ENVIRONMENTAL SUSTAINABILITY IN THE AVIATION SECTOR

ADDENDUM 2024

Official College of Aeronautical Engineers of Spain

Authors:
Óscar Castro Álvarez
Juan Sebastián Montero
Antonio Mota Sandoval y
Javier Díaz Díez

Contents

1. FOREWORD

Following the path initiated in 2022, when COIAE published its report on the state of the art of environmental sustainability in the aeronautical sector —which has been updated annually— this addendum presents the progress made in 2024 towards sustainability.

The path towards sustainability in the aeronautical sector is marked by the undeniable commitment of all stakeholders, which has materialised in ambitious pledges related to CO_2 emission reductions. These commitments are demanding significant efforts from the industry in terms of innovation and technology, as the vast majority of the levers required for decarbonisation involve new technologies never used in aviation —such as the use of sustainable aviation fuels (SAF), electric propulsion, or hydrogen.

Setting and assuming such commitments requires continuous monitoring of the progress being made in order to provide credibility to the sector's ability to meet its stated objectives.

The annual addendum to the original report, prepared by COIAE, aim to highlight and communicate this progress to society, with the intention of offering readers a realistic view of the feasibility of achieving the aviation sector's decarbonisation commitments.

Perhaps the most notable developments of 2024 relate to the natural consolidation of projects and stakeholders, as well as a narrowing focus on specific technological areas for development. These have occurred alongside insufficient political and financial momentum, and a growing realisation that hydrogen propulsion will require a longer timeframe. Moreover, the development of higher energy density batteries —essential for viable commercial electric operations— does not appear likely to meet the initially forecast timelines.

On the other hand, significant progress has been made in the production and use of SAF, which allows for optimism regarding compliance with the regulatory goals of the Fit for 55 package.

Likewise, there has been meaningful advancement in the implementation of regulatory and compensatory mechanisms such as RefuelEU Aviation, the EU ETS, and CORSIA. In terms of airport decarbonisation, Aena has brought forward its decarbonisation target by ten years.

The development efforts not related to new fuels are also clearly defined: aerodynamic improvements (more efficient wings); operational improvements (collaborative avionics and the Single European Sky); and new engine designs (open rotor). Efforts also continue in electric aviation, hybrid aviation, and fuel cells.

The roadmap toward decarbonisation appears well defined, and significant progress is being made in key areas. The information presented in this addendum supports these conclusions and offers readers a realistic perspective on where we stand and the distance still to be covered.

2. INTRODUCTION: SUSTAINABLE AVIATION IN CONTEXT

2.1. INTRODUCTION

2024 was a complex year on the path toward sustainable commercial aviation. On one hand, regulatory[i], technological, and industrial developments continued in pursuit of previously established decarbonisation milestones (see [3]). On the other hand, there were setbacks, such as the financial difficulties faced by several companies at the forefront of sustainable aviation —such as Universal Hydrogen[ii] and Lilium— or delays in certification plans, like that of Deutsche Aircraft's D328eco[iii].

Figure 1. Ecopulse hybrid-electric demonstrator by Daher/Safran/Airbus (AIRBUS)

Leaving aside efforts related to the production of Sustainable Aviation Fuel (SAF), in general terms one could speak of a certain rationalisation of business initiatives aimed at aviation decarbonisation through new technologies, with a reduction in active players and ongoing[iv] projects as the target for entry into service approaches. That said, and as this report will show, new projects and initiatives continue to emerge in the quest for CO_2-free commercial aircraft.

Political and financial momentum to stay on the path toward sustainable aviation is now more necessary than ever, particularly given the growing evidence of the effects of global warming, which may even be directly impacting aviation through the increasing frequency and intensity of in-flight turbulence.[v] In this regard, the European Union maintains a clear leadership role[vi], which —as will be discussed later— involves promoting technological projects, issuing mandates for the gradual introduction of sustainable fuels, enhancing air traffic control efficiency, and, importantly, monitoring compliance with emissions offset regulations in Europe and verifying the accuracy of sustainability claims made by aerospace industry players[vii].

At the national level, 2024 was also a year of progress in the field of aviation decarbonisation. In addition to the numerous industrial projects presented here, there was also an expansion of initiatives such as the Alliance for the Sustainability of Air Transport in Spain[viii], and developments within the academic research sector[ix].

2.2. PATHWAYS TO DECARBONISATION

The roadmaps for decarbonising aviation —along with the planning of technological and industrial developments to make it possible— have always featured a wide range of proposals from numerous organisations and companies. These roadmaps generally converge on the goal of achieving net-zero emissions by 2050 (see [2], p. 8). However, in contrast to the optimism of recent years, 2024 brought some doubts regarding the feasibility of certain intermediate milestones on the path to environmental sustainability.

One such example is the aspirational goal set by ICAO at the end of 2023, aiming for a 5% reduction in the carbon intensity of aviation fuels by 2030.

Past June, the International Air Transport Association (IATA) pointed to the lack of decisive political action to promote SAF production as a major barrier to achieving that target[x].

In a subsequent report, IATA again highlighted the vast differences among the various roadmaps —particularly in the projected role of SAF[xi], which could range from as little as 24% to as much as 70%, the latter figure aligning closely with IATA's own forecast (Figure 2). Notably, IATA's roadmap gives significant importance to carbon capture, which would allow airlines to maintain their current business model. However, it makes no mention of demand management —an increasingly prominent topic in the debate on aviation's climate impact, as will be discussed later.

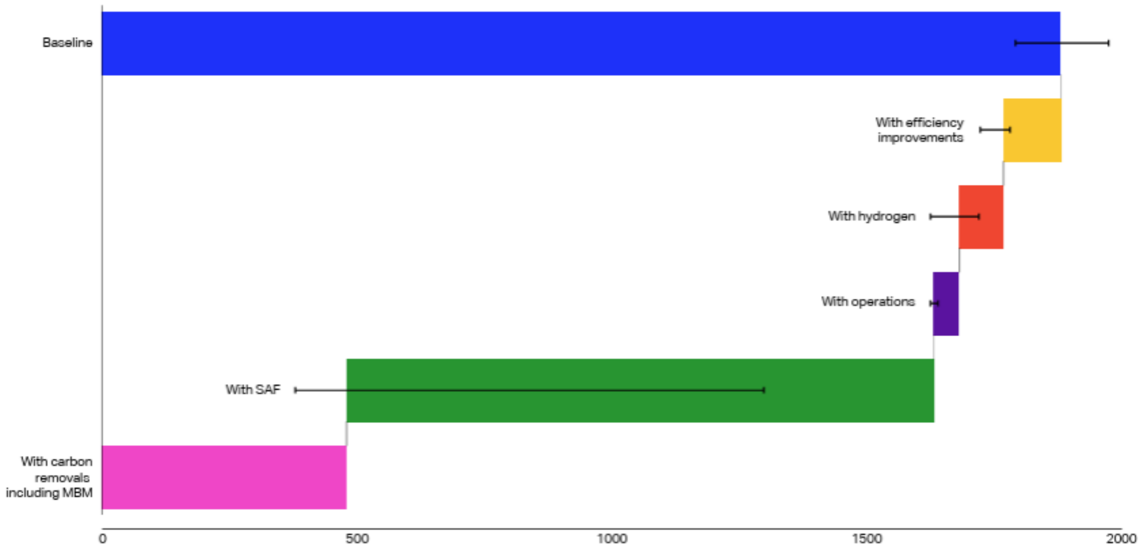

Figure 2. Distribution of CO_2 Reductions (in tonnes), by Type of Action, to Achieve Net-Zero Emissions in Commercial Aviation by 2050 (IATA)

To complete the contributions made by the international airline association in 2024, IATA also published a series of detailed action guides, broken down by area of responsibility, which it considers essential to achieve the goal of decarbonisation by 2050 (Figure 3). Similarly, the University of Cambridge published last year what it sees as the four urgent measures necessary to reach that goal[xii]. This action plan to reverse the current emissions trend should be implemented before 2030 and would include the promotion of SAF, efficiency improvements, investment in disruptive technologies, and addressing contrail formation —this last issue having gained increasing prominence in the sustainable aviation debate, and one that will be explored in the following section.

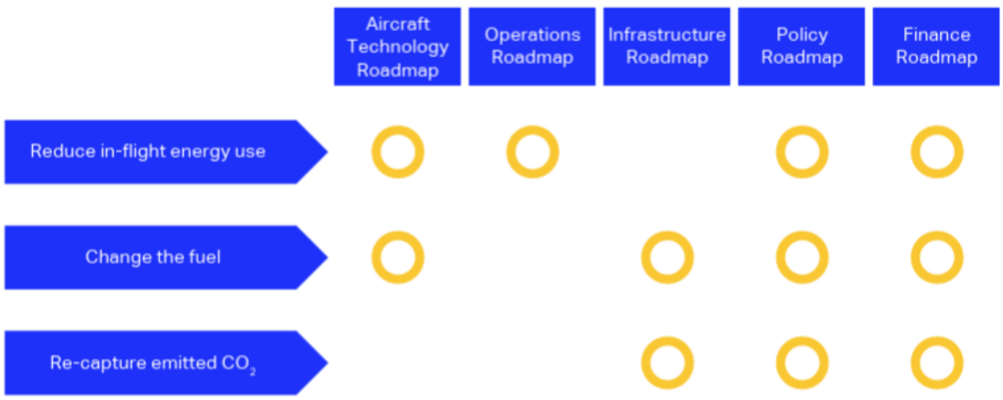

Figure 3. Roadmaps by Area of Action Proposed to Achieve Net-Zero CO_2 Emissions in Commercial Aviation by 2050 (IATA)

Another example of this revision of forecasts and commitments regarding CO_2 emissions in commercial aviation occurred in August of last year, when Air New Zealand withdrew its 2030 targets, citing slow progress in both the availability of new aircraft technologies and the scaling up of SAF production. Nevertheless, the airline announced it is still collaborating on the development of zero-emissions aircraft and remains committed to achieving carbon neutrality by 2050[xiii].

Overall, however, efforts to advance toward sustainable aviation continued —and even accelerated— over the past year. Notable examples include the reconfiguration of the UK[xiv] government's Jet Zero Taskforce and the new plans and commitments announced by the Australian government[xv].

In this regard, and as already mentioned, the development of new technologies remains a key pillar for aviation decarbonisation. The European Union has been financially supporting the required innovation and development for many years, currently under the umbrella of the ***Clean Aviation*** programme[xvi]. In December, the third call for proposals was launched, with a budget of €305 million, to support high-impact projects in regional and short-to-medium haul aviation, as well as to promote fast-track technology deployment (Figure 4).

Figure 4. Technological Focus Areas for the Third Clean Aviation Call for Proposals (EU)

2.3. NON-CO2 IMPACT

Over the past year, the debate intensified regarding the negative impacts of aviation emissions beyond carbon dioxide. Attention has increasingly focused on contrails ([2], p. 6). Although the quantification of their contribution to global warming is not yet fully established ([3], p. 7), there is no doubt about their significant relevance —on a scale comparable to that of CO_2.

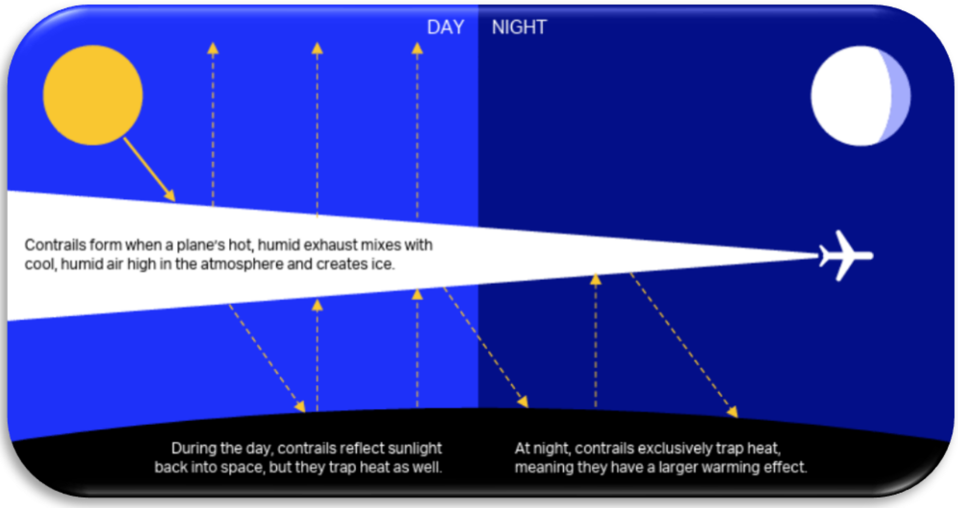

Figure 5. Climate Impact Mechanisms of Contrails During Day and Night (American Airlines)

In this context, the EU introduced in 2024 new regulations and tools for the monitoring, reporting, and verification (MRV[xvii]) of all non-CO_2 emissions, which will become mandatory for airlines operating within the European Union starting on 1 January 2025[xviii]. The NEATS system will enable simplified communication to comply with this requirement, which will not be subject to any financial obligations under the EU ETS —at least until the next legislative review scheduled for 2028.

In an April 2024 report, the International Air Transport Association (IATA) clearly opposed the requirement, arguing that further research is needed to fully understand the climate effects of contrails[xix]. Furthermore, IATA warned of potential legal implications if the obligation were to apply to all flights departing from or arriving in the EU, as originally planned, since this would fall under the jurisdiction of CORSIA.

On the other side, an unusual alliance of environmental organisations and low-cost airlines —mostly operating intra-European routes— argued that the success of the MRV system would only be possible if it covered all flights, both short- and long-haul, to ensure a proper understanding of the impact of each segment of commercial aviation[xx].

Ultimately, in July 2024, the EU confirmed that the obligation to monitor and report non-CO_2 emissions would remain but agreed to limit its scope to intra-European flights[xxi].

In addition, in December 2024, a group of 50 aviation and climate change scientists signed a letter urging action to mitigate the global warming effects caused by contrails[xxii]. According to a study by the organisation Transport & Environment[xxiii], this impact could be reduced by up to 50% by 2040 if predictive and rerouting techniques were implemented on a very limited number of flights —those responsible for 80% of the total effect (Figure 6).

To ensure a net positive global benefit, the additional fuel consumption— and therefore CO_2 emissions —caused by these flight path changes must also be considered.

In fact, the technologies and systems needed to manage flight paths that avoid contrail formation have been under development for some time, with promising results in various trials conducted in Europe —led, for example, by the company SATAVIA[xxiv]— and in the United States in collaboration with Google[xxv]. With minimal additional fuel consumption on a small number of flights, and virtually no cost to passengers, the expected reductions in the climate impact of contrails were confirmed.

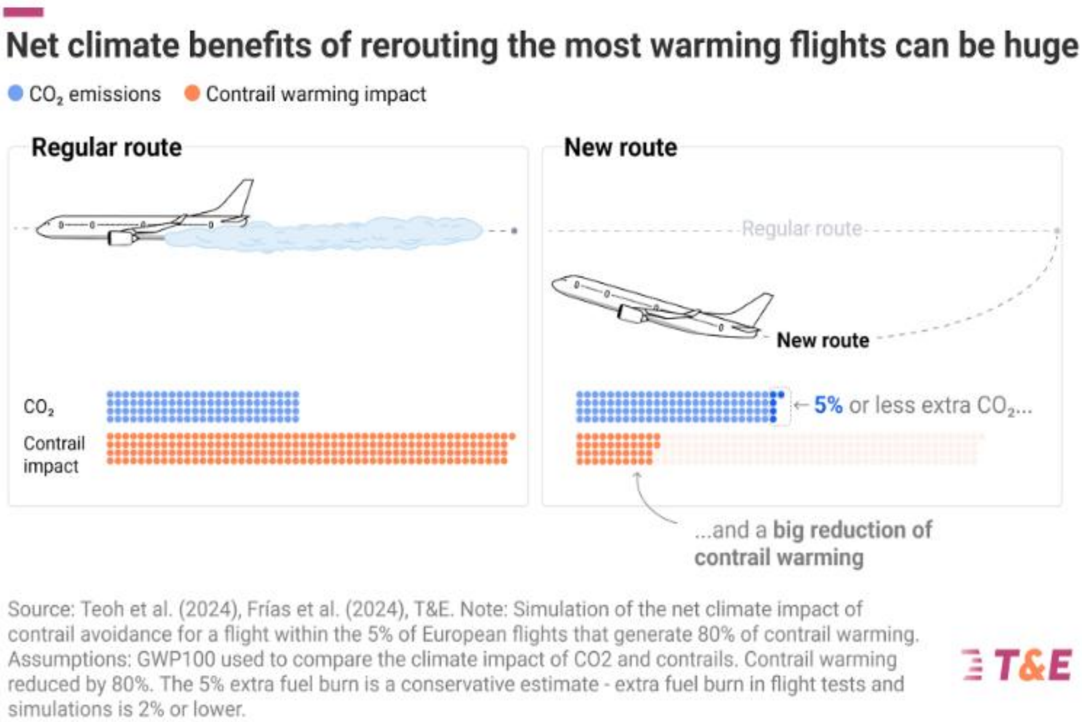

Ilustración 1. Cambio de ruta para evitar la formación de estelas de condensación (T&E)

Other initiatives launched last year in the field of non-CO_2 impact mitigation include a public funding programme for research in the United Kingdom[xxvi], as well as various flight testing and data collection programmes in both the United States and Europe aimed at improving the characterisation of contrails[xxvii]. Evaluations were also announced to assess the potential of SAF to mitigate these effects, both through ground testing[xxviii] and, more promisingly, through flight trials[xxix].

Finally, it is worth highlighting the list of airlines committed to mitigating contrail effects, published by the non-governmental organisation Blue Lines[xxx]. The list includes up to 30 operators with varying levels of involvement, ranging from participation in test programmes to the establishment of specific reduction targets.

3. ACTIONS, INNOVATIONS AND TECHNOLOGY

3.1. EMISIONS OFFSETING AND ECONOMIC MEASURES

3.1.1. Offsetting

The ultimate goal of sustainable aviation is to emit neither carbon dioxide nor any other pollutants or climate-altering substances. However, given the urgency of the current climate crisis, the aviation industry as a whole must develop transitional solutions that reduce net emissions along the path to full sustainability. This is where offsetting comes into play: reliably and verifiably removing or avoiding the emission into the atmosphere of an amount of CO_2 equivalent to that generated by commercial flights.

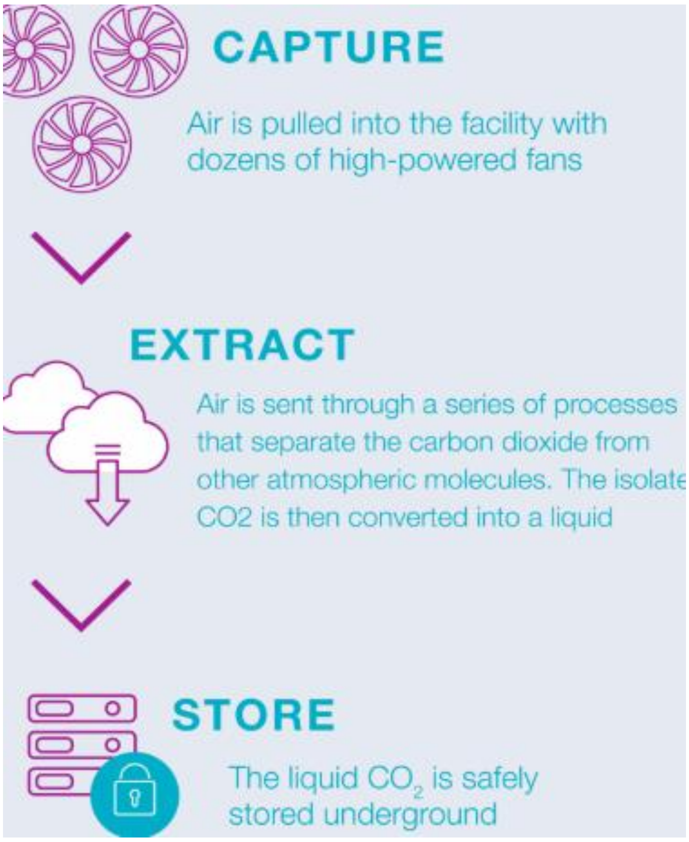

Figure 7. Carbon Capture and Storage Offset Offering (Airbus)

In addition to conventional options —such as emission-reduction projects in established industrial processes or carbon removal through forestry— there is a growing sector focused on directly capturing carbon dioxide from the atmosphere and storing it in various forms (DACCS[xxxi]). Airbus is promoting these strategies through its carbon capture offering[xxxii], which companies like EasyJet joined in 2024.

The nature of CO_2 capture and offsetting projects has thus diversified significantly, with providers developing different lines of action. One such example is CUR8, with which British Airways signed an agreement last September for the offsetting rights corresponding to 33,000 tonnes of carbon dioxide[xxxiii]. Meanwhile, as an underlying trend, the conventional offset market has recently experienced a decline in the availability of high-quality credits, leading to a degree of public mistrust in this emissions mitigation strategy. In response, organisations such as the **ICVCM**[xxxiv] are promoting a set of basic principles for these types of projects (Figure 8), to ensure the integrity and effectiveness of carbon credits.

Figure 8. The 10 Core Principles of ICVCM for CO_2 Offsetting (ICVCM)

3.1.2. CORSIA and EU ETS

In 2024, Phase I of the international aviation emissions reduction and offsetting scheme, CORSIA, was launched (see [2], p. 13). Like the previous pilot phase, it remains voluntary for ICAO member states. Nevertheless, it is worth noting that 126 countries already participated in this CO_2 offsetting system last year, covering a total of 670 aircraft operators[xxxv].

Although, as previously mentioned, the carbon credit market has experienced some recent turbulence, a return to stability is expected in order to maximise CORSIA's impact. Additionally, it is important to highlight the regulations developed to qualify aviation fuels as sustainable, thereby enabling them to contribute toward meeting airline offsetting obligations. SAF, by definition, removes CO_2 from the atmosphere during its production, which partially or fully compensates for the emissions produced during its use in aviation.

The EU ETS, also described in earlier documents ([1], p. 17), is a cap-and-trade system that limits total emissions from several high-carbon sectors in Europe, including commercial aviation. Under this system, airlines must trade emissions allowances with other entities to cover their intra-European operations. Accordingly, 2024 was a key year for airlines regarding their EU ETS[xxxvi] obligations, marked by a 25% reduction in free emissions allowances for airlines —which will be fully phased out by 2026— and preparations for the monitoring of non-CO_2 aviation effects, which became mandatory on 1 January 2025. As previously noted, this reporting obligation will not apply to extra-European flights, maintaining a provisional boundary with respect to CORSIA.

In April 2024, the sustainable transport NGO Transport & Environment (T&E) published an analysis of the share of CO_2 emissions from European airlines that were actually subject to charges under the EU ETS[xxxvii]. This percentage drops significantly for carriers with a high volume of extra-European flights —currently not covered by EU legislation— such as national flag carriers (Figure 9). As a result, less than one third of those emissions represented a financial burden for operators in 2023. However, this percentage will certainly rise in the coming years, due to the progressive elimination of free emissions allowances already mentioned.

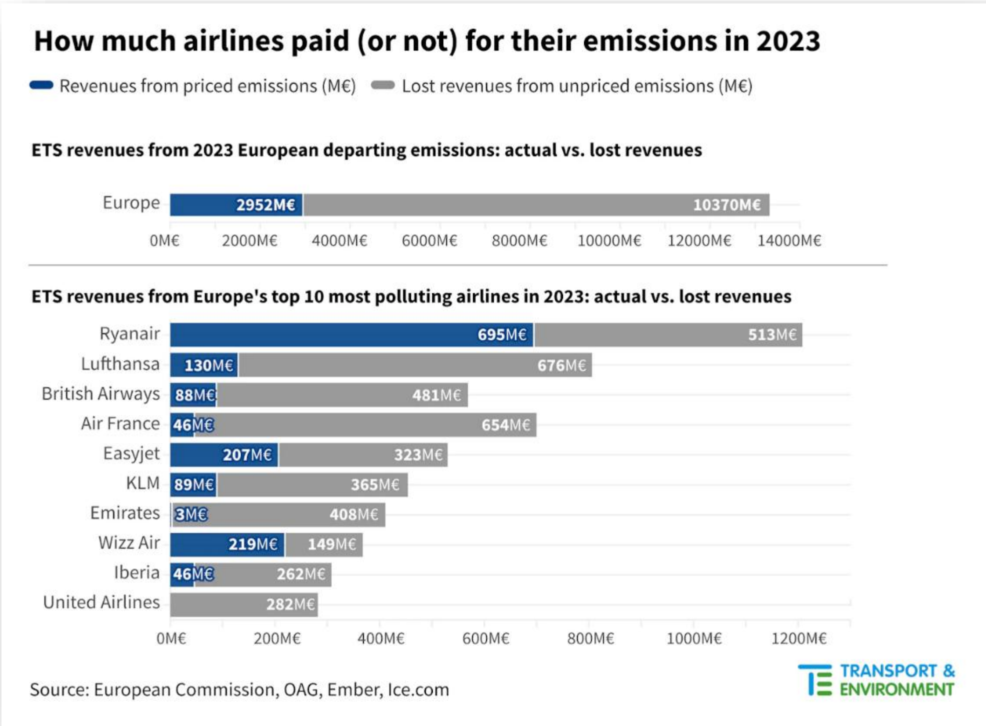

Figure 9. Analysis of the Share of CO_2 Emissions Taxed for European Airlines Under the EU ETS (T&E)

3.1.3. Policy Measures and Demand Capacity

The introduction of CO_2 emissions offsetting obligations for airlines (EU ETS, CORSIA), along with the SAF mandate in Europe —which will require a 2% share of sustainable aviation fuel in all aircraft departing from EU territory starting in 2025— has sparked debate over the total cost of these measures and whether they will be passed on to passengers.

In June 2024, in what could set a precedent for other airlines, the Lufthansa Group announced the introduction of an environmental surcharge on all tickets departing from the EU, Switzerland, the United Kingdom, and Norway, starting 1 January 2025. This additional cost, ranging from €1 to €72 depending on the type of flight, will help cover the added expenses associated with the use of sustainable fuels and compliance with emissions regulations[xxxviii].

This surcharge should not be confused with the voluntary contributions some airlines offer passengers to offset the emissions from their flights. That practice prompted the EU last year to send a letter to 20 airlines, urging them to ensure the accuracy of the information provided to avoid misleading consumers, potentially constituting greenwashing[xxxix]. In line with these efforts for greater transparency, the EU also approved in December 2024 the implementation of an environmental label on European flight tickets, clearly indicating the emissions associated with each flight[xl].

The underlying issue is how to finance the additional costs resulting from taxes and regulations, and whether these might ultimately reduce demand for air travel. This is a scenario the industry fears, but that environmental groups would welcome.

Air traffic is currently growing strongly again and is expected to return to pre-pandemic levels by 2025. It should also be noted that increasing ticket prices could restrict access to air transport for lower-income passengers, and therefore limit the associated socioeconomic benefits, potentially returning aviation to its former status as an elitist mode of travel.

To avoid this outcome —while still reducing air traffic and thus greenhouse gas emissions— a coalition of environmental organisations proposed in October 2024 the introduction of a Frequent Flyer Levy (FFL[xli]). This progressive tax would apply starting with a passenger's third flight of the year, beginning at €50 and increasing to €400 from the ninth flight onward, with additional penalties for long-haul flights or premium classes.

The effectiveness of such a measure remains under discussion, as does its estimated emissions reduction potential. Furthermore, it would require addressing several legal implications, such as the hypothetical creation of a centralised passenger registry to make implementation possible.

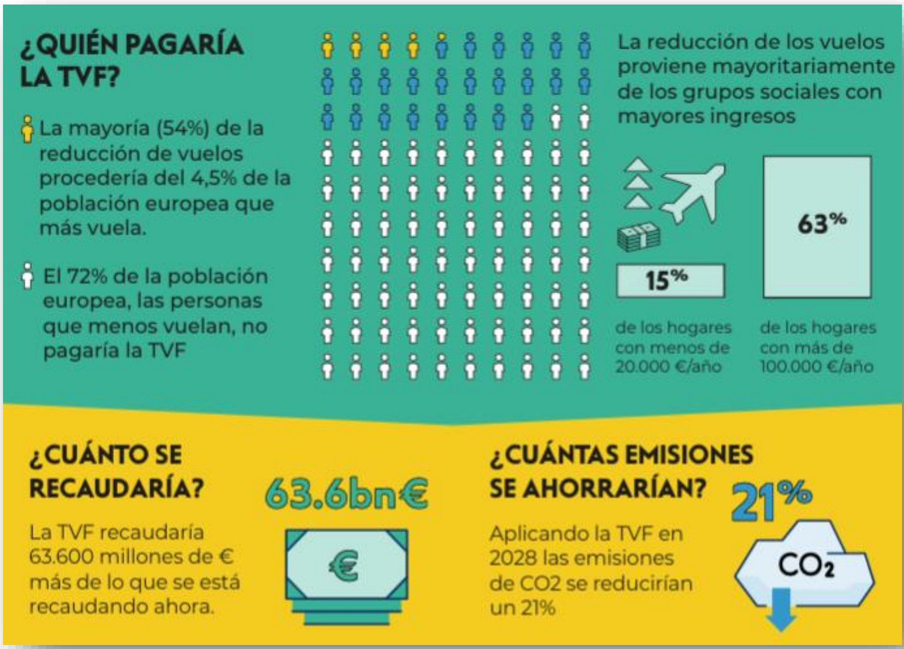

Figure 10. Key Data from the Frequent Flyer Levy Proposal (Ecologistas en Acción)

The direct imposition of a kerosene tax, which has historically been exempt, was also debated at the European level during 2024. Such a tax would be easier to implement but would have an indiscriminate effect on passengers, who would bear the cost, with significant economic impact[xlii]. These consequences, along with the lack of unanimity among EU countries to introduce it, suggest that the exemption will likely remain in place, at least in the short to medium term[xliii].

To conclude the section on taxation measures in air transport, it is worth noting the 20% increase in the German national air passenger tax, effective from May 2024. The surcharge ranges from €15 to €71 depending on the destination[xliv].

Another proposal to reduce air traffic —now from the political sphere in Spain— was introduced last year: a ban on domestic flights where a viable rail alternative of less than two and a half hours exists, with some notable exceptions[xlv]. The legislative initiative, agreed by the governing coalition in February 2024, still needs to undergo various stages of approval, and it is unclear when —or if— it will be implemented. It has been criticised by various sectors for its economic impact and environmental inefficiency. Nonetheless, in September, a new legislative proposal was presented, which would directly ban flights of less than one hour[xlvi].

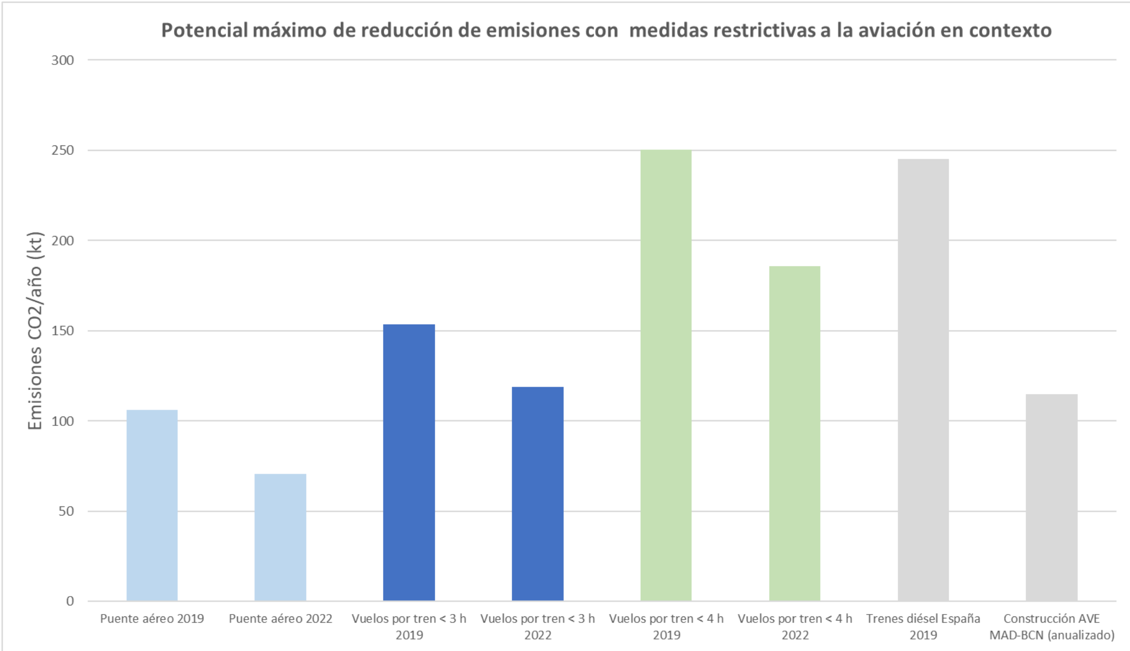

Figure 11. Maximum Potential CO_2 Emissions Reduction from Replacing Domestic Flights in Spain with Rail Alternatives in Context (COIAE)

To assess the effectiveness of such measures, COIAE published an updated version of its report on these types of proposals. The study estimated the maximum potential benefit at less than 0.7% of aviation emissions in Spain, and around 0.13% of CO_2 emissions from the national transport sector (see [4]). Given these figures—which do not even take into account the considerable emissions associated with the construction of the alternative rail infrastructure—one might question whether this is yet another case of greenwashing that avoids addressing the truly necessary measures for achieving environmentally sustainable aviation.

To provide context for the debate, Aena's data for 2024 shows a 9.2% increase in the number of passengers in Spain compared to the previous year, a figure consistent with the year-on-year rise in aviation fuel (kerosene) consumption last August, which reached 13%[xlvii]. There is no doubt that aviation continues to expand following the pandemic, and managing this surge in demand poses challenges on many fronts, including environmental sustainability.

Figure 12. Map of Air Routes in 2022 (Adam Symington)

3.2. NAVIGATION, OPERATIONS AND AIRPORTS

3.2.1. Navigation

In October 2024, the European Parliament finally approved the reform of the **Single European Sky** (SES[xlviii]). The goal is to improve flight management within the continent by reducing costs, increasing capacity, and —more importantly— enabling more environmentally efficient routes through reduced charges.

Launched in 1999, the Single European Sky initiative aims to rationalise air navigation within a geographically small area containing many countries and their respective air traffic control authorities. After many delays and resistance from some states, mainly due to concerns over sovereignty, and despite not reaching the level of reform requested by some airlines, the path is now open to achieving up to a 10% reduction in CO_2 emissions. **Eurocontrol** will play a central role in this new framework[xlix]. Route optimisation is, of course, a powerful tool to reduce fuel consumption and emissions. One example is a test flight by SAS from Copenhagen to Los Angeles, which achieved a 20% improvement in fuel efficiency, largely due to the selection of a more northerly flight path[l].

At the national level, **ENAIRE**, Spain's air navigation service provider, has launched its *Fly Clean* programme, which aims to rationalise traffic and airline routes to improve overall efficiency[li]. In 2024, ENAIRE also participated in the 14th Air Navigation Conference of the International Civil Aviation Organization (ICAO), which promoted measures for more environmentally efficient navigation, such as reducing longitudinal separation distances between aircraft.

This separation distance is also the cornerstone of the ***GEESE*** programme[lii], the successor to Airbus's *fello'fly* project. Backed by EU funding, *GEESE* will conduct three years of trials with various airlines, during which commercial aircraft will fly in formation —such as migrating geese— to benefit from the wake energy of the lead aircraft and reduce fuel consumption (Figure 13). While *fello'fly* demonstrated fuel savings of up to 10%, *GEESE* now aims to develop the full set of operational procedures needed to efficiently and safely link commercial aircraft on long-haul flights.

Figure 13. Wake Energy Retrieval Mechanism Targeted by the GEESE Programme (Airbus)

3.2.2. Operations

The operation of an aircraft —from the moment it leaves the airport terminal until its arrival at the destination— offers numerous opportunities to optimise procedures, thereby reducing fuel consumption and associated emissions. Airlines are increasingly working to capitalise on these opportunities through the use of specialised equipment and software that provides pilots with real-time guidance on the most efficient alternatives. One example is Emirates' *Green Ops* procedures, which aim to optimise variables such as centre of gravity, flap configuration, and braking technique to enhance efficiency[liii] (Figure 14).

Among Spanish airlines, for example, Air Europa uses the *OptiClimb* system, which offers similar functionalities. Volotea, for its part, signed an agreement in October 2024 to implement Airbus's *Descent Profile Optimization* (DPO) system, which operates similarly but focuses exclusively on the descent phase of flight[liv]. Fleet management also presents opportunities for improving overall efficiency. Tools such as *SkyBreathe* use operational data to reduce total fuel consumption by up to 5% in theory. In 2024[lv], Air Nostrum adopted this software, joining over 60 airlines worldwide already using the system.

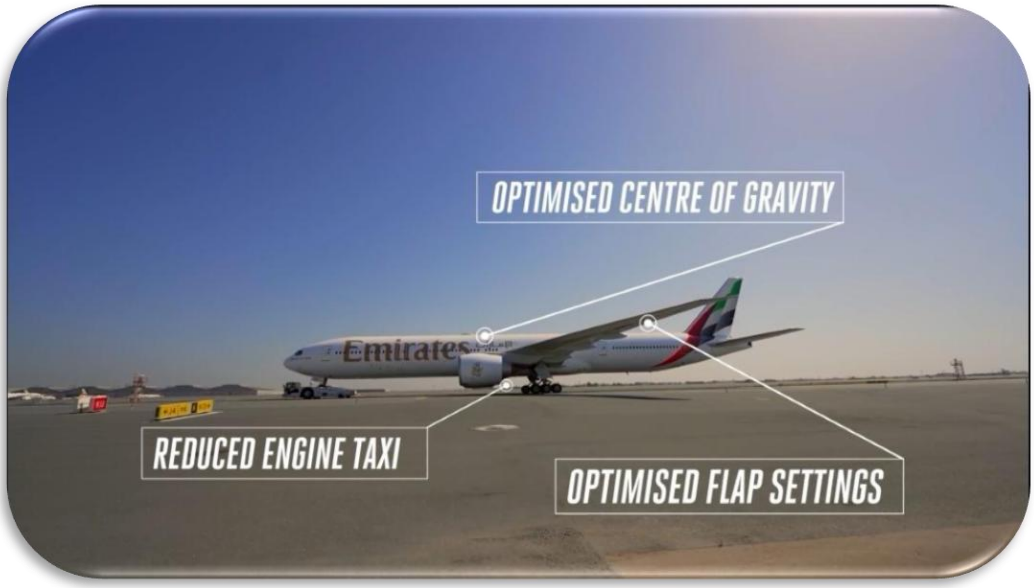

Figure 14. Parameters Monitored by Emirates' Green Ops System to Reduce Fuel Consumption (A21)

3.2.3. Airports

Air traffic in Spain, following the disruption caused by the pandemic, has once again broken records, pointing toward a projected 300 million passengers transiting through Spanish airports in 2025[lvi]. While these figures are economically positive, they also highlight the urgent need to accelerate emission reduction efforts within the sector.

In this direction, the Spanish airport operator Aena announced in 2024 that it is bringing forward its goal of achieving carbon-neutral airports by 10 years, now targeting 2030 in its Strategic Plan. To this end, Aena is promoting the reduction of both direct emissions (Scopes 1 and 2) through actions such as the installation of photovoltaic power plants (e.g., in Valencia) and the transition to LED lighting on airport aprons (e.g., in Reus), and third-party emissions (Scope 3), for which it received an award last year[lvii].

One of the simplest strategies to improve the environmental sustainability of airports involves decarbonising the airside vehicle fleet, which includes all the vehicles assisting aircraft and maintaining runways[lviii].

Efforts to support more sustainable, hydrogen-based aviation also require airports to play a key role, not only by ensuring hydrogen fuel availability but potentially becoming hubs for its production and distribution. The first steps are already being taken, as demonstrated by the acquisition of electrolysers at Lleida Airport, where the existing solar power plant will be used to produce green hydrogen[lix].

Many airports are exploring the introduction of hydrogen into their operations. Examples include Brussels Airport as part of its Stargate[lx] sustainability programme, and Bristol Airport[lxi], where pilot projects were launched last year to test procedures and refuelling stations for ground support vehicles.

Airbus, a leading advocate of hydrogen's role in future sustainable aviation, is also working with airports and other stakeholders to ensure fuel availability and the operational readiness of hydrogen refuelling systems. This is the objective of the GOLIAT project, launched in 2024[lxii], as well as the *Hydrogen Hub at Airports*[lxiii] programme (see Figure 15), which involves agreements with airport authorities and other partners arond the world.

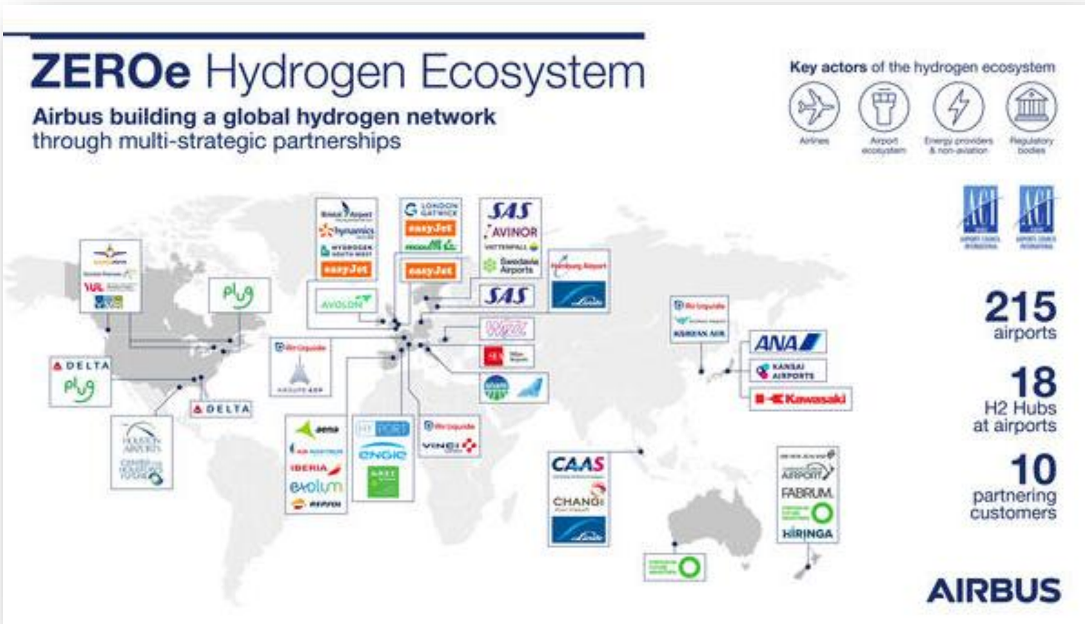

Figure 15. Airports and Stakeholders Involved in Airbus Programmes for Hydrogen Introduction and Availability at Airports (Airbus)

3.3. GRADUAL IMPROVEMENTS IN EFFICIENCY AND DESIGN

The continuous progress in reducing emissions per passenger-kilometre in commercial aviation—approximately 2% annually [1]—has been achieved largely through optimisations in engine design, materials, and overall aerodynamics. This does not mean that reaching net-zero emissions won’t require fundamental changes in aircraft design concepts or propulsion systems and fuels. Rather, it highlights that all efforts, both major and incremental, must move in the same direction.

The impact of these gradual improvements on emissions reduction is evident in fleet renewal, through the introduction of modern aircraft. In a study conducted by the analytics company Cirium, comparing specific emissions per seat-kilometre on departing flights from Adolfo Suárez Madrid-Barajas Airport in the first quarters of 2019 and 2024, it was found that the average value dropped by 10%, reaching 73 gCO_2/seat·km[lxiv].

Figure 16 presents the data grouped by aircraft type, number of flights, and specific emissions. As shown, the complete replacement of A340-600s with new A350-900s, along with the emerging substitution of older A320s with their upgraded versions (A320/A321neo), significantly reduced specific CO_2 emissions.

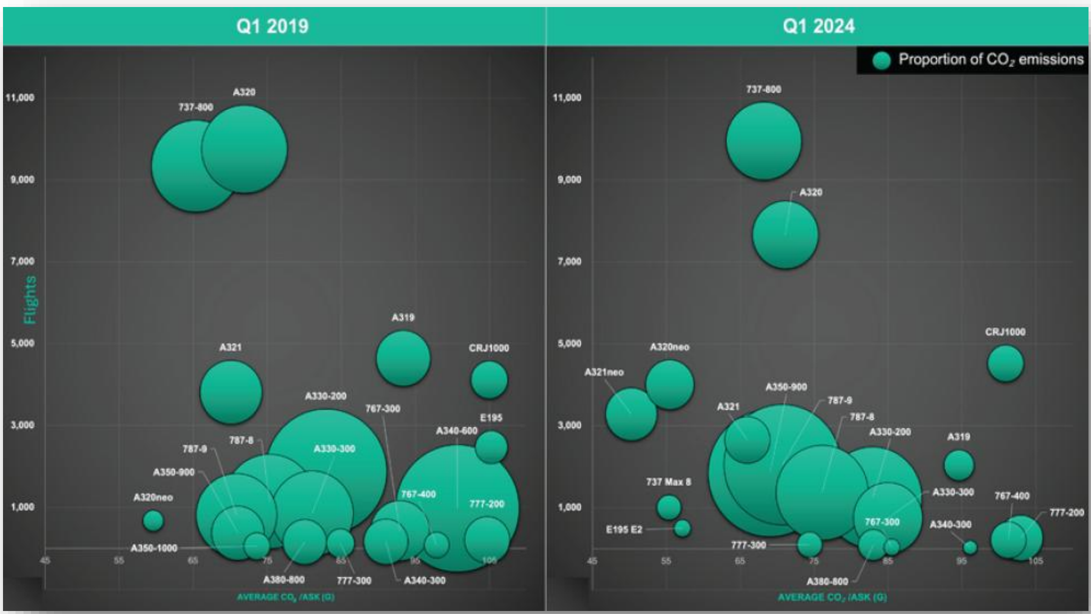

Figure 16. Comparison of Emissions by Aircraft Type on Flights from Madrid-Barajas in Q1 2019 and 2024 (Cirium)

Figure 17. TaxiBot System Towing an Aircraft During Taxiing (Brussels Airport)

In absolute terms, the number of operations at Madrid-Barajas in 2024 was still below 2019 levels, although the airport handled 7.2% more passengers[lxv]. This highlights the growing need for continuous improvements in the environmental efficiency of air transport. One example of such initiative is the *TaxiBot* system — a sustainable solution for towing aircraft during taxiing between the runway and the terminal. It consists of a semi-robotic hybrid tow vehicle that eliminates the need to use the aircraft's engines during ground movement, thereby reducing fuel consumption, emissions, and noise. As of 2024, it is undergoing testing at Brussels Airport[lxvi]. Among these types of gradual improvements is the AeroShark coating system, applied to aircraft fuselages, which reduces fuel consumption —and therefore emissions— by around 1% on long-haul flights. After being approved a year earlier, its application was expanded in 2024 to airlines such as LATAM and ANA.

Figure 18. Wind Tunnel Tests of the X-66 Featuring Truss-Braced Wings (NASA)

On the other hand, the ambition to achieve much greater emissions reductions is driving the design of the X-66 experimental aircraft, developed by **NASA** and **Boeing** among other partners. Launched in early 2024 with U.S. government support, this demonstrator will be built from an MD-90 airframe and will incorporate a series of features aimed at reducing fuel consumption. In particular, its extra-long truss-braced wing design could reduce emissions by up to 10%[lxvii].

Wind tunnel tests completed last year (see Figure 18) appear to confirm this potential. The potential of this wing configuration is also being explored in the European *HERWINGT* project, funded under the *Clean Aviation* programme. This project includes additional modifications to wing design and aims for even greater improvements —up to 15%— by optimising structure, systems, and aerodynamics[lxviii]. In 2024, the project entered the construction phase for several technological demonstrators.

An even more radical design change is proposed by the U.S.-based company *JetZero*, which moves beyond the traditional cylindrical fuselage and wing configuration to explore a more integrated concept: the *Blended-Wing Body* (see Figure 19). In this case, fuel savings compared to a current 200-passenger aircraft could reach an impressive 50%[lxix]. The possibility of using hydrogen as the propulsion fuel is also under consideration[lxx].

This type of design has been studied in the past, including for military aircraft and by manufacturers like Airbus, but its development must overcome major technical challenges, such as designing a pressurised cabin without the structural advantages of a circular cross-section. Nevertheless, JetZero's proposal is attracting growing interest from both airlines and investors. In April 2024, the company received authorisation from the U.S. Federal Aviation Administration (FAA) to conduct experimental flights with a scaled model[lxxi].

Figure 19. JetZero's Proposed Design Featuring an Integrated Wing and Wide Fuselage Configuration (JetZero)

At the far end of emission reduction through alternative designs lies the proposal to reintroduce airships as a viable option for air transport. While not intended to replace conventional aircraft —given their obvious limitations in speed— several companies are advancing with airship projects, some of which even conducted flight tests over the past year.

3.4. SUSTAINABLE FUELS

In 2024, the sustainable aviation fuel (SAF) sector experienced significant growth due to increasing pressure to reduce the carbon footprint of the aviation industry. The RefuelEU Aviation regulation, which enters into force in 2025, will play a crucial role in this growth. This regulation requires airlines to use a minimum percentage of SAF in their operations within the European Union.

RefuelEU Aviation is a key component of the European Union's *Fit for 55* package, designed to help meet the EU's 2030 climate targets. Its main goal is to promote the gradual adoption of sustainable aviation fuels at EU airports, thereby reducing CO_2 emissions from aviation. The regulation sets the following minimum SAF blending targets:

- Starting in 2025, aviation fuel suppliers must ensure that fuel available to aircraft operators at EU airports contains at least 2% SAF, increasing progressively to reach 70% by 2050.
- Additionally, from 2030, at least 0.7% of that SAF must be synthetic aviation fuel, with the share rising to 35% by 2050.

The aviation industry is preparing to meet these new requirements by investing in SAF production technologies and optimising operations to lower greenhouse gas emissions. New feedstocks —such as biomass and agricultural waste— are also being explored to ensure a sustainable and sufficient SAF supply.

At the end of 2024, EASA published its report *"Status of the SAF Market in the EU in 2023"* [5], which included the following key points:

- Reference prices for the different types of fuels eligible under Regulation (EU) 2023/2405.
- An assessment of SAF production capacity in the EU.
- An analysis of emerging trends in the SAF production market.

In summary, EASA concludes that the announced production capacity is expected to meet the 6% minimum required for 2030. However, it emphasises the urgency of taking action to meet the 0.7% minimum for synthetic sustainable fuel by that same year.

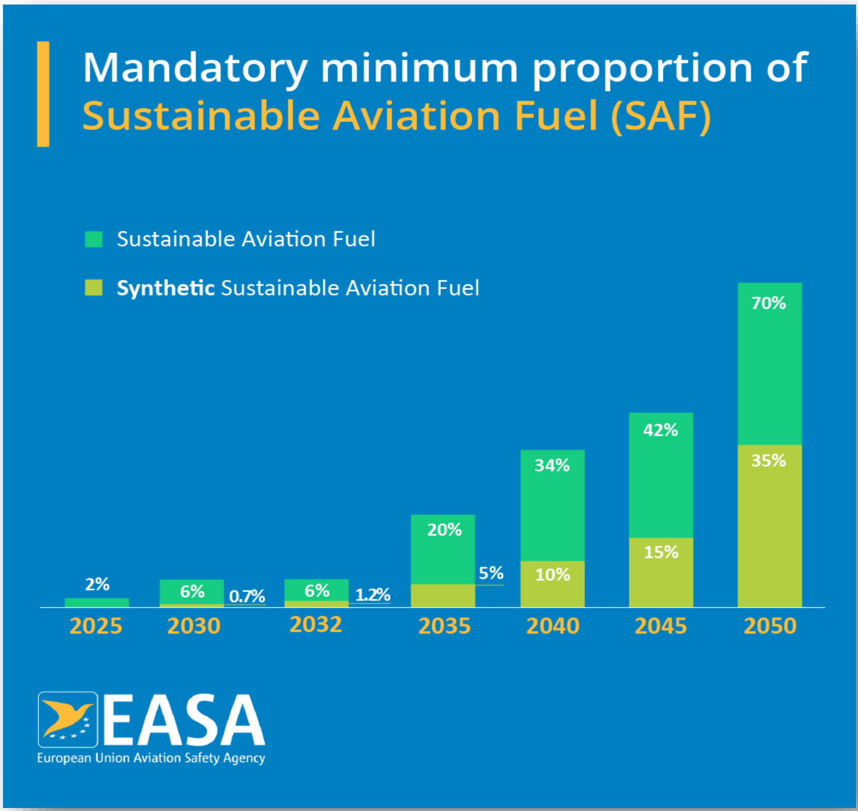

Figure 20. SAF Mandate under RefuelEU Aviation (EASA)

To conclude this brief introduction, and regarding the current state of SAF in Spain, it is worth highlighting the initiative led by the British Embassy and the Spanish Association of Aeronautical Engineers, which in June 2024 published a detailed report on potential collaborations —both in production and regulatory frameworks— between the two countries [6].

3.4.1. Key Agreements and Partnerships

To achieve the mandated blending targets and broader decarbonisation goals, coordination among the various stakeholders is essential. Below are some examples of such alignment, with commercial agreements reached in 2024 between airlines and SAF producers:

Sustainable Aviation Buyers Alliance (SABA)

In April 2024, SABA announced a landmark agreement[lxxii] to purchase SAF certificates, involving companies such as Deloitte, JetBlue, and World Energy. These multi-year contracts

—covering nearly 850,000 gallons of SAF— support the financing of new production plants and send a strong signal to the industry, paving the way for further agreements.

IAG and Twelve

In February 2024, IAG (International Airlines Group, parent company of Iberia and British Airways) signed an agreement to acquire 980 million litres of eSAF from Twelve[lxxiii], achieving one-third of its 2030 target.

3.4.2. Production

On the other hand, despite existing uncertainties, the industry continues to invest in the construction of new plants. At the national level, **Repsol** began large-scale production of renewable fuels at its facility in Cartagena[lxxiv], the first plant of its kind on the Iberian Peninsula. The new refinery has the capacity to produce 250,000 tonnes of renewable fuels per year from waste materials such as used cooking oil. These fuels can be used in aircraft, ships, buses, trucks, and cars, helping to avoid up to 900,000 tonnes of CO_2 emissions annually.

Figure 21. SAF Production Plant in Cartagena (Repsol)

At the international level, the United States is home to the **Phillips 66** industrial facility in Rodeo, California. This plant emerged from the conversion of a conventional refinery into a site for renewable fuel production, including SAF. The facility has already begun processing exclusively renewable feedstocks and is currently producing approximately 30,000 barrels per day of renewable diesel. By the end of Q2 2024, the plan was to increase production to over 50,000 barrels per day of renewable fuels, including SAF[lxxv].

This case serves as an example of the significant progress in SAF production planning in the U.S., positioning the country to meet its goal of more than 11 billion litres of SAF by 2030[lxxvi], as set out in the U.S. SAF Grand Challenge. However, the change in government in early 2025 has created substantial uncertainty regarding the continuity of environmental sustainability policies.

The consequences of an uncertain regulatory future, and therefore uncertain market conditions, may help explain decisions such as that of oil company Shell, which in July 2024 paused construction of its SAF and renewable diesel plant in the Netherlands. Despite the project being well advanced, with production scheduled to begin later that year, the company opted to revise the timeline to "control costs and optimise project sequencing," resulting in delays[lxxvii]. This serves as a strong example of the challenges and barriers that still exist today in achieving industrial-scale SAF production.

3.4.3. Data and Projections

To conclude this section, the following SAF production data and future projections are taken from the IATA press release *Disappointingly Slow Growth in SAF Production*[lxxviii]:

- In 2024, SAF production reached 1 million tonnes (1.3 billion litres), doubling the 2023 output.
- SAF accounted for 0.3% of global aviation fuel production and 11% of total global renewable fuel capacity.
- In 2025, SAF production is expected to reach 2.1 million tonnes (2.7 billion litres), representing 0.7% of total aviation fuel production and 13% of global renewable fuel capacity.

The main future challenges include:

- Establishing greater governmental clarity. The lack of a clear stance on potential support, penalties, incentives, etc., is hindering oil companies from investing in new production plants.
- Reducing subsidies for fossil fuels and increasing incentives for renewable energy production.
- Scaling up co-processing in existing refineries ([2], p. 26).

- Refineries also produce other types of sustainable fuels (e.g. gasoline or diesel). Restrictions on internal combustion engines in other transport sectors may have knock-on effects for aviation.
- Diversifying SAF production through multiple certified methods and researching new production pathways.
- Creating a global accounting framework for SAF: the existence of multiple registries and sustainability chains causes confusion.

3.5. ELECTRIC AVIATION

Electric aviation continues to advance in the small aircraft segment and in the development of hybrid propulsion technologies. In 2024, there was significant activity, both in product development and commercial efforts, to accelerate the maturity of the most viable solutions and secure funding for the completion of key projects. The main area of development in electric aviation is currently focused on vertical take-off and landing vehicles, known as ***eVTOLs***[lxxix], designed for urban air mobility applications on short-distance routes (with ranges up to 100 km). To date, global investment in this emerging aviation segment has exceeded €12 billion.

3.5.1. Electrified Aircraft Propulsion

Electric-powered aircraft continue to make slow but steady progress, with practical applications primarily in the sectors of urban air mobility and general aviation, particularly for training and instructional operations, which have relatively low range requirements. Given the current limitations in battery energy density, small aircraft designed for short-duration flights and limited range are the most suitable candidates for the introduction of this new technology. Some recent milestones achieved in this still-emerging sector include:

Figure 22. Joby eVTOL Prototype

A) **Joby** has continued the development and certification of its S4 model, a vehicle designed for air taxi services with capacity for one pilot and four passengers. The aircraft is equipped with six electrically powered rotors, two of them fixed and four tilting. The company claims design targets of a 240 km range and a 450 kg payload. It is currently undergoing FAA type certification, with the goal of receiving approval before the end of 2026. Joby has also announced the start of pre-commercial operations in the United Arab Emirates in 2026.

B) In December 2024, **Archer Aviation** announced it had reached the capacity to begin the pre-production phase of its Midnight model at its Covington facility in Georgia (USA). The Midnight is an air taxi designed to carry five people, including the pilot. Like Joby, Archer plans to begin pre-commercial operations in the United Arab Emirates in 2026.

Figure 23. Midnight Model by Archer Aviation

C) Beta Technologies continues the parallel development of its two electric aircraft models: a conventional take-off airplane (ALIA CX300) and a vertical take-off eVTOL (ALIA 250). Both models share a high degree of commonality. The ALIA 250 completed its first crewed transition flight in April 2024. Meanwhile, the CX300 conducted its first flight in November 2024. The company aims to obtain FAA certification for the ALIA CX300 by 2025 and states on its website that it has an order backlog of 600 units, with clients including the USAF, US Army, Amazon, UPS, and Air New Zealand. In November, Beta announced the addition of $318 million in funding from various investors.

Figure 24. ALIA CX300 and ALIA 250 by Beta Technologies

D) Vertical Aerospace, based in the United Kingdom, has continued test flights of its VX4 prototype over the past few months.

Figure 25. VX4 Prototype by Vertical Aerospace

E) Volocopter conducted demonstration flights in Paris during the Olympic period, albeit in a limited capacity, which nonetheless showcased the potential use of this type of aircraft in urban environments.

Figure 26. Test Flight of the VoloCity Model in Versailles (Volocopter)

Figure 28. Prosperity Model by AutoFlight

Figure 27. Flight of eHang's Remotely Piloted eVTOL Model

Figure 29. eDA-40 Model by Diamond

F) In China, **eHang** continues to lead the practical application of eVTOL models—specifically with an unmanned aircraft designed for two passengers, of which more than 200 units have already been produced.

G) Also in China, **AutoFlight** has expanded its portfolio with two electric aircraft models: the Prosperity, with capacity for four passengers and one pilot, and the Carry All, an autonomous cargo aircraft. AutoFlight obtained type certification for the Carry All from the Civil Aviation Administration of China (CAAC) in March 2024 and announced production certification for the Prosperity in December 2024. The company also announced the sale of 12 units (including both types) to the United Arab Emirates, with a unit price of $1.8 million.

H) Diamond announced that it expects to certify its electric aircraft, the eDA-40, with EASA in 2025. Last year, the model was evaluated by Lufthansa Aviation Training and AirBaltic Airlines, the latter having signed a letter of intent to purchase three units.

I) The company **Dufour** is using its fully electric Aero 1 aircraft as a test platform for technologies that will be incorporated into its future hybrid propulsion models, Aero 2 and Aero 3.

Figure 30. Aero 1 Aerobatic Aircraft by Dufour

J) The **Integral E** aircraft developed by Aura Aero completed its first flight on 3 December 2024 from Toulouse, powered by a 100 kW ENGINeUS electric motor supplied by Safran. This is a two-seat trainer aircraft intended for flying clubs and pilot training schools, with some aerobatic capability. It is equipped with a lithium-ion battery offering an expected endurance of one hour, with a 30-minute recharge time. The motor features integrated control electronics and its own cooling system. The aircraft is also equipped with Safran's GENeUSGRID power distribution and protection system, which manages energy supply to the motor based on operational needs.

Ilustración 2. Modelo Integral E de Aura Aero

3.5.2. Hybrid Aircraft Propulsion

As previously mentioned, the Swiss company **Dufour** is developing two hybrid-propulsion aircraft: the *Aero 2*, an unmanned cargo transport aircraft, and the *Aero 3*, designed for passenger transport. Both aircraft share a similar eVTOL configuration with convertible wings. The announced specifications for the *Aero 2* include a maximum take-off weight of 208 kg, a payload of 40 kg, and a range of 400 km. For the *Aero 3*, the maximum take-off weight will be 2,800 kg, with a maximum payload of 700 kg and a range of up to 1,000 km. *Aero 2* prototypes have undergone various flight tests, including transition flights and sensor integration demonstrations, while the *Aero 3* is currently in the preliminary design phase.

Figure 32. Aero 2 (left) and Aero 3 (right) Designs by Dufour

The ***Electra EL9*** is a STOL[lxxx] (Short Take-Off and Landing) aircraft model designed for nine passengers, based on the technology developed with the two-seat demonstrator prototype *EL2 Goldfinch*. The aircraft is powered by eight electric motors and includes a battery system composed of four battery packs, as well as a conventional turbine-driven electric generator. It is expected to offer a range of 330 miles at full payload and a maximum range of 1,100 miles when empty. Certification under FAA Part 23 regulations is targeted for 2029, with a first flight planned in 2027. The company reports a total of 2,100 orders from 52 operators, with a combined value of $8 billion.

Figure 33. EL9 STOL Design by Electra

The Swedish company **Heart Aerospace** is continuing the development of its 30-seat commercial aircraft, the *ES-30*. The company claims a range of 400 km with hybrid propulsion, extendable to 800 km when passenger capacity is reduced to 25, and a range of

200 km in fully electric mode. Heart Aerospace reports 250 firm orders, along with 120 purchase options and 190 letters of intent for this model.

Figure 34. ES-30 Model by Heart Aerospace

The manufacturer has developed an experimental model called X-1, which began ground testing in November 2024 and is scheduled for its first flight in mid-2025. Heart Aerospace will operate the aircraft from Plattsburgh International Airport in Champlain Valley, New York.

Figure 35. X-1 Prototype by Heart Aerospace

Additionally, the Swedish company plans to introduce a second prototype, the X-2, by 2026 with hybrid propulsion. The development of the X-1 has been partially funded through grants provided by the Swedish innovation agency Vinnova. Heart Aerospace aims to achieve certification for the ES-30 by 2029. The company is also leading a research project in Sweden called ELISE, in collaboration with Braathens Regional Airlines, SAS, and the national airport operator, focused on developing the infrastructure required to support electric aviation in the airports of the future. Trials conducted at Säve Airport in Gothenburg included verification and testing of electric charging procedures, evaluation of turnaround processes, passenger and cargo handling procedures, and experience in ground support and maintenance guidelines.

The company has submitted two design applications in the EU, as well as a patent application for a new engine nacelle integration concept, which, according to Heart, will significantly improve the flight characteristics of the ES-30 and allow it to operate from shorter runways.

VoltAero, based in France (Saint-Agnant), near Rochefort Airport, has announced the development of three versions of its Cassio model, as well as the completion of its local facility, which will be capable of producing 150 aircraft per year.

Figure 36. Cassio 600 Design by VoltAero

The Cassio models will have a passenger capacity ranging from 5 to 12. The Cassio 330 will offer 5 seats and 330 kW of power; the Cassio 480 will have 6 seats; and the Cassio 600 will accommodate 12 passengers with 600 kW of power. These aircraft are intended for regional commercial transport, air taxi services, charter operations, and private or utility flights. Their ranges will vary between 200 and 1,200 km depending on payload and configuration.

The propulsion system is based on Safran ENGINeUS electric motors combined with combustion engines from Kawasaki Motors. The aircraft will be certified under EASA CS23 as single-engine aircraft, although no specific certification date has been confirmed.

ATR has announced the launch of the feasibility study phase for its new EVO model, with the goal of achieving a 20% reduction in fuel consumption and an entry into service by 2030. The design concept is based on the use of a new, efficient conventional thermal engine combined with an electric motor powered by batteries. The aim is to optimise the sizing of the thermal engine core by using supplemental electric power, thereby maximising the overall energy efficiency of the propulsion system. As previously mentioned, in early 2025 ATR announced a five-year delay in the development timeline for the ATR EVO.

Figure 3. ATR's EVO Design

In November of last year, **General Electric (**GE) confirmed the successful testing of a hybrid powerplant under the Turboshaft Electrification Project, delivering one megawatt of power. The project is part of a $5.1 million research and development contract promoted by the United States Army. It involves combining a conventional CT7 turboshaft engine with an electric motor designed by GE, along with the necessary power electronics. This project is part of the broader set of initiatives promoted by NASA under the Electrified Powertrain Flight Demonstration program, which aims to develop a hybrid propulsion system for regional commercial aviation by the end of this decade.

Illustration 38. DHC Dash 7 modified by Magnix for the Electrified Powertrain Flight Demonstration program (NASA)

3.6. HYDROGEN

3.6.1. Supply and Promotion

The introduction of hydrogen as a fuel is one of the most direct paths toward sustainable aviation; provided, of course, that its production is also sustainable, which is referred to as green hydrogen. This color-coding system (see Ref. [1], p. 66) helps identify its origin and production process, although what truly matters, which is also captured in the EU **hydrogen taxonomy**[lxxxi], is the total emissions associated with the fuel's entire life cycle.

This regulatory framework, which includes concepts such as low-carbon hydrogen, is covered in an April 2024 article (Ref. [7]), where the inclusion of additional options like turquoise hydrogen, produced via methane pyrolysis, is also advocated, precisely on the basis of its full life-cycle emissions (Illustration 39).

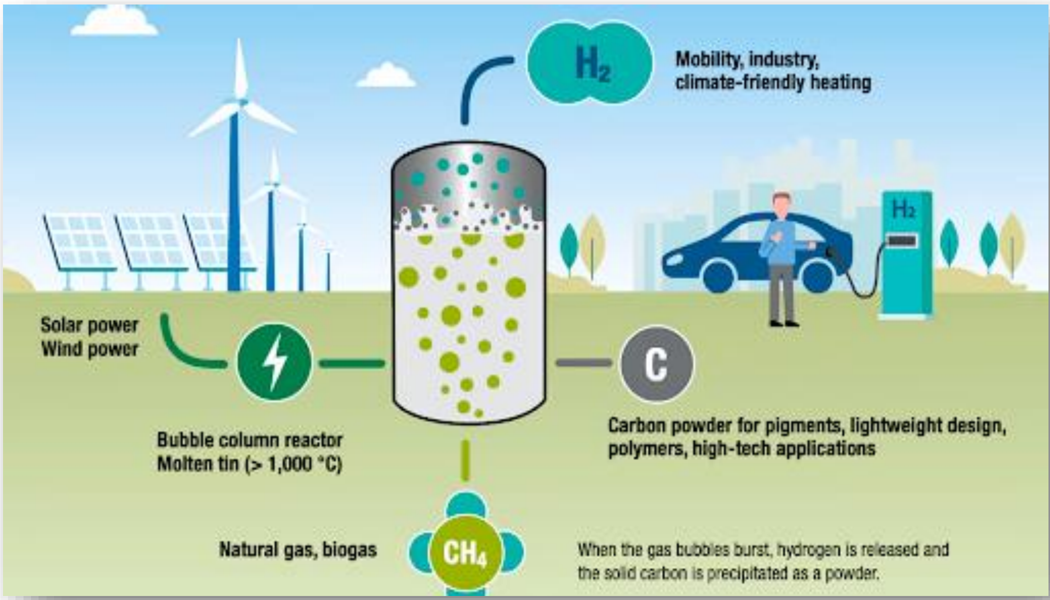

Ilustración 4. Proceso de generación de hidrógeno turquesa para minimizar su impacto medioambiental (Fastech)

Last year also saw progress in another pathway to obtain this fuel with no emissions impact, identified as white hydrogen[lxxxii]. This approach focuses on the discovery and exploitation of naturally occurring underground hydrogen deposits formed through geological processes. One such commercial extraction project currently under study is located in the town of Monzón, in Aragón, Spain[lxxxiii].

Achieving a hydrogen-powered air transport model based on clean hydrogen will, in any case, require significant financial and institutional support to ensure its availability. In this regard, 2024 saw the first grants awarded by the **European Hydrogen Bank**[lxxxiv] to seven green hydrogen projects (two of which are located in Spain[lxxxv]) through the initial call of its Innovation Fund[lxxxvi]. Notably, this fund is financed through revenues from the EU ETS (Emissions Trading System) and aims to bridge the gap between the cost of sustainable hydrogen production and its current market price. A second call, with a total of €1.2 billion, was launched in December. This type of government support is not limited to Europe. Other countries such as the United Kingdom[lxxxvii] and Japan are also firmly committed to hydrogen-powered aviation, supporting the entire cycle, from hydrogen supply infrastructure at airports to the development of aircraft specifically designed for hydrogen propulsion[lxxxviii].

In Spain, the **CDTI** (Centre for the Development of Industrial Technology), through its Aeronautical Technology Programme (PTA), funded projects such as CLAH2RENH3CE, aimed at developing hydrogen storage and distribution technologies. In addition, a consortium of energy and airport operators signed an agreement with Airbus in July 2024 to explore the creation of the first hydrogen hub in Spain[lxxxix] (see Illustration 40), as part of the Hydrogen Hub at Airports programme previously mentioned.

Also worth highlighting is the work of the Spanish ***Alliance for the Use of Green Hydrogen in Aviation***, which brings together the sector's key players under four working groups: hydrogen production, its supply to airports, contribution to the manufacture of synthetic aviation fuels, and hydrogen-based aircraft technologies[xc].

Illustration 40. Airbus' Hydrogen Hub at Airports program, aimed at creating integrated hydrogen production and distribution centers at airports (Airbus)

Lastly, it is important to highlight the enormous effort that will be required to establish the regulatory framework and ensure compliance with it for the certification of both ground supply infrastructure and, above all, hydrogen-powered aircraft. This aspect, which is sometimes overlooked, will be key to developing a sustainable aviation sector that inspires confidence and does not compromise the safety standards of commercial aviation. EASA, the main aviation regulatory authority in Europe, held its first dedicated meeting on the certification of hydrogen-powered aircraft at the end of last year[xci].

3.6.2. Fuel Cells

ZeroAvia has continued to make progress with its demonstrator aircraft based on the Dornier 228, completing 14 test flights throughout 2024. In parallel, the company has established its powerplant product line based on three categories:

On the other hand, the company has established its powerplant product line based on three categories: ZA600, for aircraft carrying 10 to 20 passengers with 600 kW of power; ZA2000, for regional aircraft carrying 40 to 80 passengers with a power output of 2 to 5 MW; and ZA2000RJ, for regional aircraft with 90 passengers. The company has also set a product availability timeline with the following targets: ZA600 available in 2026, ZA2000 in 2028, and ZA2000RJ in 2030. The company stated that in 2024, it initiated the certification process for the ZA600 with both the U.S. FAA[xcii] and the UK CAA.

It has also defined a timeline for the availability of these products: ZA600 by 2026, ZA2000 by 2028, and ZA2000RJ by 2030. The company announced that in 2024 it began the certification process for the ZA600 with both the U.S. FAA and the UK CAA. In 2024, ZeroAvia published a report titled *Scaling Hydrogen–Electric Propulsion for Large Aircraft* [8], outlining its vision for powering large commercial aircraft using hydrogen fuel cells.

Finally, in July last year, U.S. airline **American Airlines** signed a conditional purchase agreement with ZeroAvia for 100 hydrogen-electric engines to power regional aircraft[xciii]. American Airlines has been funding ZeroAvia since 2022.

Figure 41. Dornier 228 modified by ZeroAvia for testing hydrogen fuel cell electric propulsion

Universal Hydrogen, following its historic 2023 flight with a modified Dash 8 powered by hydrogen fuel cells, and the first ground test of its one-megawatt fuel cell propulsion system on its Iron Bird in February 2024xciv, Universal Hydrogen shut down and liquidated its commercial activities after depleting available cash and failing to secure additional financial support[xcv]. Its dual objective, to develop an H_2 container system for directly refueling aircraft and an onboard propulsion system, appears to have exceeded its capabilities. Universal Hydrogen's business model was based on the premise that there was insufficient hydrogen refueling infrastructure at airports, and that existing technology was too slow to refuel aircraft efficiently. The company presented itself as a plug-and-play solution requiring minimal airport adaptation, targeting 2026 for product entry into service. It raised around $100 million in funding from high-profile partners such as Airbus Ventures, American Airlines, JetBlue Ventures, GE Aviation, and Toyota Ventures, but these funds proved insufficient to meet its goals.

Joby Aviation is a pioneering company in the eVTOL sector which has modified one of its S4 prototypes to install a 40 kg hydrogen tank and a fuel cell from its German subsidiary, H2Fly. In July 2024, the company announced that the prototype completed a 523-mile flight. This hydrogen fuel project is funded by the USAF's Agility Prime program.

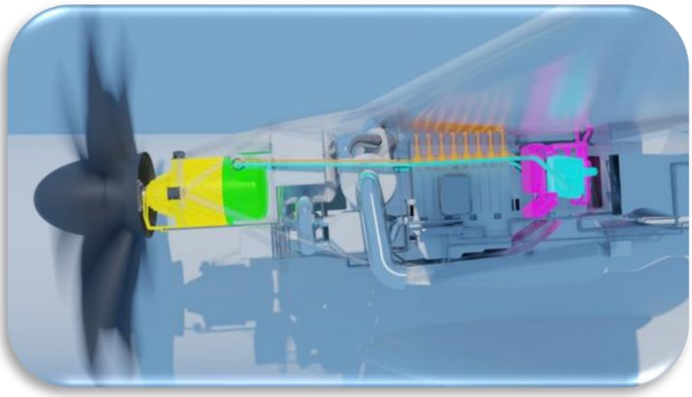

Illustration 42. Cryoprop superconducting electric propulsion system by Airbus UpNext (Airbus)

AIRBUS reported having completed the first phase of hydrogen fuel cell testing at its Ottobrunn facilities, achieving a maximum output of 1.2 MW. The fuel cell is being developed by an Airbus subsidiary, Aerostack GmbH, which is also partially owned by the German company ElringKlinger AG.

Meanwhile, UpNext, Airbus's fully owned subsidiary, has launched a new demonstrator named **Cryoprop** to accelerate the development of superconducting technologies for use in hydrogen-powered electric propulsion systems[xcvi]. The demonstrator will integrate and develop a two-megawatt superconducting system cooled by liquid hydrogen through a helium recirculation circuit. To this end, a collaboration agreement has been signed with Toshiba Energy Systems & Solutions Corporation[xcvii].

H3 Dynamics. As part of the European Union's Clean Aviation initiative, the Hypotrade project, led by Honeywell and Pipistrel, aims to develop a hydrogen-powered electric propulsion system for regional aircraft. For this purpose, H3 Dynamics has been selected as the fuel cell supplier for the technology demonstrator. The project's goal is to design and build a 500 kW propulsion system intended for EASA CS-23 category aircraft. The plan foresees ground tests beginning in 2026, followed by flight tests in 2030. Pipistrel (a subsidiary of Textron eAviation) will provide a 19-seat demonstration aircraft, conceptually named *Miniliner*, for the flight testing phase[xcviii]. Additionally, H3 is collaborating with AIRBUS on the development of a 500 kW APU[xcix] intended for wide-body aircraft such as the A330[c].

Illustration 43. Miniliner concept for 19 passengers by Pipistrel (AIN)

Sirius Aviation. This Swiss company unveiled the design of the *Sirius Jet* in January 2024, a hydrogen-electric powered VTOL business aircraft[ci]. The company aims to certify and bring the aircraft into service by 2028, offering two variants: one intended for private use and another for commercial air-taxi services.

The **Sirius Business Jet**, for private use, will seat one pilot and up to three passengers, with a projected flight range of 1,850 km. The **Sirius Millennium Jet**, for commercial services, will accommodate five passengers and reach up to 1,050 km. Both versions will feature a service ceiling of 9,000 meters and a cruising speed of 520 km/h.

The propulsion system includes 28 ducted electric propeller engines —20 mounted on the aircraft's main wing and eight on the canard. Another notable feature of this aircraft is its low noise level: 60 decibels at a distance of 100 meters[cii].

Illustration 44. Hydrogen-powered VTOL concept by Sirius Jet (now Stellarjet)

Cranfield Aerospace Solutions. This company, primarily focused on aircraft modification, announced a project to retrofit a Britten-Norman Islander to be powered by hydrogen fuel cells[ciii]. The modified Islander will incorporate two integrated propulsion systems housed within the original engine nacelles. Each propulsion system includes a 240 kW fuel cell, an electric motor, and the corresponding power electronics and control systems. The company has begun modifying the left nacelle of a prototype to carry out an initial series of ground tests. Its goal is to certify the Islander modification via STC[civ] (Supplemental Type Certificate) by 2027. The modified aircraft will have a capacity for 9 passengers and a range of 400 km.

Illustration 45. Retrofitting project with H_2 fuel cells on a Britten-Norman Islander by Cranfield Aerospace

Piasecki Aircraft Corp is specialized in the design and construction of experimental aircraft, announced last year its plans to commercialize a hydrogen-powered PA-890 helicopter by the end of this decade[cv]. The helicopter will be capable of carrying one pilot and up to seven passengers over distances exceeding 375 km. It will have a payload capacity of 850 kg and a maximum takeoff weight of 3,300 kg.

The PA-890 will feature a four-blade main rotor, a variable-incidence wing that rotates up to 90 degrees during hover flight, and a pivoting tail rotor that provides anti-torque and yaw control. When transitioning to forward flight, the wing rotates to a horizontal position, providing lift to offload the main rotor, while the tail rotor pivots to provide horizontal propulsion. By alleviating lift and thrust demands from the main rotor, its rotation speed will be reduced.

The company is currently developing a 660 kW "iron bird" ground test rig for the propulsion system. The development work carried out to date has been supported by the U.S. Air Force through collaboration with DARPA. Piasecki aims for the PA-890 prototype to begin flight testing in 2028.

Illustration 46. Slow-rotor hydrogen-powered PA-890 helicopter model by Piasecki.

3.6.3. Direct Combustion

The operation of an aviation turbine engine, such as those powering nearly all medium- and long-haul commercial aircraft, is based on the combustion of hydrocarbons or similar substances. It is this combustion of kerosene that produces, among other emissions, carbon dioxide (CO_2), which contributes to global warming (see Ref. [1], p. 10).

Replacing hydrocarbons with hydrogen in the combustion chamber is a well-known solution, tested in flight on several occasions. This would result primarily in water vapor emissions instead of CO_2. Although there are other potential emission-related issues associated with hydrogen combustion (such as NOx and contrail formation), it would represent a major step forward toward sustainable aviation by directly addressing the main contributor to climate change (Ref. [1], p. 70).

In November 2024, Pratt & Whitney Canada, one of the world's leading aircraft engine manufacturers, announced a series of hydrogen combustion tests on its PW127XT engine as part of the HyAdes project, funded by the Canadian government[cvi].

Illustration 47. Combustion chamber of the PW127XT engine (Pratt & Whitney)

In addition to ongoing initiatives such as Airbus' Zeroe program[cvii] (see [1], p. 71), which continued to advance last year with the inauguration of a dedicated technology center, new projects are exploring hydrogen propulsion[cviii], such as the Fokker Next Gen announced in 2024. The renowned Dutch manufacturer returns after decades without new designs, proposing an aircraft for between 120 and 150 passengers, with a range of 2,500 km[cix], and entry into service expected by 2035. Illustration 48 shows the proposed location for the liquid hydrogen tanks, a key element given the large volume required for this type of fuel.

Illustration 48. Fokker F100 with liquid hydrogen tanks in the rear fuselage (GreenAir[cx])

A key element in Fokker's proposal is the announced compatibility of its design with different types of fuel, allowing it to operate on standard aviation kerosene as used today, including its sustainable version (SAF). This capability would grant the aircraft significant operational flexibility, especially in cases where hydrogen supply is unavailable at certain airports, one of the major challenges for the introduction of hydrogen in aviation.

Another fundamental development for hydrogen-based aviation is the handling and distribution of hydrogen in its liquid form, which requires cryogenic temperatures. In this regard, **Rolls-Royce**, committed to developing hydrogen combustion engines for aviation, conducted tests at the beginning of last year with a pump capable of operating under such demanding conditions[cxi] (Illustration 49).

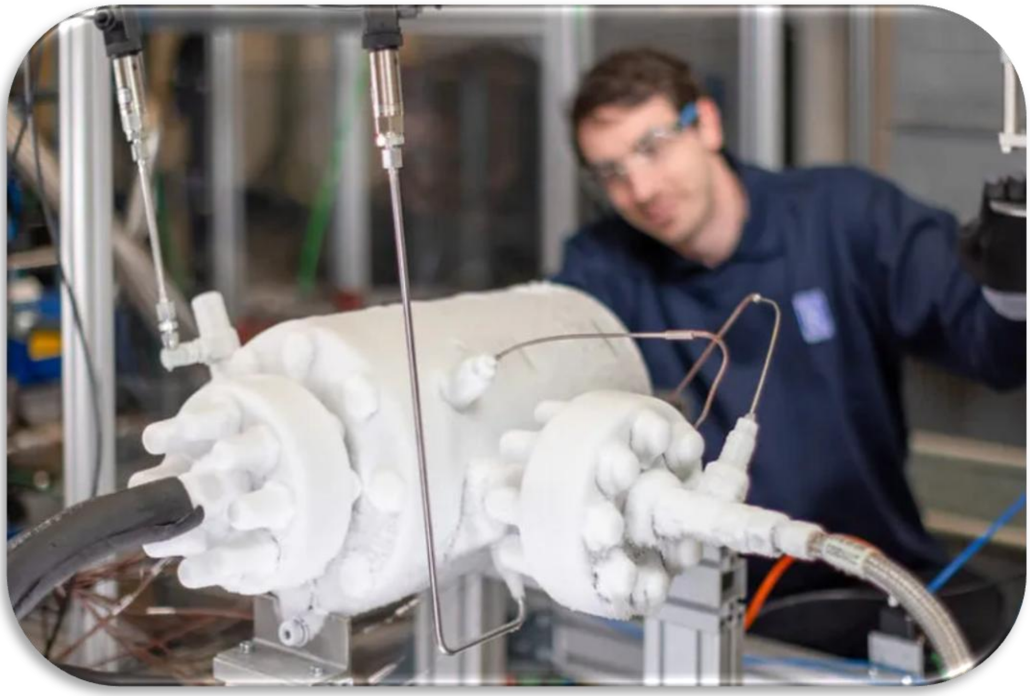

Illustration 49. Cryogenic hydrogen pump during testing (Rolls-Royce)

Finally, regarding the collateral issue of increased NOx emissions from hydrogen combustion already mentioned, in October 2024 a research team from the University of California published results demonstrating the effectiveness of zeolites in substantially improving the reduction of nitrogen oxides in post-combustion catalysts for hydrogen combustion[cxii]. Although the initial target of this project is internal combustion engines in the automotive sector, it exemplifies the mitigation potential in a hydrogen technology that is still under active development.

4. REFERENCES

4.1. BIBLIOGRAPHY

[1] O. Castro Álvarez and E. Martín Santana. **La sostenibilidad medioambiental en el sector aeronáutico**. COIAE, 2022

[2] O. Castro Álvarez. **La sostenibilidad medioambiental en el sector aeronáutico. Adenda 2022**. COIAE, 2023.

[3] E. Martín Santana and V. García Gómez. **La sostenibilidad medioambiental en el sector aeronáutico. Adenda 2023**. COIAE, 2024.

[4] O. Castro Álvarez. **Estudio de la Efectividad Medioambiental de Medidas Restrictivas a los Vuelos Domésticos en España**. 2ª Edición. COIAE, diciembre de 2023.

[5] **Estado del mercado de SAF en la UE en 2023.** EASA, 2024. (https://www.easa.europa.eu/en/newsroom-and-events/press-releases/easa-publishes-report-european-union-sustainable-aviation-fuels)

[6] **La colaboración entre Reino Unido y España en materia de producción y regulación de SAF**. UK Embassy in Madrid – COIAE, junio de 2024. (https://coiae.es/informe-la-colaboracion-entre-reino-unido-y-espana-en-materia-de-produccion-y-regulacion-de-saf)

[7] K. Talus, J. Pinto y F. Gallegos. **Realism at the end of the rainbow? An argument towards diversifying hydrogen in EU regulation.** The Journal of World Energy Law & Business, Volume 17, Issue 4, August 2024, Pages 217–233, 2024.

[8] **Scaling Hydrogen-electric Propulsion for Large Aircraft.** ZeroAvia, 2024. (https://zeroavia.com/wp-content/uploads/2024/08/ZeroAvia-Whitepaper-Scaling-hydrogen-electric-propulsion-for-large-aircraft-d.pdf)

4.2.ONLINE RESOURCES

[i]https://actualidadaeroespacial.com/la-faa-publica-la-norma-final-para-reducir-la-contaminacion-de-carbono-procedente-de-nuevos-aviones/

[ii]https://a21.com.mx/aeronautica/2024/07/02/cierra-universal-hydrogen-por-falta-de-fondos

[iii]https://www.ainonline.com/aviation-news/futureflight/2024-07-08/deutsche-aircraft-delays-service-entry-d328eco-regional

[iv]https://www.ainonline.com/aviation-news/futureflight/2024-10-08/mckinsey-says-urban-air-mobility-faces-untimely-cash-crunch

[v]https://www.elcorreo.com/sociedad/aviacion-cambio-climatico-vez-turbulencias-retrasos-desvios-20240714130353-ntrc.html

[vi]https://www.icao.int/Newsroom/Pages/ES/Encouraging-Europes-sustainable-aviation-leadership-to-support-ICAO-goals.aspx

[vii]*https://www.greenairnews.com/?p=5672*

[viii]https://www.transportes.gob.es/el-ministerio/sala-de-prensa/noticias/jue-04072024-1608

[ix]https://actualidadaeroespacial.com/aviation-group-y-urjc-impulsan-una-catedra-para-el-desarrollo-de-un-transporte-aereo-sostenible/

[x]https://www.greenairnews.com/?p=5741

[xi]https://www.iata.org/contentassets/8d19e716636a47c184e7221c77563c93/nz-roadmaps.pdf

[xii]https://report.aiazero.org/

[xiii]https://www.ainonline.com/aviation-news/futureflight/2024-08-01/air-new-zealand-keeps-electric-aircraft-plans-despite-net

[xiv]https://www.greenairnews.com/?p=6440

[xv]https://www.infrastructure.gov.au/sites/default/files/documents/awp-aviation-white-paper.pdf

[xvi]https://clean-aviation.eu/

[xvii]Monitoring, Reporting and Verification

[xviii]https://www.miteco.gob.es/es/cambio-climatico/temas/comercio-de-derechos-de-emision/operadores-aereos-mrva-impactos.html

[xix]https://www.iata.org/en/pressroom/2024-releases/2024-04-30-01/

[xx]https://www.greenairnews.com/?p=5655

[xxi]https://www.transportenvironment.org/articles/eu-walks-back-on-key-aviation-climate-law-and-excludes-long-haul-flights-from-monitoring-scheme

[xxii]https://www.transportenvironment.org/uploads/files/Open-letter_-Addressing-contrails-is-a-no-regrets-decision-that-will-help-slow-climate-change_2024-11-22-140205_ggcq.pdf

[xxiii]https://www.transportenvironment.org/articles/aviation-reduce-contrail-warming-for-less-than-eur4-per-flight-new-study

[xxiv]https://www.einpresswire.com/article/701971248/satavia-reports-successful-contrail-management-trials-with-aircraft-operators-supported-by-uk-european-space-agencies

[xxv]https://sites.research.google/contrails/

[xxvi]https://www.ati.org.uk/funding/non-co2programme/

[xxvii]https://www.greenairnews.com/?p=6428

[xxviii]https://www.aerospacetestinginternational.com/news/engine-testing/pratt-whitney-to-test-saf-emissions-with-faa.html

[xxix]https://www.airbus.com/en/newsroom/press-releases/2024-06-worlds-first-in-flight-study-of-commercial-aircraft-using-100

[xxx]https://www.blue-lines.org/airline-index

[xxxi]Direct Air Carbon Capture and Storage

[xxxii]https://aircraft.airbus.com/en/services/operate/airbus-carbon-capture-offer

[xxxiii]https://www.greenairnews.com/?p=6098

[xxxiv]https://icvcm.org/core-carbon-principles/

[xxxv]https://www.icao.int/environmental-protection/CORSIA/Pages/default.aspx

[xxxvi]https://climate.ec.europa.eu/news-your-voice/news/2024-carbon-market-report-stable-and-well-functioning-market-driving-emissions-power-and-industry-2024-11-19_en

[xxxvii]https://climate.ec.europa.eu/news-your-voice/news/2024-carbon-market-report-stable-and-well-functioning-market-driving-emissions-power-and-industry-2024-11-19_en

[xxxviii]https://actualidadaeroespacial.com/lufthansa-introduce-un-recargo-en-los-billetes-por-costes-medioambientales/

[xxxix]https://www.europapress.es/turismo/nacional/noticia-bruselas-avisa-20-aerolineas-exponen-

sanciones-ofrecer-tasas-extra-compensar-emisiones-20240430132826.html

[xl]https://ec.europa.eu/commission/presscorner/detail/es/ip_24_6523

[xli]https://www.ecologistasenaccion.org/324941/una-tasa-a-los-vuelos-frecuentes-en-europa-reduciria-un-21-las-emisiones-del-transporte-aereo-y-generaria-74-100-millones-de-euros/

[xlii]https://elperiodicodelaenergia.com/impuesto-combustible-aviacion-ue-perjudicara-espana-reducir-gasto-turistico/

[xliii]https://www.reuters.com/business/aerospace-defense/eu-countries-mull-20-year-tax-holiday-jet-fuel-document-shows-2024-09-06/

[xliv]https://www.europapress.es/turismo/nacional/noticia-alemania-aumentara-20-impuesto-billetes-avion-partir-mayo-20240108182546.html

[xlv]https://actualidadaeroespacial.com/aprueban-la-reduccion-de-vuelos-domesticos-en-favor-del-ferrocarril-cuando-hay-una-alternativa-de-menos-de-25-horas/

[xlvi]https://www.eleconomista.es/actualidad/noticias/12985625/09/24/podemos-registra-una-iniciativa-para-prohibir-los-vuelos-de-menos-de-una-hora-y-evitar-la-ampliacion-de-el-prat-por-su-impacto-medioambiental.html

[xlvii]https://cincodias.elpais.com/companias/2024-10-02/el-tiron-del-trafico-aereo-lleva-a-maximos-historicos-la-demanda-de-queroseno-en-espana.html

[xlviii]https://actualidadaeroespacial.com/el-parlamento-europeo-aprueba-la-reforma-del-cielo-unico-europeo-para-mejorar-la-eficiencia-y-reducir-las-emisiones/

[xlix]https://www.greenairnews.com/?p=5490

[l]https://fly-news.es/sostenibilidad/sas-vuela-por-el-polo-un-20-por-ciento-mas-verde/

[li]https://www.hispaviacion.es/enaire-presenta-el-programa-green-sky-para-avanzar-hacia-una-aviacion-mas-sostenible/

[lii]https://cordis.europa.eu/article/id/451359-chasing-the-slipstream-for-more-efficient-flights/es

[liii]https://aviacionaldia.com/2024/06/asi-reducen-los-pilotos-de-emirates-el-consumo-de-combustible-y-las-emisiones-durante-las-operaciones.html

[liv]https://www.aerotendencias.com/aviacion-comercial/63727-volotea-mejora-eficiencia-uso-combustible/

[lv]https://aviaciondigital.com/air-nostrum-mejora-su-programa-de-eficiencia-de-combustible-con-openairlines/

[lvi]https://www.aena.es/es/prensa/aena-preve-superar-los-300-millones-de-pasajeros-en-2025-un-ano-antes---de-lo-esperado.html

[lvii] https://aviaciondigital.com/aena-ha-sido-premiada-por-su-compromiso-con-la-reduccion-de-emisiones/

[lviii] https://www.avionrevue.com/aeropuertos/aeropuerto-el-dorado-estrena-flota-de-plataforma-100-electrica/

[lix] https://aeroportlleida.cat/es/el-aeropuerto-de-lleida-alguaire-adquiere-la-maquinaria-para-producir-hidrogeno-verde/

[lx] https://www.greendealstargate.eu/

[lxi] https://www.bristolairport.co.uk/corporate/news-and-media/news-and-media-centre/2024/4/ground-breaking-bristol-airport-hydrogen-trial-next-critical-step-on-journey-to-achieving-zero-emission-aviation/

[lxii] https://research.airbus.com/en/products-systems/goliat

[lxiii] https://www.airbus.com/en/newsroom/stories/2024-09-developing-a-global-ecosystem-to-support-hydrogen-powered-flight

[lxiv] https://actualidadaeroespacial.com/importante-impacto-de-la-reduccion-de-emisiones-en-el-aeropuerto-de-barajas/

[lxv] https://www.aena.es/es/estadisticas/inicio.html

[lxvi] https://www.brusselsairport.be/en/pressroom/news/brussels-airport-and-tui-test-the-taxibot

[lxvii] https://www.nasa.gov/image-article/trans-sonic-truss-braced-wing-may-help-reduce-fuel-consumption/

[lxviii] https://herwingt-project.eu/home

[lxix] https://www.jetzero.aero/why-jetzero

[lxx] https://www.ainonline.com/aviation-news/futureflight/2024-09-06/easyjet-teams-jetzero-blended-wing-body-airliners

[lxxi] https://www.bbc.com/mundo/articles/c4gzpxxyw9go

[lxxii] https://flysaba.org/2024/04/17/sustainable-aviation-buyers-alliance-announces-historic-agreements-to-purchase-sustainable-aviation-fuel-certificates-to-grow-investment-in-clean-fuel-technologies/

[lxxiii] https://www.twelve.co/post/twelve-and-iag-sign-historic-long-term-multi-million-gallon-saf-offtake-agreement

[lxxiv] https://www.repsol.com/es/sala-prensa/notas-prensa/2024/repsol-comienza-produccion-gran-escala-combustibles-renovables-cartagena/index.cshtml

[lxxv]https://www.phillips66.com/refining/san-francisco-refinery

[lxxvi]https://www.greenairnews.com/?p=6249

[lxxvii]https://www.greenairnews.com/?p=5902

[lxxviii]https://www.iata.org/en/pressroom/2024-releases/2024-12-10-03/

[lxxix]Electric vertical take-off and landing

[lxxx]Short take-off and landing

[lxxxi]https://energy.ec.europa.eu/news/renewable-hydrogen-production-new-rules-formally-adopted-2023-06-20_en

[lxxxii]https://www.weforum.org/stories/2024/08/white-hydrogen-5-critical-questions-answered/

[lxxxiii]https://elperiodicodelaenergia.com/espana-peloton-cabeza-hidrogeno-natural-proyecto-helios-aragon-monzon-apunta-coste-extraccion-1-dolar-kilogramo/

[lxxxiv]https://www.miteco.gob.es/es/energia/hidrocarburos-nuevos-combustibles/hidrogeno/european-hydrogen-bank.html

[lxxxv]https://climate.ec.europa.eu/news-your-voice/news/winners-first-eu-wide-renewable-hydrogen-auction-sign-grant-agreements-paving-way-new-european-2024-10-07_es

[lxxxvi]https://climate.ec.europa.eu/news-your-voice/news/winners-first-eu-wide-renewable-hydrogen-auction-sign-grant-agreements-paving-way-new-european-2024-10-07_es

[lxxxvii]https://actualidadaeroespacial.com/informe-de-hia-para-que-el-reino-unido-lidere-la-carrera-de-la-aviacion-de-hidrogeno/

[lxxxviii]https://hidrogeno-verde.es/japon-aviacion-hidrogeno/

[lxxxix]https://www.europapress.es/turismo/nacional/noticia-airbus-aena-air-nostrum-iberia-exolum-repsol-estudian-crear-primer-hub-aeroportuario-hidrogeno-espana-20240709112511.html

[xc]https://www.energias-renovables.com/hidrogeno/alianza-para-el-uso-del-hidrogeno-20240229

[xci]https://www.easa.europa.eu/en/newsroom-and-events/press-releases/easa-holds-first-international-workshop-certifying-hydrogen

[xcii]En febrero de 2025 recibió el *issue paper G-1 stage 2* de la FAA.

[xciii]https://www.reuters.com/business/aerospace-defense/american-airlines-enters-provisional-deal-100-hydrogen-electric-engines-2024-07-02/

[xciv]www.ainonline.com/news-article/2024-02-28/universal-hydrogen-runs-first-ground-test-liquid-hydrogen-fuel-module

[xcv]https://www.avionrevue.com/aviacion-comercial/universal-hydrogen-en-liquidacion/

[xcvi]https://www.airbus.com/en/newsroom/press-releases/2024-05-airbus-takes-superconductivity-research-for-hydrogen-powered

[xcvii]https://www.airbus.com/en/newsroom/press-releases/2024-10-airbus-and-toshiba-to-partner-on-superconductivity-research

[xcviii]https://www.ainonline.com/aviation-news/futureflight/2024-08-27/eu-backed-clean-aviation-initiative-picks-hydrogen-fuel-cell

[xcix]Auxiliary Power Unit

[c]https://www.ainonline.com/aviation-news/air-transport/2024-05-16/airbus-prepares-start-testing-hydrogen-apu-a330-airliner

[ci]https://evtol.news/sirius-aviation-sirius-business-jet-concept-design

[cii]En enero de 2025 Sirius Jet realizó un cambio corporativo, convirtiéndose en Stellarjet.

[ciii]https://www.ainonline.com/aviation-news/futureflight/2024-07-10/new-funding-allows-cranfield-team-build-hydrogen-airliner

[civ]Supplemental type certificate

[cv]https://www.ainonline.com/news-article/2024-02-11/military-backing-piasecki-steps-development-hydrogen-powered-pa-890

[cvi]https://www.ainonline.com/aviation-news/aerospace/2024-11-07/hydrogen-combustion-test-start-pw127xt-turboprop-engine

[cvii]https://www.airbus.com/en/innovation/energy-transition/hydrogen/zeroe

[cviii]https://actualidadaeroespacial.com/airbus-abre-un-nuevo-centro-de-desarrollo-zeroe-en-alemania-para-tecnologias-innovadoras-de-hidrogeno/

[cix]https://www.fokkernextgen.com/blog/fokker-next-gen-and-airbaltic-sign-mou

[cx]https://www.greenairnews.com/?p=5680

[cxi]https://www.aerospacetestinginternational.com/news/electric-hybrid/rolls-royce-begins-testing-hydrogen-fuel-pump-systems.html

[cxii]https://www.ainonline.com/aviation-news/futureflight/2024-10-11/scientists-devise-cleaner-hydrogen-combustion-engines