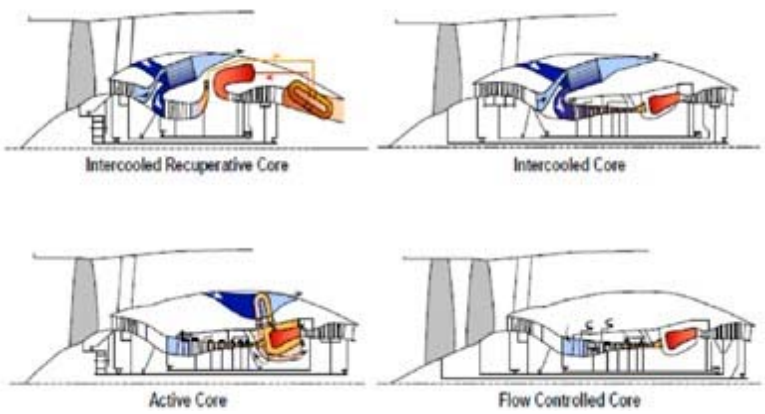


Figure 28. Core concepts in NEWAC.

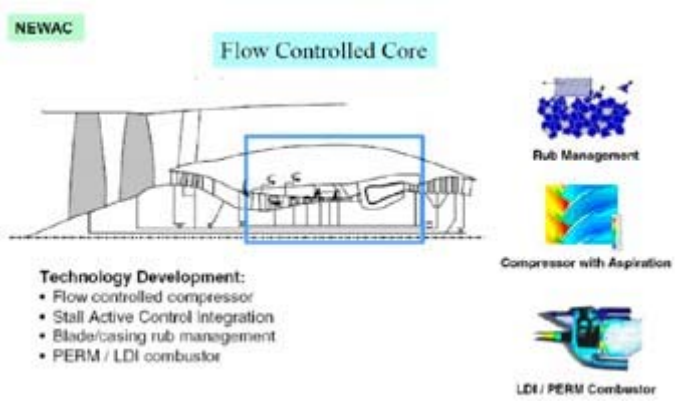


Figure29. Scheme of the controlled flow core concept and its technological developments.

SMALL-CORE GAS TURBINE.

Another way to get greater fuel efficiency from an engine is to change its configuration, so that the air flow through it, changes along with pressures, and temperatures. For years, jet engines have increased engine efficiency, by changing the amount of air flowing through the engine's hot jet core by diverting the flow, resulting in the ByPass Ratio (BPR) concept.

In general, the larger the bypass ratio, the more efficient the engine can be to generate thrust, but there is a limit to this bypass ratio due to the maximum size of the nacelle, and this disadvantage is overcome by making the core smaller in diameter, and by using previous studies on materials and internal geometries to control the increase in temperatures and pressures.

Figure 30. Small-core gas turbine.

La NASA is exploring ways to reduce the diameter of the core of high-shifting turbofan engines to increase fuel efficiency[8].

REVOLUTIONARY PROPULSION TECHNOLOGIES.

The new propulsion concepts are expected to have a significant impact on fuel reduction for the future fleet. Today, open rotor, boundary layer ingestion and electric aircraft are the most important innovations in aircraft propulsion technologies.

ELECTRIC, HYBRID OR AIRCRAFT PROPULSION BATTERY-POWERED.

Conventional and electric motors are used during flight in different ways, electric or Hybrid-Electric. These types of propulsion systems are among the most promising technologies (see Chapter 4.5).

INGESTION OF BOUNDARY LAYER.

With the aim of reducing the weight and strength associated with the high propulsion efficiencies, generated by conventional systems embedded in the aircraft, distributing propulsive thrust across the main fuselage structures, is considered a promising approach. This idea is known as the "Propulsor Fuselage Concept" (PFC), which allows the entire fuselage to act as propelling thrust. The most direct way to implement the concept is by the complete Boundary Layer Ingestion (BLI). The BLI trail-filling concept has been extensively researched in several projects, including NASA's Fusefan and STARC-ABL, Bauhaus Luftfahrt's Claire Liner, and MIT's D8 concept.

With BLI technology, the engines are positioned close to the rear of the aircraft, so that the air flowing over the fuselage becomes part of the air mixture that is ingested at the engine air intake and is speeded backwards. According to analytical studies at NASA, BLI technology is able to reduce aircraft fuel consumption by up to 8,5% compared to current aircraft. As part of the Horizon 2020 Program, a project dedicated to demonstrating the validation of the PFC concept, called CENTRELINE (ConcEpt validatioN sTudy foR fuselagE wakefilLIng propulsioN intEgration), is being carried out. This project explores a design of two-engine turboelectric PFC systems with a BLI aft fuselage propeller.

Photographic archive

Figure 19. http://www.tandemaerodays19-20.eu/presentations/
Figure 28. Nagpurwala, Q. H., State of art and future trends,ht tp://164.100.133.129:81/eCONTENT/Uploads/16-PT12-Future%20 Tech%2044%20%5BCompatibility%20Mode%5D.pdf
Figure 29. Nagpurwala, Q. H., State of art and future trends,ht tp://164.100.133.129:81/eCONTENT/Uploads/16-PT12-Future%20 Tech%2044%20%5BCompatibility%20Mode%5D.pdf

8 https://www.nasa.gov/aero/nextgen-aircraft-design-is-key-to-aviation-sustainability

4.3.3. Aerodynamic

Aerodynamic technologies have been in continuous development throughout the history of aviation. Nowadays, research efforts with an impact on fuel consumption, are focused on areas, such as the following.

- Computational Fluid Dynamics, CFD.
- Profile/Wing Technology.
- High-lift devices of leading edge and trailing edge.
- Aerodynamic tunnel tests at high Reynolds numbers.
- Improved structural concepts.
- More integrated wing/motor/pylon configurations.
- Multidisciplinary optimization.

Based on these advances, aerodynamic technologies have been developed, they have favored the reduction of fuel consumption and, therefore, of emissions, affecting the reduction of aerodynamic drag and the integration of propulsion, as well as multidisciplinary optimization.

Advances in aerodynamics, as well as in materials and structures, allow a significant reduction in the strength induced by the support:

- Maximizing the effective extension of wingspan with composites.
- Incorporating advanced wing tip devices (winglets), which increase aerodynamic efficiency and reduce fuel treatment.

Variable curvature technology on the outlet edge. Another method of decreasing resistance. NASA has developed and combined the concept of variable continuous curvature flap or slat, with the concept of active wing shape control, to reduce strength and fuel consumption. Active wing shape control is designed to aeroelastically change a wing shape in flight, in order to achieve a desired shape for optimum strength reduction.

Technology of grooved structures (riblets) on the wing surface, which has been shown by tunnel and flight tests to reduce local turbulent wall friction by 6% [26], thereby decreasing the drag of the turbulent flow. Research carried out by DLR in Berlin achieved turbulent drag reductions of up to 10% by optimizing the shape of the riblets.

Laminar flow.
An important field of R & D is laminar flow, since its application in various parts of the aircraft, also contributes to the reduction of drag by reducing fuel consumption. Natural laminar flow control is achieved only by designing the surfaces of the wings, and other parts of the aircraft in an appropriate shape.

This technology is being studied, for example, in the laminar wing project, BLADE (Breakthrough Laminar Aircraft Demonstrator in Europe). This demonstrator is tasked with evaluating the feasibility of introducing laminar flow wing technology, with the aim of reducing aircraft drag by 10%, and CO_2 emissions by up to 5% [8]. It is the first in the world to combine a transonic laminar wing profile with a true internal primary structure, in which the sections of the outer wing, about 10 meters wide, were replaced by laminar profiles. The size of the laminar sections is representative of the wing dimensions of single aisle aircraft, which can apply laminar flow technology. From these tests, it is estimated that the fuel saving potential of natural laminar flow (NLF) for an 800-nautical-mile flight would be about 4,6%.

Hybrid Laminar Flow Control (HLFC) uses boundary layer suction to maintain laminar flow over the surface of the aircraft. This technology is particularly suitable for swept wings and the empennage. NASA, as part of its Environmentally Responsible Aviation (ERA) research program, conducted a series of flight tests on a B757 equipped with an HLFC system.

Scale and swept wings have been shown to affect the application of laminar flow (NLF vs HLFC), and it has also been observed that the environmental impact benefits depend on the scale of application. The estimated net potential benefit of this fuel consumption application for subsonic transport is about 5-12%.

Currently, research activities on laminar flow are being strengthened in Europe within Clean Sky. In Clean Sky 2, NLF and HLFC activities are being carried out as shown in Figure 31 and Figure 32 respectively, which are at an advanced stage of development.

the installation of high-BPR engines. Therefore, the integration of the propulsion system is important, as otherwise the increase in engine efficiency may be offset by the increase in drag due to the installation. Several projects have been carried out under the EU Framework Programmes

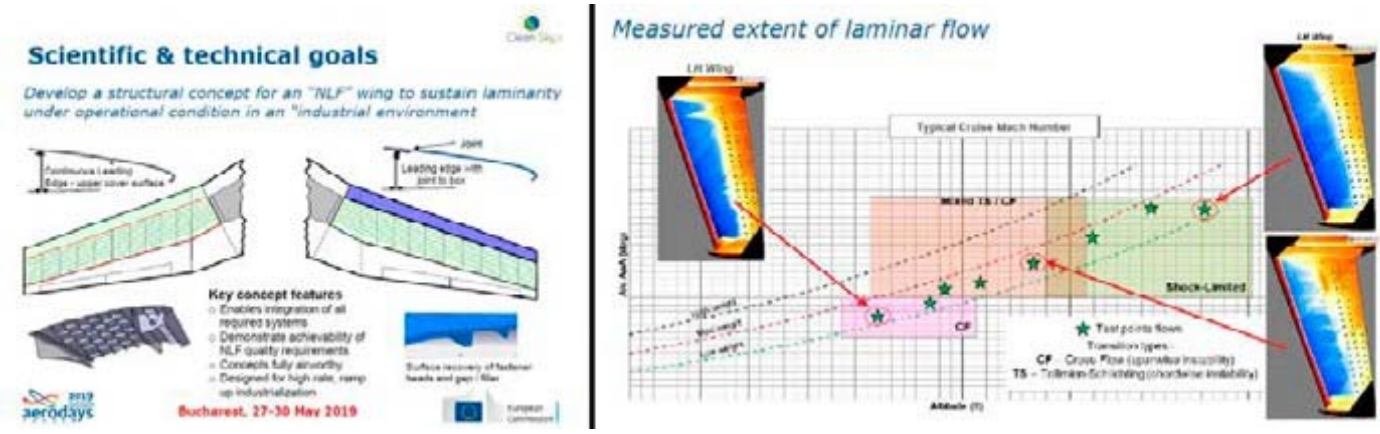


Figure 31. Natural laminar flow activities in Clean Sky 2. [27]

Aerodynamic effects on propulsion-cell integration.

For the development of new or modified transport aircraft, the use of the new UHBR engines implies (given their large diameter) the need for a close wing coupling.

which are wholly or partly dedicated to the integration of propulsion, such as ENIFAIR (ENgine Integration on Future Transport Aircraft) with the main aim of mitigating the aerodynamic impact of engine-pylon-wing interference. On the other hand,

Figure 32. Hybrid laminar flow activities in Clean Sky2. [28]

The increasing outer diameter of the nacelle due to the increased bypass ratio (BPR), the limitations of the landing gear height and the demand for sufficient ground clearance, require a close adaptation between the wing and the engine for

the potential or risk of new unconventional aircraft configurations related to the installation of engines, has also been investigated, as in the ROSAS project (Research On Silent Aircraft Concepts) as shown in Figure 33.

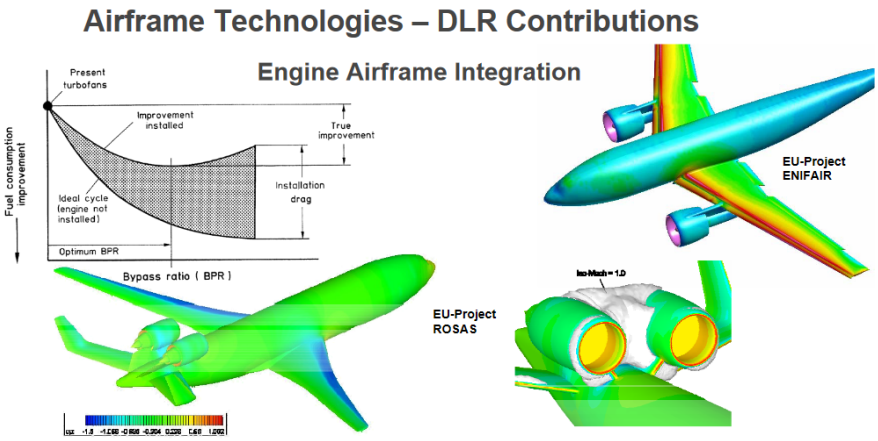


Figure 33. Propulsion-cell integration in conventional and unconventional configurations. [29]

REVOLUTIONARY AERONAUTIC CONFIGURATIONS.

Since about 2000, NASA has been promoting research into revolutionary configurations in the US, through public-private partnership programmes, with industry R & D activities. These technologies include[9]:

The Struct Braced Wing (SBW) concept allows to increase the wingspan, without increasing weight and less thrust is required. Boeing's "Subsonic Ultra Green Aircraft Research" (SUGAR) project. This configuration is approximately 29% more fuel efficient on a 900 nm mission (3,500 nm design range) than a Boeing 737-800 with CFM56 engines. Wing weight optimization combined with an open rotor engine, could lead to block fuel savings of up to 53% compared to the reference fleet.

The Blended Wing Body (BWB), also known as the Hybrid Wing Body (HWB), is primarily a large flying wing, which contains a payload area (passenger cabin or cargo storage area) within its central section. The shape of the central body and the outer wings blend smoothly.

Fuel consumption for several large BWBs is forecast to be between 27% and 50% lower than current aircraft of similar size and range. For the small BWB, fuel efficiency estimates are about 30% better than the current reference aircraft.

There are also initiatives to combine the benefits of electric propulsion and the design of the wing-body concept, BWB or HWB. NASA has been studying BWB concepts with distributed turboelectric propulsion systems over the last decade, and the expected fuel savings are in the order of 70%. Recent developments 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 suited to various hybrid electric propulsion and battery concepts than large aircraft. In addition, the market potential for this seat category is large, and development costs can be expected to be shared if many units are to be produced.

Another promising flying wing concept is the "Flying-V", a double wing V-shaped 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 endurance and is 20% more fuel efficient than a comparable fuselage and wing aircraft.

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

[9] IATA Technology Roadmap for Environmental Improvement Fact Sheet, 2019-2 https://www.iata.org/contentassets/8d19e716636a47c184e7221c77563c93/technology20roadmap20to20205020no20fo-reword.pdf

Box-/Joined-Wing, this wing configuration box, which was first proposed by Ludwig Prandtl in 1924, connects the ends of the two wings. For a given lift and wingspan, this configuration ensures minimum induced drag, and fuel economy compared to conventional aircraft. It achieves the same size, as an Airbus A320 or Boeing B737, with the capacity of a larger category aircraft, such as an Airbus A330 or Boeing 767, and the fuel consumption of smaller aircraft.

Transonic Truss-Braced Wing.
Studies to increase aerodynamic efficiency through the Transonic Truss-Braced Wing (TTBW) aircraft concept.

The TTBW is essentially a classic aircraft with tubes and wings, 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. This type of wing creates the same amount of lift as the thicker, currently shorter wings seen on passenger planes, but it does so with much less endurance.

Although other revolutionary aircraft designs, such as the double bubble body and the combined wing, have been studied, the TTBW technology is the one that could be developed earlier, in about 10 years, while the previous ones would need another 5 to 10 years.

4.3.4. Structures and materials

Additive 3D manufacturing.

This new technique for building aerospace parts involves adding material, layer after layer, in precise geometric shapes. This allows complex components to be produced directly from computer-aided design information. It allows faster and more flexible production and reduces material waste, compared to traditional approaches such as milling. It also results in much lighter parts that reduce the weight of the aircraft and, consequently, fuel consumption. The 3D printed parts are already flying on the Airbus A320neo and A350 XWB test aircraft (e. g. cabin mounts, purge tubes, fuel nozzles on the CFM LEAP engine).

Increased use of composite materials in aircraft structures.

Although better metals and manufacturing processes are available, composite materials have been used in aviation for decades, and more complex and structurally better and lighter structures, than metal ones are being made. The use of composite materials (composites) is increasingly preferred for structural components in all new designs. According to ICCAIA, 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 [10]. Other weight-reduction technologies are under consideration that could produce savings of around 2,5% for small aircraft, and 4% for large aircraft [10]. Currently, aircraft such as the Boeing 787 Dreamliner or the A350 have 50%, and 53% of composite parts compared to 1% in the 747 and 11% in the 777 [30].

There are three challenges when we are working with composite materials: the time from the part concept to its certification, including process optimization; the length of the manufacturing process and the length of the recycling process. NASA has completed the Advanced Composites Project on the first challenge, using new design methods, improved modeling capabilities, inspection methods, and processes for automation to reduce certification time.

Use of advanced materials in Motors.

In addition to the use of advanced materials in the aircraft structure, the use of these materials in the engines is also of extreme importance, such as Ceramic Matrix Composites (CMCs), already mentioned above, titanium alloys or other nickel-based alloys, etc. , as well as coatings that maintain the resistance to high temperature creep breakage and the resistance to oxidation/corrosion due to the great stresses in the form of high stresses, and very high temperatures that have to be withstood. Significant development efforts have been made to improve materials or coatings on the fan, compressor, combustion chamber and turbines by adopting new materials and processes.

REVOLUTIONARY TECHNOLOGIES IN STRUCTURES AND MATERIALS.

NASA's Spanwise Adaptive-Wing (SAW) project is researching wings that can be adapted to each phase of flight, by modifying the shape of different parts of the flight, with the aim of reducing weight and strength, thus improving fuel efficiency. Revolutionary material such as a nickel-titanium alloy SMA, shape memory alloy, which can be "trained" to return to its shape after a deformation when heated.

Another promising technology is the morphing wing, which is being studied by NASA and MIT. This new wing architecture could greatly simplify the manufacturing process, and reduce fuel consumption by 2-8%, improving wing aerodynamics and improving maneuverability. This transformation mechanism would involve the entire wing, which would be covered by a skin made of overlapping parts, in ways that would be able to deform to make a pure lift and roll, increasing the efficiency of flight by reducing fuel consumption.

4.4. Sustainable fuels

As we have seen previously, the strategy to turn commercial aviation into a fully sustainable activity is based on different issues and coordinated actions over time. While emissions compensation could mitigate the impact of emissions in the short term, fuels with low or no net CO2 emissions are a key element in the short-medium term. Sustainable aviation fuels (SAF), already in use in commercial aviation, include proposals of different types under the same purpose: to decrease or eradicate the net impact of combustion in conventional aviation engines. This is the key factor that makes SAFs so interesting for the sustainability of the aeronautical sector, since it would not be necessary to replace the current fleet of commercial aircraft to improve their environmental performance.

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

There are basically two types of sustainable aviation fuels: those produced from biological compounds, whether grown directly especially for this purpose or residuals, and those produced synthetically from CO2 and hydrogen, which are known as electrofuels, "e-fuels" or also "synfuels". Its commercial use is based on the "drop-in" concept, whereby the standards of its manufacture allow direct mixing with the conventional fuel in all the aeronautical jet engines, in a proportion that could theoretically reach up to 100% [4].

Facing the palliative compensation of emissions, and awaiting a decisive technological leap in the area of propulsion in the long term, sustainable fuels are presented as a viable option in a short-term horizon to effectively reduce the environmental impact of high capacity and long range flights.

Figure 34. Biofuel delivery at Los Ángeles airport.

Ptotographic Archive

Figura 34. https://www.dailybreeze.com/2019/06/05/lax-welcomes-ecofriendly-united-airlines-flight-powered-by-biofuel/

1 Alternative Fuels Task Force, dentro del Committee on Aviation Environmental Protection (CAEP)

2 https://www.icao.int/environmental-protection/Pages/CAEP-FTG.aspx

4.4.1. Biofuels

The principle by which biofuels reduce net CO2 emissions is simple: the plants or derivatives on which their manufacture is based, first capture carbon dioxide from the atmosphere during their growth. Once transformed into biofuel, its combustion in the engines releases this same CO2, consequently a neutral impact is theoretically achieved. Of course, it is essential to evaluate the complete cycle of biofuel production to ensure that the carbon footprint associated with this process maintains an acceptable balance of emission reduction.

Biofuels have been used intensively for years in countries like Brazil, with sugar cane-based ethanol for automobiles since the 1970s; together with other crops such as corn or soybeans, they form the raw material for first-generation biofuels. Impact problems on land use, and competition with food production, associated with these crops, led to the search for alternatives, which resulted in the second generation of biological origin fuels such as those prepared from amelin, jatropha, microalgae or miscellaneous waste.

At present, there are many processes for the generation of biofuels for industrial use (mainly HEFA-SPK[3]), and others in development and implementation stage. The use in commercial aviation is authorized with mixtures of, for now, up to 50% of biofuel [1]. Depending on the raw material and the production process used, different reductions in CO2 emissions can be achieved by comparison with petroleum-based fuel. It is important to point out again that this calculation must take into account the complete 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 emissions issued for deforesting an area to cultivate these suitable vegetables for the manufacture of biofuel.

The results in Figure 35, where the broken line indicates the related emissions with conventional aviation fuel, show the complete calculation of greenhouse gases associated with the use of different biofuels (LCA4). Reductions can be observed in some cases reaching neutral CO2 levels, but also biofuels with unacceptable carbon footprints. This is why, before launching the industrial production of any sustainable fuel, it is critical to carry out a thorough analysis of viability and environmental efficiency, with uniform criteria, including indirect effects such as the displacement of food crops.

The graph also highlights some cases with negative net balances in greenhouse gas emissions. That is, fuels whose complete cycle of production and use, extracts these compounds from the atmosphere. The explanation to this is that by-products from its manufacture are used to, for example, generate additional energy and replace fossil fuels.

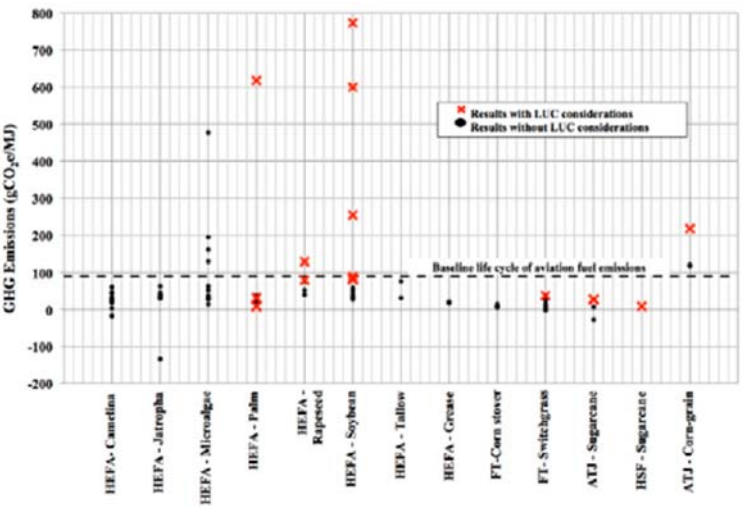


Figure 35. Green-house effect gas emissions due to complete bio-fuel life-cycle.[31]

3 HEFA-SPK: Hydroprocessed Esters and Fatty Acids - Synthetic Paraffinic Kerosene

4 Life Cycle Assessment

Another way to obtain biofuels with a complete negative CO2 cycle, still at the development phase, consists of optimizing the process to include carbon sequestration (BECCS[5]). During sustainable fuel production, from biomass, biochar is obtained as a by-product. This compound is stable for millennia, effectively removing CO2 from the atmosphere, and it could be used in agriculture without releasing new emissions[6].

In the field of projects already at the industrial stage, 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 its emissions[7] with respect to the conventional equivalent. Although its commercial application has been a success, its price and production scalability are aspects that still represent a challenge [32].

Since the first flight with biofuels was made in 2008[8], a great progress has been made in its introduction for commercial use, estimating that the total number of flights made with some percentage of this type of fuel exceeds a number of 200,000, and it is supplied on a regular basis at 5 airports[9]. Despite this, the 15 million liters produced in 2018 accounted for less than 0.1% of the total aviation fuel used in that year. Increasing production to 2% of consumption will allow the biofuels market to be launched definitively, which seems achievable in view of the 6,000 million liters already committed to in agreements with airlines in the medium-term [33], and the incentives for their use through mechanisms such as CORSIA and EU ETS (the use of these sustainable fuels is rewarded when calculating offsets). Industry forecasts estimate that biofuels could represent from 19% to 50% of its CO2 emission reduction target [4], and IATA places the expansion of these SAFs up to 30% of total consumption in aviation by 2030 [34]. In Europe, the aviation biofuel production capacity in 2019 could potentially have covered 4% of the total aviation fuel needs on the continent [8].

A key factor in enabling biofuels to take off is the improvement of their economic competitiveness compared to aviation kerosene. With usual oil prices (50-100 $ / barrel) the production cost of conventional fuel moves in the range of $ 0.3-0.6 / l, compared to $ 0.7-1.0 / l for HEFA-SPK [33]. This proportion is consistent with other studies on SAF obtained from used oil, with a cost between

Figure 36. Data from European Aviation Environmental Report 2016. EASA, EEA, Eurocontrol.

50% and 75% higher than that of fossil origin fuels [8].

The economic disadvantage of biofuel, which has been reduced considerably in recent years [35], could be totally overcome in scenarios of higher oil prices, through decisive political actions that prioritize its use (establishment of quotas, compulsory mixing quotas, bonuses for their use or taxes on carbon emissions) but also through technological advancement and the entry into play of scale economies. It should be remembered that aviation kerosene historically enjoys an exceptional tax exemption that makes its replacement difficult, unlike any fuel for ground transportation. The European Commission is reviewing this situation, which could be an opportunity to improve the competitiveness of sustainable fuels, while it is been prepared the legislative initiative "ReFuelEU Aviation 10" that seeks to promote its use in aviation. Norway, for its part, has led the way with its regulations that will oblige airlines to a minimum of 30% SAF in their domestic and international operations by 2030 [1].

5 BECCS: Bioenergy with Carbon Capture and Storage
6 https://www.stiesdal.com/material/2019/02/Stiesdal-Sky-Clean-01.01.19.pdf
7 https://rsb.org/2018/01/29/altair-rsb-certification-biofuel-refinery/
8 http://news.bbc.co.uk/2/hi/7261214.stm
9 ATAG (2019), https://www.atag.org/component/news/?view=pressrelease&id=117
10 https://ec.europa.eu/info/law/better-regulation/have-your-say/initiatives/12303-ReFuelEU-Aviation-Sustainable-Aviation-Fuels

An alternative way to extend its use would consist of airlines transferring the extra cost of biofuels to the price of the ticket, appealing to the environmental sensitivity of the passengers. The forecast indicates that the extra cost of flying between London and New York with a 15% SAF would increase the individual ticket $10 [33].

The advances in the production of biofuels based on urban waste and by-products from the agricultural and wood industry are of particular interest, since they allow an access to a large volume of supplies, at low cost and without implying any competition for land use. A study on the energetic potential of different wastes in the US, with the available technology, estimated that only with the slurry from cattle and pig farms 10% of the country's aviation fuel needs could be covered in 2016 [36]. On this side of the Atlantic, it is estimated that with the volume of used cooking oil available it could be produced enough SAF to cover 2% of aviation demand on the European continent [8].

An added environmental advantage of biofuels is that, according to an international study led by NASA, their use can be associated with a mitigation of other negative effects for climate change such as the formation of condensation trails and associated cloud cover [37]. This benefit would be achieved thanks to the fact that its combustion produces fewer and smaller soot particles than that of regular kerosene. In flight experiments carried out to validate the research, mixtures of 50-70% biofuel were used. Other studies coincide in pointing out this advantage, apart from additional ones such as the reduction of sulfur oxide emissions [38] or even the increase in fuel efficiency between 1 and 3% [1].

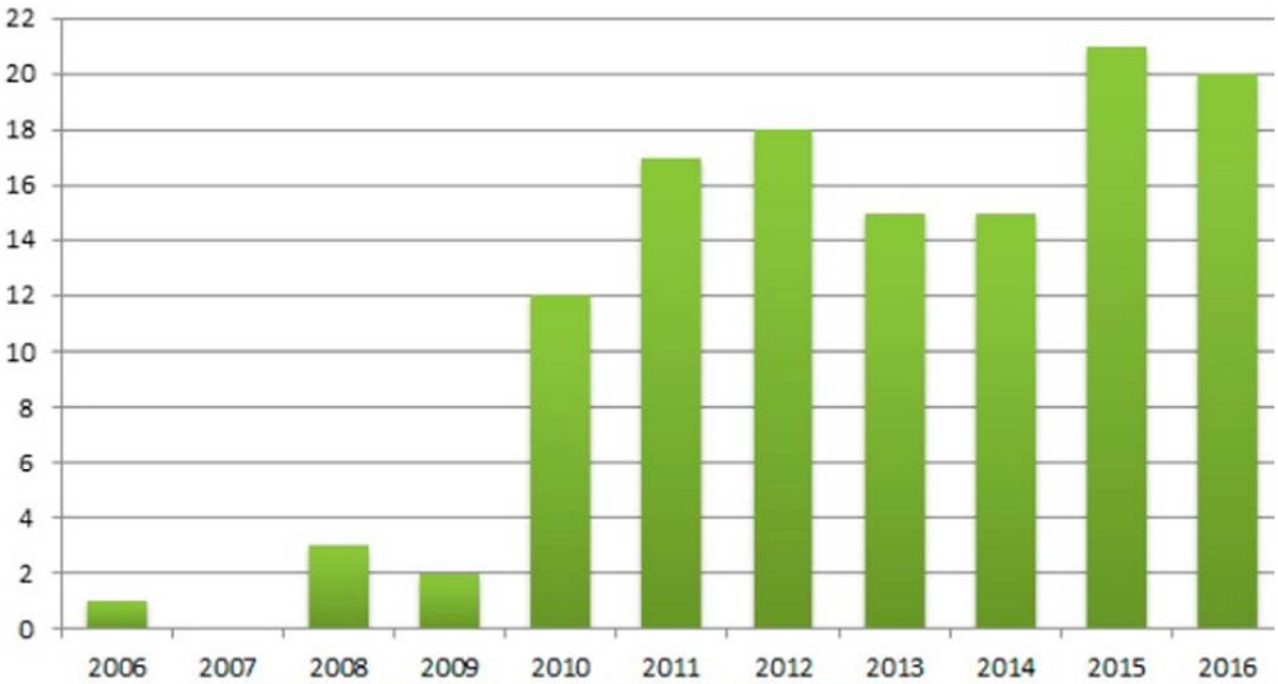


Figure 37. Number of active initiatives to promote the use of biofuels (ICAO GFAAF, 2017).[31]

Photografical Archive

Figure 36. https://www.eea.europa.eu/es/senales/senales-2017-configuracion-del-futuro/infografia-1/biocombustibles-en-europa/image_view_fullscreen

4.4.2. Electrofuels

The synthetic production of alternative fuels to those of fossil origin, also known as "e-fuels" or "power-based fuels", represents a qualitative leap in terms of aviation sustainability. In a certain way mimicking the biofuel cycle, the process involves the extraction of CO2 directly from the atmosphere or captured during industrial processes, and its conversion into hydrocarbons by combining it with hydrogen, which is obtained, for example, from water by electrolysis. The origin of the energy to feed the process, especially the generation of hydrogen, is what will determine the net balance of CO2 emissions. If renewable sources are used, such as solar or wind energy, the resulting e-fuel could be practically neutral CO2.

There are different processes of synthesis of hydrocarbons from hydrogen and CO, such as Fischer-Tropsch (FT) or the synthesis of methanol. These technologies have been tested in small-scale demonstrators, but its commercial viability has been hampered due to the high associated cost, which is estimated to be at least twice that of fossil aviation fuel [1], although other evaluations place it in a range between 3 and 6 times more expensive [8]. On the other hand, being them relatively recent developments, it is expected that technological improvements, such as high temperature electrolysis, and the scale economies associated with industrial production will be able to reduce these costs significantly [39].

Despite of being one step behind biofuels for both the industrial application and regarding the cost, electro-fuels have the advantage of occupying much less land per unit of produced fuel and, above all, they avoid all the problem related to direct and indirect effects of changing the use of arable land, in addition to demanding minimal water consumption.

An ambitious industrial project was announced in June 2020 for the manufacture of e-fuel for aviation in Norway from renewable energy. The production will start in 2023 with an annual capacity of 10 million liters, and aggressive plans for expansion contemplate multiplying it by 10 in only 3 years, in addition to being a model for other factories [11]. It is obvious to relate the viability of this industrial initiative with regulations on mandatory quota for sustainable fuel as indicated in the Scandinavian country. The same electrolysis technology applies to the demonstrator launched in May of 2019 by an international consortium around Rotterdam-The Hague airport.

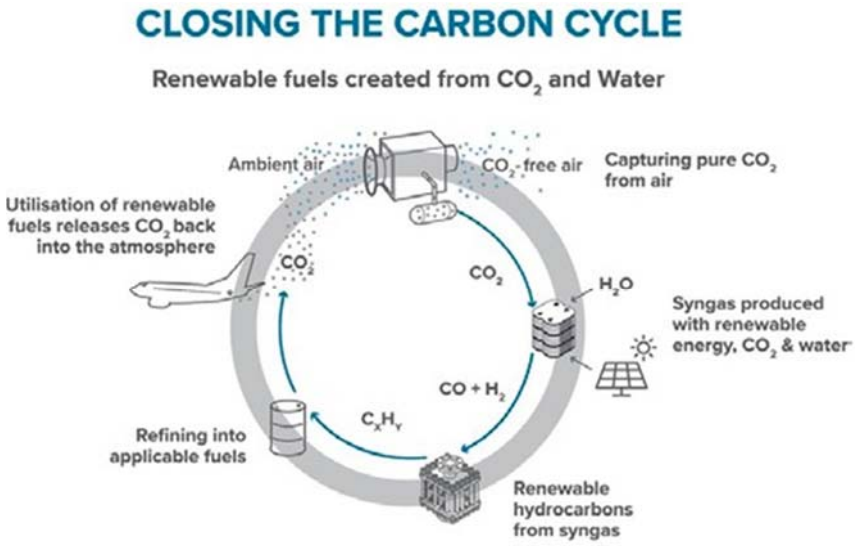


Figure 38. electrolysis e-fuel life cycle.

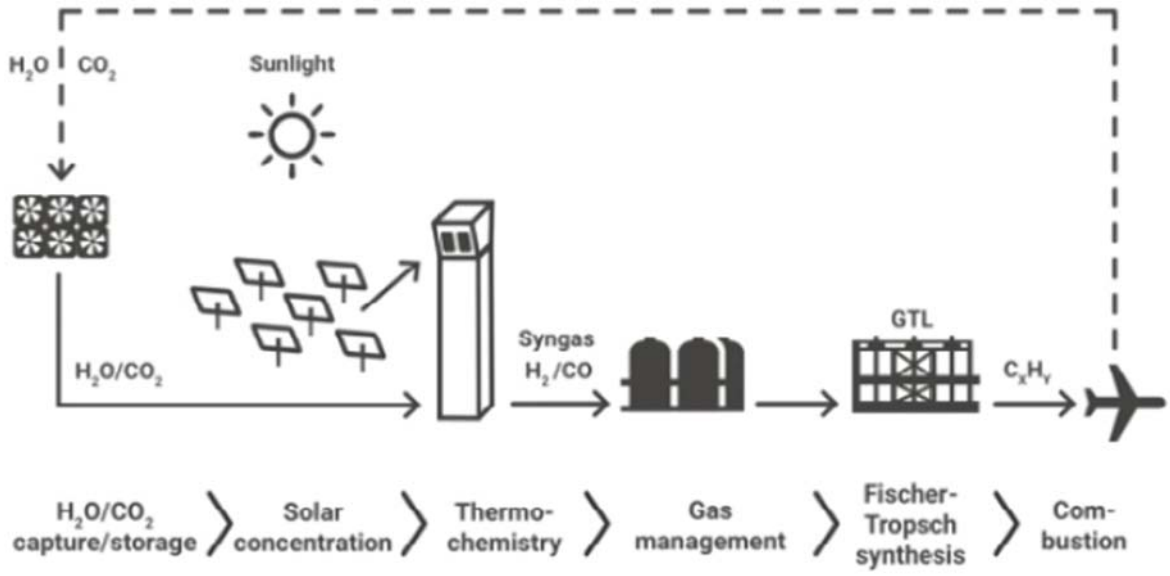
11 https://www.norsk-e-fuel.com/en/

Photografical Archive

Figure 36. https://www.eea.europa.eu/es/senales/senales-2017-configuracion-del-futuro/infografia-1/biocombustibles-en-europa/image_view_fullscreen

Another type of approach, based on thermo-chemical high temperature reactions, has been tested in the Sun-to-Liquid[12] project, with funding from the European Union and Switzerland. A reactor powered by concentrated sunlight transforms CO2 and water into synthesis gas, composed of hydrogen and carbon monoxide, before its transformation into aviation fuel by the FT process. The pilot plant is located in Móstoles, and involves an important Spanish technological contribution. At the end of 2019, the validation of the complete industrially scalable production cycle was successfully completed.

These examples illustrate the enormous research and development thrust in electro-fuels or "e-fuels", whose commercial use seems just around the corner. Its advantages over biofuels seem to reserve for them its own space in the medium term on the path to a fully sustainable aviation. However, none of the sustainable fuels would be able to eradicate other environmental impacts of aviation beyond CO2 emissions, for example the formation of clouds or soot emissions, although it could possibly reduce them as said above. Meeting this challenge will require a radical change in the way aircraft are propelled, which will be explored in the next chapter.



The fuel production chain process in the SUN-to-LIQUID solar fuel plant.

Figura 39. Sun-to-Liquid fuel production process.

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

4.5. Electric aviation

After a long period in which it remained as an aspiration, the electric revolution is now a reality in the field of land transport and, as shown in Figure 2, the interest and electrical projects have also skyrocketed in the aeronautical sector [1]. The incentives to develop this type of propulsion are diverse, although the fundamental one is environmental: today it is the only way to be able to carry out flights with a zero environmental impact, assuming that a renewable electricity supply is used and in the absence of evaluating the life cycle of batteries.

The deadlines to turn this electrical promise into reality are undoubtedly uncertain, given its dependence on the development of new technologies, but within the horizon of this same decade the start of its commercial deployment is expected. It is estimated that the entry into service of electric aircraft for 20 passengers could arrive around 2025, with developments greater than 50-80 passengers not before 2030 [1].

Of course, there are still considerable obstacles when it comes to generalizing this type of aircraft, some of which are only expected to be resolved in the long term[2].

However, given the environmental potential of electric aviation, and its ability to be combined with other technologies, the electric bet seems to be a fundamental piece in the sustainable future of aviation.

There are different strategies and approaches under this electrical denominator, each with its advantages and disadvantages, depending on the type of energy source used for propulsion [58]. Starting with the growing electrification process in conventionally powered aircraft, we will then review the different hybrid options that introduce an electrical source to powere the propellants, and we will end with the 100% electric proposals. Given the special characteristics of hydrogen as an energy vector, which allow its use by feeding fuel cells in electrical configurations or directly in turbofans, we will deal with the proposals based on this fuel in the next chapter. As we have been pointing out in this report with other initiatives to improve the sustainability of the aeronautical industry, its development should not be understood necessarily as a competition between options, but rather as elements that can cover different needs in different time frames.

1 https://www.icao.int/environmental-protection/Pages/electric-aircraft.aspx

2 https://leehamnews.com/2020/05/01/33297/

4.5.1. More electrified aircraft

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 circuits are removed thanks to the use of motors and electrical systems, with the consequent weight reduction and optimizing the use 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 process would be the thrust reversers of the A380, where the usual hydraulic system was replaced by an electric one. The Boeing 787 on its part, despite the initial problems with the batteries, was an important step in this strategy by eliminating the usual bleed from the engines to the cabin air conditioning system, replacing it with electric compressors and improving the energy efficiency of the airplane as a whole [40].

Another significant achievement of this approach is the "e-taxi" system, developed by Airbus and Safran, which will start operating in 2022. The innovation consists of electric propulsion during ground operations by means of an electric motor connected to the landing gear and powered by the APU[3]. In this way, fuel and emissions savings are achieved (up to 4% in short and medium ranges [8]) by avoiding the operation of the main engines in inefficient regimes, in addition to a considerable reduction in noise.

The next qualitative step in the use of electrical energy to reduce polluting emissions is the turboelectric system, in which a gas turbine, powered by conventional fuel, drives an electric generator that at the same time transmits the power to electric motors in order to generate thrust (Figure 40). Although the primary energy source continues to be hydrocarbons in principle, this architecture 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 using electric motors allows access to other advantages that we will review in the purely electric propulsion section.

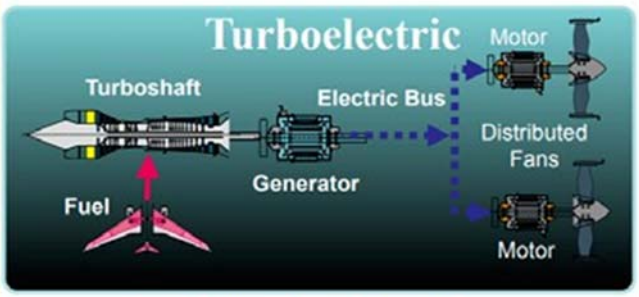


Figure 40. Turboelectric propulsion diagram.[41]

If efficiency is improved compared to conventional aircraft, and therefore emissions are reduced, the turboelectric concept avoids the main problem of 100% electric propulsion: autonomy. On the other hand, their environmental performance can be further improved by using sustainable fuels. Different case studies have been carried out for its commercial application, among which the ESAero ECO-150 stands out (Figure 42), which expects to halve the consumption of a Boeing 737-700 on an equivalent journey [41].

NASA's futuristic N3-X (Figure 41), 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 [41], although the technological horizon to make it technically feasible is very far away.

More in the short term, one could expect the entry into service of proposals similar to the STARC-ABL also from NASA (Figure 43), a hybrid system in which two conventional turbofans also feed an electric motor in the tail of the fuselage.

3 Auxiliary Power Unit.

Ingesting the fuselage boundary layer increases the efficiency of the rear thruster and reduces fuel consumption by 10% [41]. This strategy is hardly applicable to a conventional turbofan due to its need for a clean central air flow.

Despite the relevance of the advances described, and the interesting possibilities that the turboelectric concept opens up, the environmental common denominator of all the models reviewed is that the origin of all the energy used for propulsion continues to come from of the combustion of hydrocarbons.

Figure 42. ESAero ECO-150.[42]

Figure 41.NASA N3-X.

Figure 43 STARC-ABL de NASA.

Photographical Archive

Figura 41. https://www.nasa.gov/content/hybrid-wing-body-goes-hybrid
Figura 43. https://sacd.larc.nasa.gov/asab/asab-projects-2/

4.5.2. Hybrids

The next fundamental milestone towards sustainability in this gradual air transport strategy will probably occur with the incorporation of electric propulsion, during at least some phases of flight, sustained by batteries or fuel cells. This hybrid propulsion architecture, in its different variants, would, for example, make it possible to take advantage of the higher specific energy of kerosene to overcome phases of high demand, such as take-off and climb. Reserving the electric thrust for the cruise would eliminate harmful emissions at heights and, which would be a great advance, also other negative effects associated with jet propulsion such as contrails and condensation associated cloudiness.

There are several types of hybrid architecture depending on the combination of different energy sources and the type of engines used for propulsion. The two 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 turbofan engines to obtain thrust, but they would operate in two different regimes according to the needs: the first one conventionally with fuel, and the other one driven by electric motors coupled to the shaft of the first compressor, which would act as propeller. The electrical energy supply would come from batteries or fuel cells (Figure 44).

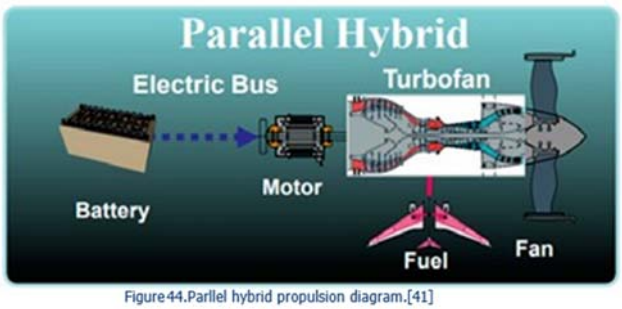


Figure 44.Parllel hybrid propulsion diagram.[41]

This parallel system has the advantage of keeping the propulsive capacity of the current engines intact, as well as the autonomy derived from the consumption of hydrocarbons, while reserving the use of electrical power for those flight conditions which are more critical in terms of environmental impact. The electrical support would also make it possible to optimize the size of the jet engines, currently sized to achieve the peak thrust required during the take-off. As an example of this architecture, we can point out the SUGAR Volt (Figure 45), a Boeing proposal that estimates a potential fuel saving of around 60% compared to its conventional equivalent [41]. The technological viability of this proposal depends on the development of high-power motors and electrical systems.

Figure 45. Boeing Sugar Volt. Parallel Hybrid propulsion system.[41]

The other main hybrid option consists of entrusting the propulsion exclusively to electric motors, which in turn would be powered alternatively from batteries or by a conventional engine connected to an electric generator. These systems are called series hybrids (Figure 46), and they share with the turboelectric option the advantage of being able to optimize the design point of the conventional engine, either internal combustion or gas turbine, as it is dedicated exclusively to the production of electricity. As in the previous option, the sections powered by batteries would achieve the total elimination of emissions during some phases of the flight, although the price to pay for having two energy sources in the aircraft is to add complexity to the entire system, which makes maintenance difficult and increases weight.

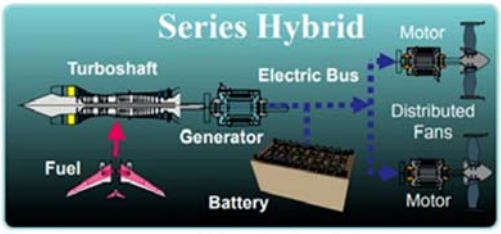


Figure 46. Series Hybrid propulsion diagram.[41]

The first flight test of an aircraft with this configuration, the E-star, dates back to 2011[4] (Figure 47). Currently there are several companies, with commercial projects under development, that have already carried out in-flight tests of series hybrid propulsion systems (Ampaire in 2019, Voltaero in 2020), albeit in low-capacity and low-power aircraft.

Figure 47. E-star (2011).

Keeping conventional fuel as part of the energy supply allows the flight range to be extended significantly, thus avoiding one of the main problems faced by 100% electric propulsion. However, as it also happens to that one, there is still a lot of work 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[5] (Figure 49), 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. In the long term this technology could be applied to innovative designs such as the Airbus E-Thrust 6 (Figure 50).

Finally, it is also worth highlighting two types of strategies adopted in the different projects with a hybrid approach. On the one hand, work is being done on the incorporation of electric propulsion through

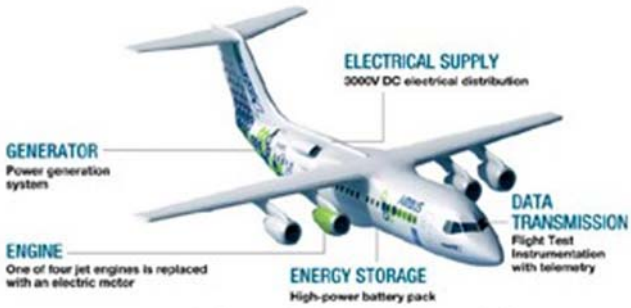


Figure 49. E-Fan X. Hybrid testing bench BAe 146 (source Airbus).

modifications to existing conventional regional aircraft, which shortens the deadlines for their entry into service. This is the plan of Ampaire and its Eco Otter with 19 seats and 370 km of autonomy[7]. On the other hand, more ambitious projects design aircraft from scratch to take full advantage of the hybrid propulsion, such as the Zunum proposal (Figure 48) with capacity for 12 passengers and 1,300 km of range.

Looking at a little longer term, the international consortium FUTPRINT508, financed by the European Union, seeks the development of the necessary tools and technologies that allow the entry into service of a hybrid-electric aircraft of 50 seats before 2040. In any of the scenarios, sustainable transport seems linked, at least as a stop point, to the hybrid concept.

Figure 50. Airbus E-Thrust. Series hybrid conceptual proposal.

Figure 48. Zunum. Siries hybrid proposal.

7

4 https://www.flyingmag.com/news/eadsdiamond-unveil-electric-hybrid/

5 https://www.airbus.com/innovation/zero-emission/electric-flight/e-fan-x.html#ove

6 https://www.airbus.com/newsroom/press-releases/en/2019/05/air-bus-and-sas-scandinavian-airlines-siqn-hybrid-and-electric-aircraft-research-aqreement.html

https://www.ampaire.com/vehicles/Eco-Otter-SX-Aircraft

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

Photographical Archive

Figure 48. https://zunum.aero/

4.5.3. Batteries

We started the evolution in stages of the electrification of aviation with the concept of more electric airplanes (MEA), to later move on to hybrid configurations and, how could it be otherwise, now reach the category of 100% electric airplanes or "All electric aircraft" (AEA). In this architecture, the energy necessary for the flight is stored in batteries or fuel cells, from where it is transmitted directly to electric motors that generate the thrust (Figure 51).

Like the series hybrid, this configuration allows the distribution of propulsion in a beneficial way for the aircraft design. Unlike with jet aircraft, there is no penalty to spread the thrust between several relatively small electric motors. Quite the contrary, since limiting its size to machines below 1 MW simplifies its implementation, the transmission of electrical power and the necessary electronic systems.

Another potential advantage of electric thrusters is that their dimensions allow them to be positioned at the end of the wing, which would open the possibility of reducing the induced drag of the wing by counteracting the wing tip vortices. These advantages will be tested with the NASA X-57 experimental aircraft, currently in assembly (Figure 52).

Figure 52. NASA X-57. Electric demonstrator.

The advancement throughout the electrification of aviation, as well as the times and niches occupied by the different technologies, are largely conditioned by a crucial parameter: the specific energy of each energy storage system. This coefficient indicates the amount of energy contained per unit of mass, and when comparing the values in Table 4, the main challenge of electric aviation with batteries can be concluded: conventional hydrocarbon fuel contains at least 40 times more energy per unit of mass, with the direct consequence that electric aircraft currently will have a limited autonomy and transport capacity.

Different studies have tried to determine from what specific energy thresholds it is possible to think about developing viable electrical solutions for the different categories of commercial aviation. This on-going race, according to some opinions [44], would be launched from batteries that reached 400 W • h / kg.

However, in the case of general and regional aviation, with lighter and smaller transport aircraft, 100% electric flights already seem feasible with the current capacities of Lithium-Ion batteries. This has been demonstrated by examples such as Pipistrel's Alpha Electro trainer in 2020, which achieved the first type certification by EASA of a newly 100% electric light aircraft designed [9] (Figure 53); or the electric re-engined of existing aircraft such as a De Havilland Beaver for 6 passengers (Harbor Air and Magnix, first flight test in 2019[10](Figure 54) or that of a Cessna Grand Caravan with up to 9 passengers (Aerotec and Magnix, first flight completed in 2020. Figure 55).

9 https://actualidadaeroespacial.com/la-easa-certifica-el-primer-avion-totalmente-electronico/
10 https://www.bbc.com/news/business-50738983

Photographies

Figura 52. www.nasa.gov

	Querosene (Jet A-1, a 15 ºC)	Ion-Litium battery	Gas Hydrogen (700 bar, 0 ºC)	Liquid hydrogen (20 ºK)
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 between different energetic vectors for commercial aviation (compiled by authors)

Figure 53. Pipistrel's Alpha Electro.EASA's certified electric trainer 2020.

Current batteries also seem capable of powering eVTOL[11], small aircraft intended for urban air transport, whose development is currently a real competition with a multitude of projects already in the flight test phase. There are large aircraft manufacturers (Airbus[12] or Boeing[13] proposals) involved as well as new players with mobility experience (Uber [14], Hyundai) and a multitude of start-ups (Joby Aviation, Volocopter, Lilium).

Figure54. DHC-2deHavillandBeaverdeHarbourAirremotorizadoeléctricoporMagnix(2019).

To make the leap and propel aircraft of around 100 passengers, it is estimated that 1,000 W • h / kg batteries and hybrid architectures will be needed.

Finally, this type of aircraft with 100% electric propulsion would require advances that raise the specific energy of the batteries to 1,800 W • h / kg [38]. This technological threshold appears far away, although there is rapid progress in alternatives such as lithium-sulphide technologies (Oxis Energy has announced a commercial application battery with 471 W • h / kg), solid-state batteries, metal-air or with graphene applications [38].

Figure55.eCaravandeAeroTecyMagnix. Electric with batteries, range 180km, up to 9 passengers.

Another crucial aspect to be developed in electrical aviation is the efficient and safe distribution and management of the necessary high demand of power, which is directly related to another fundamental parameter for electrical equipment: specific power (kW / kg). A proposed alternative to current technology is based on silicon carbide, which would facilitate the design of higher power components. Cryogenic technology, often included in the provisions for future electric aircraft, would allow to substantially improve the capabilities of electrical motors and systems, but it is still far from being technically feasible in the aeronautical environment [38].

11 Electric vertical takeoff and landing

12 https://www.airbus.com/innovation/zero-emission/urban-air-mobility/cityairbus.html

13 http://www.boeing.com/NeXt/index.html

14 https://www.uber.com/us/en/elevate/uberair/

Photographical Archives

Table 4. IATA 2015. Guidance Material for Sustainable Aviation Fuel Management 2015 https://www.cei.washington.edu/education/measures-of-solar/battery- technology/
https://energia.jcyl.es/web/es/biblioteca/combustibles-hidrogeno.html
https://energies.airliquide.com/resources-planet-hydrogen/how-hydrogen-stored

The most ambitious commercial proposals presented for 100% electric transport with batteries, go from regional transports with 9 seats and 1,000 km of range (for example Eviation, with Spanish participation and entry into service

Figure 56. Electric prototype with batteries by Wright Electric for 186 pax (EIS 2030).

proposed for 2022), aircraft with 19 seats and 400 km of range (Heart Aviation, proposed entry in 2026, Figure 57), up to 186 passenger commercial aircraft (Wright Electric, 1.5 MW distributed engines, estimated entry into service by 2030, Figure 56).

Figure 57.Electrical batteries prototype by Heart Aviation for 19pax - 400km(EIS2026).

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 self-development potential of new technologies must be taken into account, and their ability to reduce the environmental impact of regional and single-aisle commercial aviation, whose CO2 emissions in 2018 amounted to 58% of total commercial aviation [7]. To achieve this objective, regulatory and political support will undoubtedly be necessary, such as Sweden and Norway, where an integrated platform for the development of electric aviation (NEA15) has been created. In the latter country, all short-haul flights must be 100% electric from 2040 onwards.

The move to larger capacities, with long-haul, double-aisle aircraft, seems for now a very remote possibility; and the necessary improvements in the batteries specific energy would require a revolutionary technological leap. Returning to Table 4, the enormous interest aroused by hydrogen as an energy vector is now explained. Either through fuel cells, feeding an electric aircraft, or directly in turbofans, hydrogen is presented as a direct solution to the problem of energy storage. As we will see below, and despite its own limitations, this route opens up new and promising possibilities to improve the sustainability of commercial Aviation.

15 Nordic Network for Electric Aviation

4.6. Hydrogen

4.6.1. Sustainable energetic vector

Hydrogen has been proposed for decades as a possible alternative fuel to the use of hydrocarbons in transport. One of its main characteristics, which partly explains this interest, is that its combustion theoretically produces only water as waste, with the enormous environmental advantage that this entails.

It is important to clarify that, even though it is the most abundant element in the universe, hydrogen is not directly available on Earth, so it cannot be considered as an energy source, but rather as an energy vector. This means that to obtain this fuel it is necessary to invest a certain amount of energy first, for example in the electrolysis of water, so hydrogen is simply a way of storing existing energy, and this is essential when it comes to understanding that hydrogen as a fuel, by itself, does not imply sustainable transport. This will depend on the origin of the energy sources used and the emissions associated with its complete production cycle, the same as happens with propulsion with electric batteries.

If renewable sources are used and a process without environmental impact, it will be possible to obtain what is known as green or clean 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, without offering in these cases environmental advantages ("gray hydrogen"). An intermediate case, promoted to some extent by the political authorities in Europe, is that of "blue hydrogen" [1], in the process of obtaining CO2, but to be captured and stored (CCS2). The use of this production route is seen as a temporary solution to reduce the production price of low-emission hydrogen, which is still not very competitive if it is produced by electrolysis, and to ensure a sufficient volume of supply.

Table 4 explains another reason why hydrogen is so interesting in sustainable aviation: faced with the problems of energy storage in batteries, each kg of H2 has 2.7 times more energy than its equivalent Jet A1 conventional fuel. This eliminates, 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 liter — is at least four times less than that of kerosene. This implies that, even with higher specific energy, aircraft that use hydrogen as fuel will need more storage space. Furthermore, the cylindrical geometry of the cryogenic (-253 ºC) or high pressure (700 bar) tanks required to house it poses a challenge for the configuration and dimensions of today's commercial aircraft. These more complex and heavier tanks will determine in each application case whether the use of a lighter fuel such as H2 saves total weight in the aircraft. It has been estimated that the takeoff-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 [45] .

On the other hand, the introduction of hydrogen as a jet fuel would require a large investment at airports and distribution infrastructure to allow refueling. Although there are already airports with some availability (Hamburg, Memphis), a great political push would be necessary to make hydrogen accessible as a fuel for routine use. In this regard, it is worth highlighting the example of countries that promote the generalization of the use of this fuel, such as Germany or Japan, where there are incipient refueling networks for road transport. The latter country already launched in 2017 a national strategy to achieve a hydrogen economy, with milestones in the reduction of the cost of its production, technological development

1 https://www.greentechmedia.com/articles/read/eu-sets-green-hydrogen-targets-now-blue-hydrogen-has-to-keep-up
2 Carbon capture and sequestration

and construction of infrastructures that facilitate its distribution

Along the same lines, on July 8, 2020, the European Commission launched the European Clean Hydrogen Alliance [46], which launches a series of initiatives to promote the use of this energy vector with sustainable origin. Among other objectives, the current H2 production capacity through electrolysis is multiplied by 12 by 2024. This decision is part of the commitment to achieve a European society with zero net CO2 emissions by 2050, for which sustainable H2 is presented as a fundamental tool when it comes to decarbonizing industry and transport. Spain has also joined this strategic drive by approving its own roadmap for the implementation of renewable hydrogen in October 2020, which includes the installation of hydrogenerators at the main airports[3].

The use of hydrogen in 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 great advantages, but also some drawbacks that need to be resolved before practical applications. In addition, we already saw in the chapter on sustainable fuels that hydrogen was a fundamental part of the synfuels synthesis process. Given this range of possible applications, it seems clear that, in one way or another, this energy vector is going to be an important part of the sustainable future of the aeronautical industry.

Figure 58. Sustainable hydrogen plant. Fukushima (March 2020).

Photographycal Archive

Table 4. IATA 2015. Guidance Material for Sustainable Aviation Fuel Management 2015 https://www.cei.washington.edu/education/science-bytes/the-cost-of-solar/battery- technology/ https://energia.jcyl.es/web/es/biblioteca/combustible-hidrogeno.html https://energies.airliquide.com/resources-planet-hydrogen/how-hydrogen-stored

[3] https://www.lamoncloa.gob.es/consejodeministros/Paginas/enlaces/061020-enlace-hidrogeno.aspx

4.6.2. Fuel cells

Fuel cells convert the chemical energy of a compound into electricity, without combustion. In the case of hydrogen fuels, only water is obtained as the output product (Figure 59), which can be stored for reuse in the aircraft, or unloaded when it does not imply any environmental risk, avoiding the formation of condensation trails or induced cloudiness.

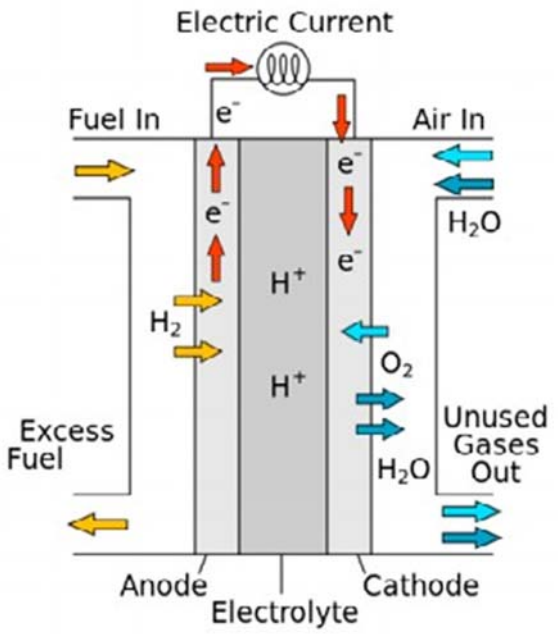


Figure 59. Fuel cell functioning scheme (MAHEPA Wikipedia).

The electrical power generated by this system can be used in an equivalent way to the batteries in the different versions of electrification and hybridization exposed in the previous chapter.

The challenges of these configurations, in terms of motorization and electrical energy management, are therefore the same that we had with the hydrogen batteries; as well as the benefits to 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 eliminates the limitations of battery autonomy.

This technology is at an advanced degree of maturity, with consolidated commercial applications in the land transport sector, both in automobiles (the Toyota Mirai has sold more than 10,000 units since 2014, and enjoys an autonomy of 500 km and refueling in 3 minutes[4]) as in buses and other industrial vehicles.

The first flight test of an aircraft powered by hydrogen cells was carried out in Spain in 2008[5], by Boeing (R&T-Europe) and its hybrid adaptation of a Diamond Dimona, also powered in parallel with batteries (Figure 60). The first flight supported exclusively by hydrogen cells was made by the Antares DLR-H2 in 2009.

Figure 60. Boeing. Hydrogen cell hybrid. 2008.

Other hydrogen-powered projects that have been developed since then include the HY4, a model developed with commercial intent for aerotaxi services in Germany (Figure 61). H2fly, responsible for this aircraft, has also joined the MAHEPA6 project, regarding the study of modular electric hybrid solutions.

Figure 61. HY4. Exclusive propulsion with hydrogen cells. 2016.

4 https://www.toyota.es/world-of-toyota/articles-news-events/new-toyota-mirai

5 https://www.abc.es/ciencia/abci-boeing-prueba-exito-espana-primer-avion-pila-hidrogeno-200804040300-1641769545030_noticia.html

6 Modular Approach to Hybrid Electric Propulsion Architecture

The extended flight range offered by hydrogen cell technology is the competitive advantage underpinning the eVTOL Skai7 project; as well as the proposal to remotorize a regional ZeroAvia aircraft (Figure 62), with a capacity of up to 20 passengers and 800 km of range by 2023 [1]. In 2020, this company demonstrated the commercial capabilities of hydrogen-powered electric propulsion by flight testing a Piper 6-passenger M-class 8. This same year it had already carried out a test of the same battery-powered model[9].

Hydrogen cells are an available and high-energy-capacity option that also opens up new possibilities for hybrid configurations. This is particularly interesting in the case of its combination with hydrogen combustion engines.

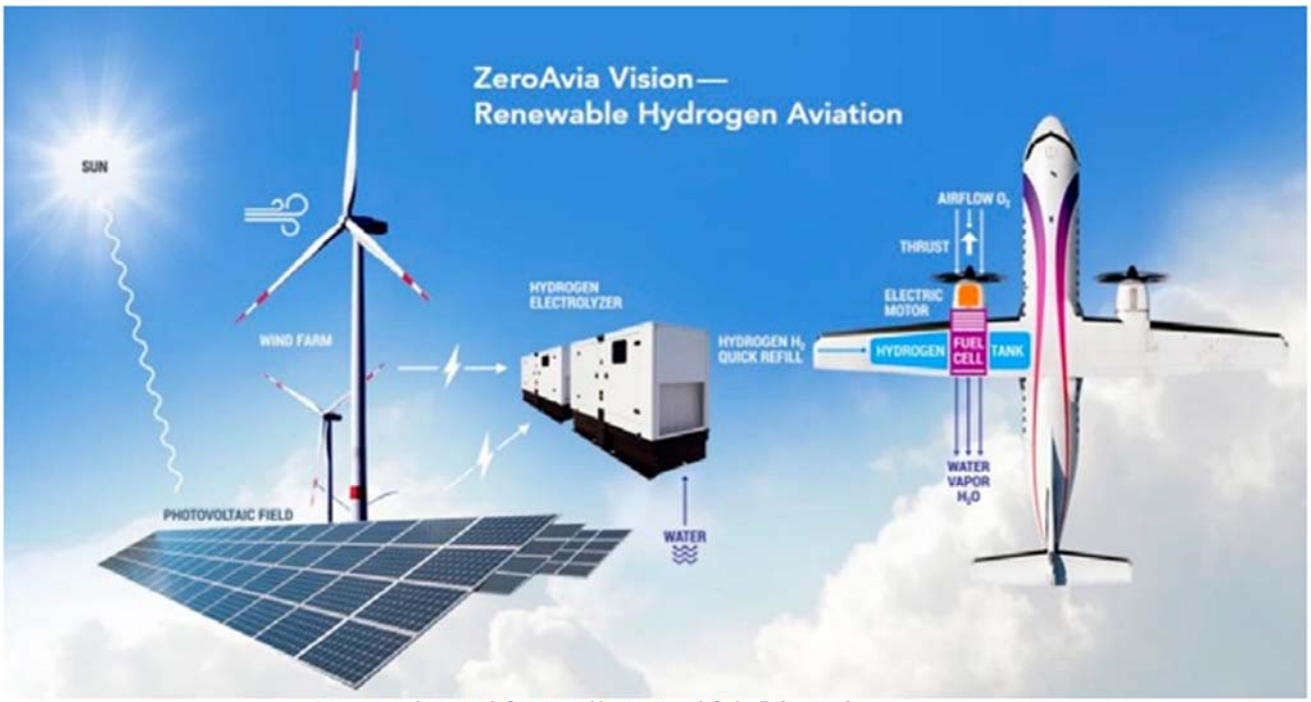


Figure 62. Hydrogen cycle for sustainable aviation with fuel cells (ZeroAvia).

7 https://www.skai.co/

8 https://www.zeroavia.com/press-release-25-09-2020

9 https://www.zeroavia.com/press-release-23-06-2020

4.6.3. Direct combustion

Hydrogen jet propulsion is a solution that has held for years as a potential substitute for the conventional one based on hydrocarbons. In fact, one of the first jet engines built in 1937 (von Ohain) initially used this fuel. Despite detailed studies in the 70s[10], it took until 1990 for the first flight test of an aircraft partially propelled by hydrogen turbofan engines, with the Tupolev Tu-155 demonstrator (Figure 63).

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 CO2 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.

To mitigate NOX emissions, as a result of the high temperatures reached in the combustion chamber, some research is being carried out that would allow its volume to be significantly reduced. New technologies for feeding the combustion chamber ("micromix combustion technology") make it possible to foresee reductions of the order of 66% [47] compared to advanced conventional engines. Other estimates the potential of these reductions at 80% [11].

On the other hand, the emission in height of water vapor-Greenhouse gas- would be 2.6 times higher with hydrogen engines [45], and also leads to the creation of condensation trails, associated cloudiness and the consequent impact on global warming. However, various studies foresee that the microcrystals that make them up will be less numerous and greater than with the combustion of hydrocarbons, and their total negative effect will at least contribute significantly to mitigating this problem. In any case, the effects of contrails and associated induced cloudiness are pending further investigation to better understand their dynamics and environmental impacts.

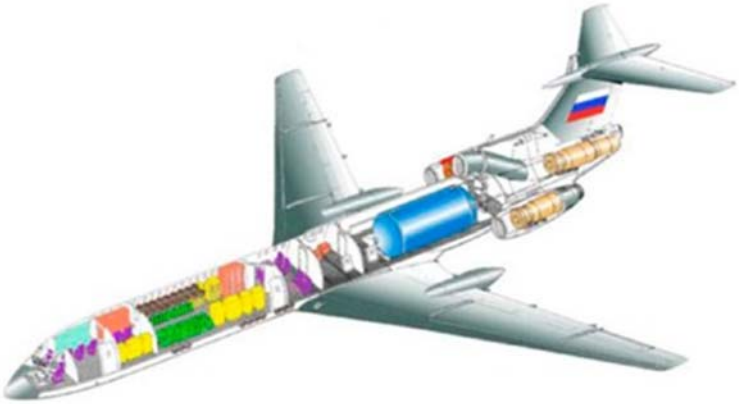


Figure 63. Experimental model Tupolev 155 Liquid hydrogen propulsion (tank in blue). 1990

The most recent interest in this mode of propulsion can be connected with the Cryoplane study [45], published in 2003 and funded by the European Union with the participation of Airbus among other public and private entities. This project systematically reviewed the feasibility of a direct hydrogen combustion engine in aviation. The main conclusion confirmed that there was no identifiable technical barrier preventing the development of this configuration. It was not estimated that it implied any penalty for weight or scope, but it did imply the need for a greater volume of storage, for which different designs were proposed.

From the economical point of view, they insisted on the need for strong support, both economic and regulatory, from the political authorities to launch a change of this caliber in the aeronautical industry. Finally, and connected with the previous point, the enormous advantages of hydrogen in the field of sustainability were confirmed, which would justify its support.

Phographies

Figure 63. https://www.globalsecurity.org/military/world/russia/tu-155.htm

10 G. D. Brewer

11 https://leehamnews.com/2020/09/18/bjorns-corner-the-challenges-of-hydrogen-part-9-hydrogen-gas-turbines/

Another aspect cleared up by the Cryoplane project was that of aircraft safety with this type of fuel, verifying that it would be at least as safe as that of aircraft with kerosene tanks. Subsequent studies even point to greater safety in the case of liquid hydrogen fueled aircraft [1].

In September 2020, Airbus regained its interest in hydrogen-burning propulsion by launching the ZEROe program (Figure 64), made up of three conceptual proposals for short- and medium-range aircraft. Liquid hydrogen would be used not only to power the turbofans responsible for propulsion, but also to provide all the necessary electrical energy through hydrogen cells. This limited hybridization, which takes advantage of fuel cells and allows optimization of the engines, fully responds to the concept of a more electric aircraft, but based on hydrogen. Although more than a commercial program it is actually a research framework, in-flight demonstrators are foreseen for 2025, and a hypothetical entry into service of this type of aircraft around 2035.

The viability of projects of this magnitude will depend, to a large extent and as already indicated, on the political and social impulse to support their development and implementation. In this aspect, the fight against climate change is a fundamental motivation. In fact, in Figure 7, it is shown that Airbus has focused its proposals on the most polluting sector in terms of CO2 emissions.

Today, everything points to the fact that there is that will and drive to make a more sustainable aviation 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 Enable H2 project, also with European public funding, which seeks to define and advance technologies for the commercial use of propulsion systems based on hydrogen. Its objective is to demonstrate, under current conditions, the technical and economic feasibility to achieve flights with zero CO2 emissions and minimal NOX impact.

Figure 64. AIRBUS. ZEROe initiative for hydrogen propulsion.

The year 2020 marked a milestone of change and acceleration towards hydrogen-powered aviation. As argued by a joint study by Fuel Cells and Hydrogen 2 and the Clean Sky 2 program in May of this year [48], political, technological and economic factors seem to finally align to realize the enormous potential in the field of the sustainability of this energy vector.

Photographic Archive

Figure 64. https://www.airbus.com/innovation/zero-emission/hydrogen/zeroe.html

4.6.3. Noise

The origin of noise in aviation comes from operations carried out in the air, operations on the ground and mixed operations. Noise mitigation opportunities can be found - considering different aspects: technology, operational improvements, planning and management of air space use, operational restrictions and a fifth related to better

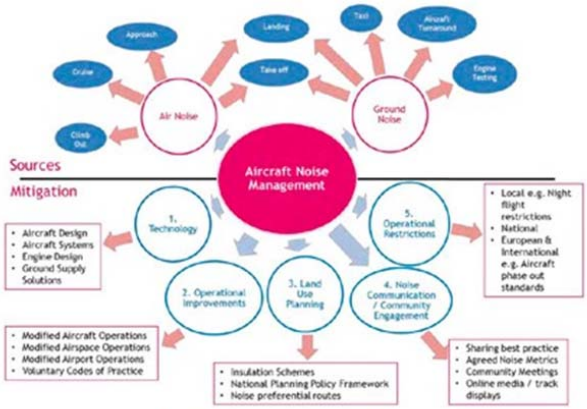


Figure 65. Noise management at airports.[49]

communication and commitment of the community [49].

In terms of technology, the main sources of noise in aircraft operation are the engines and aerodynamic noise, the latter dependent on the position of the high-lift devices, the turbulent boundary layer on the fuselage and the landing gear.

Engine noise, although it depends on the type of engine, is generally dominant during take-off operations where the climb gradient is an essential element in the noise caused both under the plane and in the lateral direction. In modern aircraft approach and landing operations, both propulsive and aerodynamic noise levels are comparable, depending on the aircraft configuration, although it is the noise from the aircraft structure the one that dominates with the landing gear making the greatest contribution.

In 2019, 50 years were celebrated since the adoption of the first global standards for aircraft noise certification, standards that have led airplanes to be 75% quieter than the first jet, and this progress continues, thus, the newest aircraft on the market have, on average, a noise footprint that is 30-50% of that of the aircraft they are replacing thanks to the new engine and airframe design and technology. Great progress has been made [50]: the following image shows the considerable 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.

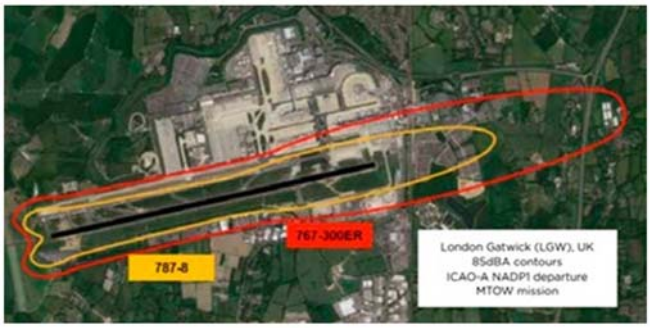


Figure 66. Noise footprint.[50]

Other examples: A320 neo's design noise footprint is almost 1 square km2 less than that of the A320, that of the Boeing 737 MAX is more than 1.7 km2 less than that of the 737 Next Gen, the A350-900 is more than 2.5 km2 smaller than that of the A340-300.

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

Thus, at the international level, ICAO (International Civil Aviation Organization) to grant a civil aircraft the type of certification necessary to enter into service, requires a complex program of tests that demonstrate that the aircraft has been designed and tested following the standards and approved procedures and, therefore, is considered safe for flight. Among these tests are some acoustic certification, demonstrating that the noise levels do not exceed the maximums established by Annex 16, Part I, to the Convention of Chicago.

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 nuisance level, the pure tones of the frequency spectrum and the duration of the noise.

Those admissible limits that appear in Annex 16 are set by the ICAO's Committee for Environmental Protection (CAEP) and are a function of the maximum take-off weight of the aircraft (MTOW).

ICAO's regulation for noise emitted by large subsonic aircraft has evolved since its inception, with the first edition of the Annex 16 which affected models certified from 1971, according to the text included in Chapter 2 of the Annex. Later, Chapter 3, more stringent, applicable from 1977, and Chapter 4, from January 1, 2006, which is the one that is currently in force, appeared. The CAEP is currently discussing a future Chapter 5 that was scheduled to go into effect this year 2020. The objective of these standards is to encourage the introduction of the best acoustic technology available in new civil aircraft designs. As a result, the requirements are becoming stricter, following advances in technology [51].

Great progress has been made, 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 background noise existing or individual perception of noise [49]. 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 with

more detail the weighting and the specific interrelationships each of the variables has on the final result.

Comparing the accumulated noise of recently certified aircraft with the current noise targets for 2020 and 2030 established by the ICAO's Committee on Aviation Environmental Protection (CAEP) in early 2013 following the recommendations of the IER2, second revision of independent noise experts, it is observed that [10], in all cases the noise levels for the four categories of aircraft considered recent: (Business jets, regional jets, one-aisle and two-aisle) aircraft are well below the ICAO's Chapter 14 regulatory noise level.

The mitigation policy adopted by ICAO, under the name of "Balanced Approach" [52], recommends

a case-by-case study of the situation at each airport and applying the most efficient mix of four elements (see Figure 67) [1]:

Figure 67. Airport noise management balanced approach.

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 endorsed this policy since 2003.

In recent years, ICAO has also stepped up their work on another essential aspect of managing the noise, community engagement.

Noise reduction at the source

Noise at the source is regulated through the aircraft type certificates as indicated above, and reducing this noise is the one with the highest priority.

Over the past 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 [49] has been reduced by 97% in operational operations. - departure ration (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 CO2 emissions. To put these reductions in context, 15dB is equivalent to a 65% reduction in nuisance [2], and 97% reduction in acoustic energy means that 33 modern aircraft simultaneously leaving an airport would together produce the noise of a jet plane the same size that departed in the sixties.

In recent years, different noise reduction technologies have been applied, such as the arrow fan, variable area nozzles. etc. (see chapter 4.3). Design technology aimed at noise reduction has mainly focused on:

Reduction of jet noise by reducing its peak velocities.

• Affects CO2 and NOX emissions by increasing the weight and aerodynamic losses if a long duct mixer is used.

• Affects CO2 and NOX emissions by a quantity less if mixing enhancement devices such as chevrons are used.

Sound absorbing, insulating or protection.

They reduce noise by absorbing or reflecting sound energy. They impact on CO2 emissions and LTO cycle emissions can be affected by increasing weight and aerodynamic losses, but lightweight structures can mitigate this effect.

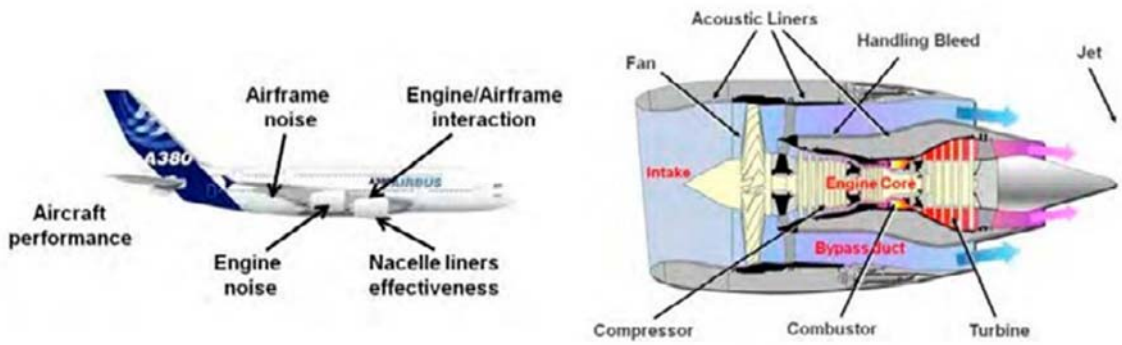


Figure 68. Relevant elements with influence on aircraft and engine noise.[45]

Designs with a higher bypass ratio (8PR) and a lower fan pressure ratio (OPR) that initially provide significant noise benefit and improved CO2.

Low weight materials and designs lower NOX / noise / CO2

Components with improved aerodynamics that decrease NOX / noise / CO2 if weight is not affected. Thus, for example, the higher pressure of the engine (OPR) and bypass ratio (BPR), the improved aerodynamics and weight reduction have decreased engine fuel consumption by about 70%, high-BPR turbofans with noise treatments have reduced source noise by around 20 dB, or low-emission combustion technology has eliminated visible smoke and reduced unburned hydrocarbons by 90%, decreased CO2 by 60% and NOXen approximately 25-30% at a fixed engine pressure ratio.

Airports also establish noise reduction policies, introducing restrictions in different ways using these noise values in arrival operations (certificates or real noise values measured by a monitoring system, to control noise from individual movements or collective impact through the use of microphones in strategic points of the airport).

Operating procedures. The different distributions of inhabited spaces around airports can allow the design of trajectories and operating procedures that reduce the number of people affected by aircraft noise. Figure 69 [10] shows different opportunities to mitigate aircraft noise by controlling procedures or operations. See chapter 4.2 for more information.

Example of currently imposed restrictions:

• Access forbidden to models that do not comply with certain limits: in the European Union models that do not comply with at least Chapter 3 are not accepted since April 2020, or by introducing a system of rates related to noise certified as in French airports.

• Establishment of categories of absolute noise levels (not based on the MTOW): Heathrow and Barajas prohibit night flights of airplanes that are not below the limits established by two parameters: the certified noise on landing and the average of the certified noise on take-off and lateral.

• Establishment of noise quotas by programming seasons for each airline, granting authorizations to companies until reaching an accumulated certified noise figure, as Charles De Gaulle does throughout the day and Barajas at night (23:00 to 07:00).

In other cases, a maximum acceptable noise level is established with actual noise values:

• A fine is received if the levels are exceeded and, if it is a repeated fact, it may even be banned from operating a certain type of aircraft, such as at the J. F. Kennedy airport in New York.

• The loudest aircraft within a certain category (for example, 100-150 twin jets seats), receive an economic penalty according to the statistics of the real noise measured in certain points of the airport complex, as it is done in Frankfurt and other German airports.

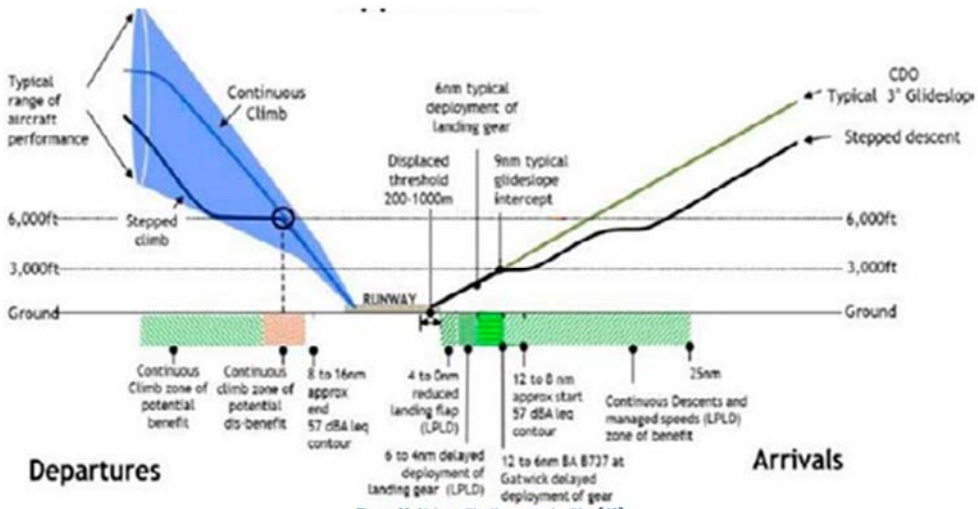


Figure 69. Noise mitigation opportunities.[49]

It is important to note that not all the opportunities indicated in the previous figure can be applied at any airport. The choice of one or another mitigation operating procedure will depend on many factors, not only on benefits in terms of noise, since there are many interdependencies to take into account such as emissions, safety, capacity, etc… so that each airport will choose the optimal procedures. Thus, during take-off, some airports will require the use of preferential runways and special procedures for the noisiest types of aircraft, with engine speed reductions, if security permits, when flying over towns.

Likewise, as mentioned in Chapter 4.2, low-power descent operations and continuous climb operations reduce fuel consumption and noise under the flight path by avoiding the need for leveled flights at low altitudes, but this option will depend on airspace management and capacity limitations. So, also the development of new on-board systems can lead to more effective noise reduction procedures. Different actions to reduce noise:

• Establishment of 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 for helping slow down the plane at night.

• Restriction on the use of auxiliar power units (APU) and running engine tests in certain areas or at certain times.

Many airports have installed an acoustic surveillance system that, together with radar tracking of the trajectories, makes it possible to determine whether each operation is precisely adjusted to the minimum acoustic impact paths designed for each aircraft model. In general, offenders are usually fined.

Planning and management of land use.

Outside the airport grounds, the management of restrictions in the use of the land is usually the competence of neighboring municipalities, whose ordinances may limit 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 municipalities 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.

Restriction of operations.

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 firstly prohibits manufacture, followed by importation and finally the operation of such aircraft. Thus, in the early 1990s, most OECD countries banned 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's Assembly of Chapter 4, applicable to new models certified after 01/01/2006, had attached the condition that this rule was not used to promote the formal mandatory retirment of models that only complied with Chapter 3.

Despite this, numerous airports (not countries) are proceeding to restrict the access of aircraft "Chapter 3 minus 5 EPNdB" or other similar mechanisms during certain periods.

In conclusion, there is a strong commitment from government and industry in many countries to address the technological aspects of this balanced ICAO's approach. The general tendency of large research initiatives is to address a global environmental agenda, considering trade-offs and interdependence aspects in scientific and technical work programs. Figure 70 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 centers (DLR, Onera, NLR, CIRA) that reflect the global commitment to continuously support technology in noise reduction.

In the long term, by 2050, they will require configuring radically new aircraft to significantly reduce noise, fuel consumption and consequently CO2 emissions (see chapter 4.3). Thus IATA, NASA and different European and American companies such as Boeing, Airbus, etc…. are carrying out activities through public-private collaboration programs, with the aim of achieving innovative and promising technologies (Bradley [57]), such as various revolutionary fuselage and propulsion configurations, especially both hybrid and fully electric propulsion (see chapter 4.5). 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 noise footprint reduction of 36% is estimated in take-off and landing compared to the most competitive best-in-class aircraft regarding noise aspects; more reduction during take-off (50% smaller) and smaller reduction during landing (15% greater) [58].

All these projects have given rise to different advances in noise reduction technology, acting on the engines (Huff [53], Gliebe [54]) with modifications in the nacelles and the fan, or on the jet noise by means of chevrons or the design of variable surface nozzles and others, acting on the structure, introducing modifications in flaps or trailing edges, designing fairings for landing gears, (Dobrzynski [55], Manoha [56]).

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

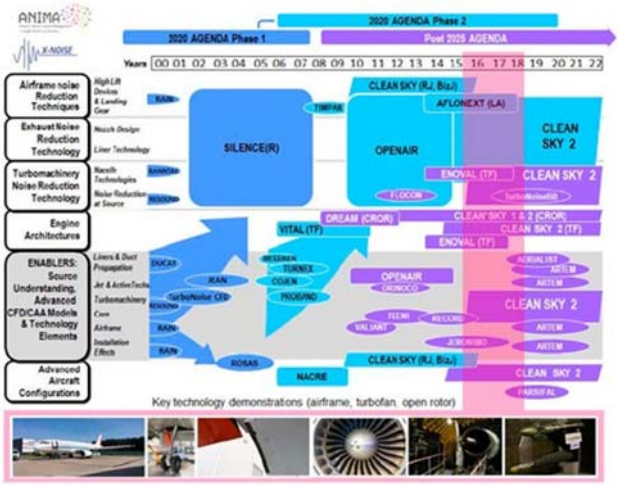


Figure 70. European projects related to noise and key technological demonstrators.[10]

5 Conclusions

The aeronautical industry was born and developed through a long history of innovation and resolution of technical problems. The challenge of sustainability and the elimination of its environmental impact is being faced in the same spirit, and the results have not been long in coming. Despite not being by far the transport sector with the greatest impact on global warming (Chapter 2), aviation was the first to have a coordinated plan with clearly established milestones to deal with climate change. The "Commitment to Action on Climate Change", signed in 2008, established short, medium and long-term objectives (Chapter 3).

In a first step, the industry committed to an annual improvement until 2020 of 1.5% in aircraft efficiency, directly related to the level of emissions. This objective has been more than achieved thanks to gradual technological development which, as we saw in chapter 4.3, will continue to make a decisive contribution to reducing fuel consumption. To the widespread application of well-known solutions (winglets, advanced and lighter materials, flight control systems), will be added aerodynamic innovations (laminar flow) and new engine developments (increased pressure and deviation ratios). Improvements in air control and operations procedures (Chap. 4.2) will bring a significant reduction in emissions, in addition to mitigating noise problems (Chap. 4.7).

For the short and medium term, 2020 was set as the reference and maximum limit for net emissions from civil aviation as a whole. To fulfill this commitment, the international civil aviation organization ICAO launched the CORSIA emissions compensation regulatory framework (Chap. 4.1), with the support of the member countries and the IATA airline association. This initiative represents a determined and immediately applicable effort that, with the necessary improvements during its implementation, is designed to contain and potentially reduce the emissions of an ever-growing commercial aviation. Within this system, the extensive implementation of sustainable fuels (Chap. 4.4), with its great potential to improve the sustainability of commercial flights, is also rewarded. On this horizon, until 2030-2035, significant technological contributions can be expected with disruptive designs (cable-stayed wings, boundary layer ingestion) and new propulsion modalities (open rotors, hybrid engines and hydrogen propulsion).

In the long term, in 2050, the ambitious goal is to reduce CO2 emissions from aviation to half the level of 2005. It is difficult to foresee such a distant evolution in a constantly changing world and aeronautical industry, but all of the elements outlined above will most likely have to do their part to achieve that goal. Furthermore, within this horizon, revolutionary technical and design solutions can be achieved and applied, covering new configurations (flying wing) or the great sustainable promise of electric propulsion (Chap. 4.5).

Table 5 and Table 6 provide an indication of the development timeframe and the potential reduction in fuel consumption - directly linked to CO2 emissions - for different technological solutions in the configuration of commercial aircraft.

	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 5. Potential fuel savings of propulsion technologies.[59]

	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 6. Potential fuel savings of aircraft design technologies.[59]

On the other hand, to achieve sustainable aviation we saw earlier that it is necessary to assess the environmental impact of the entire life cycle, including the evaluation of noise and other emissions in addition to CO2. The most promising solutions for this comprehensive approach are shown in Table 7, detailing their pros and cons, as well as their most likely application profile.

Taking all factors into account, it is estimated that the potential for reducing the climate impact for hydrogen-powered aircraft is between 75% and 90% compared to conventional models. The propulsion by combustion of hydrogen is situated in mitigations between 50% and 70%. Finally, sustainable synthetic fuels would be in the 30-60% range [48].

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 7. Comparison between new technologies and sustainable fuels.[48]

To achieve the objective of sustainable commercial aviation, the involvement and effort of the entire aeronautical industry (manufacturers, airlines, airports and air navigation services), that of governments and international organizations, as well as that of the passengers themselves will be necessary. While until recently it seemed impossible, now we see that there is a wide arsenal of tools to achieve it. We certainly do not know what the optimal solution will be, although it most likely involves combining all these strategies in different proportions and time frames.

As an example, one could imagine a civil aviation in a horizon of 10 to 20 years in which electric and hybrid propulsion prevail for regional and short-range transport, hydrogen combustion engines for intermediate and high-capacity routes, and long-range flights with sustainable fuels. All this, of course, with innovations in all aspects of both design and operation of the aircraft. This sustainable future for aviation is necessary, possible, and in our hands to make it happen.

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