COIAE

Environmental Sustainability in the Aeronautical Sector

ADDENDUM 2025

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1. FOREWORD

Continuing with the informative work begun in 2022, the Official College of Aeronautical Engineers of Spain (COIAE) presents this new addendum with the aim of reviewing the state of environmental sustainability in commercial aviation, collecting the most relevant events and advances produced throughout 2025.

If previous years were marked by notable optimism around new technological developments, 2025 has offered a more pragmatic vision of the sector's energy transition. Throughout the year there has been a readjustment of the market: various initiatives linked to disruptive propulsion, especially in the fields of hydrogen and certain electric mobility projects, have experienced significant delays in their schedules or, in some cases, cancellations due to difficulties of technical and financial feasibility. Far from representing a step backwards, this scenario highlights the true magnitude and technical-economic complexity involved in transforming a highly regulated, capital-intensive industry subject to demanding safety requirements. Despite this necessary exercise in realism compared to initial projections, air transport's commitment to the goal of reaching net-zero emissions by 2050 remains unchanged. Faced with the scalability challenges presented by the most disruptive technologies, players in the sector are redirecting a large part of their resources towards solutions with greater viability in the short and medium term.

This addendum analyzes how gradual innovation in aircraft efficiency and the constant optimization of operations, both in flight and in the airport environment, continue to be essential factors in containing the environmental impact derived from the sustained growth in passenger demand. At the same time, sustainable aviation fuels (SAF) consolidate their role as a priority and indispensable tool during this decade, although their mass adoption and the necessary qualitative leap towards synthetic fuels, or eSAF, continue to depend on more decisive public support frameworks to close the current cost gap. Another noteworthy aspect of the last year is the greater maturity achieved in the understanding of the environmental footprint of aviation. The sector is already looking decisively beyond CO_2, placing at the centre of the research and regulatory agenda the mitigation of the effects associated with contrails and other non-CO_2 gases and emissions. All this is taking place in an increasingly demanding economic context, marked by the consolidation of systems such as the EU ETS and CORSIA, as well as by the intense international debate on the application of new environmental taxes.

With this new update, the COIAE remains firm in its objective of offering society and professionals a rigorous, technical and truthful consultation tool. It is an updated x-ray that allows us to assess without bias the real progress that the aeronautical industry is making on its long, complex and unavoidable road to decarbonisation.

2. SUSTAINABLE AVIATION IN CONTEXT

2.1. INTRODUCTION

Progress in environmental actions in commercial aviation continues with aircraft that are increasingly respectful, both in terms of noise levels and emissions produced. This progress goes hand in hand with the increasingly demanding regulations of **Annex 16 (Vol. I, II and II)** to the Convention on International Civil Aviation (Chicago Convention). Thus, a new meeting of ICAO's Committee for the Environmental Protection of Aviation (CAEP) was held in 2025[i], where a double requirement integrated with updated standards for noise[ii] and aircraft emissions[iii] certification was agreed . For new aircraft designs, the **CAEP/13** standard will require a **10%** reduction in CO_2 emissions for larger aircraft from 2032[iv].

Incremental improvements in aircraft efficiency play a key role in this progression (see sections 3.2 y 3.3), an indispensable complement to disruptive technological advancement (see sections 3.5 y 3.6) and sustainable fuels (see section 3.4) on the path to decarbonization.

Figure 1. Airbus ZEROe programme design proposal (Source: Airbus)

On the other hand, the year 2025 began with a series of news in which different actors of the future sustainable aviation announced a delay in their plans to enter into service of new technologies, when it was not directly about project closures[v]. In the first category is Airbus' **ZEROe** programme, with its hydrogen propulsion proposal, which changes decade to place its entry into service in the mid-2040s. A similar case is the ATR **EVO** model, delayed to reevaluate the engine.[vi]

In the category of cancelled, or put into hibernation, in 2025 we find the eVTOL projects of **Lilium** and **Airbus NextGen**[vii], and the only 100% electric regional aircraft development to have reached the flight test phase: the **Eviation Alice**[viii]. In addition, **Textron**, the parent company of the only certified electric aircraft (**Pipistrel**'s **Velis Electro**), announced the dissolution of its electric propulsion division[ix]. This wave of bad news in sustainable aviation also reached research and development projects such as **MTU's WET** engine, but one of particular relevance: the **X-66** new technologies framework program, led by **NASA** and **Boeing**[x]. In the latter case, it is explained by the change of administration in the US and its refusal to consider issues of environmental sustainability.

However, when considering the aviation industry as a whole, it can be seen that the commitment and work to decarbonise commercial aviation remains, even if it is with renewed approaches. **Airbus** launched emission reduction initiatives in 2025 with micro-hybridization projects[xi], and for the mitigation of contrails. In the same vein, New Zealand, after abandoning its zero-emission aviation initiative, has replaced it with different projects to promote electric and hydrogen aviation, as well as a CO2 capture program[xii].

The latest air traffic data, corresponding to 2024, confirm its continued increase and, hand in hand, that of emissions in commercial aviation, which recovered to pre-COVID pandemic levels[xiii] (see Figure 5). This growth path is a key element to consider in any sustainability strategy in the sector[xiv]. Demand management has often been linked to travellers' environmental awareness, a concern reflected in surveys, although this is coupled with a reluctance to assume any extra costs[xv]. The introduction in the European Union of the emissions labelling system for airline tickets (***EU Flight Emissions Label***), opened in 2025 by **Air France-KLM**, could allow this concern to be channelled when choosing the most sustainable alternatives[xvi].

On the other hand, the sector remains concerned about an oversized perception of aviation's contribution to the greenhouse effect compared to other sectors[xvii] and, in particular, other more polluting means of transport, as can be seen in the Figure 2.

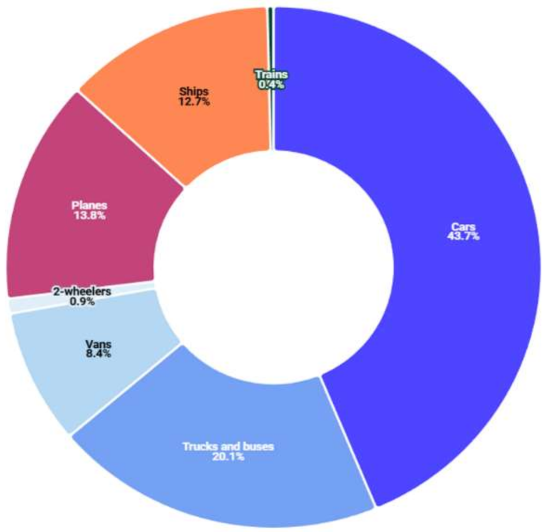

Figure 2. Breakdown of CO2 emissions from the transport sector in Europe in 2024 (Source: T&E)

In this environment of change and reanalysis, the **42nd Assembly** of the **ICAO**, the United Nations organization that manages international civil aviation. In it, the U.S. delegation spoke out against the allocation of resources in environmental and sustainability initiatives[xviii] and, in particular, against any type of taxes on business aviation or premium classes aimed at financing decarbonisation projects (see 3.1.3 for more information on these proposals). It should be noted that, also last year, the US successfully opposed the adoption of an emission limitation agreement in the equivalent organisation of international maritime traffic (**IMO**)[xix].

The final result of the assembly, on the other hand, maintained the unity and direction of the sector towards a sustainable future in international aviation, without changing the ambitious environmental commitments established, and launching new initiatives such as the **Finvest@ETAF** platform, which will connect investors with decarbonization projects and sustainable aviation fuel (**SAF**) production[xx].

In summary, in a year of uncertainty, it can be concluded that commercial aviation's will and commitment to a sustainable future remains despite everything. The magnitude of the transformation and the projects underway seem to be holding up to the pulse of a clearly unfavourable geopolitical context, even if this means adapting to less disruptive solutions, but more pragmatic, and with short-term environmental benefits. An example is the continuous increase in the turnover of recycling large old aircraft, with designs that are much less efficient in terms of emissions (Figure 3), already exceeding 600 units per year according to the *Aircraft Fleet Recycling Association*.

Figure 3. Commercial Aircraft Recycling (Source: Air Salvage International)

2.2. TOWARDS DECARBONIZATION

After a period of relative consensus, during 2025 it was possible to see the return of the debate on what is the most efficient strategy to achieve the goal of net zero emissions by 2050. Practical difficulties in realizing the promises of some disruptive propulsion technologies could support a greater focus on incremental improvements[xxi], the expansion of SAF, and the elimination of the impact of emissions beyond carbon dioxide[xxii]. While it is true that, along with this reorientation towards more achievable achievements in the short and medium term, voices have also emerged calling for a review of the ambitious emission reduction targets[xxiii].

Sustainable aviation fuel itself, a key tool in virtually all proposed decarbonisation pathways, has also not been spared from questioning its environmental and practical viability credentials[xxiv]. Debate based on solid facts and contrasted data should certainly not be shied away from, as this will help to always follow an optimised strategy that is anchored in reality. The urgency of the climate crisis, and the courage needed to address it, can never be in conflict with in-depth analysis when choosing the best path to sustainable aviation.

One of the most questioned aspects on the road to net-zero CO2 aviation is economic viability. The total value of this process is difficult to estimate, but figures are used that place it below what the development of solar and wind energy cost, and over a longer investment period[xxv]. One of the funding avenues suggested to cover this budget is the removal of tax exemptions on fossil-based aviation fuel.

The economic impact of environmental improvement measures in aviation is also analysed from the point of view of airlines, with studies that call into question the business model of some of them, in particular *Low Cost*, in view of the introduction in 2025 of European regulations such as the mandate to use SAF[xxvi]. Despite the increased awareness in general, as we have already seen, the increase in tickets may not be acceptable for a significant part of potential passengers.

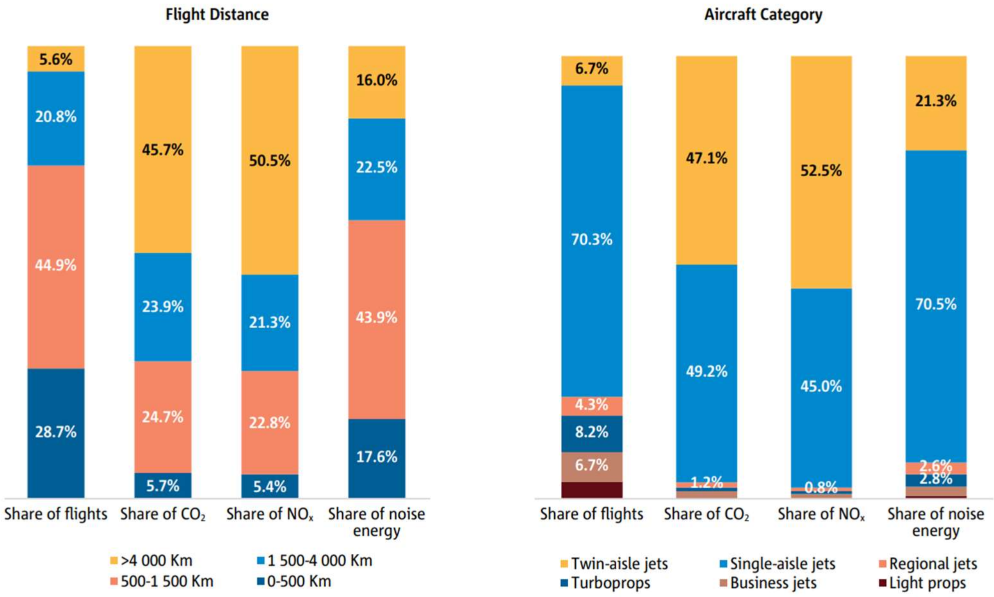

Figure 4. European aviation emissions breakdown in 2023 (Source: EASA [4])

At this point, it is useful to recall the composition of the environmental impact of aviation broken down by type of emissions, aircraft and flight distance, as shown in the Figure 4 based on European data. As can be seen, large commercial aircraft are responsible for more than the **96%** of CO2 emissions, splitting almost equally between single-aisle and dual-aisle segments. To a large extent, this distribution also fits with that of intra-European and intercontinental flights, and explains the relative reorientation, already mentioned, of decarbonisation efforts towards the introduction of SAF and the improvement of the efficiency of the bulk of air transport, to the detriment of disruptive technological solutions that would be limited, for the time being, to marginal segments.

This vision of the path to reach the net-zero CO2 emissions commitment of European aviation by 2050 is reflected in the updated estimates of the weight of the different decarbonisation solutions [5]. In the Figure 5 this prominent role of efficiency improvements and the introduction of SAF, as well as that of economic measures, can be seen both directly (e.g. through the emissions management system **EU ETS**), and indirect through the containment of demand.

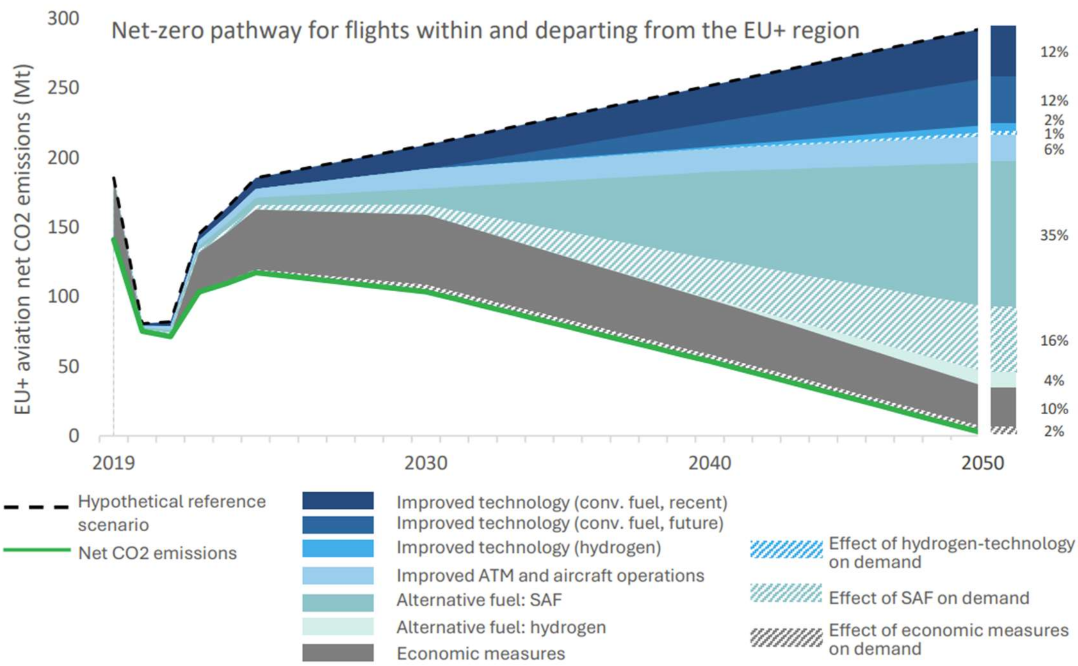

Figure 5. Roadmap towards the CO2 neutrality target by 2050 (Source: Destination 2050 [5])

In January 2025, the 4th edition of the **European Aviation Environmental Report** (EAER) prepared by the European Union Aviation Safety Agency (EASA) with the support of the European Commission, the European Environment Agency (EEA) and EUROCONTROL that analyses the progress in noise and emission reduction agreed at the European Union and ICAO level (with data up to 2023) in all areas that influence them [4]. The report reviews the challenges of the sector, the way forward in these areas, the latest scientific knowledge to mitigate noise and emissions, as well as future projections of air traffic and its environmental impact. EASA also published in 2025 the 14th edition of the European Aviation Security Plan (EPAS) setting out the strategic roadmap for aviation safety and environmental protection in Europe[xxvii].

On the other hand, thinking about the medium and long term, the research and development work of technologies that revolutionize commercial aviation, with the potential to eliminate greenhouse gas emissions, continues. In this area, the **European Union**, in the face of the aforementioned change of course in the US, continues to support this path with the **Clean Aviation programme**, which in 2025 resolved the 12 projects selected for its third phase, and which will mobilise a total of **€945 million**, of which approximately a third are European public funds[xxviii]. In addition, the fourth phase was also launched at the end of last year[xxix], still open to proposals, in a continuous effort to achieve a qualitative leap in emissions reduction (**30%** compared to 2020 levels), including hydrogen-powered aviation. The European effort in R+D to promote environmentally sustainable transport is materialized in projects such as **Path2Zero**[xxx], with which we collaborate from the **COIAE Sustainability Committee**.

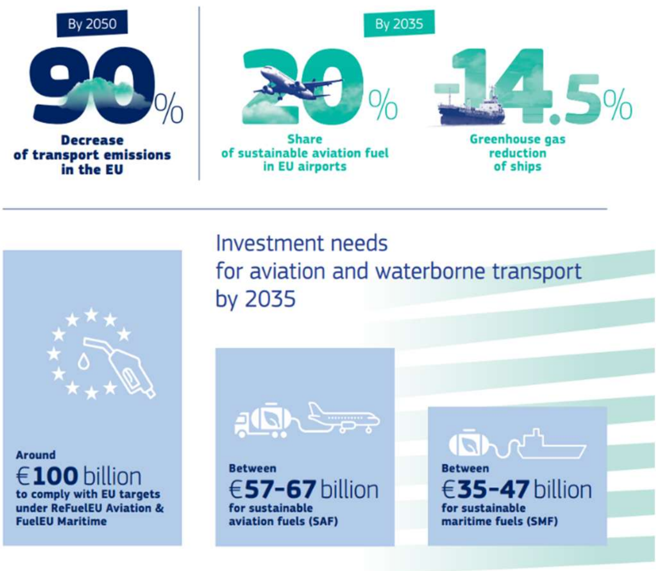

Figure 6. Main milestones of the Sustainable Transport Investment Plan of (Source: EC)

This contrast between the two sides of the Atlantic is even clearer with the launch by the European Commission of the **Sustainable Transport Investment Plan** (**STIP**)[xxxi], at the end of last year. The aim is to accelerate the energy transition of aviation and maritime transport, advancing in its decarbonisation, for which it is expected to mobilise **€2,900 M**. Among the most outstanding measures is the implementation of public mechanisms to mediate in employment contracts. **eSAF**, providing confidence for production investments (*double-sided auctions*). This synthetic version of sustainable aviation fuel, which does not depend on biomass for its production, did not appear to be making adequate progress towards the quotas indicated within the mandate **RefuelEU**. The production of other sustainable fuels, including green hydrogen, will also benefit. This strategy is complemented by measures that include the promotion of technological innovation, and the initiative to strengthen the emissions market **EU ETS**.

2.3. BEYOND CO2

In recent years, clear progress has been made towards understanding the environmental impact of aviation beyond carbon dioxide emissions. The effects of contrails, nitrogen oxides (NOx) and other emissions are finally being included in sustainability assessments in air transport. In this sense, new open-use tools include these elements, such as **Google's** Travel Impact Model[xxxii], or the **University of Surrey**'s ATP-DEC[xxxiii], providing more accurate and complete information for passengers, airlines and even regulatory bodies. On the other hand, this does not mean that interactions that are not yet well modelled are not being investigated, such as that of suspended material particles with cirrus clouds of natural origin[xxxiv], or the formation of contrails in SAF-powered aircraft, including in-flight measurements as in the **European A4Climate**[xxxv] projects. and **Crystal**, a collaboration between **Airbus** and Canadian entities launched in 2025[xxxvi]. In fact, the European manufacturer also announced last year the **PACIFIC** project, a similar investigation by the engine manufacturer **Rolls&Royce**, to evaluate the potential of sustainable aviation fuel in mitigating the formation of *contrails*[xxxvii], which could be around **25%.**[xxxviii]

Another of the ways identified to resolve the climatic impact of contrails is that of avoidance to avoid atmospheric ice supersaturation zones (**ISSRs**), which are key to their formation. Various studies[xxxix] and tests of real traffic management[xl] support this strategy, in which the additional fuel consumption due to the change of route is amply compensated, in environmental terms, by the reduction of *contrails*. In fact, this is one of the actions with the greatest potential to reduce, significantly and in the short term, aviation's contribution to global warming[xli]. Thus, in a trial carried out with flights on the Paris-Valladolid route, the environmental benefit of the direct route diversion was estimated at up to 40%.[xlii]

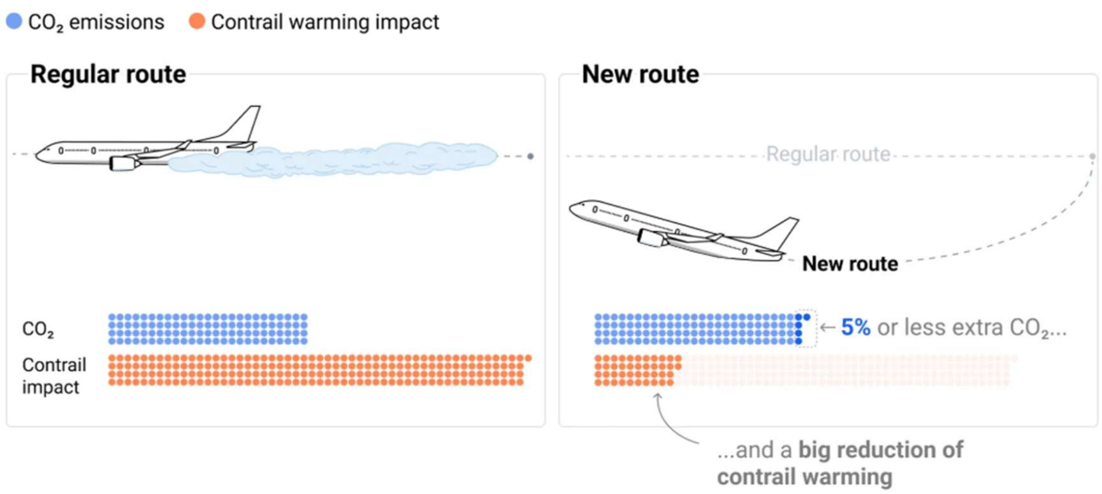

Figure 7. Evaluation of route deviation strategy to mitigate constellation wakes. (Source: T&E)

The United Kingdom, through its ATI agency, also announced in November 2025 the first projects to be funded through its ***Non-CO2 Programme***[xliii], demonstrating the growing interest in this problem. In fact, in what was a major milestone at the European level, the obligation to monitor, report and verify (**MRV**) of Non-CO2 effects on intra-EU aviation[xliv] also came into force in 2025, for which airlines were provided with the **NEATS** tool. This is a fundamental step for the future inclusion of this type of emissions within the umbrella of the **ETS system**.

3. ACTIONS, INNOVATION AND TECHNOLOGY

3.1. EMISSIONS OFFSETTING AND ECONOMIC MEASURES

3.1.1. Compensation

During the last year, and in the face of the doubts raised by other more consolidated channels[xlv], there was an increase in interest in emission compensation measures based on CO2 capture. Not surprisingly, during **COP30**[xlvi], the first global register of carbon dioxide storage facilities was presented[xlvii]. Despite the undeniable promise it represents as an offsetting tool, it cannot be ignored that many of these projects use the injection of CO2 underground to facilitate oil extraction, which would degrade their net carbon balance.

In any case, the environmental benefits of **CCS** (*carbon capture and storage*) can be developed in parallel with the rest of the decarbonization strategies[xlviii]. Research into the recycling of CO2 in fuel continues, with the emergence of new technological paths, some of them developed in Spain[xlix].

3.1.2. CORSIA AND EU ETS

2025 was a transitional year in the evolution of the two main aviation emissions offset schemes. On the one hand, **EU ETS,** the European *cap and trade* system , continued to reduce free emission permits for airlines, with the associated cost increase, and which will be completely eliminated in 2026.

On the other hand, the mechanism of *offsetting* **CORSIA** (included in Annex 16 Vol. IV of the Chicago Convention), which covers emissions on international flights under the supervision of the **ICAO**, made progress in its implementation with the collection of data for the first year of its first phase (2024-2026), in which most of the world's countries are already participating, although with some significant absences (see Figure 8). This is a fundamental milestone, as it confirmed the functionality of the monitoring, communication and verification system of emissions (**MRV**), as well as the CORSIA Central Emissions Register (**CCR**).

In 2025, 128 countries voluntarily reported their emissions for 2024, which exceeded by one **15%** the threshold set of **361 Mt CO2** (85% of the emissions recorded in 2019, see [2]), and which are the first to begin to be compensated within the system **CORSIA** from the end of 2027[l]. On an annual basis, ICAO and participating countries will communicate to airlines their compensation obligations based on the data received. The International Air Transport Organization (**IATA**) estimates that the cost of this first phase of compensation will exceed **$4 billion**[li]. Despite this estimate, and as far as European aviation emissions are concerned, the requirement of the EU ETS system far exceeds that of CORSIA, and it is estimated that a volume of emissions seven times higher would be covered if it had been applied to non-EU flights instead of ICAO regulations[lii].

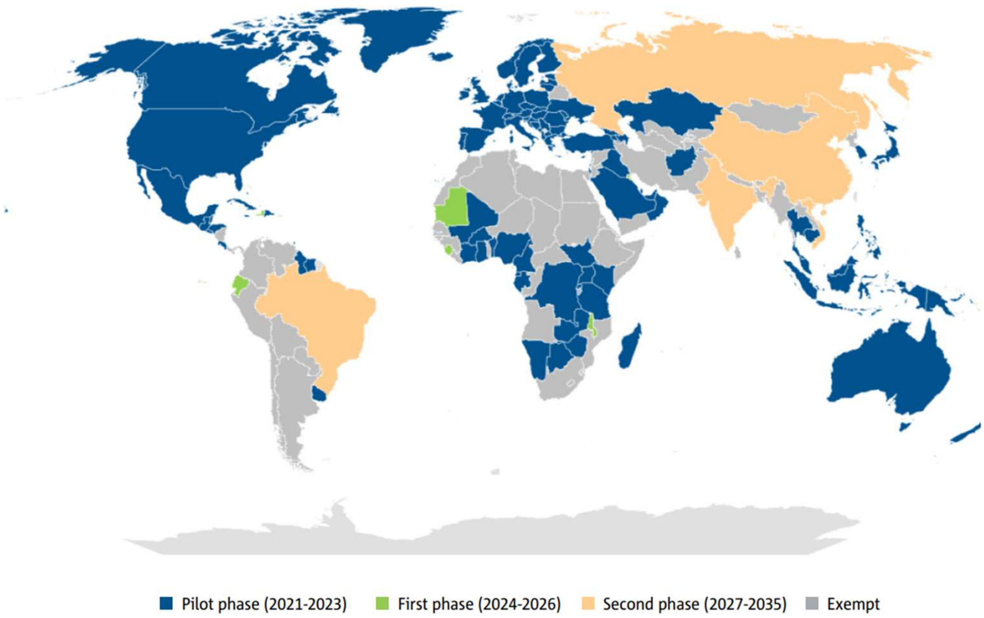

Figure 8. Countries participating in the CORSIA emissions offsetting system. (Source: EASA)

This comparison is even more important as it comes on the eve of the revision of the transitional agreement coordinating the implementation of EU ETS and CORSIA in Europe (*stop-the-clock* and *clear-cut* decisions) in July 2026. It should be recalled that, under this framework, intra-European issuances remain subject only to EU ETS, while flights departing from the European area must comply with CORSIA requirements. Many voices are calling for more environmental ambition to extend the undeniable success of European regulations to all flights taking off from EU soil, regardless of their destination. The proceeds of the EU ETS remain in the European Economic Area and are used to finance decarbonisation policies, promotion of renewable energy and adaptation to climate change. On the other side of the scale, we must consider the greater economic burden it would place on airlines, in addition to the fact that it would put the EU on a collision course with ICAO, and especially with some of its member countries, in particular the US[liii].

On the other hand, a worrying lack of Eligible *Emission Units (EEUs*) has been identified within CORSIA[liv], which could jeopardize the viability of the system. EEUs, in units of one ton of carbon dioxide, are generated with suitably certified decarbonization projects, and their acquisition by airlines allows aviation emissions to be offset. The lack of supply could send its share price soaring, which some analysts say could reach as high **as $50**, significantly cutting companies' profits as early as 2026[lv]. *Cap-and-trade* mechanisms such as EU ETS work differently, setting a total limit, distributed among the different industrial sectors included in the system (industry and power generation, aviation and maritime transport). An internal market is then established with auctions in which companies acquire the necessary emission rights.

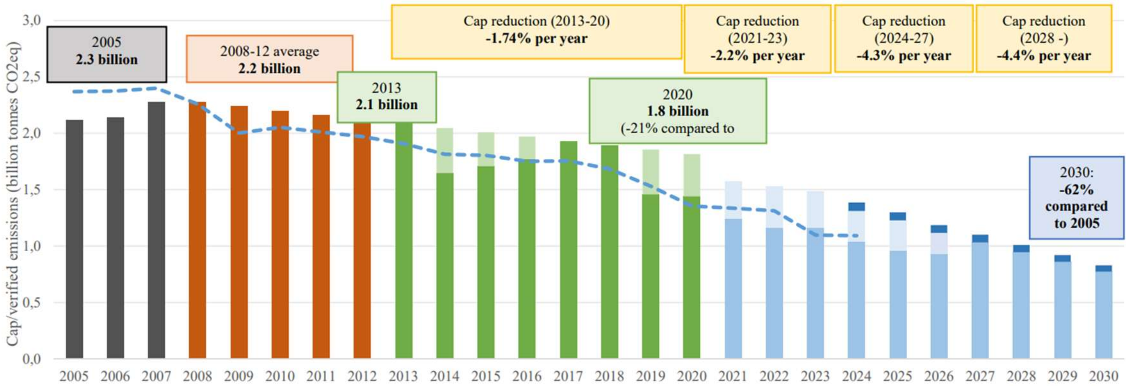

Figure 9. EU ETS. Total limit (bars) vs. verified emissions (line). Changes due to the progressive reduction of the total, but also due to the inclusion of new sectors (e.g. maritime transport in 2024) ([6])

The price of these emission allowances offered by the system (see Figure 10), is also a key aspect in motivating companies to decarbonise, but without causing an excessive economic burden. To this end, stability mechanisms are established, which inject or withdraw credits as necessary.

If, as already noted, the transitional measure of providing a number of free emission credits to aviation is already coming to an end, **EU ETS** began in 2025 to promote the use of **SAF**[lvi]. In total, 20 million units have been set aside to subsidize the purchase of sustainable fuel by airlines.

This mechanism will cover at least **50%** of the cost, reaching **70%** for advanced biofuels, and up to **95%** in the case of e-SAF. This initiative highlights both the flexibility and capability of the EU ETS system, as well as the economic challenge of introducing sustainable fuels in air transport.

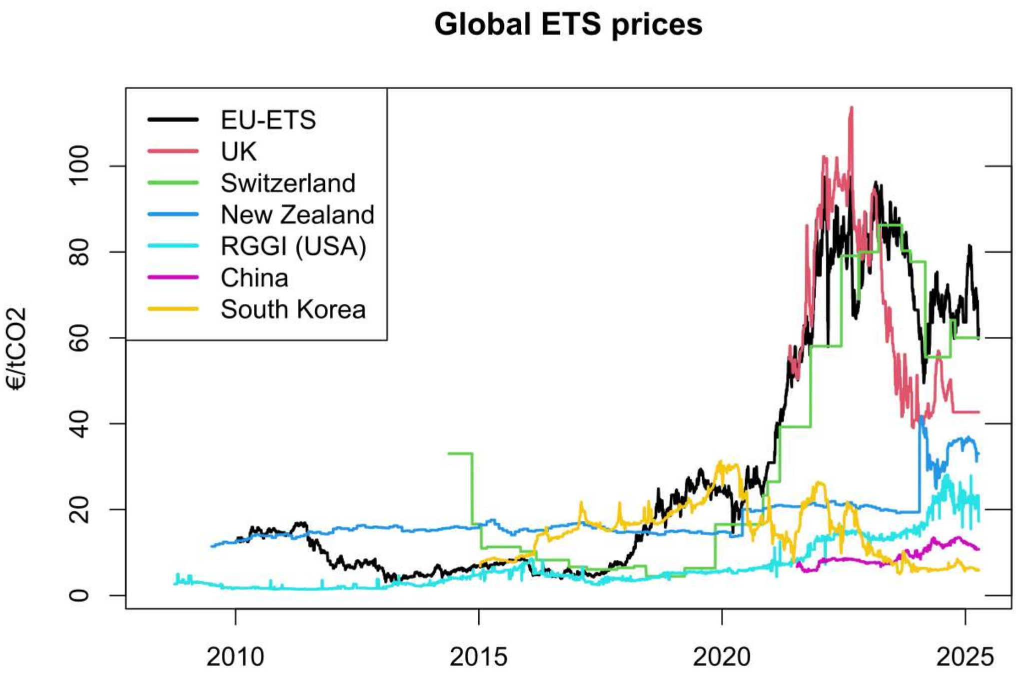

Figure 10. Price evolution in different emission markets. (Source: Wikipedia)

3.1.3. Policy measures and demand management

Aviation fuel has traditionally been duty-free in what is in fact, as argued by certain quarters, a disguised subsidy when compared to other modes of transport. Moreover, the need to raise funds to finance the transition to sustainable aviation has put the spotlight on different possibilities to address this reform [13]. Among other bodies, the **International Monetary Fund** He suggested implementing an effective taxation system, for example, through emissions, to help this transformation. Needless to say, proposals of this nature have met with strong reluctance within certain members of the **ICAO**[lvii].

One of the proposals that generated the most buzz in 2025 was the **Global Solidarity Levies Task Force**[lviii], presented in Seville in June last year, and backed by countries such as Spain and France[lix]. Under the principle that "those who pollute more, should pay more", he proposes taxes for the preferential classes and private aviation. These commercial aviation sectors contribute proportionately well above average to pollutant emissions, which would justify this penalty.

In the background, there is also the debate on demand management, although there is no evidence that aviation taxes have a significant impact on the volume of air passenger traffic[lx]. In this area, the debate and initiatives on the prohibition of domestic flights with a fast rail alternative continued during 2025, the environmental effectiveness of which was previously questioned here [3]. In fact, the preliminary draft of **Sustainable Consumption Law** in Spain it includes this possibility[lxi], enthusiastically supported by environmental organizations[lxii]. One of the main arguments for continuing to expand air traffic has also recently been called into question: increasing passenger volumes in a region does not directly generate economic growth[lxiii].

3.2. NAVIGATION, OPERATIONS, AIRPORTS AND NOISE

3.2.1. Navigation and operations

The continuous improvement in energy efficiency during aircraft operations, whether during flight, in the take-off, approach and landing phases, or in the taxiing phase at or already at the airport, has contributed decisively to containing the level of emissions and climate impact of aviation in a context of continuous growth in air traffic. The **Observatory of Safety, Efficiency and Sustainability of Air Operations**, set up by the state manager of air navigation in Spain (ENAIRE) together with the Association of Commercial Aviation Pilots (COPAC) and the Professional Association of Air Traffic Controllers (APROCTA), found an average reduction of 120 kg of CO_2 emissions per flight in the first six months of 2025[lxiv].

This figure represents a total reduction of 356 tonnes of emissions in this period, due to the progressive incorporation of new flight procedures, and the good professional practices of pilots and controllers, which have contributed to the improvement of the efficiency and sustainability of flights.

This is also corroborated by a report published in 2025 by the aviation analysis company **Cirium**[lxv]. Specifically, the data show an improvement in the **7,4%** in fuel consumption efficiency per kilometer and seat over the last 6 years. This data is the result of comparing emissions peaks in 2019 and 2025, when the daily record was broken due to commercial aviation (Figure 11). Finally, it should be noted that the average carbon intensity reflected compares very positively with respect to road transport [1].

Date	CO_2 Emissions (mt)	Flights	Avg. Flight Distance (km)	Avg. Air Min.	Avg. Flt. Weighted AC Age (yrs)	Avg. Seats	ASK (m)	CO_2/ASK (g)
02-Aug-19	2.520	99,327	1,579	136	9.9	167	31,825	79.2
18-Jul-25	2.523	103,009	1,626	138	11.6	175	34,420	73.3
% Diff	**+0.1%**	**+3.7%**	**+3.0%**	**+1.3%**	**+16.7%**	**+4.4%**	**+8.2%**	**-7.4%**

Figure 11. Comparison between aviation emissions peaks and CO2 intensity in 2019 and 2025. (Source: Cirium)

This greater efficiency in air transport is largely based on the renewal of fleets, but also on other factors such as the expansion of computer systems that help monitor and optimize aircraft operations. On the airport side, tools of this type are also being introduced, such as the one presented last year by the Swiss group **Assaia**, and which will be initially installed at Copenhagen airport[lxvi]. This system, based on cameras and AI, will capture the real use of APUs in aircraft on the ground, providing electrical power in the cabin. With the data collected, improvements and modifications to the protocols can be implemented, in order to improve access to energy outlets and reduce emissions.

On the old continent, mention cannot be missed in this area of the slow but steady path towards the integration of the single European sky. In addition to the continuity of funding for programmes to improve air management, the **SESAR consortium** published its **Roadmap 2025** to guide the organisation of aircraft traffic towards the **European Digital Sky**, with broad support from the industry[lxvii].

In October, the Single European Sky **(EES) Performance Review Board (PRB)** published its 2024 Annual Monitoring Report[lxviii], analysing the performance of the EES's air navigation services compared to revised targets following the COVID-19 pandemic, and traffic restrictions that severely affected European and global aviation.

With regard to Spain, in September the Spanish Performance Plan for the fourth reference period 2025-2029 (ESPP4) prepared by AESA was adopted[lxix]. Following an evaluation of the draft plan by the European Commission, updates to it are incorporated to fully comply with the requirements established in the Implementing Regulation, including the evaluation of performance and pricing in the Single Sky.

3.2.2. Airports

Remote digital tower installations are revolutionizing air traffic control operations, improving operational efficiency, safety and flexibility of ANSPs[lxx], air traffic management, and reducing carbon emissions. This is achieved by allowing the aerodrome control service to be provided at one or more airports, but from a remote location, as in the case of the digital remote tower at Budapest airport or the remote tower centre, located in Bodo, Norway[lxxi]. Helsinki Airport in Finland and Rajiv Gandhi International Airport in India earned the highest level 5 of the ACA Program[lxxii]. This indicates that both managed to reduce more than 90% of their direct emissions (Scope 1 and 2). At the national level, three Spanish Aena airports have reached level 4 after the last evaluation to which the nine that already participated in this program have been subjected. These were those of Barcelona-El Prat, Madrid-Barajas, and Palma de Mallorca-Son San Juan. The other seven have maintained their previous level[lxxiii].

Finally, among the multitude of initiatives to improve sustainability at the airport level, it is worth highlighting the originality of the company **Catalsys**, proposing the supply of green ammonia as an energy vector. This easily transportable compound would then be partially broken down into hydrogen, and the mixture would be used in electric generators. Looking at the long term, this system could even be used for aircraft refueling[lxxiv].

3.2.3. Noise

In 2025, ICAO published the recommendation for new standards **CAEP/13** already mentioned. For subsonic aircraft, from 1 January 2029 the proposed standards in the new Chapter 16 will require an additional margin of 6 decibels of effective perceived noise (EPNdB) for larger aircraft and 2 EPNdB for small aircraft, compared to the current Chapter 14 rules. Future supersonic aircraft will have to comply with noise limits equivalent to those of Chapter 14 from 2029. Both sets of standards will be applied by national governments as airworthiness requirements only for new type certifications[lxxv]. In any case, it is worth highlighting the continuous improvement in noise performance with the successive ICAO regulations (Annex 16 Vol. I) as shown by the Figure 12. It is worth remembering that the main sources of noise in aviation come from the propulsion system and the airframe (Figure 13).

In the research to develop noise reduction technologies in recent years, the following initiatives stand out:

- Significant efforts made in all research programmes to provide cell noise reduction solutions, in order to complement the planned engine noise reductions. This is consistent with the now very significant importance of cell noise sources under approach conditions.
- A renewed focus on acoustic engine cladding technologies to accommodate future engine and nacelle integration constraints (low-frequency sources, reduced available space, low weight requirements).

Figure 12. Reduction of noise limits for aircraft certification since 1990 (Source: ICCT)

Among the most recent technological advances to mitigate cell noise, an emerging strategy is the use of porous materials in aerodynamic surfaces. It is mainly applied to the leading and ejecting edges of hyperlift devices, although it can be used in general in any profile. A practical example is that of the wings with circulation control, which offer a significant increase in lift, and where the porous material at the end of the flap contributes to noise control [7].

Other avenues of research include biomimicry, or nature-inspired engineering, to harness the characteristics of the feathers of the barn owl, capable of surprisingly quiet flight, and thus generate noise reduction strategies in airfoils [8]. In this way, replicating their configuration, it was shown that fins mounted upstream of the trailing edge can be effective in reducing aerodynamic noise [9].

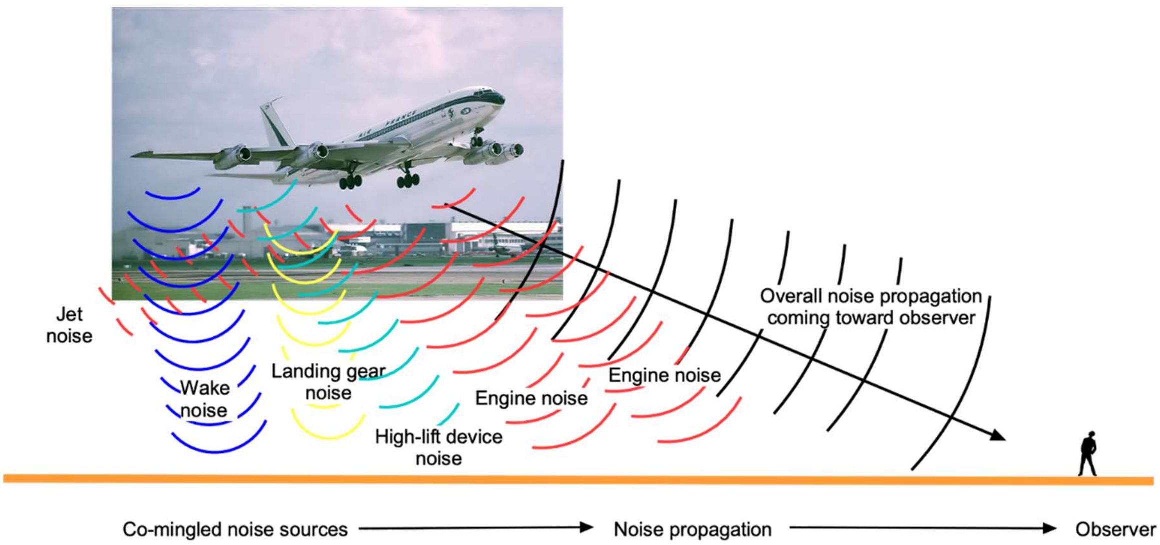

Figure 13. Noise generation in landing or take-off operations (Source: Embry-Riddle)

When it comes to engine noise, the new ultra-high bypass ratio (**UHBR)** turbofans will make major changes to the conventional architecture from a noise perspective. The fan frequency spectrum will be expanded, with a drastic reduction in the frequency of the tones, while broadband noise will remain significant at higher frequencies. The next-generation nacelles, too, will have a lower liner length-to-diameter ratio, in order to reduce weight, so the acoustic dampers need to be more efficient to maintain the current noise level.

One promising solution is micro-perforated panels for tonal, wideband, and low-frequency noise reduction. It is an innovative design that is constantly being improved [10], which addresses the bandwidth limitations of traditional absorbers, thanks to a compact and lightweight panel structure that uses variable chamber depths, and a unique porosity per chamber.

Finally, it is worth highlighting the progress made with **Metamaterials**[lxxvi], artificial compounds that scale to a size less than the wavelength, and which have demonstrated enormous potential in different applications for noise control in aircraft [11]. There are different ways to exploit this new mitigation paradigm, which includes the absorption or reduction of noise, but also its reflection in directions that are harmless to the receivers.

Among the multidisciplinary projects that have recently addressed the problem of noise in aviation we can mention **AERIALIST**[lxxvii], focused on the application of metamaterials, and **ARTEM**[lxxviii], in which different attenuation concepts were explored. Both were launched within the European Horizon **2020 research and innovation programme**.

3.3. GRADUAL AND DESIGN IMPROVEMENTS IN AIRCRAFT

3.3.1. Gradual innovation

As already noted, the continuous improvement in the efficiency of passenger aircraft, taking the introduction of jet engines as a reference, has been a determining factor in containing CO2 emissions in aviation in the face of the continuous increase in air traffic. As a reference, the figure of **1,3%** in reduction of specific consumption, the result of averaging the advances of the last decades [12]. In absolute terms, the average carbon dioxide emissions in 2025 data of the airline conglomerate IAG can be taken: **77,5 gCO2/pax·km**, a value clearly lower than that of private road transport [1].

This achievement has been mainly due to gradual improvements in both propulsion and aerodynamics and the use of new, increasingly lighter materials in the structures. Gradual improvements are thus essential to continue improving the environmental performance of aircraft. This progress has been reflected in the aforementioned ICAO regulations, which are increasingly restrictive with regard to pollutant emissions, and whose latest regulations (**CAEP/13**), is an incentive to continue with this continuous process of increasing energy efficiency. The new regulations, which vary depending on the maximum take-off weight of the aircraft, have two levels of requirement in terms of CO2 emissions (Figure 15), one for application for models in production, and the other for new designs.

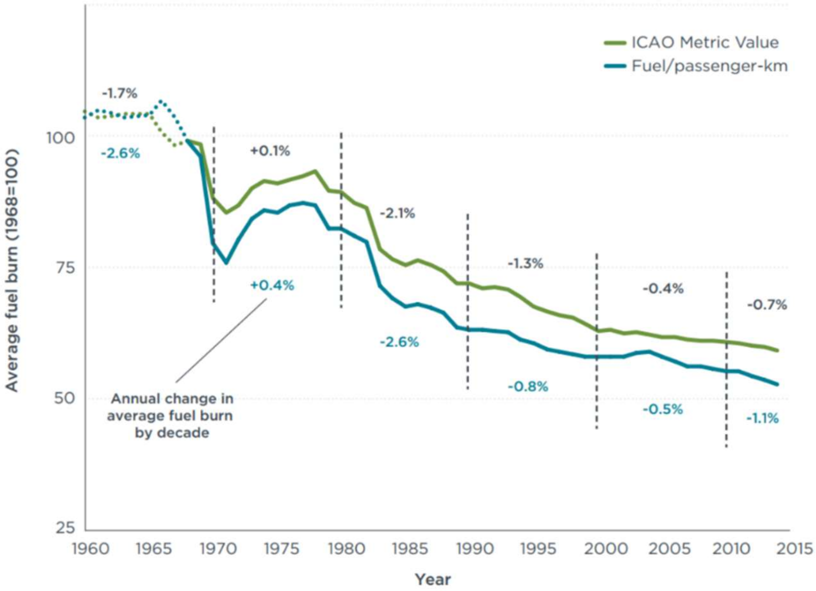

Figure 14. Evolution of average fuel consumption in new aircraft 1960-2014 (Source: ICCT)

Among the large construction companies, **Airbus** is ahead of the curve in certification with a view to the deadline imposed in Annex 16 Vol.III (CAEP/10) for aircraft currently under construction in 2028. On the other hand, in the part that touches new designs, since the corresponding regulation came into force in 2020, no new model has been certified [4]. In fact, the undeniable gradual improvement in efficiency comes up against a period of more than 20 years where designs from scratch have not prospered. This fact, understandable in view of the growing economic and certification effort it requires, is a clear impediment to the transition to more sustainable concepts[lxxix].

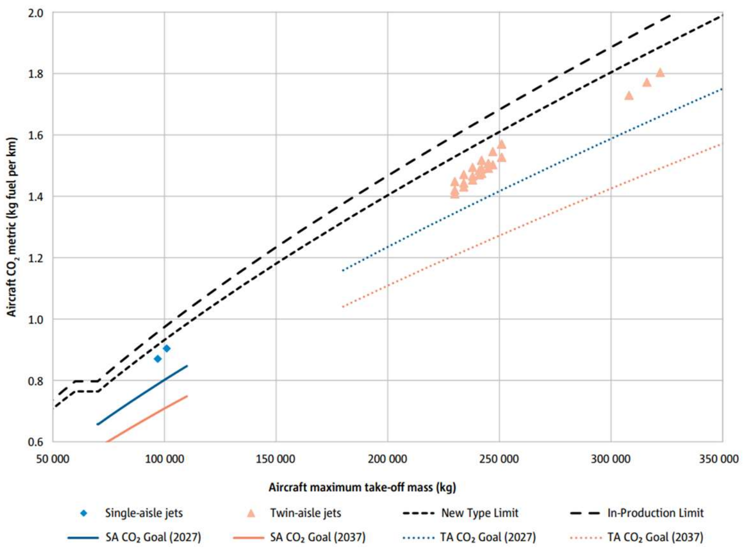

Figure 15. Aircraft in production certified to ICAO emissions standards [4] (Source: EASA)

This logic of renewing existing models is what animates the **D328eco** project, focused on sustainability and the use of SAF. The German company **Deutsche Aircraft** continues to make progress in updating this old design, with the presentation of the first full prototype in 2025[lxxx], and flight tests scheduled to start in 2026.

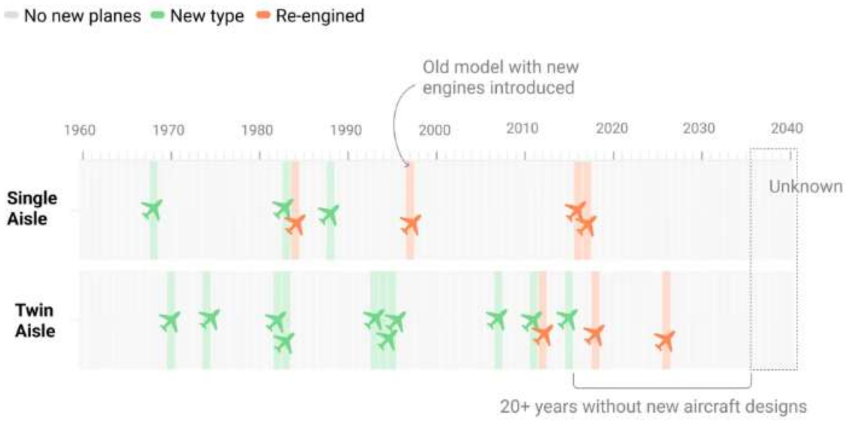

Figure 16. Introduction of new commercial aircraft designs since the 60s (Source: T&E)

This pause in new projects in recent years does not mean that there are not a multitude of proposals on the table under consideration (see a sample at Figure 17). Both dominant manufacturers and numerous start-ups are still looking for the right concept and market niche, both for commercial success and for a new leap in environmental actions. In the case of the European company **Airbus**, the readjustment in its commitment to H2 propulsion has opened the possibility of launching a new conventional design, deepening structural and propulsion improvements and full adaptation to SAF[lxxxi].

Figure 17. Some of the proposals considered for new aircraft designs[lxxxii] (Source: Leeham Co.)

Gradual advances in reducing emissions take multiple forms, from taxi systems on the ground with electric motors in the landing gear, an idea already explored in the past but gaining strength again[lxxxiii]; to advanced coatings for the external surfaces of aircraft. In 2025, the expansion of the "shark skin" continued[lxxxiv], which reduces aerodynamic drag, but also the introduction of a new type of lightweight paintwork, with the consequent decrease in overall weight[lxxxv]. In both cases, the decrease in fuel consumption directly implies less carbon dioxide released into the atmosphere.

3.3.2. New designs

The great leaps in energy efficiency usually occur with the introduction of new concepts in the configuration of the aircraft, in its propulsion, or in the aerodynamics of the whole. As an example, we are going to describe three sustainable aviation projects in these areas that made headlines, although with different fortunes, in 2025. The first of them seeks to introduce a type of aircraft architecture with recognized efficiency advantages, but with very difficult application in commercial aviation: the flying wing or integrated with the fuselage[lxxxvi]. The JetZero company has been making progress in its program for years, and gathering support inside and outside the industry[lxxxvii].

Figure 18. JetZero has received investments and orders from companies such as United Airlines (Source: JetZero)

In 2025 it successfully completed the milestone of the *Critical Design Review*, where the technical feasibility of the design is checked in detail[lxxxviii]. The capacity of the aircraft would be over 200 passengers, and a range of 9,200 km. The expected reduction in emissions, when compared to a conventional equivalent aircraft, could reach a staggering **50%.**

Another concept that has also been known for some time is that of improving propulsion efficiency by injecting water into the air flow of engines. The leap in sustainability proposed by the **MTU engine company** with its *Water-Enhanced Turbofan* (**WET)** came from recovering the water from the combustion of kerosene, and reintroducing it at the beginning of the cycle. This solution would not only reduce consumption (**10-15%)**[lxxxix] and, therefore, CO2, but also mitigate other emissions such as nitrogen oxides, and even the production of contrails.

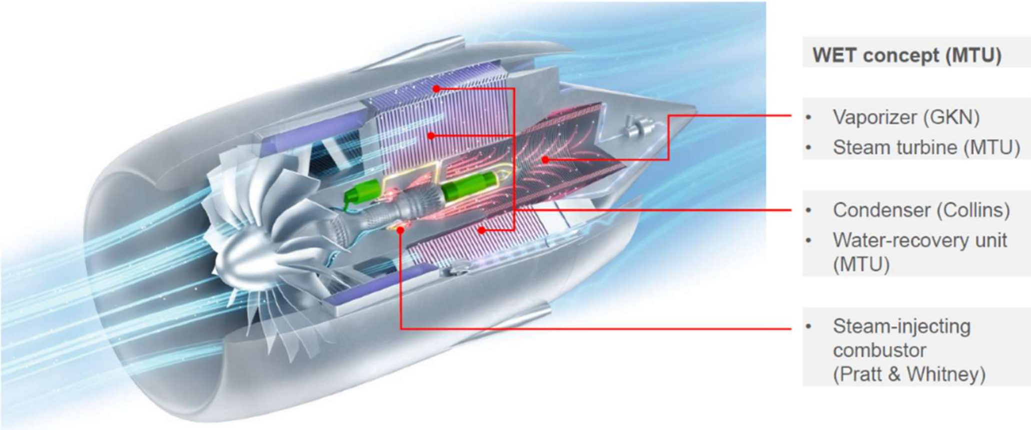

Figure 19. MTU's WET Water Recovery Turbofan Concept (Source: Leeham Co.)

Despite these advantages, and the support of European public funding[xc], the German manufacturer cancelled the project last year, in a decision motivated by the fact that the improvement in efficiency does not compensate for the development and certification of a certainly complex engine architecture, in addition to an increase in weight. Curiously, as we will see in the 3.6.3, a very similar design strategy does look really promising for the case of hydrogen combustion propulsion.

Finally, the company **Otto Aviation** continues its development of models that seek aerodynamics with a passive laminar boundary layer, a product directly of the shapes in the design. The significant reduction in drag, and therefore in consumption and emissions, could reach **35%,** according to the wind tunnel results, in its new proposal for business aviation[xci].

Figure 20. Otto Aviation's Phantom 3500 model, without windows to maintain laminar flow (Source: Fly-news)

3.4. SUSTAINABLE FUELS

3.4.1. Background

The analysis of the sectoral information published during 2025 allows us to identify the real state of maturity of sustainable aviation fuels, and to interpret the dynamics observed in the market. **SAF**[xcii] is currently the main lever available for the decarbonisation of air transport in the short and medium term. Thanks to its *drop-in* nature , it can be used in existing aircraft and infrastructures, provided that its quality and sustainability are accredited by internationally recognised certification and traceability schemes[xciii].

The regulatory framework in force in the European Union includes the regulation ***ReFuelEU Aviation***[xciv], which sets out increasing mandates for the incorporation of sustainable aviation fuels, starting with a **2 %** in **2025** and reaching the **70 %** in **2050** (Figure 21). The regulation also incorporates a specific sub-mandate for synthetic fuels (**eSAF**), and is complemented by the European Emissions Trading System (**EU ETS**) and with the Renewable Energy Directive (**RED III**). Despite certain difficulties and criticism of its entry into force in 2025, partly due to the complex international context, the European Commission remains fully committed to this key measure for the decarbonisation of commercial aviation in Europe[xcv].

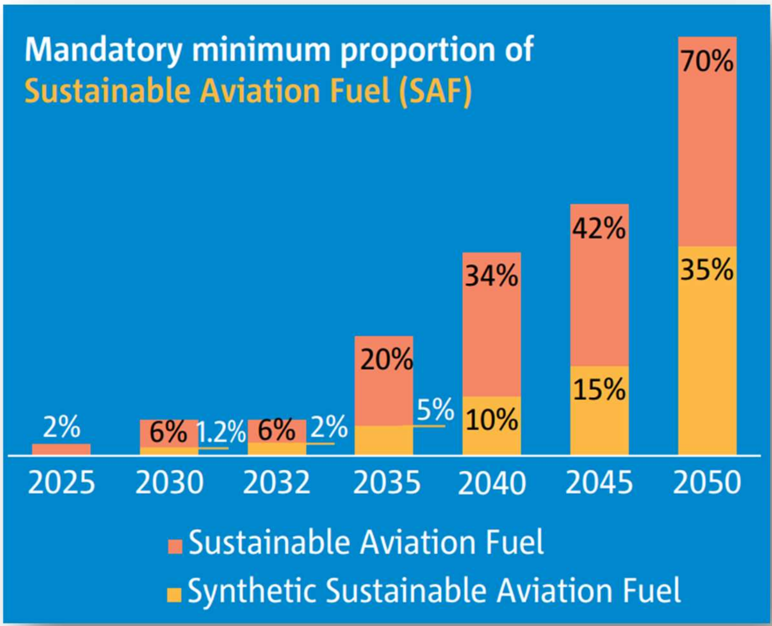

Figure 21. Mandate for the incorporation of SAF in the European Union (Source: [4])

Globally, the ambitious goal of reaching **10%** SAF by 2030, self-imposed by the International Airline Association (**IATA)** itself, was also called into question due to the slow rate of increase in production[xcvi]. IATA's position is in line with the reluctance already discussed regarding sustainability and emissions offsetting requirements for airlines, although without giving up on achieving the ultimate goal of carbon-neutral international aviation by 2050.

Finally, the year 2025 confirms the regulatory and technological progress of sustainable aviation fuels, but also highlights structural challenges: limitations in the scalability of **bioSAF**, commercial immaturity of efuels, and cost tensions in the value chain. A balanced combination of mandates, economic incentives, regulatory coherence and robust traceability systems will be decisive in consolidating air transport's transition towards a climate-sustainable model.

3.4.2. Biofuels

During the past year, the SAF used commercially was mostly of the biofuel type, produced from used cooking oils (**UCO)**[xcvii] and animal fats. Within BioSAF, the **HEFA** route currently dominates production. However, various analyses published during 2025 warn of limited scalability (*tipping point*) over the medium-term horizon, due to the lack of sustainable availability of raw materials[xcviii], and in the context of growing demand due to regulatory mandates. At the same time, post-HEFA routes, such as *Alcohol to Jet* (**ATJ),** are beginning to consolidate, with the crucial milestone of the start-up of its commercial-scale production from ethanol[xcix].

This achievement is a positive sign in the transition to alternative routes, expanding the potential range of raw materials, and improving the resilience of the supply system as a whole. In short, **bioSAF** is consolidated as the only solution available on a commercial scale in the short term, with a majority use of waste raw materials. This reality confirms that, despite the growing interest in synthetic fuels, the immediate implementation of mandates depends almost exclusively on mature biological routes, with a high geographical concentration of supply, and a significant dependence on raw material imports. This situation reinforces the need to diversify routes and raw materials to avoid structural bottlenecks in the system.

Figure 22. Inauguration of Lanzajet's ATJ industrial plant (Source: GreenAir)

3.4.3. Electrofuels

As for synthetic fuels, considered essential to meet the long-term decarbonisation objectives of the aviation sector, their progress in 2025 was still very modest, although with significant achievements[c]. Also known as *Power-to-Liquid fuels* (**Damn it**), its implementation is still in a very incipient phase, without commercial volumes, despite the high number of projects announced at European and global level[ci]. Its deployment is conditioned by high production costs, and by critical dependencies on the supply of CO_2, sustainable hydrogen and electricity from renewable sources. The sectoral consensus points to the need for specific public mechanisms to reduce risks and close the cost gap. Along these lines is the aforementioned European mechanism to support the production of eSAF (Section 2.2), launched late last year.

It is interesting to note that the development of a powerful e-fuel production sector can be approached as an opportunity, not only in environmental terms, but also in terms of competitiveness and energy independence for the old continent[cii]. Thus, during 2025 there was a proliferation of announcements of eSAF projects in Europe, driven by the sub-mandates included in **ReFuelEU Aviation**, although still mostly in pilot or demonstration phases, with reduced scales and the absence of industrial plants that allow, for now, a relevant contribution to the aviation fuel mix.

Finally, as already indicated, a message widely shared by industry and various analysts seems to prevail: the effective deployment of *efuels* will require specific public support mechanisms to close the cost gap compared to conventional kerosene and reduce the risks associated with first-generation projects. Without these instruments, final investment decision-making will continue to be limited, compromising the future availability of the eSAF needed to meet the post-2030 targets.

3.5. ELECTRIC AVIATION

3.5.1. Background

Electric aviation refers to the use of electric propulsion systems—powered by batteries, fuel cells, or hybrid configurations—to replace or complement traditional petroleum-based aircraft propulsion systems.

This emerging field encompasses a wide range of aircraft types, from small eVTOL vehicles[ciii] to larger fixed-wing aircraft. It should be noted that the small **Pipistrel Velis Electro**, the first electric model certified as early as 2020, has sold more than 150 units. Thus, these technologies offer the potential for quieter, cleaner and more efficient alternatives, with applications in both urban and regional transport networks. As advances in energy storage, electronics and lightweight materials continue to accelerate, electric aviation is generating expectations in the light and short-range aviation sector.

Figure 23. Proposal for an EVIO hybrid-electric model for regional transport (Source: Evio Aero)

Throughout 2025, there has been notable progress in this segment, particularly in the vertical take-off and landing aircraft sector (popularly known as "electric taxis"), driven by initiatives for urban electric mobility. It should also be noted that the year 2025 has been marked by significant crises and challenges in the sector, including the aforementioned cases of the freezing of the **Eviation electricity project** [civ] and the bankruptcy of **Lilium**, which was subject to serious liquidity problems and ended with the liquidation of the company. Incidentally, its battery production unit was later acquired by the company **Vaeridion**, which reinforces its Microliner electric regional aircraft project, currently under development in collaboration with **Deutsche Aircraft**[cv].

Figure 24. Vaeridion Microliner electric regional model proposal (Source: AIN)

Although other companies in the sector are also suffering from a lack of financing, it should be noted that, in other cases, particularly in US projects, they continue to receive great investment support[cvi], even from the military sector. Economic support and some slack in available liquidity is key to maintaining engineering work and preparation for production, while waiting to be able to certify the aircraft and start delivering the first examples to customers. A symptom of this uncertainty in the field of electric aviation was the aforementioned reorganization within the aeronautical conglomerate **Textron**, owner of the **Pipistrel** brand, which dismantled its electric aviation division, distributing its assets among other areas[cvii].

3.5.2. Batteries

Electric aviation has always been conditioned by the slow progress in the development of high energy density batteries, anchored in the 250 W·h/kg standard of current lithium-ion units. This limitation prevents the expansion of its performance (payload – radius of action) compared to aircraft with conventional propulsion. However, during the last year there was again positive news, which includes not only laboratory results but, very importantly, also commercial developments.

In fact, the specific energy limit seems to have been exceeded in batteries for aeronautical use, and this is attested to by the launch on the market of the improved version of the **SiCore model** from **Amprius Technologies**, which nominally reaches **450 W·h/kg**. In addition, the battery expert company announced that the performance of this unit, in terms of power and discharge speed, make it ideal for electric aviation applications[cviii].

In the same vein, the electric powertrain company **Magnix** continues to make progress in the capacity of its **Samson** family of batteries. If in 2024 it debuted with a model with a specific energy of 300 W·h/kg, in 2025 it surprised with the announcement of a **400 W·h/kg version**[cix].

To end the advances in this area, now at the research level, MIT announced a new concept of **metal-air** battery, based on liquid sodium, that could revolutionize electric aviation, with laboratory tests that yielded a specific energy consistent with **1,000 W·h/kg** at the complete [cx]system level. Although the capacity of this architecture has been well known for some time, the problems appeared on a practical level due to the difficulty in recharging the devices.

In this new approach from the MIT group, **sodium** is simply renewed once consumed, which would actually turn the system into a fuel cell. This would bring an additional benefit, as emissions would consist of sodium oxides, which would combine with CO2, thus removing it from the atmosphere. The researchers, who argue that the system would be inherently safe, are already taking the next steps for its industrial-level rollout, including the metal's supply chain, which is widely available in nature.

Another achievement achieved last year came from the Swiss company **H55**, which successfully completed certification tests of its propulsion battery module under **EASA** supervision in December, in what is a milestone for electric aviation[cxi]. With a duration of more than 6 months, these tests confirm the safety of the batteries in case of failure, and their safe operation under any operating conditions. This model is intended for installation in BRM **Aero**'s **CS23** category project. Finally, in an announcement at last year's Paris Air Show, **Dovetail Electric Aviation** and **Engineered Fluids** presented their collaboration to produce a dipped battery cooling system, which would significantly reduce the weight and volume required for thermal control of batteries[cxii].

Figure 25. Testing of a sodium-air electrical system for the creation of electric current (Source: MIT)

3.5.3. Engines

During 2025, there were several advances in the field of electric aviation thrusters. Probably the most significant was the certification of the engine **ENGINeUS 100** of **SAFRAN** (Figure 26). With a power of up to **125 kW** and aimed at use in light aircraft and urban mobility, will facilitate the electrification of existing propeller aircraft. This achievement is the result of a four-year collaboration with **EASA**, during which the regulations and requirements that this type of electric motorization in aviation must comply with were consolidated[cxiii].

Figure 26. SAFRAN's ENGINeUS electric aviation thruster (Source: SAFRAN)

On the other side of the Atlantic, the **Magnix** company announced the development of **Helistorm** engines, with an estimated power of **330 kW** and high rotational speed, as their objective is the electrification of helicopter models[cxiv]. Rising in power, **Collins Aerospace** also announced a family of electric motors up to **1 MW.** Finally, the highest rank is occupied by the Wright **Electric** company, with a **2.5 MW** model developed in collaboration with **ARPA-e** and **NASA**, currently in ground tests, and which could be tested in flight with a Hercules model.

Figure 27. Proposal to test the WN2500 electric motor on a C-130 Hercules (Source: Wright Electric)

3.5.4. eVTOL

The "air taxi" sector, despite financial challenges, saw clear progress during 2025, achieving a number of tangible commercial and regulatory milestones:

- The U.S. aviation authority FAA published comprehensive guidance for the certification of *powered-lift aircraft* in July, setting out the operational framework for their definitive commercial takeoff. Leading companies such as **Joby** and **Archer Aviation** completed critical phases of their certification. Joby, for example, exceeded 9,000 km in test flights this year, and finalized the operation and maintenance manuals required for the final type inspection authorization (**TIA**).
- The models from Chinese eVTOL manufacturers **EHang** and **AutoFlight**, along with the **RX4E** electric plane, have certified their aircraft, and have commercial air operator certificates in China. However, it should be noted that the certification standards in China are not comparable to the Western EASA or FAA standards.
- First Passenger Flights: **Beta Technologies** made the first flight of its **ALIA** aircraft carrying passengers between East Hampton and New York's JFK airport, marking a move toward commercial service.

- Vertiport Infrastructure: Plans for modular charging networks in cities such as New York and Los Angeles have been accelerated. In Madrid, the City Council prepared a document on urban air mobility[cxv].
- Another important company in the eVTOL sector in Europe, **Volocopter**, was acquired in March 2025 by the Chinese group Wanfeng (owner of Diamond Aircraft), which prevented its disappearance, although it underwent a thorough restructuring process that included the dismissal of a large part of its workforce.

3.5.5. Hybrid drive

In the hybrid-electric field, where electric propulsion and/or storage are combined with hydrocarbon-powered units [1], the designs revolve around operational economics and business applications. Although, in general, their maturation is being more discreet, they continue to produce announcements of new projects such as the regional aircraft of **EVIO** (Figure 23). Launched in late 2025. This *Start-up* Canadian is backed by the industry of **Boeing** y **Pratt & Whitney**, as well as that of various airlines[cxvi].

As for the hybrid type regional aircraft projects, some other models were launched such as the **Cormorant**[cxvii]**,** the **SY30J Pangea**[cxviii] and the **Smartflyer SF-1**[cxix]. In addition to these emerging initiatives, some projects seem to maintain a firm direction towards commercial use, as in the case of the company **Electra Aero**. In 2025 it doubled its headcount, expanded its facilities and submitted a type certificate application to the **FAA for its nine-passenger** EL9 Ultra Short **hybrid-electric aircraft** . The U.S. company is moving towards the finalization of the design, with the aim of making its first flight in 2027.

There were also surprises in this sector, such as Heart **Aerospace's decision** to move its headquarters from Sweden to Los Angeles[cxx]. The Swedish company is developing the **ES-30 model**, one of the most promising projects in hybrid commercial aviation. This move makes sense in the face of the contrast in investment available between the US and Europe, already mentioned.

Another European company, **Elysian**, continued during 2025 with the work to define its **E9X** model, incorporating the Spanish Aernnova for the structural design[cxxi]. While the concept is of a battery-powered electric commercial aircraft, the mandatory range reserve would be covered by a conventional turbogenerator.

In terms of high-capacity hybrid powertrains, **GE Aerospace** completed tests of the hybrid-electric propulsion system based on the Passport turbofan at the end of 2025. This fundamental step is part of the company's various projects to advance technologies for future narrow-body aircraft engines[cxxii].

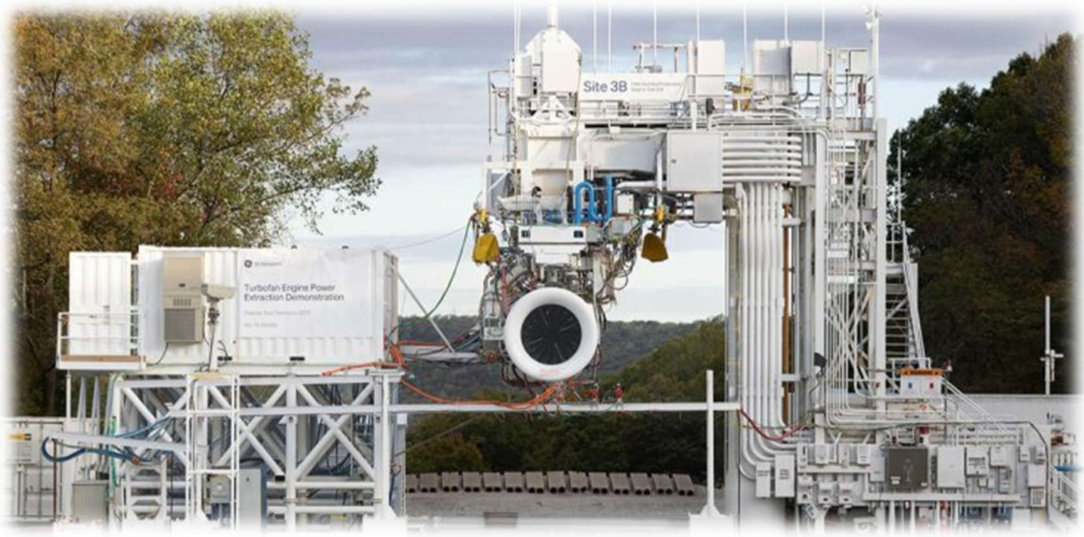

Figure 28. Ground test bench of a GE hybrid-electric powertrain (Source: General Electric)

In addition, delays were observed in different projects with respect to the dates scheduled for the first flights of the prototypes, as usual. As an example, the European manufacturer **ATR** announced that its ATR 72-600 hybrid-electric prototype will fly in 2029, and the decision date for its new **ATR EVO design** will not be before 2030[cxxiii]. In the case of the **Eve Air Mobility** project (backed by Embraer), its commercial certification target was also delayed until 2028 in order to complete its flight test program.

3.6. HYDROGEN

3.6.1. Promotion and supply

The introduction of renewable hydrogen [1] as an aviation fuel, with the well-known environmental advance by completely eliminating CO2 emissions, has been at the forefront of efforts to achieve sustainable aviation in recent years[cxxiv]. The European aerospace company **Airbus** has led, to a large extent, this path. His vision included the creation of an ecosystem covering the production, distribution and aeronautical application of the H2. After a period of study of the different technical solutions, the demanding certification process would be carried out, all within the program **ZERO**.

However, in 2025 this plan suffered a serious setback when a considerable delay in its implementation plans was announced, postponing its adoption in commercial aircraft until at least the 2040s[cxxv]. In practice, this means that the European manufacturer's new design, expected in the next decade, will have a hydrocarbon-based propulsion, although possibly with a high degree of innovation and completely adapted to SAF. While the difficulties were well known, this change in direction generates some uncertainty about the direction of aviation decarbonization efforts[cxxvi] and the role of the different actors involved in achieving it[cxxvii].

Figure 29. Airbus' ZEROe program H2 battery design (Source: Airbus)

One of the main stumbling blocks to the adoption of hydrogen in transport, not only in aviation, but also in the huge road freight transport sector, is the lack of sustainable production. In fact, in the face of the objective of the **EU** to have an electrolysis capacity of 2025 **6 GW** to produce green hydrogen, the reality is that only **308 MW** [14], and expectations for 2030 are not rosy[cxxviii]. The cost of producing renewable H2 is still four times that of fossil origin, which explains why there has been a certain cooling of industrial initiatives[cxxix].

Once again, it is essential to break these dynamics with government support, such as that offered by the EU with the allocation, in 2025, of **€992 million** for renewable hydrogen production projects through a new financing competition organised by **the European Hydrogen Bank**. It should be noted that, of the 15 selected projects, 8 are located in Spain, where progress is also being made in the same direction by private initiatives such as **ALL4Zero**[cxxx].

This effort to promote green hydrogen extends to other countries such as the United Kingdom, where technological production alternatives are being explored[cxxxi], while funding for research and development of air transport powered by this renewable energy vector is expanded. The second phase of the **Hydrogen Challenge Program** was confirmed in February last year[cxxxii].

3.6.2. Fuel Cells

The alternative of electric propulsion powered by hydrogen cells is one of the most promising for zero-emission aviation, solving the limitation in autonomy of battery-powered aircraft. An example of commercial application is the agreement between the company **ZeroAvia** and the Norwegian consortium **ODIN**, whereby 15 Cessna Grand Caravans with their **ZA600** hydrogen boosters will be retrofitted to establish a sustainable flight network in Norway. This project, financed with funds raised by **EU ETS**, will also include all the necessary logistics infrastructure on land[cxxxiii]. The U.S. company is also studying the application of its engines in Airlander's cargo airship model[cxxxiv].

The financial difficulties mentioned above could also extend to aeronautical companies involved with hydrogen, from **ZeroAvia** itself struggling to secure new investment[cxxxv], to the difficulties of

Cranfield Aerospace, which halted its development of a powertrain for the **Islander** model, refocusing its efforts towards the field of drones[cxxxvi]. In this complex environment, for disruptive industrial initiatives to thrive, it is essential that programmes such as **the** European Union's Clean Aviation serve to complement the research and development of new sustainable concepts. Within the hydrogen fuel cell propulsion sector, the **Newborn** project continues to make progress towards its goals of validating all powertrain elements by 2026[cxxxvii]. After this, the companies that make up the consortium hope to be able to continue until flight tests in 2028.

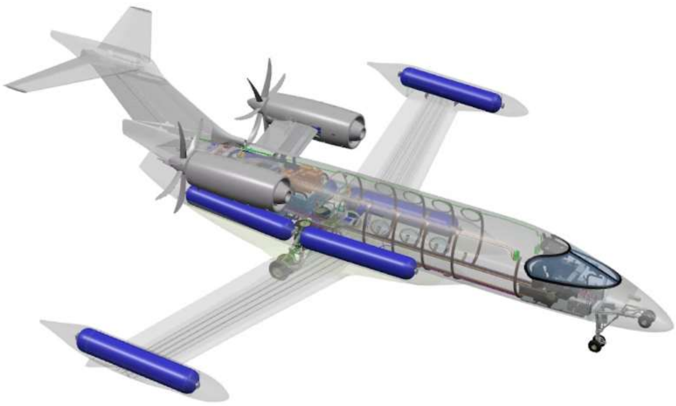

Figure 30. Design of the BYA-1 model with the arrangement of compressed H2 tanks. (Source: Beyond Aero)

Other aeronautical companies working with hydrogen-electric propulsion can be divided between those pursuing a strategy of repowering existing models (e.g., the Australian **Stralis**[cxxxviii]), and those that start from scratch with new designs that can optimize the benefits of this solution. The latter case is that of **Beyond Aero**, with your business jet **BYA-1** (Figure 30).

An interesting feature of this project is its commitment to the use of compressed hydrogen tanks (700 bar) instead of the cryogenic solution. Although storage capacity decreases, it seems that the practical aspects of operation have prevailed, given the simplicity of working with fuel at room temperature. In October, the Toulouse-based company announced the start of ground tests of a full-scale prototype of a thruster[cxxxix]. It is worth noting that this company acquired facilities, test data and the entire patent portfolio of the defunct **Universal Hydrogen**.

3.6.3. Direct Combustion

2025 began with an important milestone in the use of direct combustion of hydrogen for aeronautical propulsion, when the first ground tests of a turboprop engine designed for light aircraft[cxl] powered by this fuel in liquid state were carried out.

This work is part of the ***BeautHyFuel*** project, funded by the French government for the development of H2-powered aerial engine systems, and which involves the main industrial players in France. However, the greatest advance in this type of propulsion came shortly after with the arrival of the bench test results of the **HYSIITe**[cxli] project, an H2-powered aviation turbojet with water recovery and injection.

Figure 31. Ground tests of an H2-powered turboprop engine (Source: BeautHyFuel)

According to **Pratt & Whitney**, this design demonstrated **35%** higher efficiency than the equivalent kerosene motor[cxlii]. This leap in energy savings is essential, as it could justify the enormous cost of development, but above all that of adapting the supply and management of hydrogen in aviation. The key is to improve the performance of the system with the contribution of H2O to the intake airflow, mentioned above. Although this effect was already well known, it is now used continuously and in large proportion (up to 20% water vapour[cxliii]) thanks to its recovery after combustion through a complex system of condensation, separation and evaporation. In addition, this mixture improves the stability of the hydrogen flame, which is always a challenge, and takes advantage of the smaller size of the core to allow extreme shunt ratios, up to **50:1**, with the consequent improvement in efficiency.

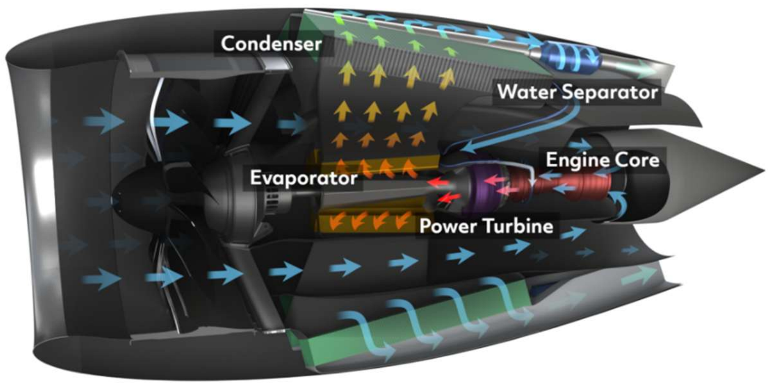

Figure 32. HYSIITe. H2 turbojet with water recovery and injection (Source: Pratt & Whitney)

Heat management is another important aspect of this architecture, as it is used both to produce the water vapor from the mixture and for heating the cryogenic liquid hydrogen before combustion, but also by water cooling of the intermediate stages of compression, all of which improves the energy management of the engine. Finally, and an aspect of great importance, the results showed that combustion with water practically eliminates nitrogen oxide emissions **(99.3%),** one of the main drawbacks of hydrogen combustion. Thus, the **HYSIITe** would solve this problem, significantly improving overall efficiency, and potentially mitigating, in addition, the creation of contrails. This project is funded by the US government agency **ARPA-e**, and its horizon of commercial introduction is in the long term, in 2 or 3 decades. This is due to the novelty and complexity of the technology involved, in addition to requiring, as we have already seen, an entire industrial environment for the production and distribution of renewable hydrogen.

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