ENVIRONMENTAL SUSTAINABILITY IN THE AERONAUTICAL SECTOR

ADDENDUM 2022

Colegio Oficial de Ingenieros Aeronáuticos de España Report.

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1. PROLOGUE

From the Colegio Oficial de Ingenieros Aeronáuticos de España we are witnessing with concern the avalanche of information that affects the message that aviation is the mode of transport that pollutes the most and that, therefore, it should be regulated by prohibiting flying on some routes and reducing the frequencies in others, in a word: limiting the free development of air transport activity.

While it is true that civil aviation vs. other modes of transport is the mode that pollutes the most per passenger/Km (although we disagree with the rigor with which the accounts are made), it is also true that it is the mode that generates the least emissions: 2.4% of total emissions worldwide in 2019. At the European Union level, the civil aviation sector generated, in the same year, 13.4% of the total emissions of the transport sector, a sector that contributed 29, 6% of total emissions, that is, civil aviation was responsible for 3.9% of the total emissions generated in the European Union in 2019.

These values have not influenced the commitment to reduce emissions from civil aviation, if only because of the interest in reducing fuel consumption, to reduce costs and, therefore, improve the profits of the air transport industry. Civil aviation has always been (and is) committed to the fight against climate change, having been involved in numerous initiatives aimed at achieving 100% emission-free civil aviation by 2050.

This report has been prepared with the aim of making civil society aware of the state of the art of the various initiatives that are being investigated to introduce new technologies that will promote a revolutionary change in civil aviation and that will allow achieving the committed sustainability objective.

The intention of this association is to prepare a new report every two years, to ensure that society has a source of accurate and up-to-date information, which makes it possible to monitor the degree of maturity of new technologies and progress in compliance with the sustainability goals.

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Decano del Colegio Oficial de Ingenieros Aeronáuticos de España

2. EXECUTIVE SUMMARY

Like other sectors, aviation is committed to reversing climate change, making it imperative to find innovative and sustainable solutions to address the environmental challenges we face today. Although emissions from aviation are currently much lower than those from road transport, there are more and more people traveling the world, and the demand for air transport is expected to increase significantly in the coming years.

In this common effort to reduce emissions that contribute to climate change, aviation is not being left behind and, in the midst of these challenges, a source of hope has also emerged: the new technologies in sustainability that are transforming the aviation landscape. These innovations are paving the way for a greener, more responsible future in the aerospace industry.

This addendum to the "COIAE 2022 Environmental Sustainability Report" delves into the analysis of new sustainability technologies in aviation, exploring the cutting-edge solutions that are revolutionizing the way we fly. From advances in engine efficiency to the implementation of biofuels and the development of electric aircraft, we are on the threshold of a new era of more sustainable air travel.

The report updates the evolution of research, projects and developments in the field of sustainable aviation carried out in recent months.

As sustainability efforts become a global priority, aerospace companies and governments are working together to encourage innovation and set stricter standards in terms of emissions and energy consumption.

Throughout these pages, we will expose how aviation is reinventing itself to reduce its impact on the environment and address climate change. We will examine the technical, economic and operational challenges that must be overcome to achieve more sustainable aviation, as well as the potential benefits that this can generate.

This update also discusses the ongoing policies and regulations that are driving the adoption of sustainable technologies in the aviation industry.

Hoping that reading this COIAE’s report update provides a clear and enriching vision of the exciting future that awaits us, where sustainability and innovation intertwine to build a greener and cleaner aerospace horizon. Together, we can drive the change needed to ensure more sustainable air travel and a healthier planet for generations to come.

Welcome to this journey towards a sustainable future in aviation!

Content

3. INTRODUCTION

The evolution of aviation towards environmental sustainability is a trend that is materializing through multiple approaches and strategies. The objective of this COIAE's report, as a continuation of previous publications, is to describe and provide context for the challenges and ongoing initiatives to achieve truly sustainable aviation. In particular, this edition will focus on everything that has happened in this field during the year 2022, filled with developments and advancements. A broader perspective on this topic can be found in previous reports, which include, for example, detailed information on noise pollution [1].

It should be clarified that the aviation sustainability sector covers much more ground than what is discussed here, starting with the social and economic pillars of utmost importance but beyond the scope of our objective. This work's focus is on the urgent battle to mitigate the impact of emissions from commercial aviation, primarily regarding global warming. However, as it will be presented in some of the topics addressed, the aviation environmental sustainability should be approached with a life cycle analysis, taking into account everything from aircraft production to recycling, but that would require a much broader treatment than what is intended here.

Finally, it is necessary to clarify that the field being addressed, despite the mentioned limitations, is fortunately of considerable breadth, with a multitude of proposals and achievements made in the past year. With this report, which cannot and does not aim to be exhaustive, the goal is simply to provide an updated overview of the exciting journey towards environmentally sustainable aviation.

4. ENVIRONMENTAL IMPACT OF AVIATION IN CONTEXT

Scientific knowledge regarding the impact of aviation emissions has reached a high level of maturity, although, as mentioned before, there are areas that still require further advancement (for example, contrail formation and aerosol-cloud interaction[1]). This solidity is crucial for effectively directing development efforts towards environmentally sustainable aviation.

At the end of 2021, an extensive review of scientific consensus [1] was published, confirming that aviation CO2 emissions account for 2.4% of the total human-induced emissions. When considering effects beyond carbon dioxide, the report estimated their contribution to global warming at 4%. Nevertheless, the authors of the study emphasized the importance of focusing on reducing CO2 emissions due to their significant persistence in the atmosphere. Figure 1 illustrates the relationship between these factors (highly dependent on global traffic growth) and different future projections. The benefits of increased use of sustainable aviation fuels (SAF) and containing CO2 emissions through a better management of air traffic volume or other means become evident, offering realistic possibilities to decisively curb the climate footprint of commercial aviation.

[1] https://www.gfdl.noaa.gov/aerosols-and-climate/

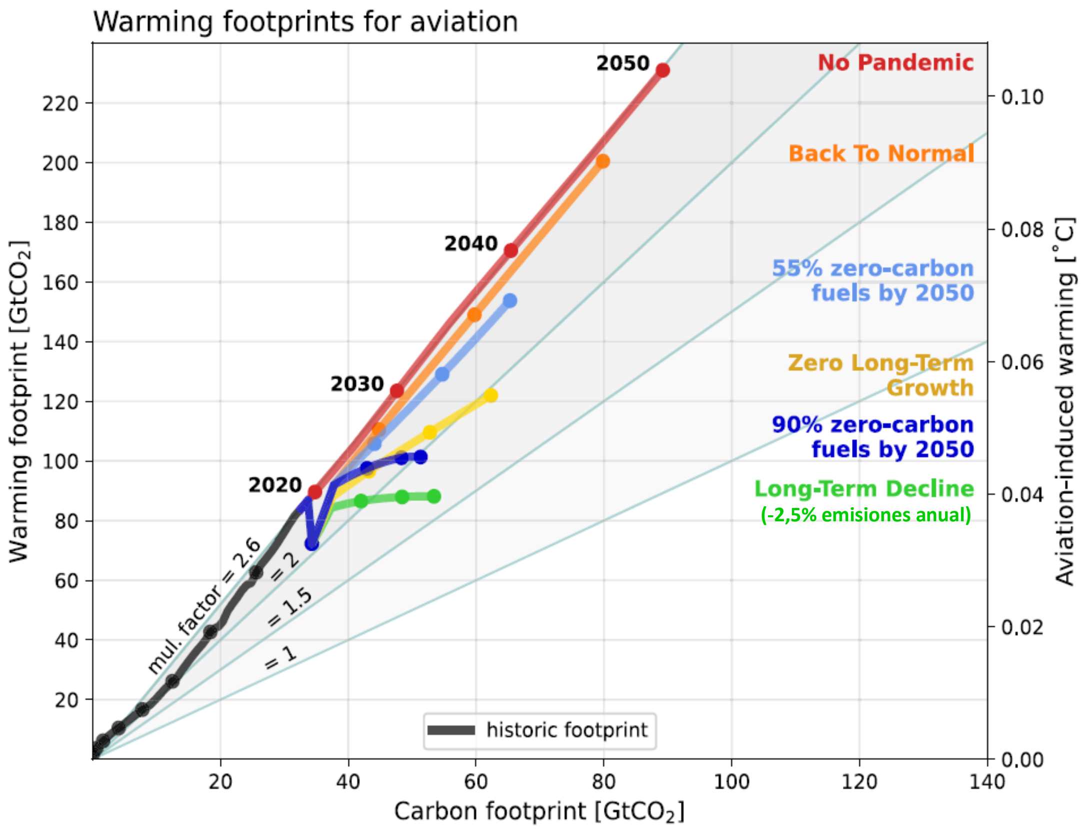

Figure 1. Historical impact of aviation emissions and contributing non-CO2 factors. Future projections with different scenarios (Incorporation of SAF, containment and reduction of air traffic) until 2050 [1].

The main non-CO2 impact comes from contrail formation and the induced cloudiness associated with it[2]. These ice cloud formations, resulting from the freezing of water vapor produced during hydrocarbon combustion, contribute to global warming by trapping outgoing infrared radiation from the Earth's surface to a greater extent than the solar radiation they reflect during the day. According to the mentioned study, these short-lived effects act as multipliers of CO2, amplifying the atmospheric temperature increase associated with growing air traffic while also significantly mitigating the overall impact of aviation emissions in a scenario of emission reduction.

Figure 1 also shows the long-lasting mitigating effect of reduced air traffic during the COVID-19 pandemic.

In 2022, updated emission comparisons among different modes of transportation were also published (Figure 2), with some studies emphasizing the increasing relevance of the primary contributor to environmental impact: road transportation[3].

[2] https://www.climateworks.org/blog/how-aviations-impact-on-global-warming-goes-beyond-carbon-emissions/

[3] https://www.transportenvironment.org/discover/black-friday-exposes-dark-side-of-trucking/

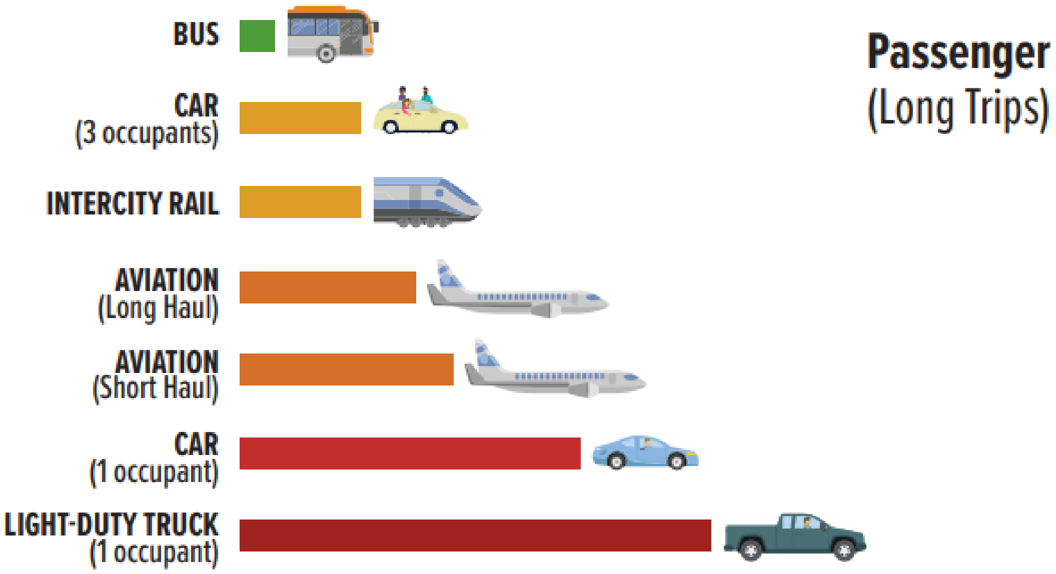

Figure 2. Comparison of greenhouse gas emissions, per passenger and km, between different means of transport [3].

5. TOWARDS A SUSTAINABLE AVIATION

During 2022, significant agreements and commitments were made to pave the way towards sustainable aviation. In February, the Toulouse Declaration was announced, in which 37 European countries and nearly 150 private entities from the aerospace industry committed to achieving net-zero carbon emissions for aviation by 2050, along with meeting certain intermediate targets. Furthermore, towards the end of last year, the Zero-Emission Aviation Partnership was launched in Europe, a public-private organization aiming to facilitate the development and introduction of electric and hydrogen-powered aircraft[4].

These announcements complement similar commitments made by the United States in late 2021[5], as well as by the aviation industry as a whole through the Air Transport Action Group (ATAG[6]). Globally, in October 2022, the 41st assembly of the International Civil Aviation Organization (ICAO) approved the Long-Term Aspirational Goal (LTAG) to decarbonize commercial aviation by 2050[7].

Overall, these commitments are based on short-term measures (implementation of operational and conventional aircraft improvements), medium-term measures (gradual introduction of sustainable aviation fuels), and long-term measures (disruptive propulsion systems, both electric and hydrogen-based). Additionally, emissions offset systems, including mandatory schemes like the EU ETS and CORSIA, are being reinforced, with other alternatives such as managing air traffic volume or direct air capture (DAC) of carbon from the atmosphere to achieve emissions balance. Of course, all these plans and proposals will require top-level political, business, and public commitment to achieve such ambitious yet necessary objectives.

[4] https://defence-industry-space.ec.europa.eu/eu-aeronautics-industry/alliance-zero-emission-aviation_en
[5] https://www.faa.gov/sustainability/aviation-climate-action-plan
[6] https://aviationbenefits.org/FlyNetZero
[7] https://www.icao.int/environmental-protection/Pages/LTAG.aspx

In fact, numerous reports and studies were presented last year, aiming to identify pathways to decarbonize aviation. Among them are reports from Eurocontrol [4], ERA[8] [5], ICCT[9] [7], the ICAO itself [6], and even online tools for building different scenarios[10]. One notable meta-study conducted by Roland Berger analyzed the overall characteristics of these proposals[11].

This consultancy firm divides the proposals into the "Art of the Probable" (more conservative, with a greater emphasis on emissions offsetting, Figure 3) and the "Art of the Possible" (more ambitious, placing the focus on reducing CO2 through new propulsion technologies and sustainable aviation fuels, Figure 4).

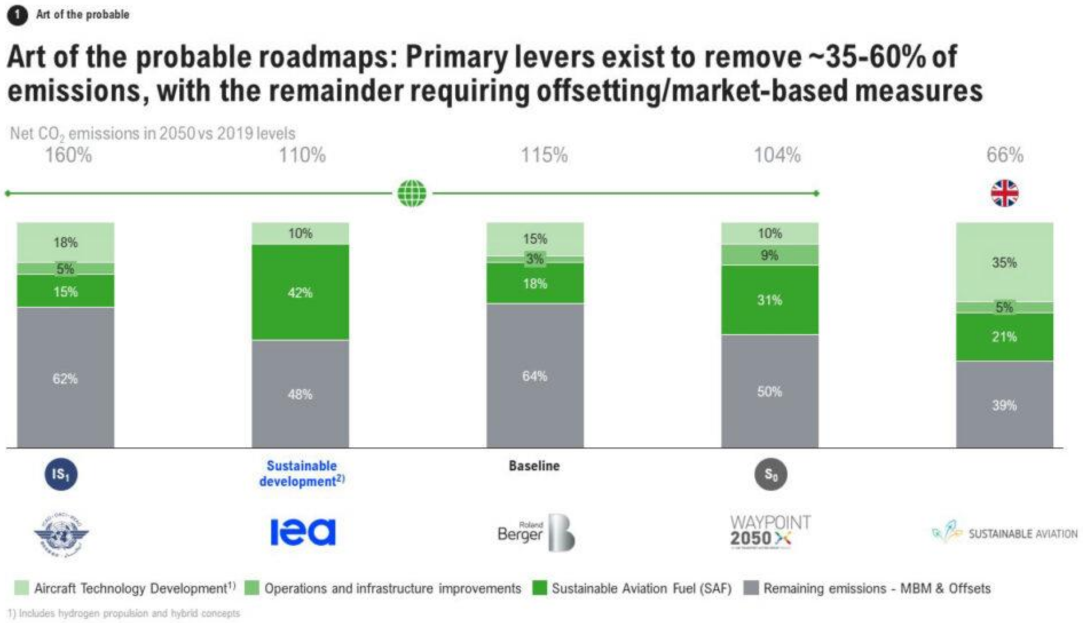

Figure 3. Art of the probable. Estimates towards offset-based aviation net-zero emissions.

[8] European Regional Airline Association

[9] The International Council on Clean Transportation

[10] https://dash-mpp.plotly.host/mpp-aviation-net-zero-explorer/global_regional_lens

[11] https://www.greenairnews.com/?p=3170

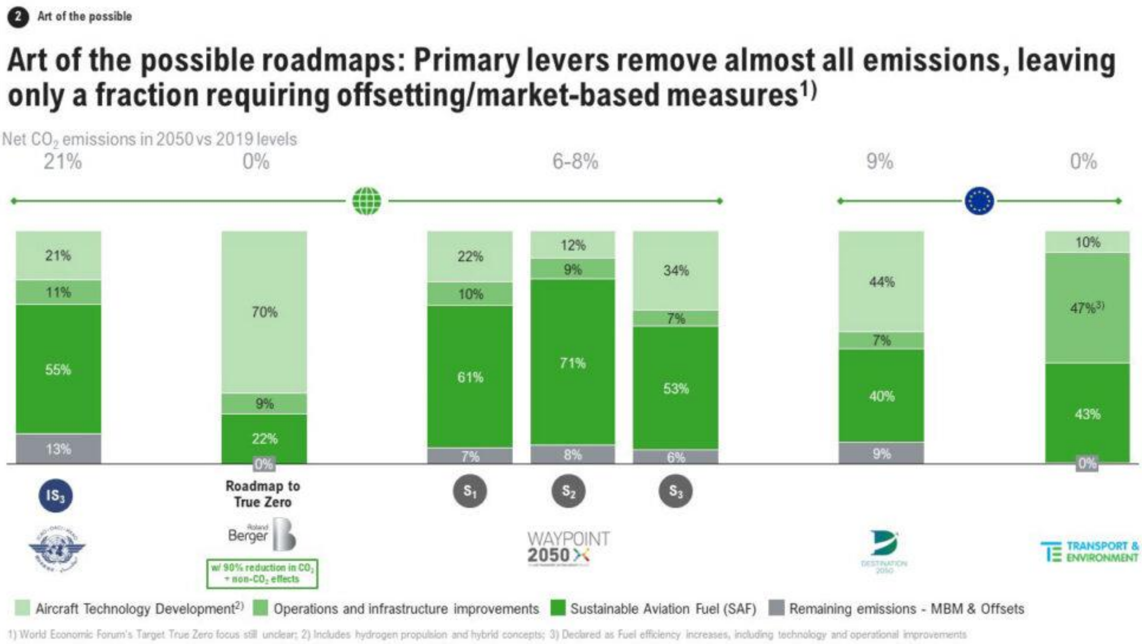

Figure 4. Art of the possible. Estimates towards net zero emissions in aviation based on SAF and disruptive technologies.

Among other noteworthy points in the different reports, there are the interim targets (55% CO2 reduction by 2030), the production capacity of sustainable aviation fuels (SAF), cost calculations including taxes associated with fossil fuel, and demand management. A crucial aspect in the economic calculations is the projected evolution of emission rights prices (EU ETS), which in some cases is estimated to reach €200/tCO2 (it was around €85 by the end of 2022), resulting in additional operational costs for airlines and a consequent incentive for emission reduction.

Airlines, in fact, are leading various initiatives to advance decarbonization objectives. These include fleet renewal with more efficient aircraft, large-scale SAF procurement agreements, investments in CO2 capture technologies, and agreements for the development of disruptive propulsion systems (e.g., Air New Zealand[12]). It is interesting to note that, following this diversified model, other stakeholders are also investing in battery and hydrogen technologies simultaneously (e.g., Monte Aircraft Leasing[13]).

In the sector of aircraft manufacturers, 2022 witnessed the consolidation of proposals such as *Embraer's Energy* program[14], which focuses on hybrid-electric and hydrogen fuel cell solutions. Additionally, the sector is experiencing an expansion of proposals that seek to capitalize on available technologies. For example, there is the proposal to reintroduce passenger airships (Airlander), with Air Nostrum being the launch customer[15].

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[12] https://www.airnewzealand.co.nz/press-release-2022-air-new-zealand-announces-mission-next-gen-aircraft-partners
[13] https://www.greenairnews.com/?p=3623
[14] https://www.aviacionline.com/2022/12/embraer-refina-su-familia-energia-y-apuesta-a-dos-conceptos-de-19-y-30-asientos/
[15]https://cincodias.elpais.com/cincodias/2022/06/15/companias/1655287650_937336.html

Figure 5. Airlander airship for the transport of up to 100 passengers [Air Nostrum]

As already mentioned, the study and the projects to mitigate the non-CO2 effects of commercial aviation have also gained relevance during the past year. In particular, the DLR and Eurocontrol carried out tests to redirect flights at heights where they do not produce contrails from the Maastricht air control center, with positive results. Similar pilot projects have been planned in Germany and in the North Atlantic[16].

Other measures under investigation are the use of SAF or fuels with a low content of aromatic compounds, which reduce and modify the emission of soot, key to the nucleation of the ice that makes up these clouds (ECLIF3 Project[17]).

All these strategies are especially relevant given the proposals presented to include non-CO2 effects in the EU ETS emissions market, which would imply, in the future, a great incentive for their implementation by airlines in Europe. In fact, as part of the preliminary agreement between Parliament and the European Council to reform the rules of the EU Emissions Trading System (EU ETS) applicable to the aviation sector, the European Commission will prepare a monitoring system, reporting and verification of these emissions by 2025[18].

6. ACTIONS, INNOVATION AND TECHNOLOGY

Technological progress to achieve sustainable aviation follows an accelerated process with the development of multiple solutions with proven efficiency, while new avenues to explore emerge. By way of example, during the past year industrial advances and proposals emerged to introduce ammonia as a sustainable energy vector, both to facilitate the transport and management of green hydrogen, and for its use directly in aircraft propulsion[19].

To promote this progress, institutional support plays a decisive role, which in Europe is materialized through projects covered under the framework of the Clean Aviation program[20], successor to Clean Sky 1 and 2. In 2022, the first call was launched under this new framework. with a budget of 735 million euros focused on three areas:

- Regional electric-hybrid aviation
- Ultra-efficient short and medium range aircraft

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[16] Flight International. Marzo 2022.
[17] https://www.airbus.com/sites/g/files/jlcbta136/files/2021-11/EN-ECLIF3-study.pdf
[18] https://www.consilium.europa.eu/es/press/press-releases/2022/12/07/ets-aviation-council-and-parliament-strike-provisional-deal-to-reduce-flight-emissions/
[19] https://www.elconfidencial.com/tecnologia/novaceno/2022-05-10/avion-amoniaco-bateria-electrico_3421430/
[20] https://clean-aviation.eu/sites/default/files/2023-04/Highlights2022_en.pdf

- Disruptive technologies in hydrogen propulsion

The following sections will review the advances, both in this type of technological proposals and in the more conventional measures to mitigate the climate impact of aviation, as well as in their compensation or regulation.

6.1. EMISSIONS OFFSET AND ECONOMIC MEASURES

6.1.1. Awareness and compensation

Passenger awareness requires more and more information about the environmental impact of their trips, as well as the options to mitigate it. In this sense, a recent study revealed that almost 40% of them would be willing to increase their rates by 2% to offset their CO2[21] emissions. Responding to this demand, most major airlines offer these options, in the same way that tools have been developed for flight search platforms to offer this information on emissions in a comparative way[22] . Finally, to contribute to the robustness of the estimates, in 2022 the airlines association IATA presented an exhaustive methodology for calculating the carbon footprint for passengers[23], as well as the Aviation Carbon Exchange, a centralized service for buying and selling rights of emissions and management of CO2 offsets for airlines, both in mandatory and voluntary schemes[24].

To the conventional option for the voluntary compensation of emissions by passengers, with CO2 reduction schemes outside the aviation industry, the subsidy for sustainable fuels (book-and-claim) has now been added both for commercial flights[25] and business ones[26]. Compensation for direct capture of carbon dioxide from the atmosphere has also recently emerged[27].

Decarbonization projects, despite their increasing control and the strict certification processes to which they are subjected, are not exempt from criticism regarding their effectiveness[28]. In fact, some companies are shifting their main compensation effort toward new technologies[29]. However, as highlighted in the main studies already mentioned, offsetting emissions continues to be a fundamental tool on the path towards sustainable aviation.

Direct carbon dioxide capture, both for use and storage, is being considered as a new way to cover aviation emissions. Companies in the sector, such as Airbus, have committed

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[21] https://www.mckinsey.com/industries/travel-logistics-and-infrastructure/our-insights/opportunities-for-industry-leaders-as-new-travelers-take-to-the-skies
[22] https://travalyst.org/work/aviation-industry/
[23] https://www.iata.org/globalassets/iata/you--iata/travelers-covid/qa-iata-rp-per-passenger-co2-calculation-methodology.pdf
[24] https://www.iata.org/en/programs/environment/ace/
[25] https://rsb.org/book-claim/
[26] https://aveliasolutions.com/
[27] https://ba.chooose.today/
[28] https://www.nytimes.com/2022/05/18/climate/offset-carbon-footprint-air-travel.html
[29] https://mediacentre.easyjet.com/story/15575/

investments in the technology necessary for its implementation[30] and its application by airlines[31].

There is also the option of avoiding the emission from power plants, particularly those that use biomass to close an even more sustainable cycle (BECCS[32]). The mitigation potential of these CDR[33] options is yet to be confirmed, but they have aroused great expectations and the consideration of the IPCC[34] to compensate for sectors that are difficult to decarbonise, such as transport [8].

The European Commission, for its part, presented in 2022 a regulation proposal[35] to certify the efficiency of CO2 capture projects based on four principles:

1. Quantification: reliable measurement of all activities and of the balance of carbon dioxide removed from the atmosphere.
2. Additionality: new projects must represent a change in usual practices and exceed legal requirements.
3. Long-term: storage must ensure a sufficient duration to be effective.
4. Sustainability: all carbon removal activities must contribute to the achievement of sustainable objectives such as the circular economy, adaptation to climate change or the maintenance of biodiversity.

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[30] https://www.airbus.com/en/newsroom/stories/2022-07-direct-air-carbon-capture-and-storage-for-aviation-explained
[31] https://www.airbus.com/en/newsroom/press-releases/2022-07-airbus-air-canada-air-france-klm-easyjet-international-airlines
[32] Bioenergy carbon capture and storage
[33] Carbon dioxide removal
[34] International Panel for Climate Change
[35] https://ec.europa.eu/commission/presscorner/detail/en/ip_22_7156

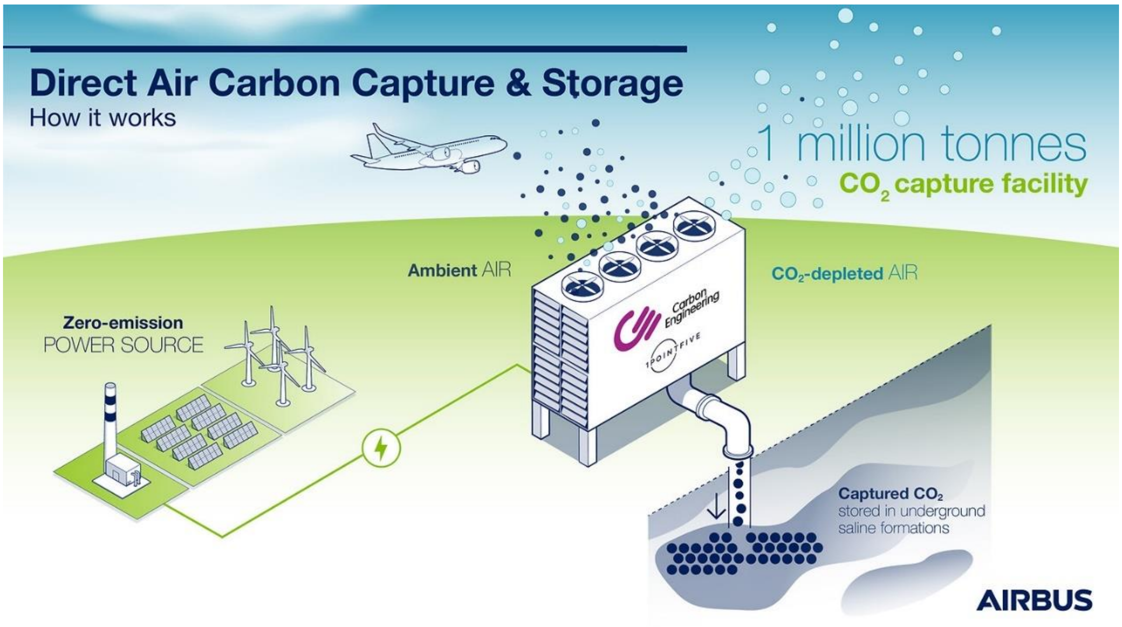

Figure 6. Diagram of the operation of the capture and storage of CO2 (DACCS) (Airbus)

6.1.2. CORSIA and EU ETS

Regarding the mandatory emission compensation schemes, in October 2022, during the aforementioned ICAO general assembly, the CORSIA program was reviewed and modified. Implemented gradually since 2021, many expectations had been generated since its effectiveness in encouraging the decarbonization of international flights, the field in which it is applied, was very limited.

The core of the debate centered on the reference to apply as an emission limit, from which the airlines must compensate them. If initially it was an average between the years 2019 and 2020, the dry stop of flights during the COVID19 pandemic forced a modification to leave only the emissions of the former as a reference. The decision finally adopted in 2022 by the assembly was to lower this level, tightening the compensation requirement, to 85% of CO2 emissions in 2019[36].

Although it is a step in the right direction, CORSIA will still not affect the bulk of international aviation emissions, since it only requires offsetting the part that exceeds the reference level, unlike the European market for emissions allowances EU ETS , which limits total emissions (*cap and trade*). Based on air traffic recovery projections, some studies suggest that by 2030 only 22% of them should be compensated under the ICAO scheme. In addition, the low price and quality of the decarbonization credits used are pointed out as additional problems to be solved in the coming years. As an example, a transatlantic flight under CORSIA would imply a cost per passenger of less than €2, compared to almost €50 if the EU ETS[37] scheme were applied.

[36] https://www.icao.int/Newsroom/Pages/ES/States-adopts-netzero-2050-aspirational-goal-for-international-flight-operations.aspx
[37] https://www.transportenvironment.org/discover/un-body-icao-hails-empty-goal-and-cheap-offsetting-scheme-to-green-aviation/

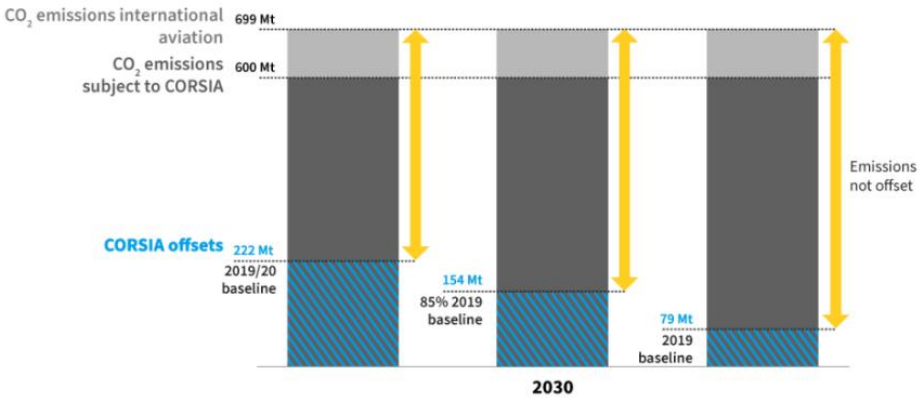

Figure 7. Volume of international emissions covered by CORSIA in 2030 estimated according to the different references (T&E[38])

As already noted, the price of acquiring emission allowances for airlines under the EU ETS program has skyrocketed in recent times (Figure 8), with a trend indicating that it will position itself as one of their main operating costs.

Figure 8. Historical evolution of the price of CO2 emission rights in the EU ETS [9]

During 2022, a series of negotiations took place at the European level to fit this mechanism with the international CORSIA, ending with the moratorium on the launch of the latter ("stop-the-clock"). Faced with an ambitious initial proposal by the European Parliament, the agreement reached in December entails a precise delimitation between the scopes of application of both emission control mechanisms ("clean cut" option), according to which intra-European flights (including to Switzerland and United Kingdom) will continue to be regulated by EU ETS and external ones by CORSIA. In addition, free rights to airlines will be eliminated and incentives for the use of SAF will be included. This decision will be reviewed starting in 2025 taking into account the implementation and efficiency of CORSIA.

The rate of reduction of the total permitted emissions will be accelerated until reaching a 60% reduction in 2030 with respect to the CO2 emissions of 2005. In addition, a measurement and verification system for non-CO2 emissions will be put into operation. Finally, the EU ETS will

[38]https://www.transportenvironment.org/discover/un-body-icao-hails-empty-goal-and-cheap-offsetting-scheme-to-green-aviation

also be expanded to cover emissions from shipping and road transport[39]. Revenues from this mechanism will be used to pay for energy efficiency and climate change mitigation projects[40].

6.1.1. Political measures and demand management

On the political front, in 2022 Denmark joined countries with set targets for the introduction of environmentally sustainable aviation. Decarbonized domestic flights should be available in 2025, which will be the only ones allowed by 2030[41]. Belgium, for its part, introduced a tax of €10 per passenger for all flights of less than 500 km, in line with other countries that seek to promote a change towards the high-speed rail network. The debate regarding the feasibility and real benefits of these measures continues, although intermodality is consolidated as a key aspect to achieve sustainable transport [10].

Business aviation has recently attracted a lot of media attention due to its volume of emissions, until now in the background, with a CO2 impact per passenger up to 10 times higher than that of a commercial flight (T&E 2021). In the wake of the restrictions during the coronavirus pandemic, the reduction of this traffic is posed as an achievable option[42]. Demand management remains one of the most controversial but critically important factors in the evolution of the environmental impact of commercial aviation.

In this scenario, the imposition of taxes on passengers, as in the Belgian case, is defended as a directly applicable tool for air traffic volume management, although this relationship is not fully demonstrated [12]. There are different modalities under study on how to apply them:

- Flat rate (APD[43]): it is applied per flight and to all passengers equally.
- Rate per distance (AML[44]): would be taxed incrementally in a proportional and individual way to the distance flown during a given period by a passenger.
- Frequency Rate (FFL[45]): would tax passengers proportionally and individually according to the number of flights made in a given period.

In general, the sophistication of the tax system will make it more difficult to implement, especially if a centralized record of passenger data is necessary. Other parameters to consider for the fees could be the type of flights, with a focus on business aviation, as well as the destination of the funds collected, which could be used to finance the decarbonization efforts of the sector as a whole [11]. In any case, and as the case of Belgium demonstrates, the debate is very topical, and it is worth facing it rigorously to ensure that the measures that are introduced are well designed.

6.2. NAVIGATION AND OPERATIONS

Pending the introduction of the Single European Sky[46], with the consequent reduction in consumption and emissions [1], in 2022 there were advances in the field of environmental

[39] https://www.transportenvironment.org/discover/eu-set-for-major-expansion-of-carbon-market/
[40] https://ec.europa.eu/commission/presscorner/detail/en/ip_22_7796
[41] https://www.greenairnews.com/?p=2336
[42] https://www.transportenvironment.org/discover/decision-time-board-a-flight-or-dial-in-on-zoom/
[43] Air Passenger Duty
[44] Air Miles Levy
[45] Frequent Flyer Levy
[46] https://www.enaire.es/sobre_enaire/presencia_internacional/cielo_unico_europeo

efficiency of aircraft operations. The services of companies that optimize routes, ground handling and even maintenance to, in an integrated way, reduce the carbon footprint of flights became widespread[47]. These new providers take advantage of available weather data[48], analyze previous flight data in bulk[49], and some even offer flight optimization to minimize the creation of contrails and other non-CO2 effects[50].

In fact, last year steps began to be taken to certify these reductions in environmental impact beyond carbon dioxide, opening up possibilities for regulation and compensation[51].

Lastly, and among other environmental efficiency developments, the idea of the e-taxi was recovered, with an autonomous ground operation of the aircraft with electric traction through the front gear, and which will see its application in Spanish airlines[52].

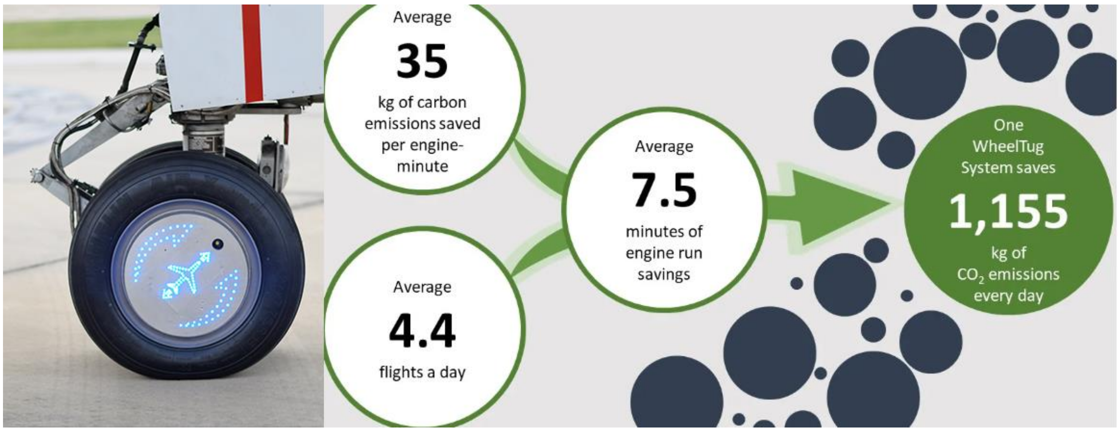

Figure 9 e-taxi system and estimation of CO2 reduction [Wheeltug]

6.3. GRADUAL AND DESIGN EFFICIENCY IMPROVEMENTS

The potential of incremental measures to reduce the CO2 footprint of commercial aviation is often underestimated, if not dismissed as mere industry makeup. However, in the short term, innovation based on the technologies currently in use can achieve a key mitigation of the impact of flights, as an intermediate step, until the implementation of more disruptive strategies.

The two test flights carried out by AirFrance in May 2022 serve as proof of the above, in which 45% reductions in CO2 emissions were achieved on routes from Paris to Lisbon and Montreal, respectively. Part of this reduction was achieved simply by operating more modern and efficient aircraft, which consume between 20 and 25% less fuel[53].

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[47] https://www.safran-group.com/pressroom/flying-green-targets-lower-fuel-consumption-safran-s-sfco2-service-2022-06-16
[48] https://www.prnewswire.com/news-releases/easyjet-adopts-skybreathe-360-eco-flying-platform-to-reduce-co2-emissions-301474353.html
[49] https://www.fuelvision.io/
[50] https://satavia.com/
[51] https://www.greenairnews.com/?p=2939
[52] https://www.wheeltug.com/
[53] https://unitingaviation.com/news/environment/among-their-actions-to-reduce-their-environmental-footprint-air-france-cuts-emissions-on-two-flights-by-half/

We will now review some of the recent environmental innovations in this continuous improvement of the propulsion, aerodynamics and structures of passenger aircraft.

6.3.1. Propulsion

Engines are the most relevant components for improving the energy efficiency of a modern aircraft. During the last decades, the specific consumption of turbofans has continuously improved, hand in hand with increases in their bypass ratio. On this path towards larger units, in 2022 the largest aviation engine built to date, the Rolls-Royce Ultrafan, with Spanish participation[54], was ready for ground tests. Its consumption, and therefore its CO2 emissions, will be 10% less than those of its most modern current equivalent (Trent XWB). In addition, the optimized combustion chamber will generate less soot and NOx emissions, also important pollutants. Lastly, 35% reduction in the generated noise level is expected.

Figure 10. Ultrafan large bypass ratio motor [Rolls-Royce]

Another of the recent advances in turbofan design is geared architecture, such as the Pratt & Whitney GTF. More disruptive is CFM's RISE propeller, with which the promising open-rotor concept [1] is recovered, and whose performance would exceed that of the previous two[55]. In 2022 Airbus and CFM have agreed to use the A380 test aircraft for flight tests scheduled for the second half of this decade.

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[54] https://www.elconfidencial.com/tecnologia/novaceno/2022-12-25/mayor-motor-avion-listo-pruebas-rolls-royce_3547197/

[55] https://leehamnews.com/2022/02/21/for-next-new-airplane-pratt-appears-to-trail-cfm-for-next-new-engine

Figure 11. CFM RISE Open Rotor Motor [Airbus]

Another well-known strategy to increase jet engine boost, water injection, is once again at the center of a new turbofan project: MTU's WET. In this case with a circular strategy, since the H2O would be extracted from the engine's own central flow, where it is generated by the combustion of hydrocarbons[56]. To the improvement in efficiency are added advantages in the environmental aspect due to the reduction of NOx and solid particle emissions.

At the end of 2022 the SWITCH consortium, funded by EU Clean Aviation, was launched, in which some of the main players in the propulsion and aircraft construction sector extended the WET concept, to include an electric hybridization and a thermal energy recovery system that further reduce your fuel consumption.

[56] https://www.flightglobal.com/paid-content/water-enhanced-turbofan-revolutionary-propulsion-concept-based-on-a-gas-turbine-engine/150047.article

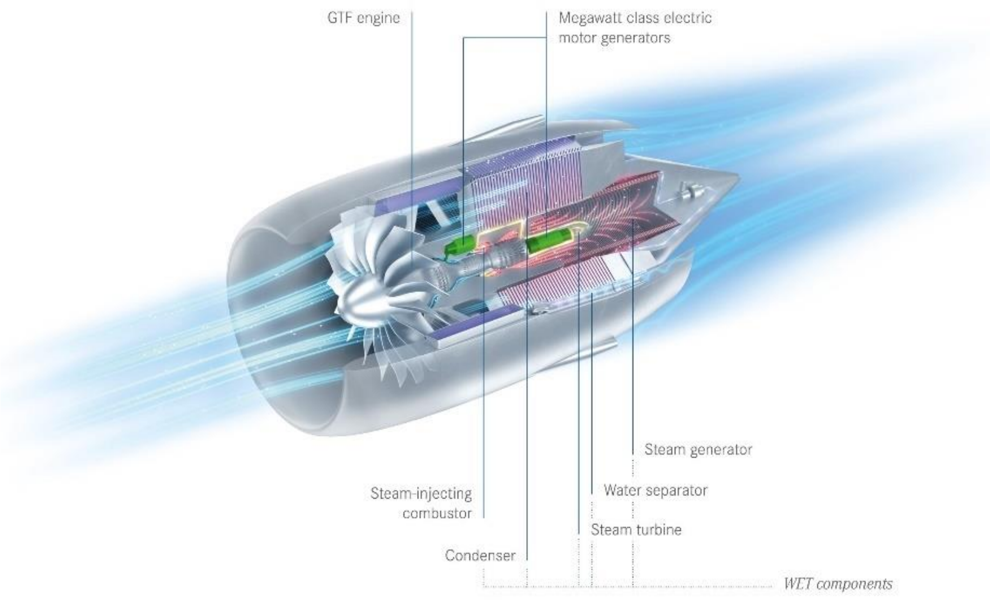

Figure 12. SWITCH project, funded by the European Clean Aviation program [SWITCH]

The resulting engine is also expected to generate fewer contrails[57]. As already noted, effects beyond CO2 are receiving increasing attention and research efforts, as demonstrated in November of last year during Clean Aviation's symposium on advanced combustion systems[58]. In fact, a recent study indicated that Double Ring Combustion (DAC[59]) engines, a technology currently in use in some commercial thrusters, are particularly effective in mitigating contrails [13]. In any case, either with consolidated but redirected developments, or with totally innovative concepts, the drive towards a more sustainable aviation propulsion does not cease.

6.3.2. Aerodynamics and Wing Control

At the end of 2022, the European Aviation Safety Agency (EASA) granted certification for the aircraft external surface coating system known as AeroShark. Developed by Lufthasa Technik and BASF, and inspired by the rough skin of sharks, this treatment seeks to reduce aerodynamic resistance by more than 1%, thereby saving fuel[60]. The approval was preceded by flight tests that validated its efficiency and safety. The first aircraft to receive the AeroShark belong to the Lufthansa and Swiss fleets.

[57] https://simpleflying.com/engine-makers-collaboarate-project-switch/
[58] https://www.clean-aviation.eu/media/news/advanced-combustion-technologies-workshop
[59] Double Annular Combustor
[60] https://www.elconfidencial.com/tecnologia/novaceno/2022-12-27/piel-tiburon-aviones-ahorra-combustible-emisiones_3547998/

Figure 13. Commercial aircraft with AeroShark surface treatment [Lufthansa]

On the other hand, in April of that same year, the wind tunnel tests of the Airbus *eXtra Performance Wing* model were completed. This project, largely inspired by birds, seeks to improve the aerodynamic performance of the wing by adapting its shape according to the flight conditions, for example, by means of a folding tip. In addition, the design will incorporate early detection of gusts and an active response to mitigate the generated charges. All these innovations seek the objective of reducing aerodynamic resistance and the weight of the wing structure, with the consequent greater energy efficiency and lower emissions[61].

Figure 14. eXtra Performance Wing model in wind tunnel [Airbus]

6.4. SUSTAINABLE FUELS

Among the different strategies on the table to decarbonise aviation, the use of sustainable fuels (SAF) clearly stands out. This solution makes it possible to continue operating with the current aircraft fleet, which greatly shortens lead times, and is not pending any great

[61] https://www.airbus.com/en/newsroom/press-releases/2022-04-nature-inspired-wing-demonstrator-completes-wind-tunnel-tests

technological development since, both in its biofuel version and to a lesser extent for electrofuels (PtL [62]), there are already industrial plants or demonstrators in operation [1].

It is understood from all of the above that the SAFs are entrusted with the bulk of the reduction of CO2 emissions in order to achieve their zero impact by 2050, as shown by the IATA prediction in Figure 15.

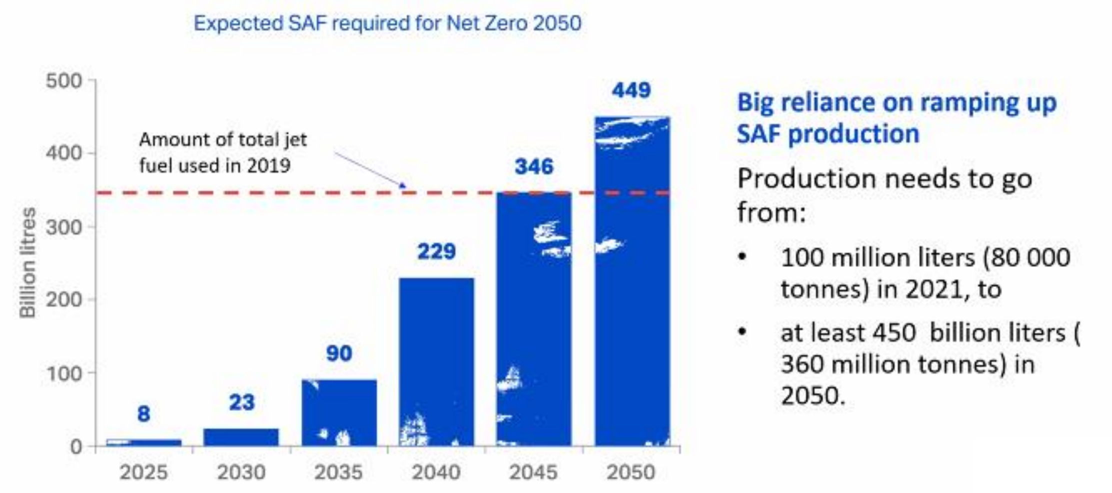

Figure 15. SAF consumption evolution to achieve decarbonization in 2050 [IATA]

And this is where the main and formidable challenge for the generalization of the SAF lies: the ability to sustainably produce the huge amount necessary to supply the world fleet of aircraft, even leaving aside the additional demand for this solution for decarbonization by other means of transport. In the following sections we will review the current status of this key issue, the measures to make it possible, and other issues around one of the major tools towards sustainable aviation.

6.4.1. Production

In 2022, SAF production was increased to a total of between 300 and 450 million liters, compared to 100 ML in 2021[63]. This undoubtedly formidable increase must be contextualized with the total consumption of commercial aviation during the last year, estimated by IATA at 276 billion liters. The SAF produced this year is therefore below 0.2% of the fuel consumed, which highlights the difficulty and the effort required to achieve, from the outset, the short-term objectives of 2% in 2025 .

On the credit side, it should be noted that initiatives to produce and distribute sustainable aviation fuels have multiplied in recent months (Figure 16).

[62] Power to Liquid
[63] https://www.iata.org/en/pressroom/2022-releases/2022-12-07-01/

Figure 16. SAF production projects globally [IATA]

The number of airports where these fuels can be loaded continues to increase, as do the political actions to promote them and the SAF pre-purchase agreements between airlines and suppliers (Figure 17): at the end of 2022 delivery commitments were recorded in the future for some 42 billion liters, of which approximately half were signed during the last year[64].

Figure 17. Data on SAF implementation at the end of 2022 [ICAO]

Within the SAF, it is worth noting the industrial maturity of the biofuel production projects, with plants under construction with the capacity to deliver up to one billion liters per year[65]. Although more delayed, electrofuels or e-fuels are also beginning their commercial phase. In addition to the standard process of electrolysis and capture of CO2 from the atmosphere, projects with capture at emission points of carbon-intensive industries such as cement factories were presented last year[66] (Figure 18).

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[64] https://www.icao.int/environmental-protection/GFAAF/Pages/Offtake-Agreements.aspx
[65] https://www.airproducts.com/campaigns/casaf
[66] https://www.concrete-chemicals.eu/

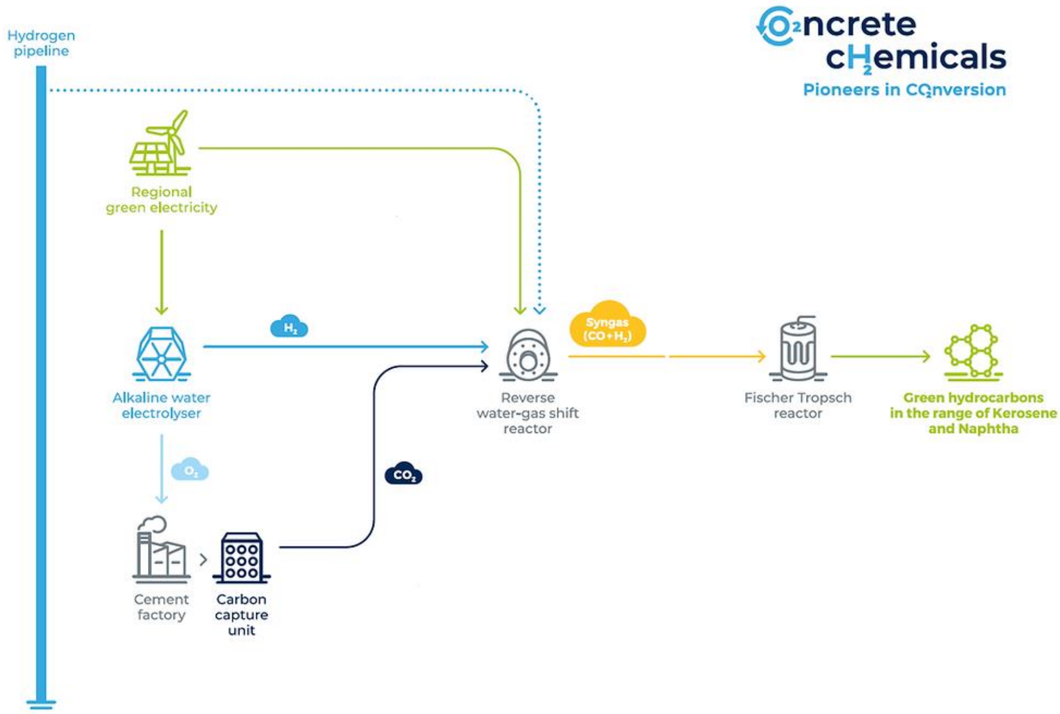

Figure 18. Electrofuel production process with CO2 capture at the point of emissions [Concrete Chemicals]

For its part, the production technology of these synthetic sustainable fuels using solar thermal reactors is taking new steps towards their industrialization, including distribution agreements with airlines[67].

Germany, with its production incentives, leads the development of electric fuels[68]. At a global level, its role is expected to cease to be testimonial with relevant productions around 2030.

6.4.2. Mandates and Incentives

There are two main approaches to promoting the introduction of SAF in commercial aviation, including the development of production capacity, which generally apply in contrasting ways on both sides of the Atlantic. If in Europe mandatory use mandates by airlines (RefuelEU[69] [1]) are opted for, counting on forcing a demand that generates supply, in the US the strategy consists of providing economic incentives to the companies involved. Figure 19 reflects on the map this diversity of paths to achieve the same objective.

[67] https://www.flightglobal.com/flight-international/does-efuel-production-have-a-bright-future-for-aerospace/148517.article
[68] https://www.euractiv.com/section/aviation/news/germany-charges-ahead-in-decarbonising-domestic-flights-with-new-e-fuel-roadmap/
[69] https://www.europarl.europa.eu/thinktank/en/document/EPRS_BRI(2022)698900

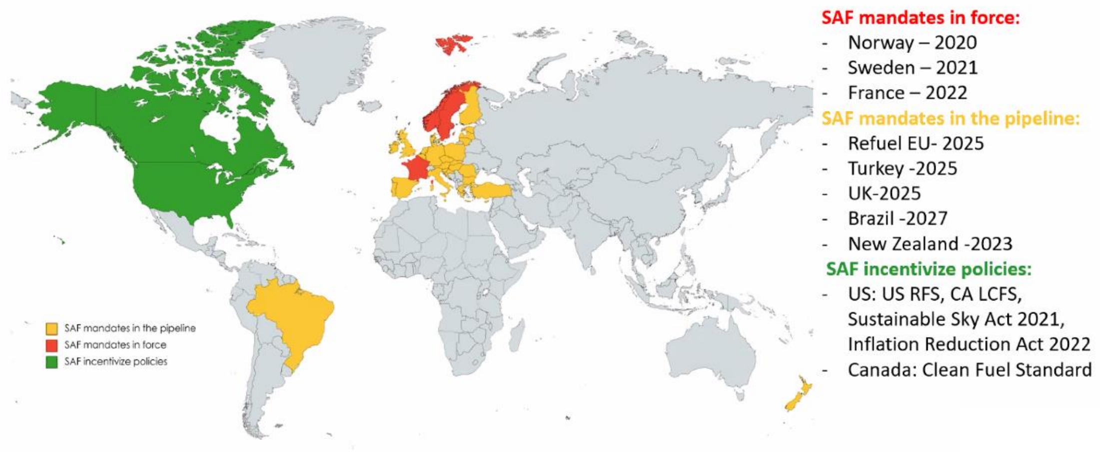

Figure 19. Countries with mandates and incentives for the production and use of SAF [IATA]

In Europe, in addition to the European Union regulations whose entry into force is expected shortly, by mid-2022 France and Sweden already had 1% mandates on their commercial flights, with 0.5% in Norway. Although in general this strategy is assumed to be effective, it is essential to control and analyze the origin of the raw material used to generate biofuels, and thus avoid collateral environmental damage[70].

Meanwhile, in the US, a roadmap was launched to meet the objectives of the US SAF Grand Challenge, which seeks to produce some 11 billion liters in 2030, multiplying this figure by a factor of 10 by 2050 [14].

Other countries have also set self-imposed targets for the introduction of the SAF, such as Japan, which seeks to reach 10% by 2030[71].

6.4.3. Life cycle and technologies

As previously indicated, the decarbonizing potential of each SAF fuel is conditioned by a rigorous and comprehensive study of its environmental impact, from its production to its final consumption. It is what is known as the life cycle analysis, which accounts for the associated emissions not only of CO_2, but also of other pollutants [15].

In the case of biofuels, the key aspect is the origin of the raw material used in their production. At the European level, and after years of debate in this regard, in 2022 the European Parliament clearly ruled out biofuels from soybeans, with a well-known impact on land use, qualifying it as an agent of deforestation[72]. Figure 20 shows the origin of the biofuels consumed in Europe during the past decade.

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[70] https://www.transportenvironment.org/discover/the-good-bad-and-the-ugly-of-saf-mandates/
[71] https://www.greenairnews.com/?p=2908
[72] https://www.euractiv.com/section/biofuels/news/eu-lawmakers-vote-to-blacklist-soy-biodiesel-over-sustainability-concerns/

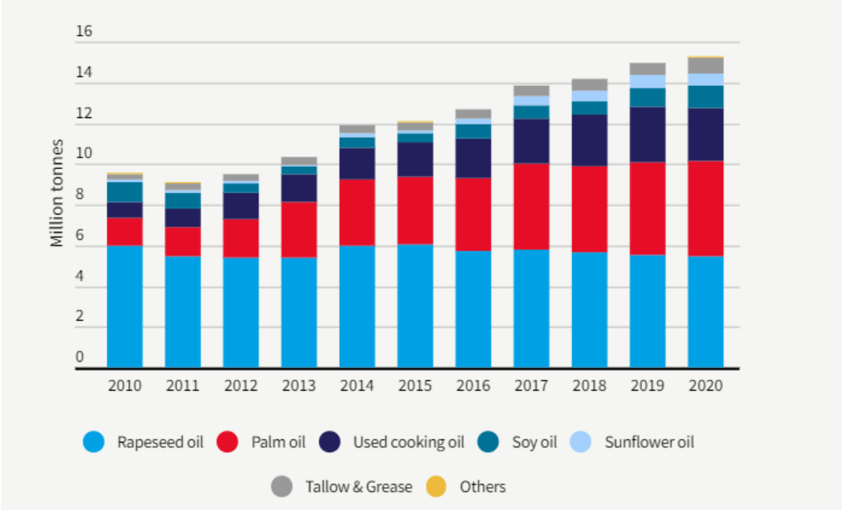

Figure 20. Origin of biofuels consumed in Europe [T&E]

As already noted, the processes approved for the production of SAF have expanded in recent years, with technologies seeking to access new raw materials and resources to increase production capacity. Figure 21 shows the characteristics of the main types of biofuel and PtL.

	HEFA	Alcohol-to-jet[i] / Gasification/FT	Power-to-liquid
Opportunity description	Safe, proven, and scalable technology	Potential in the mid-term, however significant techno-economical uncertainty	Proof of concept 2025+, primarily where cheap high-volume electricity is available
Technology maturity	Mature	Commercial pilot	In development
Feedstock	Waste and residue lipids, purposely grown oil energy plants[ii] Transportable and with existing supply chains Potential to cover 5%-10% of total jet fuel demand	Agricultural and forestry residues, municipal solid waste[iv], purposely grown cellulosic energy crops[v] High availability of cheap feedstock, but fragmented collection	CO_2 and green electricity Unlimited potential via direct air capture Point source capture as bridging technology
% LCA GHG reduction vs. fossil jet	73%–84%[iii]	85%-94%[vi]	99%[vii]

i. Ethanol route; ii. Oilseed bearing trees on low-ILUC degraded land or as rotational oil cover crops; iii. Excluding all edible oil crops; iv. Mainly used for gas./FT; v. As rotational cover crops; vi. Excluding all edible sugars; vii. Up to 100% with a fully decarbonized supply chain

Source: CORSIA; RED II; De Jong et al. 2017; GLOBIUM 2015; ICCT 2017; ICCT 2019; E4tech 2020; Hayward et al. 2014; ENERGINET renewables catalogue; Van Dyk et al., 2019; NRL 2010; Umweltbundesamt 2016

Figure 21. Main production methods of SAF [Clean Skies for Tomorrow]

Despite this, currently and in the short term it is expected that the biofuel produced by the HEFA process will clearly continue to dominate, as is clear in Figure 22.

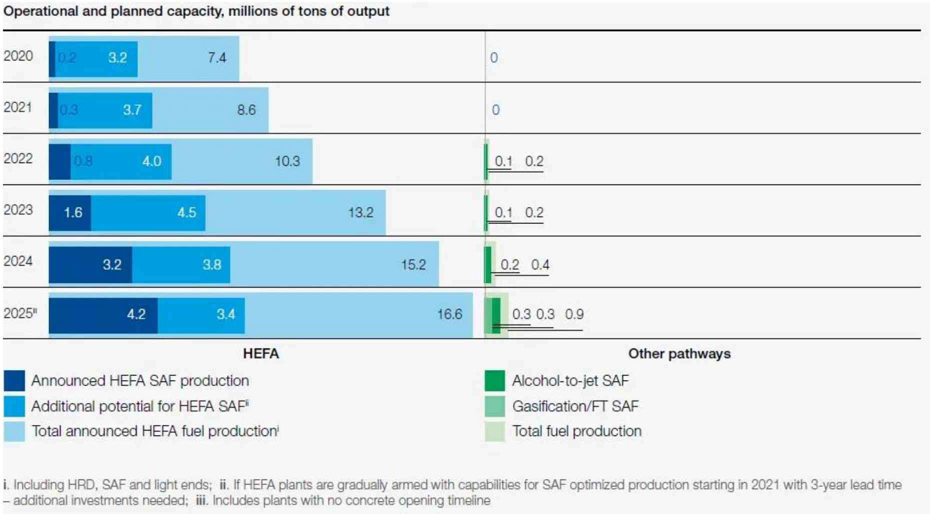

Figure 22. Production expectations of the different types of biofuels until 2025 [Leeham news]

One of the processes that arouses the most expectations is alcohol-to-jet (ATJ), with industrial plants in production as of 2023[73], and which will be able to take advantage of more types of raw materials of sustainable origin. In addition, this technology also allows the addition of carbon capture from carbon-intensive industries for the production of SAF[74].

Waste of all kinds, including urban solids, is one of the raw materials with the greatest projection, and which can be transformed through the process known as gasification/FT. In summary, the field of technologies for the production of SAF is very broad, and it continues to grow with new innovations such as the conversion of plastic waste into sustainable fuels[75], or the design of microbes to biologically process captured CO2 and obtain hydrocarbons. This last example shows the strategy of some airlines, betting on many ways of decarbonization to ensure an advantageous position in the future[76].

On the other hand, it is interesting to review other industrial initiatives that focus on producing fossil fuels with less environmental impact. Examples of this are Co-processing, which allows the partial decarbonization of aviation fuels by jointly refining oil and organic matter, for example, used oils[77]. And in a similar vein, hydrotreating processes (with hydrogen) reduce aromatic compounds and sulfides in conventional kerosene, which results in less creation of condensation trails. The minimum required percentage of aromatics in aviation kerosene is 8%, and experimental studies place the usual percentage between 16 and 20%, which gives an idea of the margin for environmental improvement, something that has already been proposed to extend the European legislation RefuelEU [16]. In addition, all of these procedures make it possible to take advantage of the existing infrastructure, while advancing in the reduction of the net impact of the aviation fuels produced.

A key aspect in the success of each of these routes of SAF production is the cost of production. Faced with the clear current advantage of HEFA, progress is expected in other technologies, particularly in electric fuels, currently the most expensive to produce[78]. Of course, the

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[73] https://www.lanzajet.com/news-and-insights/
[74] https://www.greenairnews.com/?p=2501
[75] https://thebusinesstravelmag.com/virgin-group-to-reuse-plastic-waste-for-lower-carbon-fuel/
[76] https://www.cemvita.com/news/turning-carbon-dioxide-into-sustainable-fuel-united-and-oxy-low-carbon-ventures-announce-collaboration-with-biotech-firm-to-create-new-fuel-sources
[77] https://www.bp.com/en/global/air-bp/news-and-views/press-releases/bp-refinery-in-lingen-starts-production-of-saf.html
[78] https://leehamnews.com/2023/01/27/bjorns-corner-sustainable-air-transport-part-54-sustainable-aviation-fuel-feedstocks/

production cost of the fossil-based kerosene shown in Figure 23 is entirely dependent on oil prices, but it is for reference.

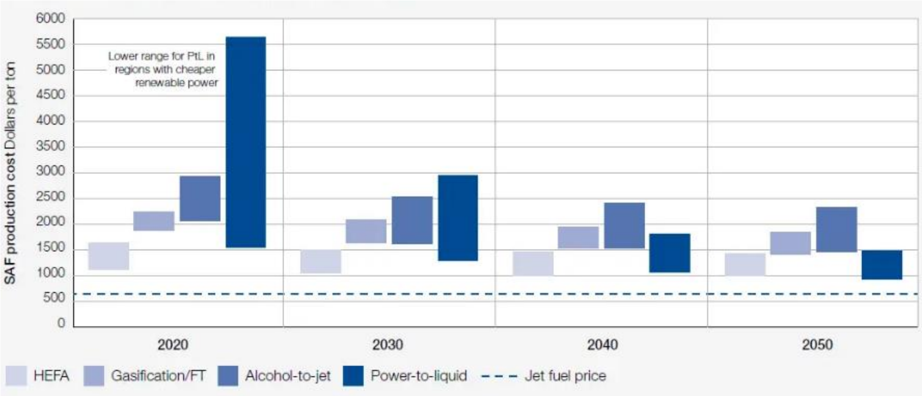

Figure 23. SAF production cost ranges vs. fossil fuel kerosene. Estimated evolution for the different pathways [Leeham news]

6.4.4. SAF trials

During 2022, the range of engines and aircraft in which tests were carried out with 100% SAF fuels continued to expand. Despite being perfectly comparable to conventional kerosene in terms of its hydrocarbon composition, SAFs usually contain a lower percentage of aromatic compounds, which is, on the one hand, an advantage from the point of view of condensation trails, as already described, but on the other hand, it complicates the maintenance of fuel tank and circuit sealants[79].

It should be remembered that currently the use of mixtures of up to 50% is fully certified (ASTM), and that the percentages of SAF available in the coming years mean that this does not entail any limitation in the medium term. However, the aeronautical industry continues to dedicate efforts to demonstrate that both the designs in service, and especially the new models of engines and aircraft under development, are compatible with 100% sustainable fuels.

Among the multitude of tests on different models during the past year, the first flight with 100% SAF on an Airbus A380 engine[80] can be highlighted as an example (completing previous tests on other models) or, among engine manufacturers, the GE ground tests with its Passport model[81].

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[79] https://leehamnews.com/2023/01/13/bjorns-corner-sustainable-air-transport-part-53-sustainable-aviation-fuel/

[80] https://www.airbus.com/en/newsroom/press-releases/2022-03-first-a380-powered-by-100-sustainable-aviation-fuel-takes-to-the

[81] https://www.geaerospace.com/press-release/business-general-aviation/ge-aviation-completes-testing-passport-engine-using-100

Figure 24. Future ATR EVO, 100% SAF compatible

Another example of the rapid progress in this regard were the tests on the ATR 72-600, in a first phase with only one of the two engines consuming SAF[82], and later in a flight carried out with sustainable fuel in all propellants[83]. These tests pave the way for full compatibility of this fuel, as the same manufacturer announces for its future ATR EVO model.

In the field of research, and as previously indicated, flight campaigns continue to be carried out for the experimental verification of emissions in SAF-powered aircraft, including their potential to mitigate non-CO2[84] effects. It should be remembered that a 50% sustainable fuel ratio can lead to a 30% reduction in contrail impact [2].

6.5. ELECTRIC AVIATION

Electric aviation continues to overcome stages in its development towards the entry into service of its first commercial models. Thus, in 2022 the first flight of the Eviation Alice stands out, a 100% battery-electric regional plane, with a planned range of 460 km for nine passengers[85]. With conventional lithium-ion technology, the batteries account for approximately half the weight of the aircraft but contribute structurally. This flight represents a first order milestone, not only for the project but for electric aviation as a whole. Eviation claims to have over 300 confirmed orders and aims to start commercial operations between 2025 and 2026, depending on the variants[86].

[82] https://www.atr-aircraft.com/presspost/atr-successfully-performs-test-flights-with-100-saf-in-one-engine/
[83] https://www.greenairnews.com/?p=3224
[84] https://www.dlr.de/en/media/videos/video-volcan-project
[85] https://www.flyingmag.com/breaking-eviations-alice-electric-demonstrator-flies-for-the-first-time/
[86] https://www.eviation.com/

Figure 25. First flight of the Eviation Alice [David Honan]

6.5.1. Tecnology

The progress of electric aviation, perhaps even more than the rest of aviation, depends substantially on the evolution of the technology involved. And specifically the batteries and their specific energy, which in the case of the Alice remains within the conventional limit, around 260 W·h/kg.

However, during 2022 there were announcements that suggest that the promise of overcoming this barrier could finally come true and achieve more energy without the weight ballast that limits the range of current electric aircraft. In this direction, they point to advances that would extend the capacity of lithium-ion to 450 W h/kg and fast charging[87], or solid-state lithium batteries of up to 500 W h/kg developed both in Japan[88] and by NASA[89]. with lithium and graphene and greater safety of operation. The experimental model X57[90] could be used as a test bed for the latter.

Beyond these values, work continues on other technologies such as aluminum-air batteries[91], with specific energies of up to 1350 W·h/kg, although without the possibility of recharging them on site. The electric aviation company Wright Electric seems to be committed to this route to solve the limitation of range and capacity of this type of aircraft. In any case, these announcements really open the door to much more ambitious possibilities for battery-electric propulsion.

[87] https://verticalmag.com/features/explaining-amprius-extreme-fast-charge-battery-technology/
[88] https://www.sciencedaily.com/releases/2022/01/220120140724.htm
[89] https://www.elconfidencial.com/tecnologia/novaceno/2022-10-12/nasa-bateria-increible-500wh-triple-capacidad_3504748/
[90] https://www.nasa.gov/specials/X57/
[91] https://energypost.eu/can-aluminium-air-batteries-outperform-li-ion-for-evs/

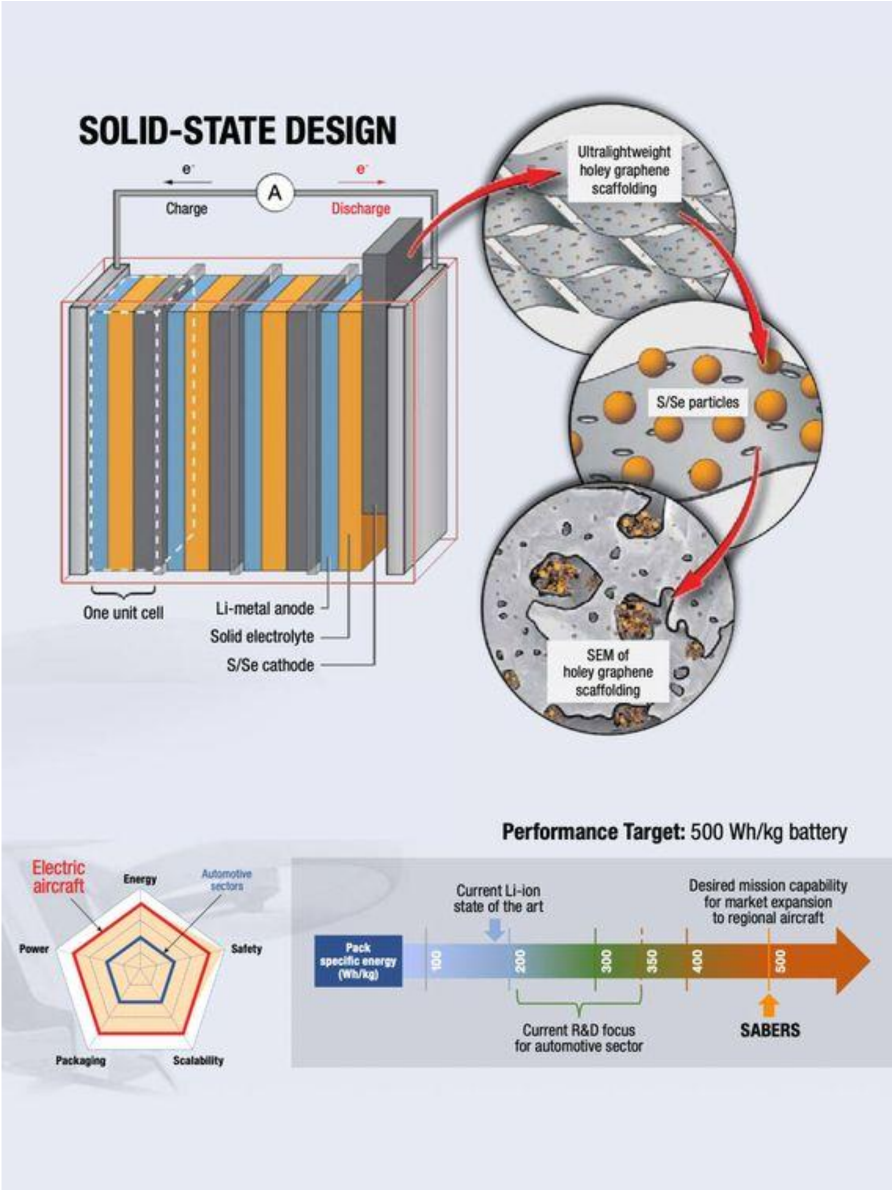

Figure 26. SABERS Solid State Battery Technology [NASA]

Regarding the electrification of systems in aircraft, which allows weight and emissions reduction, progress continues both in the basic research regarding electromechanical systems[92], and in its real application in cases such as the rudders of the Airbus A320 family. The one known as “E-rudder” will reduce approximately 40 kg per aircraft[93].

Large companies in the propulsion sector are also clearly positioning themselves with new developments for electric aviation. The British Rolls-Royce created in 2022 Electrical, its subsidiary in charge of carrying out its different projects with hybrid solutions, or its PGS1 demonstrator with up to 2 MW of power[94].

[92] https://www.clean-aviation.eu/media/news/electrifying-actuation-systems-for-greener-flights-with-reprise
[93] Flight International, Julio de 2022.
[94] Flight International, Julio de 2022.

Rolls-Royce PGS1 [Flight International]

Another interesting proposal for hybrid powertrain, announced last year, is the STEP-tech[95] concept, by Collins and Pratt & Whitney (Figure 27). This turboelectric system boasts a scalable conception to adapt to different types of needs.

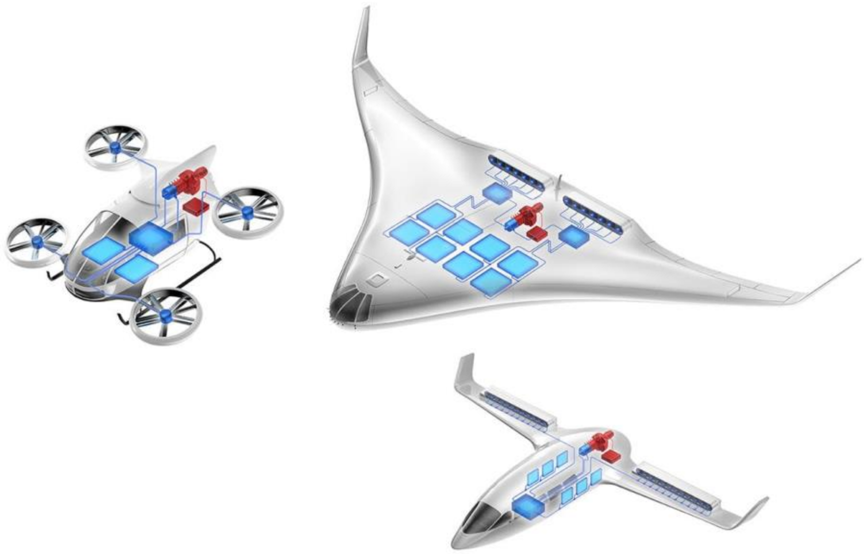

Figure 27. STEP-tech scalable hybrid propulsion system [Collins]

For its part, General Electric conducted cruising tests for its high-voltage and power electrical systems as part of NASA's Electrified Powertrain Flight Test (EPFD[96]) program. It is interesting to note that all these announcements were produced at the Farnborough Air Show, in its first post-pandemic edition, and in which sustainable aviation had a prominent place.

The most advanced research in electric propulsion is also ongoing with institutional support both in the US, through the ARPA-E[97] agency, and in Europe under the umbrella of Clean Aviation. In addition, more ambitious proposals are emerging from start-ups such as the Forerunner[98] high-efficiency superconducting electric motor.

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[95] https://www.collinsaerospace.com/news/news/2022/07/pratt-whitney-collins-expand-leadership-hybrid-electric-propulsion-technology-with-new-step-tech

[96] https://www.nasa.gov/feature/glenn/2022/nasa-ge-complete-historic-hybrid-electric-propulsion-tests

[97] https://arpa-e.energy.gov/technologies/programs/ascend

[98] https://mako-aerospace.com/forerunner/

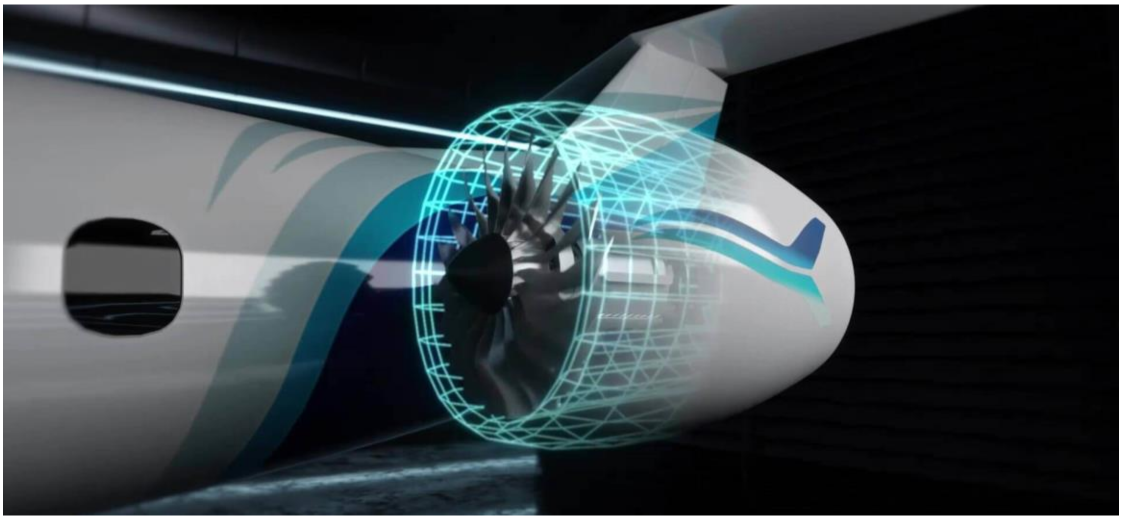

Figure 28. Forerunner electric drive [MakoAeroespace]

Again, as noted for sustainable fuels, and similarly for hydrogen aviation, life-cycle calculations are essential when rigorously evaluating the impact of different alternatives. Electric aviation must respond with sustainable solutions both to the manufacture of its components, particularly batteries, and to the extraction processes of the necessary raw materials such as lithium, or recycling after the end of its operational life[99].

6.5.2. Hybrids

Hybrid solutions present numerous advantages, optimizing the different characteristics of the available types of motorization (in series or in parallel), but always with the challenge of greater complexity and weight [1].

In 2022, the Aura Aero ERA (regional electric aircraft) project received numerous purchase commitments from different airlines[100], and a critical agreement for the program, such as the sum of SAFRAN for the motorization. It is a 19-passenger series hybrid model, which will achieve around 1,800km in hybrid operation, and around 460km in pure electric mode. The first flight is planned for 2024.

[99] https://leehamnews.com/2022/10/10/pontifications-total-life-cycle-impacts-missing-from-nearly-all-ecoaviation-discussion/

[100] https://www.futureflight.aero/news-article/2022-10-05/aura-aero-gathers-more-commitments-electric-regional-aircraft

Figure 29. Hybrid model in series of 19 pax. ERA [Aura Aero]

Pratt & Whitney Canada, for its part, is continuing with the program to develop a parallel hybrid based on the Dash 8-100 model (Figure 30), which it expects to fly test in 2024[101].

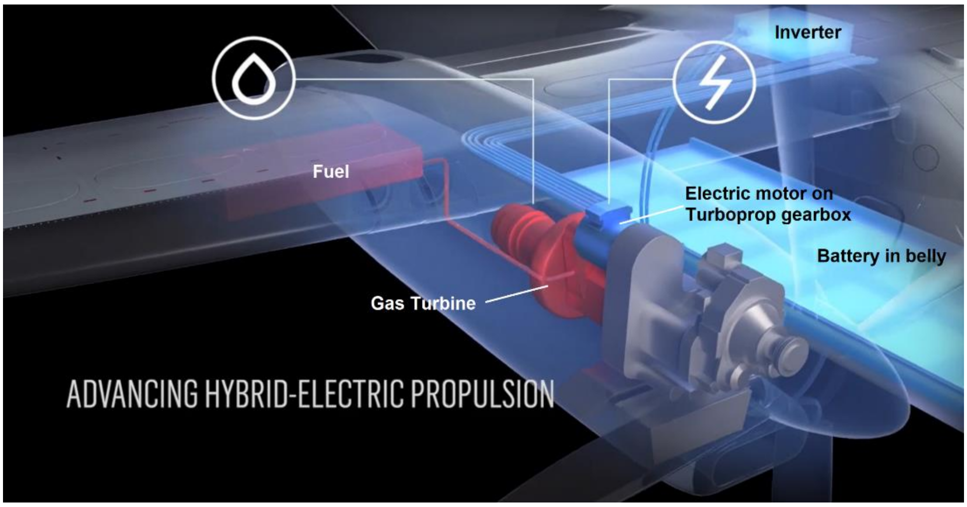

Figure 30. P&WC Parallel Hybrid Project

The aforementioned ATR EVO, with a similar capacity of around 70 passengers, could also incorporate some kind of mild hybridization to help during takeoff and climb. A much more complex degree of hybridization, and with greater potential for fuel savings, is the one proposed in the NASA's SUSAN[102] project (Figure 31). In this design the rear turbofan not only provides thrust, but also electricity to power the electric motors under the wings. However, not all are advances in the field of hybrids, with projects like Embraer's STOUT on hold until new partners and customers[103] are found.

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101 https://www.futureflight.aero/news-article/2022-05-19/h55-supply-battery-system-pratt-whitneys-hybrid-electric-regional-aircraft
102 https://www1.grc.nasa.gov/aeronautics/eap/airplane-concepts/susan/
103 Flight International, Julio de 2022.

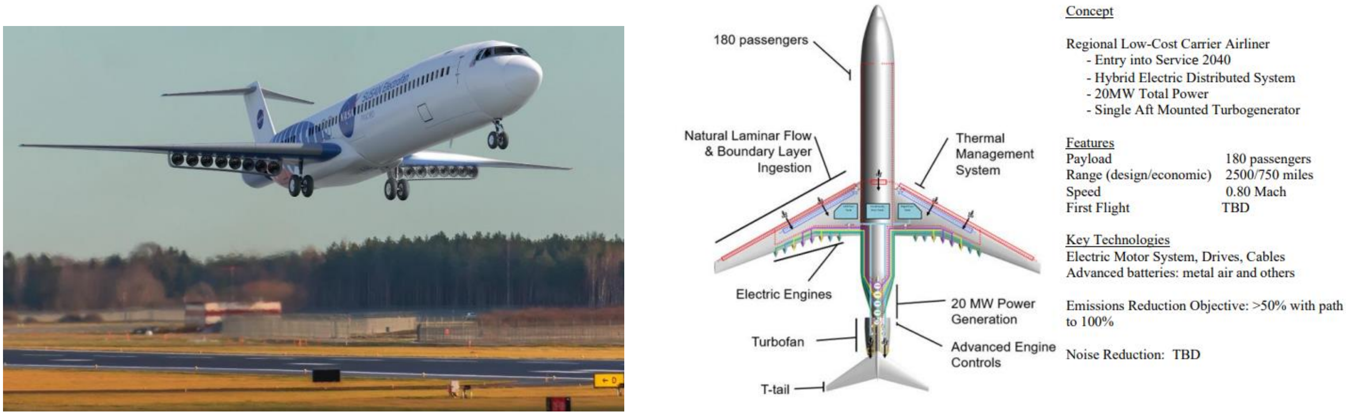

Figure 31. SUSAN hybrid project [NASA]

In the general and regional aviation segment, with models with less capacity, the proposals of VoltAero stand out, with its Cassio family, and Ampaire with the Eco Caravan. The Cassio 330 (Figure 32) mounts electric motors for taxi, takeoff, and climb, while relying on an internal combustion engine for cruise[104]. The entry into service (EIS) of this model is expected for 2024. This philosophy of parallel hybrid propulsion is also applied to the Eco Caravan, although in this case repowering a model with a long history in the market, and with savings in expected consumption of up to 70%. With an EIS similar to its competitor Cassio, the Eco Caravan completed its maiden flight in November 2022[105] (Figure 33). Ampaire plans to extend this repowering strategy to the higher-capacity Eco Otter model.

Figure 32. Casio 330 Parallel Hybrid [VoltAero]

[104] https://leehamnews.com/2022/10/10/voltaeros-cassio-hybrid-plane-is-mild/
[105] https://www.futureflight.aero/news-article/2022-11-18/ampaires-hybrid-electric-eco-caravan-makes-first-test-flight

Figure 33. First flight of the Eco Caravan [Ampaire]

6.5.3. Aviation with batteries

In addition to the decisive milestone of the first flight of Eviation's Alice already mentioned, battery aviation also made other significant progress during 2022, such as Harbor Air's DHC-2 Beaver "ePlane" test flight, with a duration of 24 minutes, to connect Vancouver and Victoria in Canada[106] (Figure 34). It is also worth mentioning, in this section, the first flight of the Robinson R44 helicopter, with 100% electric propulsion with batteries in June of last year[107].

Figure 34. DHC Beaver "ePlane" [Harbour Air]

One of the most attention-grabbing commercial aviation projects to date, Heart Aerospace, completely redesigned last year, increasing its capacity from 19 to 30 seats. The new ES-30[108] also now incorporates additional gas turbines to increase its range up to 400 km, making it a series hybrid. If its operation were carried out only with batteries, its range would be reduced by half. This twist in design, and the renewed confidence of numerous airlines and investors in the model, show the difficult balance of business viability in disruptive sustainable aviation, and the limitations of current batteries to satisfy aircraft of more significant capacity.

[106] https://harbourair.com/harbour-airs-all-electric-aircraft-operates-first-point-to-point-test-flight/
[107] https://www.futureflight.aero/news-article/2022-06-23/tier-1-achieves-first-flight-electrified-robinson-r44-helicopter
[108] https://heartaerospace.com/es-30/

Figure 35. Serial hybrid model ES-30. EIS by 2028 [Heart Aerospace]

To overcome these limitations, the Wright Spirit model could rely on the aluminum-air batteries already described. Announced at the end of 2021, the project will modify a BAE146 to equip electric motors, transporting 100 passengers in one-hour flight journeys[109]. It is interesting to note the similarity of this project with the E-Fan X from Airbus, Rolls-Royce and Siemens, canceled in 2020.

In a similar vein, the Spanish Dante Aeronautical also plans to re-engine regional aircraft with electric propulsion, for which it received financial support from Air Nostrum and Volotea at the end of 2022[110].

Figure 36. 100% electric Wright Spirit project for 100 pax. EIS 2026 [Wright Electric]

[109] https://www.greenairnews.com/?p=2187
[110] https://www.futureflight.aero/news-article/2022-12-20/spanish-airlines-back-plans-convert-regional-aircraft-electric-propulsion

The electric aviation landscape is truly diverse, with projects that deviate from conventional designs. Examples of this are some proposals such as an electric seaplane with 19 seats[111]; or even an ekranoplane[112], designed to fly at low altitudes over the sea taking advantage of the ground effect, and with capacity for 12 passengers (Figure 37). In 2022 he made the first test flight with a reduced model (a quarter) of the final design.

Figure 37. Viceroy electric ekranoplane for 12 pax and 300 km range [Regent]

One field that is currently burgeoning is that of electric vertical takeoff and landing (eVTOL) aircraft. A multitude of companies of all kinds, from start-ups to the big players in the sector, continue to develop their projects with more or less maturity. These aircraft, along with some short-takeoff[113] hybrid proposals, make up what has come to be called advanced air mobility (AAM[114]). The concept appeals to a potential market for short-distance, intra-urban emissions-free journeys with few passengers, although the sustainability of these proposals[115] must also be confirmed, not to mention their ability to benefit a general public.

Last year the final design of some of the most advanced programs was presented (for example, Archer's Midnight[116]), progress was made in autonomous flight proposals (Wisk), industrial backing was agreed (Joby[117]) and a multitude of agreements were signed. pre-purchase (eg Lilium[118]).

[111] https://www.futureflight.aero/news-article/2022-11-08/swiss-start-unveils-plans-and-seeks-backers-electric-seaplane
[112] https://www.greenairnews.com/?p=3000
[113] https://www.electra.aero/
[114] https://www.futureflight.aero/news-article/2022-12-19/another-pivotal-year-advanced-air-mobility-draws-close
[115] https://leehamnews.com/2022/11/11/bjorns-corner-sustainable-air-transport-part-45-evtol-how-green
[116] https://www.futureflight.aero/news-article/2022-11-18/archer-details-motor-and-battery-design-midnight-evtol-air-taxi
[117] https://www.futureflight.aero/news-article/2022-10-11/delta-backs-joby-investment-and-plans-airport-rides-passengers
[118] https://lilium.com/newsroom-detail/lilium-partners-saudia

Figure 38. eVTOL Midnight for 4 pax and 180 km range [Archer]

The feasibility of certifying any of these models is not guaranteed, and depends not only on their technical soundness, but also on the financial support they have[119] . One of the aspects that add uncertainty to this process is the fluidity of the regulatory environment, with the FAA changing the certification base in the US during 2022[120], and EASA still finalizing the corresponding one in Europe (SC-VTOL). In addition, the added complexity for the management and regulation of air traffic must be taken into account, especially within urban areas, given the incorporation of all kinds of drones that will foreseeably share the airspace with these new aircraft and helicopters. Security is not a negotiable factor, and for such a new concept, there is still a long way to go.

6.6. HYDROGEN

Hydrogen is, by all accounts, one of the great vectors towards the sustainable aviation of the future. Its enormous specific energy (Figure 39) eliminates the fundamental problems of batteries, although it must overcome its limitations due to the volume of storage required, the development of logistics to supply it at airports, and achieve a sufficient production of truly sustainable green hydrogen, which maintains the new aircraft (Figure 40) [1].

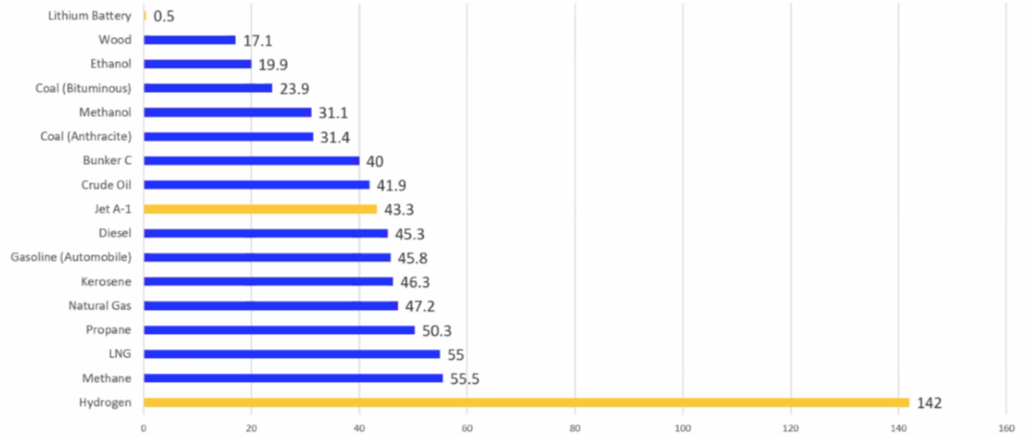

Figure 39. Specific energy (MJ/kg) of different fuels and batteries [IATA]

The use of H2 in sustainable aviation covers many possibilities, from the obvious use as a fuel, to its role in the production of SAF, or even for the reduction of the impact of fossil fuels

[119] https://aviationweek.com/aerospace/evtol-certification-who-are-leaders
[120] https://www.futureflight.aero/news-article/2022-05-11/faa-denies-media-report-stunning-overhaul-evtol-aircraft-certification

(hydrotreatment). Hydrogen-powered aircraft design also allows for many options, with active debate on which solutions best suit each segment of aviation[121]. The main dilemmas are, on the one hand, between the direct combustion of H2 in turbofan reactors, similar to those that equip the majority of current commercial aviation, or its use to feed fuel cells that feed electric motors, in a manner equivalent to the batteries but without their weight problems. On the other hand, the storage of this gas in the aircraft itself can be carried out in tanks with compressed or liquefied H2. If the first possibility is technically simpler, its capacity is lower and the weight increases, while the second requires cryogenic temperatures, with the added complexity for all fuel systems.

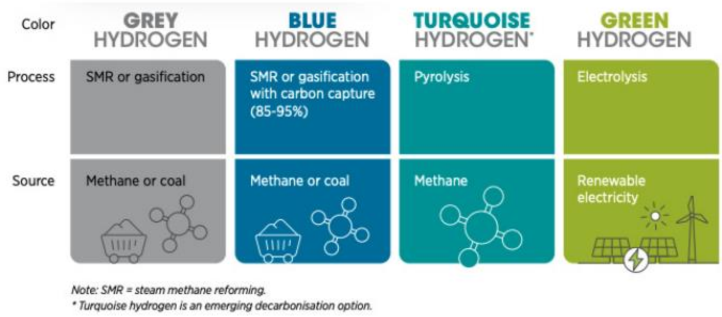

Figure 40. Some of the H2 production pathways: grey, blue, turquoise and green [IRENA]

In any case, and whatever the decisions of the most relevant programs in this sector, the advance of hydrogen aviation seems unstoppable in view of the progress in 2022. It is significant that, in March of last year, the British project UK FlyZero, which has the participation of the industry and government support, in its conclusions after the systematic study of options to decarbonise aviation in 2050, points to liquid hydrogen as the optimal fuel to carry it out[122]. This conclusion seems to be supported by another ICCT study on its application to short and medium range aviation [18]. As already stated, the debate is open, but H2, in any of its forms, seems to be inescapably linked to the future of aviation [17].

6.6.1. Future Vision

One of the main players in the world aviation industry, the European Airbus, has emerged as a mainstay of hydrogen as an aviation propellant. Since the launch of its ZEROe program in 2020, the company has not stopped weaving agreements with suppliers[123], manufacturers[124], airlines[125], airports[126], research entities and all kinds of actors, in what is known as the H2 ecosystem.

This vision for the sustainable future of aviation contrasts with that of its great competitor, Boeing, which points to the great challenges associated with the implementation of H2 in

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[121] Flight International. Marzo, 2022.
[122] https://www.greenairnews.com/?p=2799
[123] https://www.airbus.com/en/newsroom/press-releases/2022-04-airbus-kawasaki-heavy-industries-partner-to-study-use-of-hydrogen
[124] https://www.airbus.com/en/newsroom/press-releases/2022-02-airbus-and-cfm-international-to-pioneer-hydrogen-combustion
[125] https://www.upstreamonline.com/hydrogen/delta-air-lines-airbus-work-toward-hydrogen-fuelled-aircraft/2-1-1187403
[126] https://www.airbus.com/en/newsroom/press-releases/2022-02-airbus-signs-agreement-to-study-hydrogen-hub-in-singapore

commercial aviation[127], and delays the commissioning of large hydrogen-powered aircraft. until 2050. His commitment to the SAF for decarbonization, on the contrary, is also supported by the European manufacturer, with a more diversified strategy.

This competition between SAF and hydrogen covers energy and cost aspects (see Figure 41, presented by a company in the H2 sector), but also environmental benefits. If the vast majority of SAFs fail to eliminate 100% of net CO2 emissions, and only a partial reduction of non-CO2 effects, hydrogen can boast of facilitating truly zero-emission flights, as long as its production is also zero.

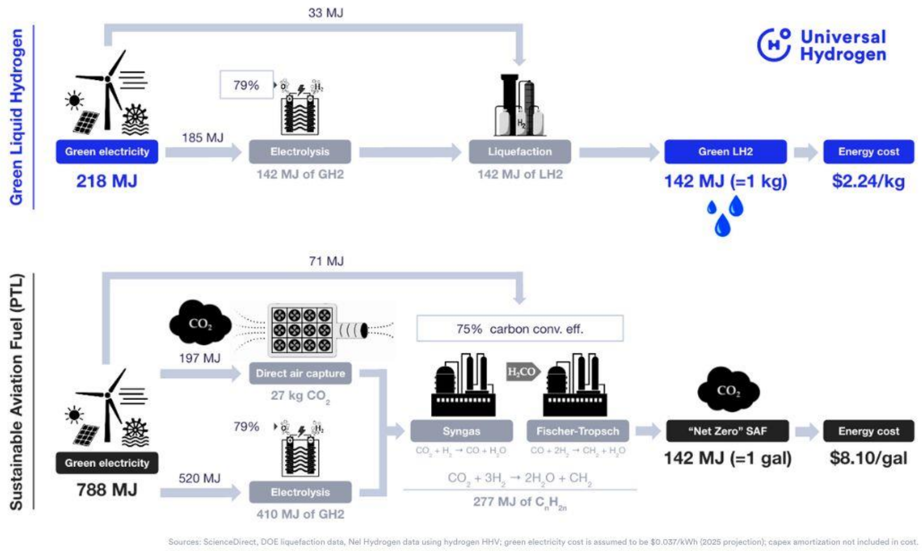

Figure 41. Comparison of energy and economic efficiency SAF vs. H2 [Universal Hydrogen]

The only exception would be the uncertainty about the generation of nitrogen oxides and condensation trails in engines with hydrogen combustion, which emits much more water than kerosene, but without soot or solid particles, so its impact is expected to be much less [19]. This possible negative impact is part of Boeing's argument about the H2, and in fact Airbus is investigating it through its Blue Condor project[128] (Figure 42), with which it will carry out flight tests with hydrogen and kerosene combustion to be able to compare the non-CO2 effects in commercial flight conditions.

Figure 42. Project Blue Condor glider, fitted with jet engine [Airbus]

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[127] https://www.ainonline.com/aviation-news/air-transport/2022-06-23/boeing-preaches-pragmatism-setting-sustainability-priorities
[128] https://www.airbus.com/en/newsroom/stories/2022-07-how-blue-condor-will-accelerate-airbus-first-hydrogen-powered-test-flights

The outcome of this confrontation of visions may depend on the progress of some key technologies associated with H2, such as the development of light liquid hydrogen tanks[129]. Another fundamental challenge is the entire distribution chain of the same, for which conventional solutions of hydroducts and tanks are also joined by more disruptive ideas such as the H2 Clipper airship. This airship, also powered by hydrogen, could carry up to 250 t of cryogenic H2. Its promoter company, focused on logistics solutions, signed a collaboration agreement with the Fundación Hidrógeno de Aragón[130] in 2022.

Figure 43. Airship project for the transport of H2 [H2 Clipper]

Lastly, and as an example of the evolution of technical solutions in the projects, the company H2Fly, one of the few with an operating model fueled by hydrogen (HY4), will change the storage in the small aircraft from compressed gas to tanks cryogenic. The European HEAVEN[131] project, under which this modification will be carried out, also seeks to develop a new fuel cell propulsion train to jointly serve as a prototype to power different classes of aircraft.

Finally, all these innovations will require specialized maintenance and adapted services at the airport. To evaluate it, the Lufthansa Technik company, research entities and the Hamburg airport will experimentally install H2 tanks, fuel cells and all the necessary systems for refueling an A320[132].

6.6.2. Fuel cells

Hydrogen fuel cells appear to have achieved a leading position in the early use of hydrogen for aviation, combining the weight advantages of H2 with the zero emissions of electric aviation. Numerous projects are underway for its application, including already flight tests.

The type of fuel cell best adapted for aeronautical use is the proton exchange membrane (PEM), in its low-temperature (more mature) and high-temperature (under development, but with greater potential[133]) variants.

[129] https://newatlas.com/aircraft/hypoint-gtl-lightweight-liquid-hydrogen-tank/
[130] https://www.eleconomista.es/energia/noticias/11769436/05/22/La-Fundacion-del-Hidrogeno-de-Aragon-y-H2-Clipper-firman-un-acuerdo-para-el-transporte-de-esta-tecnologia.html
[131] https://heaven-fch-project.eu/about-us/
[132] https://www.hibridosyelectricos.com/coches/lufthansa-reconvierte-airbus-a320-probar-hidrogeno-aviones_64199_102.html
[133] https://leehamnews.com/2022/05/13/bjorns-corner-sustainable-air-transport-part-19-fuel-cell-propulsion-systems

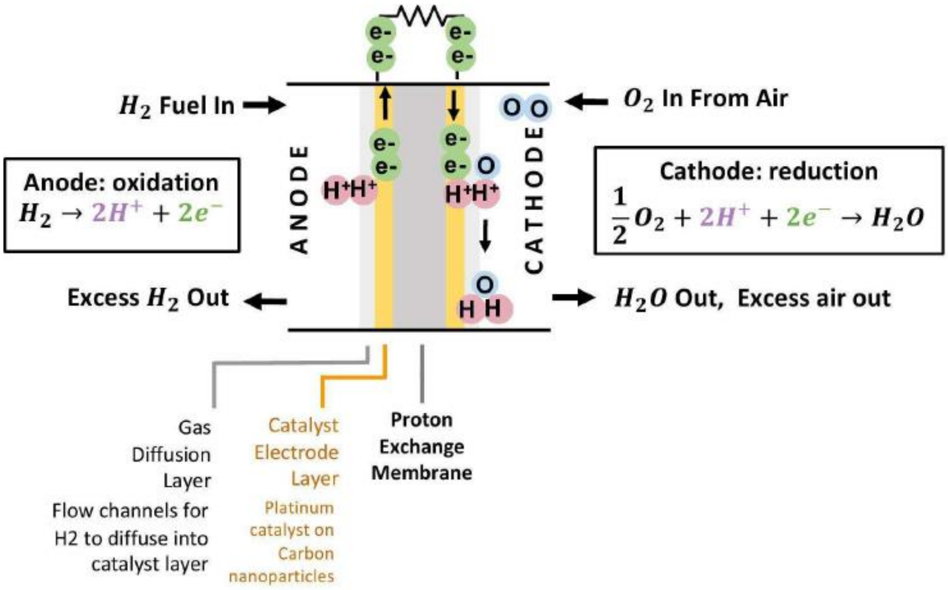

Figure 44. How an H2 stack works PEM [NASA]

One of the most active companies during 2022 in the field of hydrogen-powered aviation was ZeroAvia. Since its first flight tests in a Piper M-class in 2020, its strategy includes the development of complete propulsion trains to re-power aircraft already certified and widely used among airlines. The next step on this path was the repowering of a Dornier 228 (19 pax.), whose first flight was completed in January 2023. Other models selected to undertake this reconversion, and with signed commercial agreements, are the Caravan[134], the CRJ[135] series, Dash 8-400[136] and ATR 72[137].

Figure 45. First flight of the Dornier 228 with an electric motor powered by H2 cells [ZeroAvia]

This evolution would lead to achieving zero-emission aircraft with a capacity for around 80 passengers, which represents a very important quantum leap. To make it possible, the company continues to develop its ZA2000 engine with a capacity of more than 2 MW of power.

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[134] https://www.zeroavia.com/news/textron-aviation-agreement
[135] https://actualidadaeroespacial.com/zeroavia-avanza-en-el-desarrollo-de-los-motores-electricos-de-hidrogeno-para-aviones-regionales/
[136] https://www.aviacionline.com/2021/12/de-havilland-canada-y-zeroavia-trabajaran-en-el-desarrollo-de-motores-sin-emisiones-para-los-aviones-dash-8-400
[137] https://www.aviacionline.com/2021/11/zeroavia-y-asl-airlines-colaboraran-para-propulsar-aviones-atr-72-de-carga-con-hidrogeno-y-electricidad/

To complete these advances, it also closed contracts for the supply of advanced hydrogen fuel cells[138], the design of hydrogen refueling solutions, both stationary and mobile[139], as well as incorporating new inverters[140].

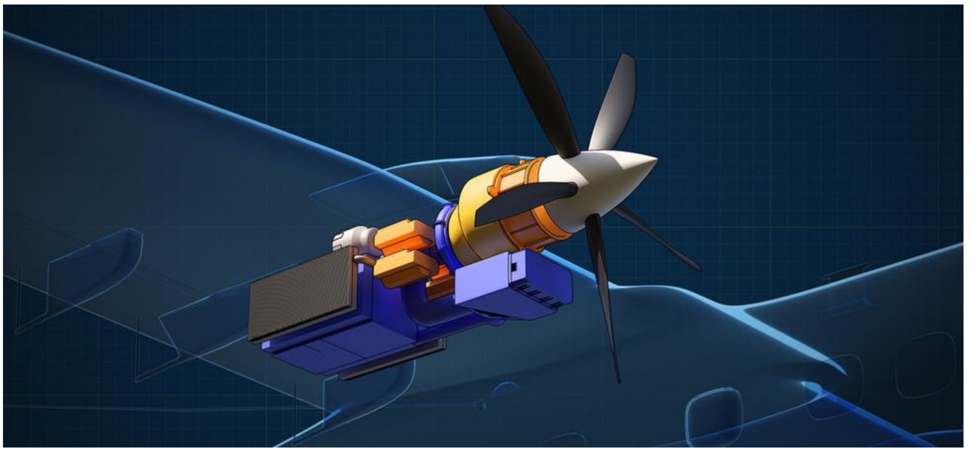

Figure 46. Integration of electric motor with hydrogen cells [ZeroAvia]

The other big player in hydrogen-powered aviation in 2022 was Universal Hydrogen. During the past year, it has developed the partial repowering of a Dash 8-300 with a capacity for 40 passengers (the prototype managed to complete its first flight in March 2023), in addition to carrying out tests of its container refueling concept in an ATR 72.

Figure 47. Refueling test using hydrogen containers [Universal Hydrogen]

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[138] https://www.zeroavia.com/news/powercell-mou
[139] https://www.greenairnews.com/?p=2981
[140] https://www.zeroavia.com/united-airlines

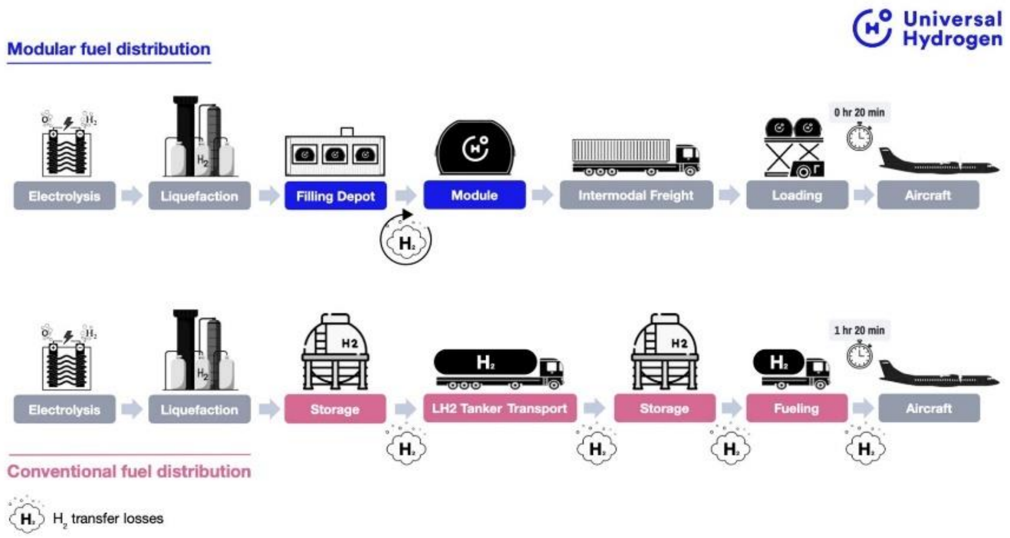

Figure 48. Comparison between conventional H2 distribution systems and through containers [Universal Hydrogen]

Like its competitor, Universal Hydrogen also continues to close deals for the development of its propellant[141], contracts with airlines[142] and investors[143].

Other companies with similar programs in development are Deutsche Aircraft with the Dornier 328, or Cranfield Aerospace with the Britten-Norman Islander[144]. Even big players in the industry are betting on developing their own propulsion trains with H2 batteries like GKN or MTU[145].

Figure 49. Ground tests of an electric thruster with H2 batteries of 1 MW power [Universal Hydrogen]

141 https://www.businesswire.com/news/home/20220315006284/en/Universal-Hydrogen-and-H3-Dynamics-Announce-Hydrogen-Aviation-Partnership
142 https://simpleflying.com/connect-airlines-atr-hydrogen-conversion/
143 https://www.greenairnews.com/?p=3512
144 https://www.futureflight.aero/news-article/2022-11-03/aircraft-finance-and-leasing-group-signs-cranfields-hydrogen-powered
145 Flight International. Diciembre, 2021.

Airbus' ZEROe programme, for the introduction of a hydrogen-powered aircraft by 2035, also has a fuel cell-powered option. This engine is currently under development and will be tested in flight tests planned for 2026[146].

Figure 50. Flight test of H2 battery propulsion scheduled for 2026 [Airbus]

6.6.3. Direct combustion

H2 combustion propulsion has a long history in aviation, including flight testing [1]. From this point of view, its application in current aircraft does not pose a great challenge from the point of view of propulsion, with turbofan engines very similar to current ones. Compared to the option of hydrogen cells, this is an advantage since it does not have thrust limitations, does not depend on the development of new high-power electrical systems, nor does it need to dissipate the large thermal energy produced by H2 cells[147]. On the debit side are the already mentioned environmental uncertainties regarding NOx and contrails.

Again Airbus, and its ZEROe program, mark the advance of this technology to equip the future sustainable aviation. In February 2022, it announced, hand in hand with the CFM engine manufacturer, the development and flight testing of a hydrogen combustion turbofan scheduled for 2026[148]. Together with the already mentioned hydrogen fuel cell propellant, these flight tests will be decisive for the European company to decide on one of the possible technologies and designs for the future large capacity hydrogen passenger aircraft.

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[146] https://www.airbus.com/en/newsroom/stories/2022-11-airbus-prepares-for-its-first-megawatt-class-hydrogen-fuel-cell-engine
[147] Flight International. Marzo, 2022.
[148] https://leehamnews.com/2022/02/22/airbus-and-cfm-reveal-zeroe-demonstrator-aircraft

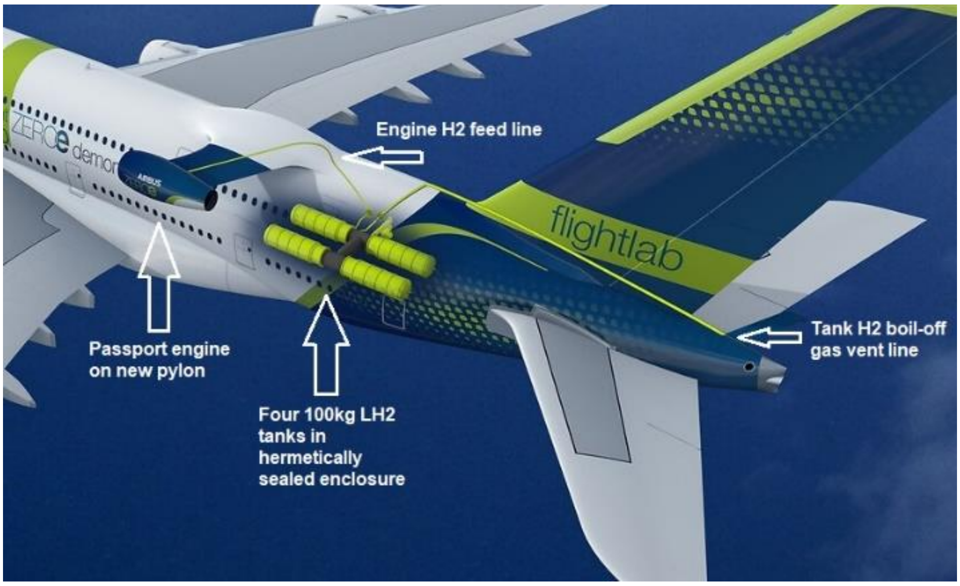

Figure 51. CFM H2 Combustion Reactor Planned Flight Test [Airbus]

Another company that is committed to the two hydrogen propulsion options is GKN, which is leading a project for the development of technologies for H2-powered turbofans[149]. Similarly, Rolls-Royce is also making progress with H2 combustion. In November 2022, in collaboration with EasyJet, it conducted a ground test of its AE 2100 engine with this fuel[150].

At the level of research projects, among others, the LEAFINNOX project of Clean Aviation could be highlighted. Their goal is to develop a new combustion process that significantly reduces nitrogen oxides and solid particles emitted. Jet engines equipped with this technology could use both hydrogen and SAF[151].

On the other side of the Atlantic, research is also being carried out in this field. As an example, the government's ARPA-E program funds P&W's HySIITE project, with an innovative water reinjection hydrogen combustion system that would improve efficiency and dramatically reduce NOx emissions. The expected entry into service of the final version of this engine would also be in 2035[152].

7. CONCLUSIONS

The path towards sustainable aviation, so necessary in our time of climate emergency, is undoubtedly irreversible, as demonstrated by the firm commitments made in 2022, both within the industry and at the governmental and international level.

These objectives, with greater or lesser intensity, are also reflected in policies and regulations that, together with the awareness of passengers, mean that no relevant actor in the aeronautical sector can remain on the sidelines.

The past year continued the spate of project announcements and pre-purchase agreements from SAF. Its production routes continue to expand and consolidate, confirming the industrial

[149] https://www.gknaerospace.com/en/newsroom/news-releases/2021/gkn-aerospace-leads-new-swedish-national-project-on-hydrogen-propulsion/
[150] https://www.greenairnews.com/?p=3656
[151] https://clean-aviation.eu/media/news/a-new-100-hydrogen-combustor-for-aviation
[152] https://arpa-e.energy.gov/technologies/projects/hydrogen-steam-and-inter-cooled-turbine-engine-hysite

leap that was necessary for this solution to fulfill the leading role that is assumed in the decarbonization of aviation.

Along with the advancement of technologies that reduce environmental impact, during 2022 great progress was made in zero-emission projects, both in electric aviation and in hydrogen-powered fuel cells. The number of companies that are turning into reality what only a few years ago were dismissed as marketing exercises is growing.

On the other hand, new options such as direct CO2 capture were incorporated into the range of decarbonisation strategies, although the technical and certification challenges faced by compensation in all its variants should not be underestimated.

As a summary, and following the trend of recent years, the strategies to mitigate and eliminate aircraft emissions continue to expand and advance in their introduction in the industry. And this reality seems to mark the decisions of many players in the sector: to diversify their sustainability approaches, both based on their suitability for different segments, and on the maturity of their development.

This does not mean that there is not a lot of work to be done, especially with air traffic in full recovery after the pandemic, but it does mean that sustainable aviation is beginning to be less of a promise and much more of a reality.

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