Enabling a zero-carbon future for aviation

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Aviators are innovators. Within a single lifetime, aviation has evolved and reinvented itself many times over. It has progressed from canvas-and-wood aircraft powered by piston engines and wooden propellers to multi-engine swept-wing passenger planes, routine transatlantic crossings, and today's cutting-edge cabin technology.

Modern aircraft are built from ultra-light, ultra-resistant composite materials, with engines operating at temperatures exceeding the melting point of their metal components. Passenger capacities now approach 500, offering unprecedented levels of comfort and safety. This is possible at a fraction of the cost, energy, and environmental impact it would have had eight decades ago. What do we imagine aviation to be like in eighty years' time? What do we need to do today to secure that future? The authors of this article coincide with the same view: maximum safety and efficiency levels with lowest environmental and noise impacts. This article highlights recent progress on zero-carbon air travel and the steps which must continue to happen today to ensure a sustainable future for our sector.

Progress since the 2022 Environmental Report

IATA and ACI have identified 44 airports and 35 airlines which have expressed interest in a hydrogen future for aviation. These numbers areI think three times higher than they were in 2022. Public announcements cite initiatives going from feasibility studies and memorandums of understanding to investment in technology companies. Some airports[1] are already building hydrogen infrastructure on-site for ground support equipment and ground transportation, preparing for a hydrogen future for travelers.

In its Net Zero Roadmap (2023), IATA highlights130 individual milestones required to reach net zero by 2050. These milestones are spread into technology, operations, infrastructure and policy items which must be met at specific times for us to be on track. Fortunately, we have identified progress across these milestones in 44 individual aircraft concepts from 23 companies which are advancing the critical technologies needed for a zero-carbon future. While it is acknowledged that many of these projects will not result in a commercial-flying product, and that many of the target dates might change, what matters is that technologies are being matured and tested, and we see progress.

The contribution that these aircraft will make towards the ICAO Long Term Aspirational Goal (LTAG) depends on how soon they come into the market, how many passengers they will carry, how far they can fly, and how fast production rates can be scaled-up. Their successful implementation will also be limited by the aviation sector's access to affordable low-carbon hydrogen and energy, for which enabling policies are urgently required.

IATA studied a *Regional Aircraft-First* strategy, where hydrogen and battery-powered aircraft start entering service in the 2030s, first with regional aircraft (less than 69 passengers), followed by single aisles nearly a decade later. This scenario resulted in around 20% of the fleet being powered by hydrogen or batteries in 2050 (about 10,00 aircraft), resulting in a 6% reduction in CO_2 emissions, compared to a case where these aircraft don't exist. This

1 See Rotterdam Airport, Toulouse Airport, Kansai Airport, Toronto Pearson Airport.https://www.iata.org/globalassets/iata/publications/sustainability/concept-of-operations-of-battery-and-hydrogen-powered-aircraft-at-aerodromes.pdf https://store.aci.aero/product/integration-of-hydrogen-aircraft-into-the-air-transport-system-an-airports-operations-and-infrastructure-review/#:~:text=ACI%20world%2C%20in%20partnership%20with,should%20they%20come%20into%20service.

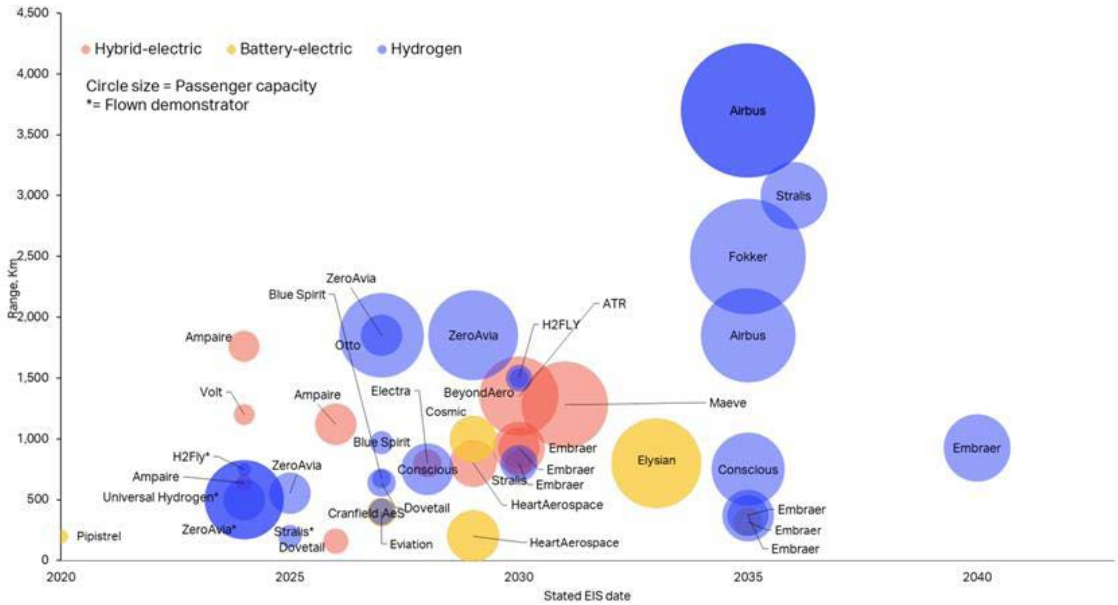

FIGURE 1: Future aircraft concepts, their passenger capacity, announced entry into service date, and energy source. Source: IATA Sustainability and Economics.[1]

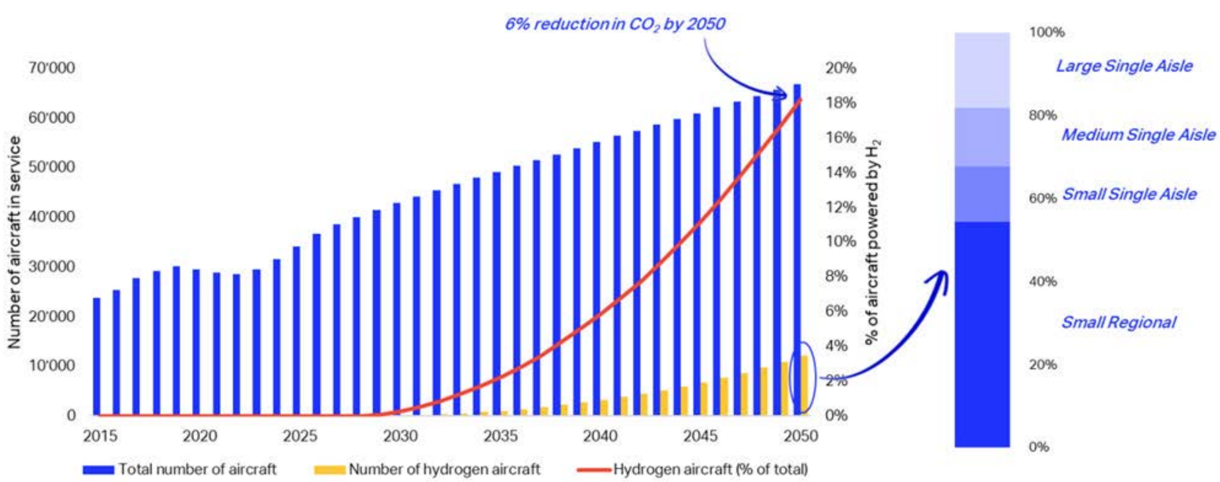

FIGURE 2: Deployment of hydrogen fleet according to the IATA Roadmaps. Source: IATA Sustainability and Economics:[3]

number could change considerably if the dates are delayed or accelerated, and if the aircraft class is changed.

To make this a reality, we need to develop infrastructure at airports, procedures and standards, regulation, personnel skillset, and an economically feasible and reliable hydrogen supply chain.

How is the ecosystem preparing for this?

While each stakeholder will adapt at its own pace, clear patterns are emerging in how the ecosystem prepares for the energy transition. Some of the key steps are outlined below, taken from examples observed of action all over the world, and some of which can be found in the ICAO

2 https://www.iata.org/en/iata-repository/publications/economic-reports/aviation-is-innovation-a-peek-into-future-aircraft-concepts/
3 https://www.iata.org/en/iata-repository/publications/economic-reports/evolution-of-hydrogen-aircraft-fleet-to-2050/

Eco-Airport Toolkit e-collection publication on new energies at airports and the hydrogen and battery-powered aircraft CONOPS[4]

1. **Funding research and boosting innovation and technology:** The first building block to make zero-carbon flight a reality is to mature the critical enabling technologies which will enable these aircraft to fly. Public and private initiatives are raising funds both through government and private finance to materialize their roadmaps.
2. **Formation of alliances, consortiums, working groups:** Effective collaboration and coordination across the full supply chain (States, airports, airlines, technology developers, energy and hydrogen providers, regulators, investors, etc.) to accelerate the introduction of non-conventional aircraft in a timely and safe way is critical and should be backed up by roadmaps and concrete milestones, strong financing partners, and government support. The reader is directed to examples of good practices like: H2CanFly (Canada), Hydrogen Flight Alliance (Australia), AZEA (Europe), Jet Zero Council (United Kingdom).
3. **Deploying hydrogen and/or battery-powered vehicles at the airport:** Several airports are taking the lead on deploying hydrogen- or battery-powered ground support equipment, both airside and landside. These activities will not only help airports decarbonize their operations and eventually improve local air quality (once the fleet is large enough), but also provide valuable learnings on how to safely handle and operate vehicles powered by an energy source other than hydrocarbons, including permitting, firefighting and rescue procedures and training, maintenance, and community engagement considerations.
4. **Deploying hydrogen and/or battery-powered vehicles at the airport for passengers:** Some airports are taking an additional step by using hydrogen or battery-powered buses to transport passengers from the gate to the aircraft. In addition to the benefits above, it also exposes passengers to new energies, an important step for public acceptance.
5. **Deploying small hydrogen or battery-powered aircraft:** The next natural step is to use the existing infrastructure to power small aircraft, some which may not carry passengers initially, but which will operate within the commercial set-up and limitations of a large passenger airport. Many roadmaps of implementation include this milestone as an important enabler to the fully commercial introduction of a flying zero-carbon aircraft.

Shedding a light into the operations of zero-carbon aircraft

While the infrastructure challenges for airports were tackled in the 2022 ICAO Environmental report and in the *Integration of Hydrogen Aircraft into the Air Transport System*[5] joint publication from ACI and the Aerospace Technology Institute, operations surrounding battery or hydrogen aircraft at the airport require further attention. A recent industry effort led by IATA, ACI, and Airbus (as a member of ICCAIA) under the Airport Compatibility of Alternative Aviation Fuels Task-Force (ACAAF-TF) explores potential changes with respect to the aerodrome operations of these new aircraft concepts.

The publication, which was released in February 2025 and included 35 partners, focuses on hydrogen (gaseous and liquid), fully battery electric, and hybrid-battery electric aircraft. It highlights that while the approach, landing, taxiing and departure operations are not expected to change, the refueling/recharging operations are those which require particular attention[1] .Special focus also needs to be given to abnormal operations, incidents and accidents, and how these will be different to conventional aircraft.

Refueling/recharging zero-carbon aircraft

Aviation jet fuel is a well-understood substance which can be handled in an extremely safe way. There are strict standards and procedures on the quality of fuel

4 https://www.iata.org/globalassets/iata/publications/sustainability/concept-of-operations-of-battery-and-hydrogen-powered-aircraft-at-aerodromes.pdf
5 Integration of Hydrogen Aircraft into the Air Transport System: An Airports Operations and Infrastructure Review - Store | ACI World

(chemical composition, contamination, water content, and microbiological contamination) and the way to handle it, from the fuel farm to the aircraft tank. The energy carriers for zero-carbon aircraft, however, lack this experience in the aviation sector. The ACAAF-TF explored the following aircraft concepts.

- **Case 1 -** Aircraft powered by hydrogen and refueled via a hose with liquid or gaseous hydrogen
- **Case 2 -** Aircraft powered by hydrogen but refueled via the exchange of a gaseous or liquid tank module
- **Case 3 -** Aircraft fully powered by batteries
- **Case 4 -** Hybrid Aircraft powered by batteries and conventional aviation fuel or SAF

The overall activities related to refueling or recharging will remain the same, but several details on these operations still need to be better understood, for example:

For **battery-powered** aircraft, fast chargers will be required to ensure a fast turnaround. It is possible that these aircraft will require extra ground support equipment connected to the aircraft to condition the batteries for charging. Conditioning could be cooling them down during fast re-charge or warming them up if they are to be charged in extremely cold ambient temperatures. It is also still unknown how charging will be supervised, whether by a person or by remote cameras and sensors. Project TULIPS in the EU, is currently testing technologies to answer some of these questions. For hybrid-electric aircraft, it is still unknown if charging and refueling can be done at the same time, and if not, which should occur first, and what additional safety provisions will be needed (e.g., fueling safety distances).

For **hydrogen aircraft**, fuel safety zones remain an open question. Today's recommended fuel safety zone for conventional aircraft is three meters. Should this increase considerably, it could limit the number of parallel activities allowed during refueling. There are also unknowns around the cryogenic nature of liquid hydrogen, stored below -253° C. Will aircraft fuel systems need pre-chilling to prevent thermal shock? Should hydrogen sensors be placed around refueling points to detect leaks or dangerous hydrogen concentrations – and if so, where? Additionally, how would a hydrogen spill, large or small, differ from a jet fuel spill, and what new hazards might arise? Finally, what personal protective equipment will be required for into-plane refuelers, or for rechargers handling electric aircraft?

FIGURE 3: Hydrogen aircraft concept being refueled at an aerodrome: Courtesy of Airbus

While there are instances where operations will be more complex than today's, there may also be advantages to these new fuels, like improved local air quality at airports, lower exposure of ramp-workers to carbon particulates and NO_x emissions, and for hydrogen specifically, lower environmental hazards in case of a spill. While many questions still remain, we observe that never before in aviation's history has there been so many initiatives to solve them.

This article began by reflecting on aviation's evolution over the past 80 years, since ICAO's formation. Today, hundreds of highly capable professionals are working to secure aviation's sustainable future for the next 80 years. The sector's transformation will be highly complex, costly, and take time. The 130 milestones identified by IATA is just a start, and we need to keep progressing to ensure the safe, timely and efficient energy transition of the sector.