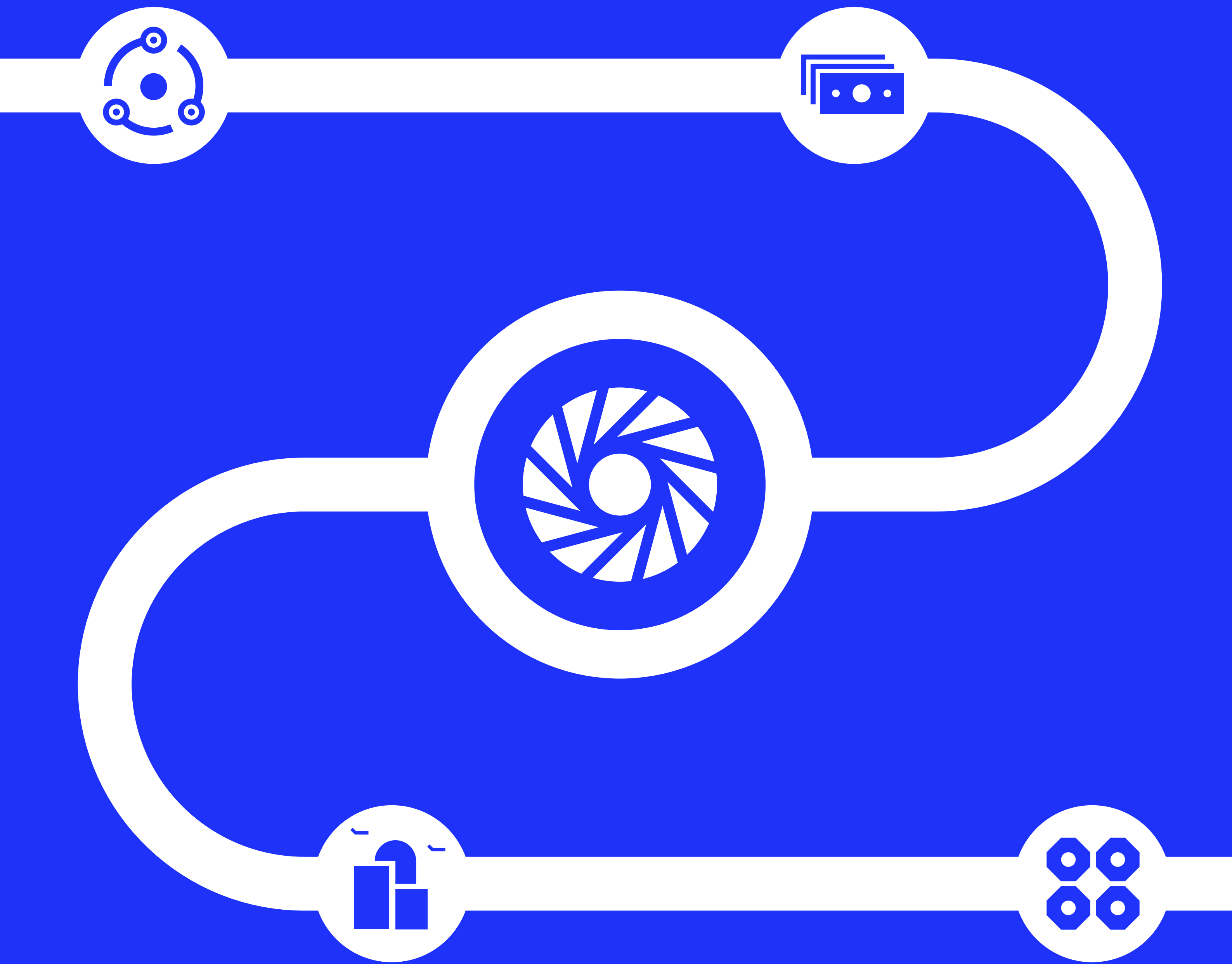
Aircraft Technology

Net Zero Roadmap



Introduction

The Aircraft Technology Roadmap highlights requirements for aircraft to be powered by SAF or conventional aviation fuel, hydrogen, or batteries. Each track on the Technology Roadmap is dedicated to a specific type of energy and the technologies needed to enable its use. The upcoming aircraft platforms capable of flying long and extra-long-haul flights should be fully or partially powered by SAF, while hydrogen options should be available for mid- and short-range flights in the near future. Commuter flights for very short range should be able to be powered by batteries. Nearing 2050, battery technology may be mature enough to power regional flights and hydrogen technologies could be scaled up to long-haul flights.

This roadmap complements the Waypoint 2050 analysis undertaken by the industry where pathways to meet net zero carbon by 2050 were identified. It provides a more granular analysis of the technology and infrastructure steps needed to meet the global pathways identified in Waypoint 2050 and should be seen as a companion report, alongside the Fueling Net Zero analysis of SAF deployment.

Access Waypoint 2050 at: www.aviationbenefits.org

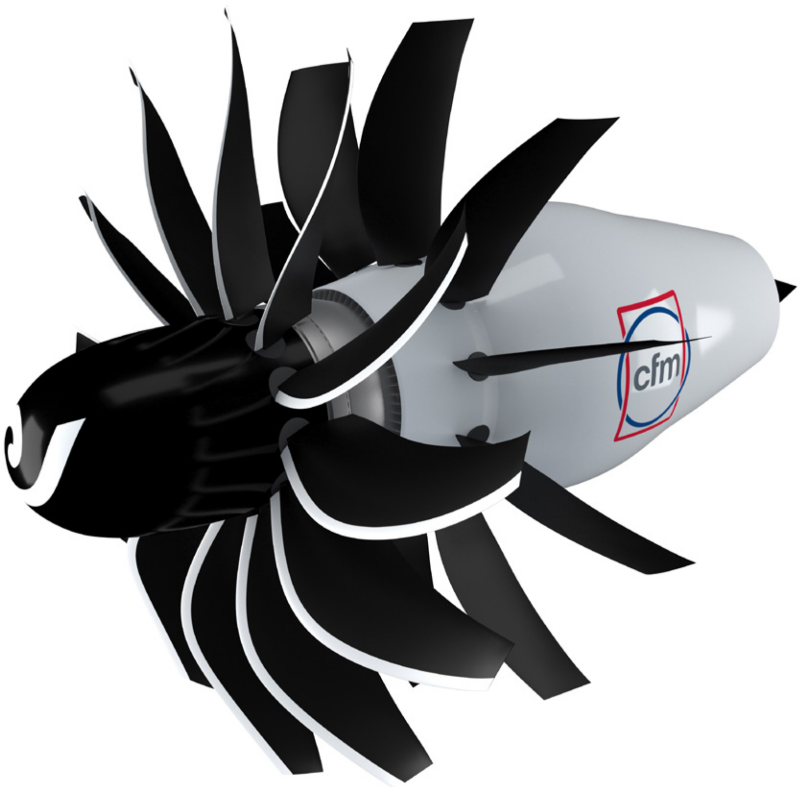
Methodology

The roadmap is based on announced technology demonstrator programs by Original Equipment Manufacturers (OEMs) and by national research centers. It was constructed by aggregating publicly available information from reports, technology strategies, company websites, and public conference presentations [1] [2] [3] [4] [5]. The roadmap was shared with experts from industry and academia and revised to reflect their input. This was done through engagements between IATA and individual organizations as well as at a workshop. In total 17 different organizations contributed to the aircraft technology roadmap (see the appendix).

Scope

The roadmap presents possible scenarios for aircraft technology development and the infrastructure to support them. They are deliberately more populated in the pre-2035 timeframe as there is more certainty and direction on some of the immediate steps, compared to what will happen closer to 2050. Many of the conclusions from the tests and demonstrators in the next 5-10 years will result in critical decision points on the way forward, and hence the scenario portrayed on the roadmaps is subject to change. The following sections describe some of the technologies and milestones that need to be achieved, with an integrated view on how these individual milestones can deliver new aircraft that can considerably contribute towards the aviation industry's net zero CO_2 emissions goal.

CFM International RISE concept



Aircraft Technology Roadmap

2023 | 2030 | 2035 | 2040 | 2045 | 2050

Reducing in-flight energy

- Engine BPR of 10+ in service. Geared turbofan in service thrust class: 150kN
- Laminar flow control in service on some aircraft and selected surfaces
- Electric actuation of some control surfaces
- Composite material wings and fuselage sections in service
- High power density small core demo
- UHBPR: low NO_x engine flight test
- Open fan flight demonstrator
- UHAR wing demonstrator
- Continuation of more electric control surfaces into all aircraft classes
- Flight test: revolutionary aircraft architecture – UHAR
- Hybrid or blended wing body demonstrator
- Multi-function structures demonstrated
- EIS of mild hybrid turboprop regional aircraft
- EIS of revolutionary narrow body aircraft
- EIS of next-gen wide body aircraft (aspirational)

Increased understanding of the climate impact of SAF and H_2 aircraft

Change the fuel

SAF & hydrogen aircraft

- Flight & ground tests on blended and unblended SAF
- 100% SAF compatible seals and metering validated
- All new delivered aircraft compatible with 100% unblended SAF
- SAF
- Flight test of 19-seater retrofit sub-MW HFC aircraft
- Flight test of 40-seater retrofit sub-MW HFC aircraft
- Major manufacturer announces exploring clean-sheet narrow body H_2 aircraft
- Aviation compatible fuel cell stacks (4 kW/kg) for multi-MW engines
- Advanced fuel cell flight test with LH_2
- Flight test: gH_2 storage tank Regional – commuter (GI: 15-20%)
- EIS retrofitted regional TP HFC aircraft
- EIS retrofitted commuter HFC aircraft
- Flight test: hydrogen engine, tanks and fuel systems
- H_2 gas turbine powered aircraft flight test
- Size & propulsion system definition for clean sheet H_2 aircraft
- Large heat management system demonstrator
- High gravimetric index of LH_2 tanks demonstrated (GI > 30%)
- Increased fuel cell stack specific power for future aircraft platforms (8k W/kg)
- EIS of clean sheet short to medium-range H_2 aircraft
- EIS of clean sheet NB H_2 aircraft – 200 pax/2000 NM
- EIS of wide body aircraft – H_2 combustion (aspirational)

Continuous engagement with certification bodies to define certification requirements

Change the fuel

Batteries & hybrid aircraft

- Longest hybrid-electric flight on record: 1,135 miles
- Electric flight speed record broken: 532 km/h
- Battery energy storage: <200 Wh/kg
- Urban air mobility (fixed & rotating wing. VTOL) flight tests
- 1-2 MW electric motor flight demonstrator
- Flight test: hybrid-electric regional aircraft
- EIS of all electric aircraft 30 pax/100 NM
- Distributed propulsion for commuter aircraft/UAM demonstrator
- Improved specific energy of batteries for 2nd generation electric aircraft ~225 Wh/kg
- EIS urban & metropolitan VTOL battery powered aircraft
- New battery chemistries enable higher specific energy for batteries > 350 Wh/kg

NET ZERO

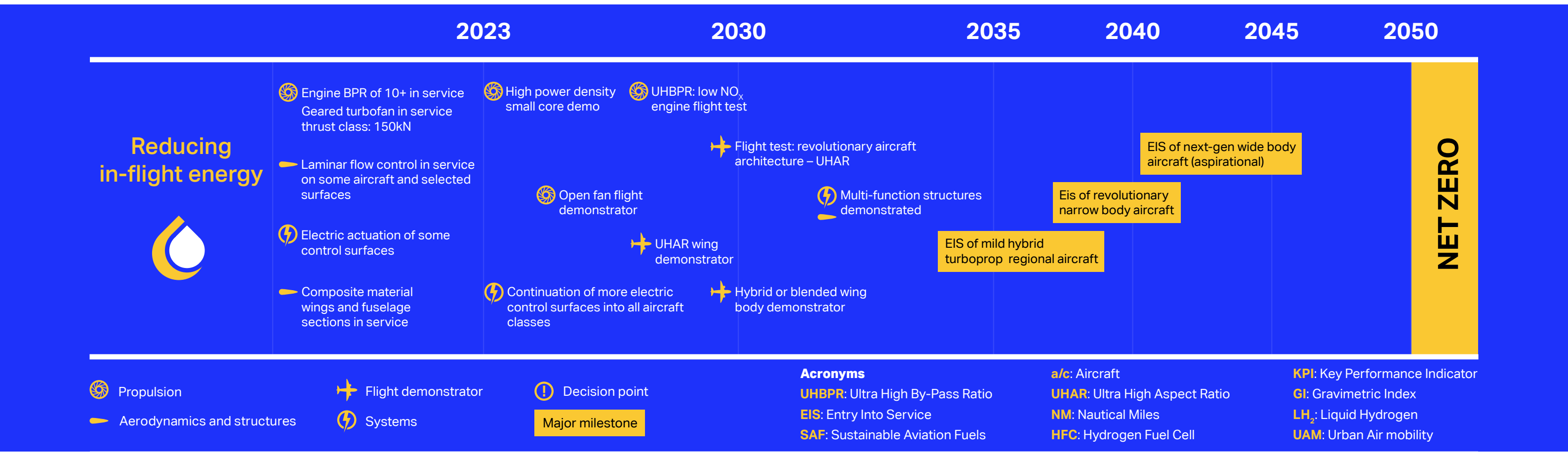
Propulsion | Aerodynamics and structures | Flight demonstrator | Systems | Decision point | Major milestone

Acronyms

- **UHBPR**: Ultra High By-Pass Ratio
- **EIS**: Entry Into Service
- **SAF**: Sustainable Aviation Fuels
- **a/c**: Aircraft
- **UHAR**: Ultra High Aspect Ratio
- **NM**: Nautical Miles
- **HFC**: Hydrogen Fuel Cell
- **KPI**: Key Performance Indicator
- **GI**: Gravimetric Index
- **LH_2**: Liquid Hydrogen
- **UAM**: Urban Air mobility

Aircraft Technology Roadmap

Reducing in-flight energy



Reducing the in-flight energy requirements

Efforts in improving the in-flight energy efficiency through investment in new propulsion, airframes, structures and systems are independent of what fuel is used for the flight. Historically, new-generation aircraft have delivered a 20% reduction in energy use compared to the aircraft they replace. The full transition to the best-in-class aircraft technology available today has not yet been finalized. For example, many Airbus A320s are still being replaced by A320neos, and Boeing 737s by 737-Max. This fleet replacement will already provide an initial reduction in in-flight energy use. Recent technology assessments for evolutionary aircraft predict another 15-20% improvement, compared to the best technology available today through the introduction of more efficient engines, lighter materials, and improved aerodynamics. More details can be found in the ICAO Long Term Aspirational Goal report, the ICAO independent expert integrated technology goals assessment, and ATAG's Waypoint 2050 report [6] [7] [8] [9]. By 2050, technological improvements in aircraft could reduce in-flight energy use by close to 7%, lowering the projected total in-flight energy use from 27 to 25 EJ[1] (in 2019 it was 13 EJ).

Depending on how the flight is powered, this could translate into considerable energy savings on the ground. The efficiency of producing fuels on the ground means that anywhere between 0.1 and 3.5 MJ of energy is required on the ground for every 1 MJ of energy required in flight. For the most energy-intensive solution today, which is Power-to-Liquid (PtL) fuels, an accumulated fleet-wide in-flight energy saving of 3 EJ could translate into close to 10 EJ of energy saved on the ground. This is comparable to the current energy consumption of Italy or Mexico in one year [10].

Propulsion

Higher by-pass ratio[2] engines of 12+ (from about 10 today) can deliver gains in propulsion efficiency and be achieved through geared turbofan technology, as is the case for the Rolls Royce Ultrafan project [11] [12]. Smaller cores with higher pressure ratios (of 50-60 compared to 40 today), will enable further improvements in thermal efficiency and help construct smaller and lighter engines. Better airframe-engine integration could reduce external engine drag and weight. New combustor technologies will need to provide low NO_x emissions and be optimized for alternative fuels. The HyTEC project is an example of an initiative looking into small ultra-efficient cores and combustion chambers [13]. These propulsion systems need to be demonstrated on the ground and in flight before they are adopted in a commercial airliner before 2030, as shown in the roadmap. Revolutionary propulsion systems such as the open fan engine architecture can provide a further 5-10% improvement in energy usage compared to a conventional engine of an equivalent year. CFM, a joint venture of SAFRAN and GE Aerospace, has been exploring this for several years and have recently launched the RISE program which will include a flight test of an open fan engine mounted on an Airbus A380 test bed before 2030 [14].

Rolls Royce Ultrafan

1 The Joule is the metric measurement for a unit of energy, an exajoule (EJ) is equal to 1018 Joules, or a quintillion Joule. Industrialized countries use an amount of electrical consumption which could go from a few EJ to tens of EJ.
2 Most of the air that enters a modern aircraft engine never gets combusted, it is compressed by the large frontal fan, by-passing the core engine and exhausted at the rear. The core engine uses most of its energy to move this frontal fan and push the by-passed air backwards. The parameter which measures how much air is by-passed versus how much air enters the core engine is the by-pass ratio.

Aerodynamics and structures

To reduce induced drag, longer and thinner wings with smart wing tip devices are targeted by manufacturers. The Boeing 777x, for example, will be the first in-service passenger aircraft with folding wingtips enabling it to have longer wings in flight, improving the lift-to-drag ratio[3] while maintaining airport compatibility. The 777x claims a 10% decrease in fuel burn thanks to the new engines and extended wings [15]. Aspect ratios[4] of 11-12 (up from 8-10 today) could still be achieved with current technologies. Drag can also be reduced on aircraft surfaces by controlling the boundary layer using flow control technologies. Ultra-high aspect ratio (UHAR) wings will need to be demonstrated with computer simulations, wind tunnel tests and flight tests (such as the Airbus Extra Performing Wing Demonstrator) before being implemented on civil aircraft, as shown in the roadmap.

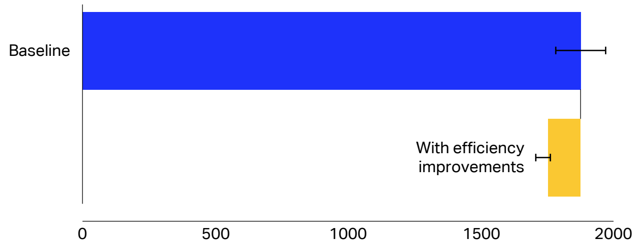
Further reductions in weight can be achieved by continuing to pursue the introduction of composite materials, particularly on the narrow-body market. Additive manufacturing, a novel manufacturing method analogous to 3D printing, can allow the production of lighter parts with shapes that were not possible with traditional manufacturing methods. Structural health management can allow smaller and lighter parts whose performance and integrity are constantly monitored. Building more integrated structures that reduce assembly part count and weight can also contribute towards better fuel efficiency [16]. An example of this are multifunction structures that combine the structural function with something else, such as fuel storage, heat transfer or integrated systems as demonstrated in the Clean Sky 2 STUNNING project. Aircraft made from composite materials, however, take longer to be built compared to metallic ones. For this reason, enabling high-rate composite parts production is also important, as shortening manufacturing time can accelerate the introduction of these aircraft. The Wing of Tomorrow project led by Airbus is an example of a future composite wing demonstrator with considerably reduced part count, incorporating innovative manufacturing methods.

Systems: Flight control, cabin and cockpit

There are opportunities to reduce aircraft weight by shrinking actuators through efficiency gains, and continuing to substitute hydraulic systems (which rely on pumps, valves, motors, actuators, pipelines and fittings) by simpler and lighter electric systems. The Boeing 787 was the first aircraft to enter into service with more electric flight control systems [17]. Therefore, there are considerable opportunities to deploy similar technologies to all future-generation aircraft, as indicated in the roadmap. Another opportunity for system weight reduction is better integration of systems within the structure, for example antennas which are embedded in the fuselage skin, thereby reducing weight and drag.

Chart 1 shows the effect of replacing the existing fleet of aircraft progressively with more advanced tube and wing aircraft. In this chart, all aircraft in service today get progressively replaced with their best-in-class next-generation aircraft, including many of the technological improvements mentioned above. This would result in 125-140 Mt of CO_2 mitigated, depending on the technology uptake scenario. More details are provided in Appendix. Bringing these more efficient aircraft to the market cuts aviation energy needs by 7-10% by 2050, with the same impact on CO_2 emissions. However, the absolute energy required, and the absolute CO_2 emissions, would still be higher in 2050 than in 2019 if nothing else were done. Without further action, aviation growth would continue to outpace fuel efficiency improvement, and the emissions curve slope would continue to trend upwards.

Chart 1: Aviation CO_2 emissions by 2050 (Mt) in the baseline scenario (top) and in a scenario with new aircraft that implement the efficiency improvements indicated in the roadmap (bottom).



Source: IATA Sustainability and Economics

Airbus A350

3 The Lift to Drag ratio (L/D) is a parameter that measures the aerodynamic efficiency of wings. The higher the L/D, the more efficient the aircraft is during flight.

4 The Aspect Ratio (AR) of a wing is a measure of the length of the wing compared to its chord (width). A high aspect ratio wing is a very long and thin wing, while a low aspect ratio wing is a short and wide wing. High AR wings increase L/D and reduce energy consumption in flight.

Limitations to further evolutionary improvements

While another 15-20% improvement in energy use in flight can be expected from the next generation of tube and wing aircraft, these gains become gradually more expensive and more difficult to achieve over time, as interdependencies start cancelling out theoretical benefits. For example, ultra-high bypass ratio engines could theoretically provide a lower specific fuel consumption, but the extra drag and weight of the engine, and the associated cascade effects on the mass of the entire aircraft could cancel these benefits. Higher aspect ratio wings would enable further reductions in drag, and thereby improve energy efficiency in flight, but these could be heavier, and could require larger engines to achieve the same take-off, climb and cruise performance. Ultra-long swept wings could also move the center of gravity aft posing further challenges to the positioning of the undercarriage and the aircraft ground stability [11]. These design interdependencies, including others such as safety requirements or cabin comfort are carefully studied and accounted for by OEMs.

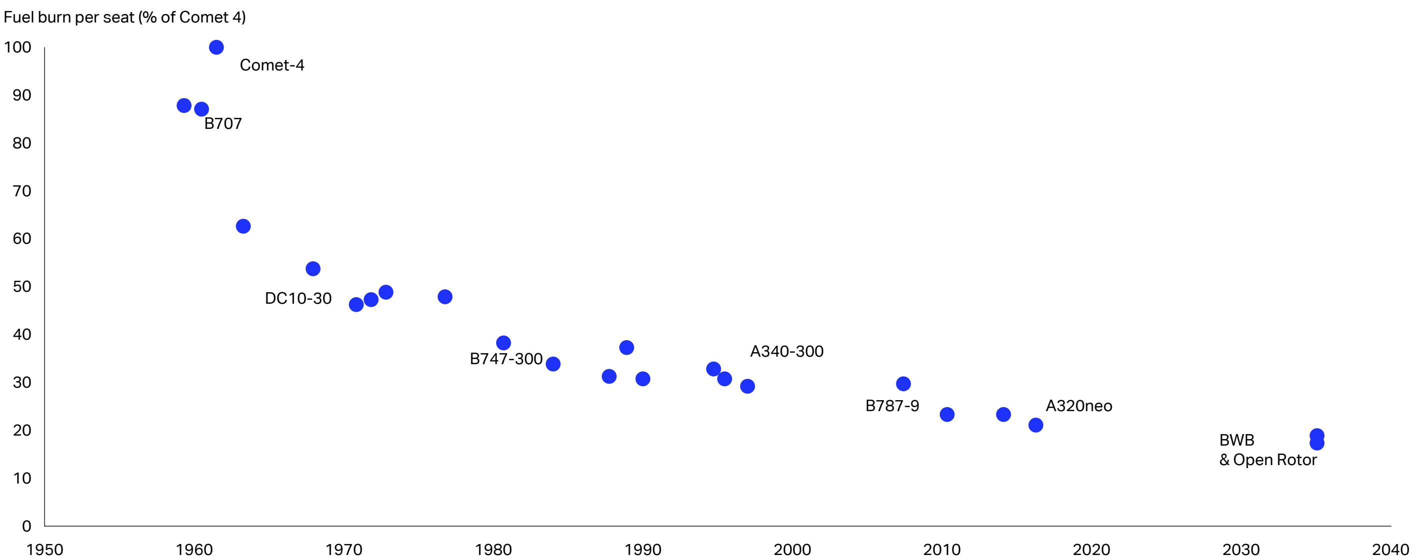
Progressive technological improvements apply over a gradually diminishing baseline number over time (Chart 2). In contrast, traffic growth applies to a larger number over time. For example, a 3% growth in 2035 represents a larger absolute growth than a 3% growth in 2019. This explains why emissions have traditionally outpaced energy efficiency gains for civil aircraft.

For this reason, revolutionary aircraft architectures are being explored which will still rely on conventional jet fuel or SAF, but which could include technological improvements to enable an extra step in efficiency of more than 10% compared to an evolutionary tube-and-wing of equivalent technology levels.

ATI's Future Wide Body Aircraft concept
© Aerospace Technology Institute

Transonic Truss-Braced Wing concept from the Sustainable Flight Demonstrator project
© Boeing

Chart 2: Fuel burn or energy consumption per seat of different aircraft compared to the Comet-4 (first jet-powered aircraft). The chart shows how energy efficiency gains are gradually diminishing over time. Modified from: [18]



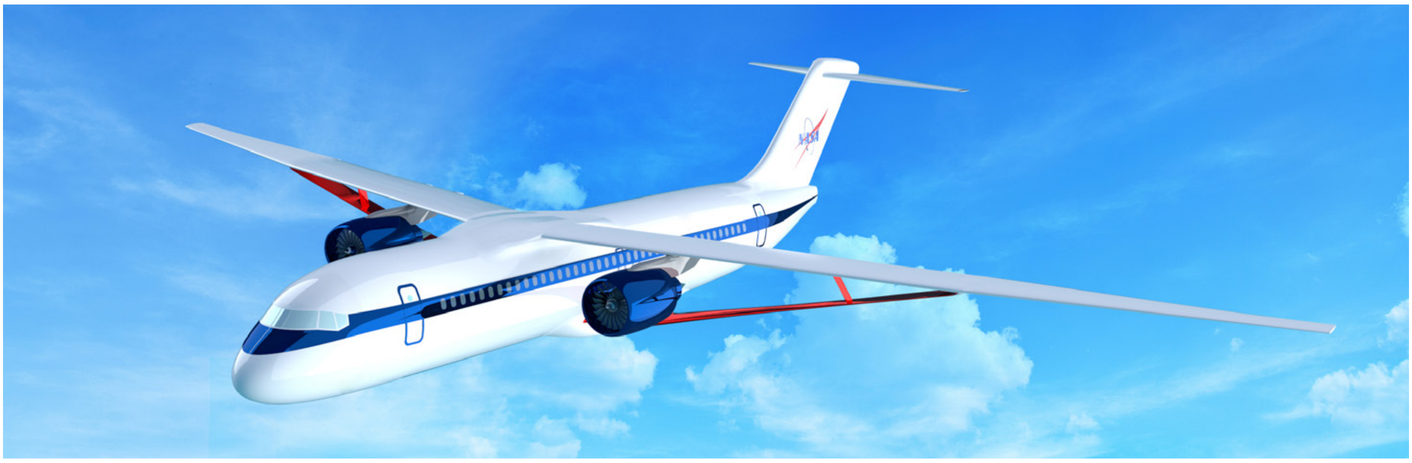
The blended wing body (BWB) aircraft, for example, has accumulated over 30 years of research, but has not matured into a replacement of conventional aircraft. The BWB configuration could be one of the most efficient aircraft with many co-benefits such as increased cargo space, lower noise level or increased space to be compatible with hydrogen. The main challenges relate to the scalability of the aircraft to create an aircraft family (say one with 150 seats, one with 180, and so on), which in turn involves considering economic restrictions, passenger perception regarding wide cabins with fewer windows, new evacuation procedures, and pressurizing a non-cylindrical fuselage [2] [9] [19]. Bombardier has flown a scaled-down version of a private blended wing body jet (Ecojet), and recently the United States Department of Defense announced a potential flight demonstrator of a BWB military aircraft, depicted on the roadmap by about 2030 [20] [21]. Other concepts such as double bubble fuselage, or box wings have previously been suggested, but never matured enough to be considered commercially.

A mix between a revolutionary and an evolutionary solution for the narrow body aircraft market has received special interest, mainly in the US. The transonic truss-braced wing (TTBW) aircraft increases the aspect ratio of the wings (longer and thinner wings) by supporting them with a truss to ensure structural integrity. This aircraft configuration also relies on conventional aviation fuel or SAF and promises a 10%+ improvement in energy consumption in flight compared to an equivalent year technology tube-and-wing aircraft [22]. This concept may require folding wing tips to be compatible with current airport stands. Part of the fuel may need to be stored in the fuselage as opposed to the wings as the wings would be too thin to accommodate the high-lift devices, their systems, and the fuel. The balance of the aerodynamic benefits of the large wings, and the ultra-high bypass ratio engines (enabled by the high position of the wing) would need to be evaluated against the performance penalties associated with the extra weight and drag of the truss, the folding wing mechanisms, and the larger engine diameter [11]. NASA and Boeing have launched a Sustainable Flight Demonstrator Project to test some of these architectures at scale, expected to fly before 2030 as shown in the roadmap [24]. Replacing all narrow body aircraft (100-199 pax) progressively with TTWB aircraft instead of an evolutionary tube and wing would unlock an extra 15 Mt of CO_2 savings by 2050 (see details in appendix).

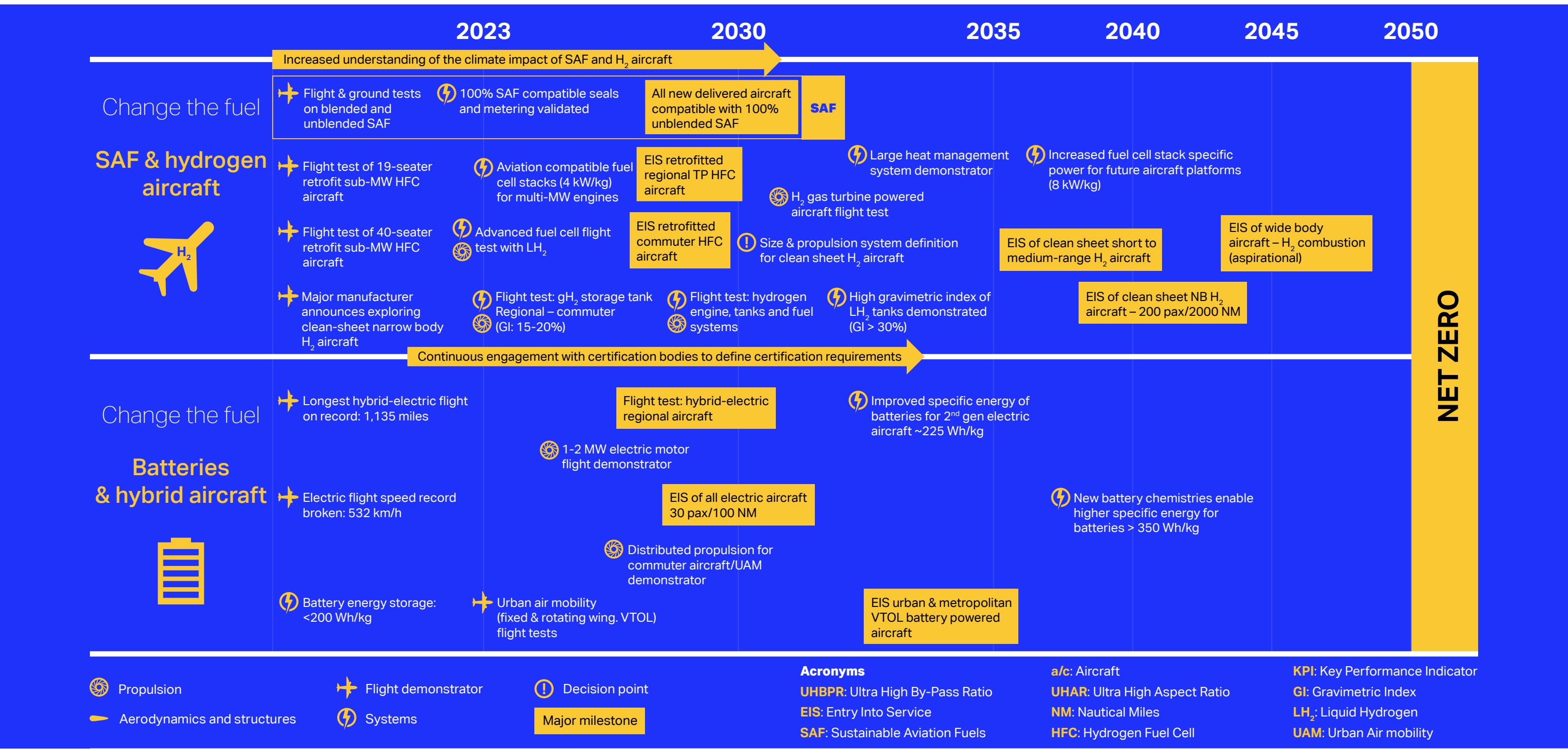
Bombardier EcoJet research project

NASA wind tunnel testing of a scale-down BWB

NASA Truss-Braced Wing Aircraft



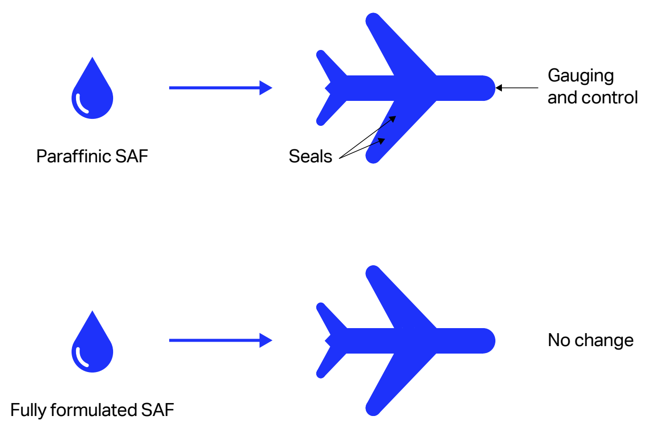
Changing the fuel (energy carrier) of the aircraft



Future fuels for existing and coming aircraft

The only way to fully decouple the aviation demand growth curve from the emissions curve is to change the source of the CO_2 emissions: the fuel. There are mainly three possible candidates to replace conventional aviation fuel: batteries, hydrogen, and SAF.

Sustainable aviation fuel can be grouped into two types based on their implications for aircraft technology: fully formulated, and paraffinic SAF [23]. The difference lies in their chemical composition and their properties. Conventional aviation fuel is a substance composed of hundreds of different hydrocarbons, roughly dominated by paraffins, naphthenes, cyclo-paraffins, and aromatics. The mix of these hydrocarbons, and the additives to the fuel give it its final properties in terms of density, freezing point, lubricity, viscosity, flashing point, etc. For a fuel to be compatible with existing aircraft, it must comply with specific characteristics outlined in the ASTM D1655 fuel standard or equivalent [23] [24].



Nearly all SAF available today is paraffinic and it lacks other hydrocarbon compounds such as aromatics, thus having properties different to conventional aviation fuel. Currently these fuels are not allowed for use in their pure form on passenger aircraft mainly for two reasons:

- The existing nitrile seals on fuel lines, valves and tanks rely on the aromatics of conventional aviation fuel to keep them healthy and avoid leakages.
- Aircraft have fuel metering systems calibrated with a fluid that has a specific range of density, electrical permittivity, and specific energy which is slightly different from that of paraffinic SAF [25]. For this reason, paraffinic SAF needs to be blended with enough conventional aviation fuel until the chemical composition is met so that the blend can be certified as jet fuel. For this reason, the Energy Institute EI/JIG Standard 1533 defines this SAF as a "Synthetic Blend Component" [24].

These technological challenges can be properly addressed in upcoming aircraft. The largest aircraft manufacturers have declared that all their civil products will be compatible with 100% paraffinic SAF by 2030, a key milestone identified in the roadmap, and an absolute necessity to reach net zero CO_2 emissions by 2050.

Fully formulated SAF, on the other hand, is a fuel that is manufactured to have the exact same composition and properties as conventional aviation fuel. In that sense, fully formulated SAF would contain aromatics along with the other hydrocarbons required. In this case, no modifications to the aircraft would be required. ASTM is currently working on standards which will enable existing aircraft to fly on 100% fully formulated synthetic fuel with expected completion of the standard before 2024.

While new technologies will reduce the in-flight energy demand of aircraft and thus the associated life-cycle emissions of the fuels to power them, these reductions alone will not be enough to drive aviation to net zero CO_2 emissions by 2050. Drop-in sustainable aviation fuels will need to be scaled up and integrated quickly but will also have a restricted emissions reduction potential. As the global uptake of SAF ramps up, the fuel will be a mix of different feedstocks and pathways. While some pathways might offer full carbon circularity, some others will not, so the global SAF mix will have residual emissions. Feedstock availability might also limit the global SAF supply and alternative pathways for synthetic fuel might not scale up fast enough. Alternative fuels and changes to aircraft architectures which do not contain nor emit carbon will also be required. The two most promising zero-carbon energy solutions for aircraft are hydrogen and batteries.

Hydrogen aircraft: De-risking technology and accelerating the transition

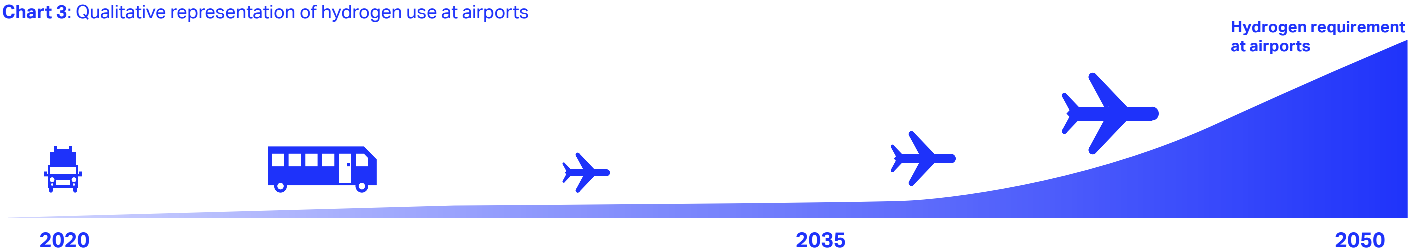
Hydrogen can be used to power aircraft in two different ways: It can be used to generate electrical energy in a fuel cell to drive an electric-powered aircraft or it can be combusted in a gas turbine much like how jet fuel is combusted today. An introduction to hydrogen uses for aviation can be found in IATA's publication "ABC of Environment & Aviation, Hydrogen: a decarbonization solution of the future" [25].

Hydrogen aircraft have been studied for decades but have never been certified to transport passengers. Earlier tests include NACA's B-57B hydrogen test flight in the 1950s, Tupolev's TU-155 flight in the 1980's, and more recently, Boeing's six technology demonstrations with crewed and uncrewed aircraft using hydrogen fuel cells and combustion engines. Recent pressure for more environmentally friendly flying (to reduce both CO_2 and non-CO_2 emissions), and a recognition of the system-level requirements for decarbonizing aviation, have resulted in strong investor interest in developing the technologies required to make this a reality. Hydrogen is also being deployed in other sectors such as road, rail, and maritime transportation, as well as for domestic use and heavy industry.

Hydrogen is already seeing a phased introduction into the air transport system starting with non-propulsive applications such as ground supporting equipment. This could be accompanied by hydrogen buses, trains, or taxis transporting passengers to and from the airport. After the mid-2020s, the introduction of sub-regional hydrogen aircraft will increase the experience of handling hydrogen at airports, and prepare the ground for the entry into service of the larger aircraft in the mid-2030s. These milestones at an infrastructure level are highlighted in the "hydrogen" section of the infrastructure roadmap.

New companies are offering a unique perspective, proposing to retrofit existing aircraft to speed up the certification process, and accelerate the entry into service of these solutions. ZeroAvia plans to deliver a 9-19 seater hydrogen fuel cell powered aircraft in 2025, and a 40-80 seater by 2027 [26]. The company flew its second retrofit aircraft, a Dornier 228 earlier in 2023, at the time of the test flight this was the largest aircraft to have flown on one propeller powered by hydrogen fuel cells. Universal Hydrogen is doing the same with an ATR-72 and a De Havilland Dash8-300, to deliver an entry into service in 2025 [27]. In March 2023, just a few months after the ZeroAvia flight, Universal Hydrogen managed to perform their first test flight, making the Dash-8 the current record holder of the largest hydrogen fuel cell powered aircraft ever to fly. Cranfield Aerospace solutions plans to have its 9-seater Britten-Norman demonstrator ready by 2023 [28].

Chart 3: Qualitative representation of hydrogen use at airports



Universal Hydrogen retrofitted aircraft concept
© Universal Hydrogen Francis Zera – Zeraphoto

ZeroAvia retrofitted aircraft concept
© ZeroAvia

All these companies are targeting entry into service dates before 2030 in the regional and sub-regional markets. While such regional emissions only account for about 7% of the total aviation emissions, these efforts will mature and de-risk some of the critical technologies required to achieve zero-carbon flight. Some of these companies have plans to scale up the narrow-body market post-2035. Examples of the milestones to achieving this, including the potential entry into service are depicted on the "hydrogen" track of the aircraft technology roadmap.

Airbus has announced plans to bring a larger (100+ pax) hydrogen aircraft into service in 2035 with an assessment on the impact of hydrogen combustion on contrail formation in 2023 [32], a hydrogen gas turbine test flight in 2025 [33], as well as a hydrogen fuel cell flight test around the same time, and the announced investment of a hydrogen fuel research center which promises to deliver the first fully functional liquid hydrogen cryogenic (extremely low temperature) tank in 2023 and the first test flight in 2026 [34].

GKN Aerospace is working on the development of an advanced fuel cell propulsion concept supporting new aircraft designs which could enter into service in the mid-2030s using a cryogenically cooled electrical system offering extremely high efficiency set to achieve TRL5 in 2025. This approach reduces the losses in propulsion enabling longer range and higher performance aircraft. This enables aircraft at the 100+ passenger scale and potentially larger.

While the effect of hydrogen aircraft on aviation global emissions will be very small even by 2040, it is possible that this will change and that a large share of aircraft will be powered by hydrogen energy by 2060 and 2070. For this to happen, there are unique technological challenges that must be overcome quickly, some of which are mentioned below [35]. In parallel, the climate science of flying on hydrogen needs to develop. Experimental flights will help to understand the non-CO_2 emissions of aircraft powered by hydrogen and SAF.

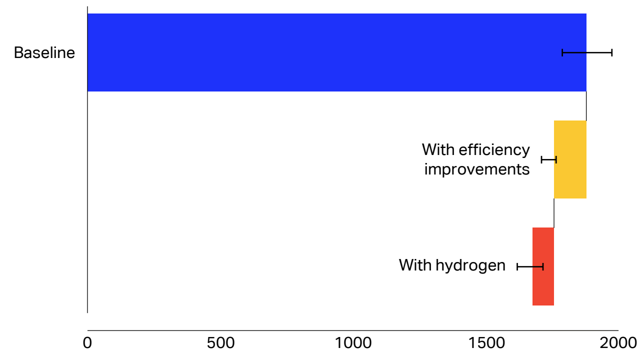
Chart 4 shows how achieving the milestones shown in the hydrogen and electric aircraft roadmap could enable the introduction of zero-emission aircraft which by 2050 could mitigate an additional 35-125 Mt of CO_2, or close to 6.5% of the total reductions by that year, depending on the hydrogen aircraft roll-out scenario. More details are provided in the appendix.

ATI concepts for clean-sheet hydrogen aircraft

Concept of Airbus ZEROe hydrogen gas turbine flight demonstrator

Embraer concepts for clean-sheet hydrogen aircraft

Chart 4: Baseline aviation emissions by 2050 (Mt) and reductions achieved through efficiency improvements and the introduction of zero-emission aircraft



Source: IATA Sustainability and Economics

Unique enabling technologies of hydrogen and battery-powered aircraft

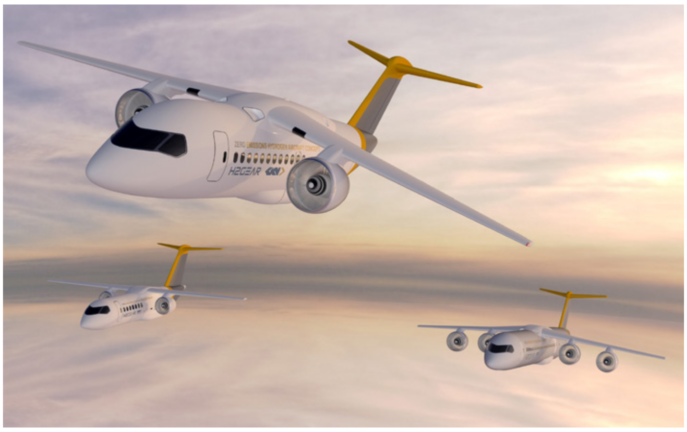
To unlock the 125 Mt of CO_2 savings that hydrogen aircraft could enable by 2050, technologies must be developed that currently do not exist at all, or that have yet to meet the specific requirements of large civil aircraft. Some of those are listed below and form part of the aircraft technology roadmap:

- **Thermal management systems** will be required to handle the heat created by high-temperature fuel cells. The cryogenic nature of liquid hydrogen could be an important enabler of this.

- **Mega-watt scale ultra-efficient electric motors and associated power distribution systems**. Fully electric aircraft powered by batteries have already flown on the 0.5 MW-scale, but this needs to rapidly scale up to enable longer flights with higher payloads [36]. Eviation Alice was the first clean-sheet fully electric commuter aircraft (9 pax, 2 crew) to fly in September 2022 powered by 2 electric propulsion units. 1-2 MW demonstrators are now being targeted, as displayed in the aircraft technology roadmap-batteries section [37]. This includes GE Aerospace and NASA's Electrified Powertrain Flight Demonstration (EPFD) project with flight demonstrators in the mid-2020s [38]. GKN aerospace also plans to demonstrate (TRL5) a hyperconducting electrical drive and distribution system by 2025.

- **Low-Temperature Fuel Cells (FC)** already exist and are in use for transporting passengers in cars or buses, however their power density is still low (4 kW/kg – stack) compared to what will be required for large aircraft. A theoretical step-up in energy density is still possible through high-temperature fuel cells but these are a unique requirement of aviation which will need rapid investment and development [41]. This could raise the power density to 10+ kW/kg (stack), which would unlock longer ranges and payloads [39]. GKN's H2GEAR project, is focused amongst other things on increasing fuel cell performance to enable large hydrogen fuel cell aircraft [40]. ZeroAvia is also developing in-house HT fuel cell technologies capable of air cooling.

H2GEAR hydrogen fuel cell concept project
© GKN



- **Liquid (Cryogenic) LH_2 tanks** are required to store the hydrogen in its liquid form instead of its gaseous form in order to minimize the volume for storage. These tanks need to be matured and tested. Some of the crucial challenges are to maintain the hydrogen at extremely low temperatures (-253° C) minimizing boil-off and avoiding leakages. This is especially an issue during landing, when most of the hydrogen has been consumed and the remaining hydrogen could quickly evaporate if warmed. Another challenge will be to keep the gravimetric efficiency as high as possible. This is the metric which describes the fuel weight in comparison to the combined fuel, tank and systems weight. For conventional aircraft this is very close to 100%. Recent research has predicted a viable gravimetric efficiency for hydrogen of 70% which would mean a good compromise between the lighter fuel weight and the added tank weight, but these will likely only be the case post-2040, with values closer to 50% in the near future. The Overleaf project is a Horizon Europe project aiming at maturing low-pressure cryogenic liquid hydrogen storage tanks for aviation incorporating innovative lightweight insulating materials and sensing for hydrogen leaks [42]. Boeing also recently tested, along with NASA, a 4.3-meter diameter full-composite cryogenic hydrogen tank [58].

- **Hydrogen low NO_x combustion** will be an absolute requirement to minimize the non-CO_2 emissions of hydrogen (and SAF) aircraft. Studies predict that hydrogen gas turbines could provide a 70% improvement in NO_x emissions over comparable year technology turbofans with kerosene fuels (SAF or conventional aviation fuel) [43]. Combustors which can enhance H_2 and air mixing, improve flame stability, and have good thermoacoustic properties need developing, testing and implementing. A flagship project on this was ENABLEH2, an 8-party consortium project led by Cranfield University which had specific work packages on numerical and experimental analysis on low NO_x hydrogen combustion and which concluded in 2022 [44].

- **Dry wings** are wings which do not store fuel. Due to the larger volume than hydrogen occupies, the hydrogen will not be stored inside the wings, but rather the tanks will be stored inside the fuselage. The fact that wings will not store fuel allows for lower thickness wings that could have improved aerodynamic performance but will require research and demonstration [35].

Considerable investment is being directed into maturing and de-risking these technologies, but more will be required in the years to come. According to the International Energy Agency (IEA), a total of 87 hydrogen fuel cell and hydrogen gas turbine patents were filed in 2020 compared to 22 filed in 2011.

Heart Aerospace is also advancing their full-electric aircraft design. Current battery technology allows a 200 km flight range which could be increased with a hybrid-range extension unit at the rear of the aircraft. Progress in battery specific power could enable longer rangers in the near future.

Conclusions

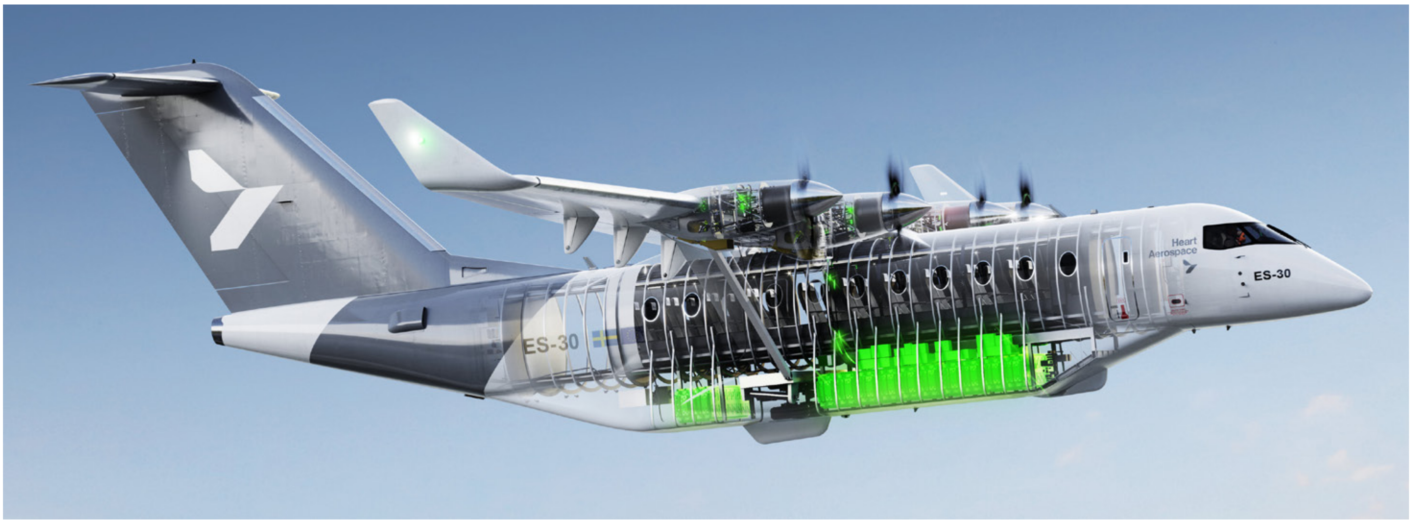
Aviators are innovators. The aviation sector is characterized by successive innovation waves that have transformed the industry. The sector has gone from one-seater aircraft made of steel, canvas, and wood, to large transatlantic aircraft flying near the speed of sound with 300 passengers, at altitudes above 10km, and for over 15 hours! This has happened thanks to a deep transformation of the aviation ecosystem. IATA's net zero CO_2 emissions goal will also require a massive transformation, which will be achieved through a combination of new aircraft technologies, operational measures, alternative fuels, and carbon removals.

Continuing to pursue efficiency gains in flight and on the ground will become increasingly important as the fuel to power the aircraft changes from fossil-based kerosene to Sustainable Aviation Fuels, hydrogen, and batteries. These new fuels will require less energy input for their manufacture than conventional fuels, thereby multiplying in flight efficiency gains throughout the fuel supply chain. Pushing aircraft efficiency improvements could reduce the entire fleet's energy use by 2050 by up to 10%, with further gains downstream. Equally, a scenario which includes hydrogen aircraft would result in additional CO_2 reductions. The use of hydrogen could alleviate demand pressure on a potentially feedstock-strained SAF supply by 2050, and curtail the energy requirements of global aviation by lowering demand for power-to-liquid. Even in an aggressive hydrogen scenario, only a small fraction of the active fleet by 2050 would be powered by this zero-carbon energy carrier that is hydrogen. From now until then, and for a few decades after, aviation will continue to rely on drop-in hydrocarbon fuels such as SAF. SAF is the only way to curb emissions of the existing and near-future fleet of aircraft which amounted to ~30,000 aircraft in 2019, and could reach ~65,000 aircraft in 2050. The scale-up of SAF, and the exploitation of new advanced feedstock pathways, is an absolute necessity for air transport to achieve net zero CO_2 emissions by 2050.

While this roadmap will be revised along the way to 2050 in step with developments and evolving scenarios, it is highly likely that the critical advancements identified here will need to happen. For this to become a reality, the roadmaps pertaining to infrastructure, operations, policy, and finance will also need to advance accordingly, as they are all interdependent. Reaching net zero CO_2 emissions in air transport by 2050 is achievable, and depends on all industry partners and stakeholders being united in this ambition.

ES-30 ELECTRIC AIRCRAFT CONCEPT

© Heart Aerospace



Appendix

List of contributing organizations to the technology and infrastructure roadmaps

- Aerospace Technology Institute
- Airbus
- Air Liquide
- ACI Airports Council International
- ATAG Air Transport Action Group
- Air Transportation Systems Lab @ UCL www.ATSLab.org
- BlueSky Data 2 Decisions
- Boeing
- Carbon Engineering
- climeworks
- Cranfield University
- DLR
- GE Aerospace
- GKN Aerospace
- Jacobs
- NASA
- to70
- Universal Hydrogen
- ZeroAvia

Technology assumptions

IATA built ten scenarios to evaluate the effect that the technologies identified in the roadmaps could have on emissions in the route to 2050. These scenarios were modeled using the University College London's (UCL) open source Aviation Integrated Model (AIM) tool. A thorough description of this tool, with the assumptions behind it and relevant scientific peer-reviewed publications which resulted from its use can be found on the AIM's website. The AIM is one of the world's most widely used aviation emissions tool, having produced over 30 international peer-reviewed publications in some of the most prestigious scientific journals.

The scenarios designed by IATA include three types of innovations:

- **Best in Class 2023 (BiC'23) aircraft** which are the latest aircraft to have entered into service in all aircraft classes. (For example, 737-Max or the neo series, B787 and A350). The baseline scenario assumes that all aircraft will get progressively substituted by the best-in-class available aircraft today, but no further technological innovations happen. This transition has already begun in most aircraft classes.
- **Future aircraft (FA)** which are more efficient than the best in class (BiC'23) available today. These aircraft are tube-and-wing which have improved engine efficiencies, improved aerodynamics and lighter weight structures and systems in line with the Reducing in-flight energy roadmap. These aircraft do not currently exist and are assumed to enter into service in different timeframes depending on the aircraft size with entry into service (EIS) around the 2030-40 timeframes.
- **Future aircraft with additional energy efficiency innovations (FA+)**. Some scenarios include aircraft in the narrow-body market which incorporate additional efficiency gains compared to the future aircraft models (FA), enabled by even more efficient engines and ultra-long aspect ratio wings, supported by stabilizer trusses, like the Transonic-Truss-Braced-Wing (TTBW) aircraft concept. In these cases, it is assumed that the FA+ aircraft is adopted instead of the FA aircraft for certain seat categories.
- **Hydrogen aircraft (HA)**. Some scenarios include hydrogen aircraft which have the same flight efficiency as the best in class aircraft available today (BiC'23), but are powered by hydrogen.

To estimate the levels of efficiency gains obtained by the future aircraft (FA & FA+) platforms, several published reports were analyzed and compared, including ATAG's Waypoint 2050 report, the ICAO Long Term Aspirational Goal report, the ICAO Independent Integrated Expert Review in technology, the ATI's technology strategy and the UK's Sustainable Aviation technology report, amongst others. The efficiency gains from all these reports are comparable and aligned with the assumptions in the AIM technology models, and as such the AIM future aircraft models were adopted unmodified. The table below compares the averaged full-flight efficiency improvements according to some of the literature consulted for the narrow and wide body markets, which are responsible for most of aviation emissions.

Table 1: Review of possible efficiency gains of Future Aircraft models

Narrow body		Wide body		Source
FA vs A320neo	20%	FA vs 787	16%	ATI
FA vs A320neo	25%	FA vs 787	25%	SA
FA vs A320neo	16%	FA vs 787	18%	ATA-Ellondee
Open Rotor vs LEAP	14%	BWB vs 787	18%	ATA-Ellondee
FA+ (TTWB)	Similar to neo	BWB vs 787	13%	IATA Tech roadmap, 2018
FA+ (TTWB) vs neo	11%	–	–	IATA Tech roadmap, 2018
Double Bubble vs neo	20%	–	–	IATA Tech roadmap, 2018
FA vs A320neo (2027)	14%	FA vs A350 (2027)	12%	ICAO IEIR
FA vs A320neo (2037)	24%	FA vs A350 (2037)	21%	ICAO IEIR
FA vs A320neo (2030)	10.70%	FA vs A350 (2030)	9.35%	ICAO LTAG – AppM3
FA vs A320neo (2040)	18.87%	FA vs A350 (2040)	22.02%	ICAO LTAG – AppM3
BWB, TTBW, Double Bubble vs future platform	5-15%	–	–	ICAO LTAG – AppM3

AIM aircraft models

Table 2: Average efficiency gains per aircraft type adopted in the AIM model

Aircraft	Seat	Reference aircraft	Best-in-class 2023 vs ref	Future Aircraft (FA) vs ref	Future Aircraft (FA) vs BiC'23	TTWB vs BiC'23 (FA)
Small regional	30-69	CRJ700	16%	28%	14%	–
Large regional	70-109	E190	16%	28%	14%	–
Small narrow body	110-129	A319	20%	32%	15%	26%
Medium narrow body	130-159	A320	20%	32%	15%	26%
Large narrow body	160-199	B737-800	20%	30%	12.5%	26%
Small twin aisle	200-249	B787-800	–	17%	–	–
Medium twin aisle	259-299	A330-300	12%	27%	17%	–
Large twin aisle	300-399	B777-300ER	21%	39%	22.8%	–
Very large aircraft	400+	A380-800	–	–	–	–

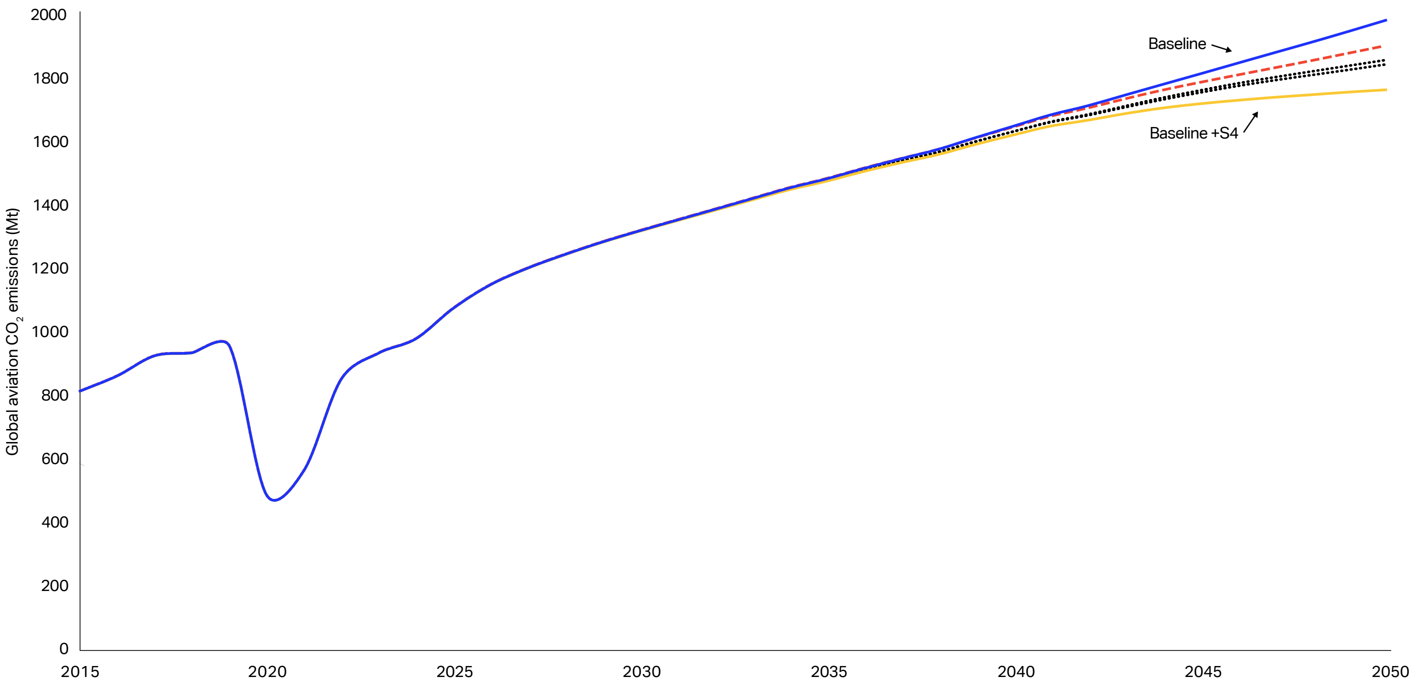
The scenarios modeled with the entry into service of each aircraft type are displayed below. For each scenario a sensitivity analysis was done by varying manufacturing ramp-up times from 0 to 5 years for all aircraft classes, and 0-10 years for unconventional aircraft (hydrogen and TTWB) to account for the effect of ramping up production of new products and account for "first movers" delays (operators waiting to adopt new technologies which may be already available).

Table 3: Summary of IATA scenarios

Seat	Ref A/C	Baseline (BL) S1	Dates	BL+S2	Dates	BL+S3	Dates	BL+S4	Dates	BL+S5	Dates
30-69	CRJ700	BiC	2017	H2	2030	H2	2030	H2	2028	BiC	2028
70-109	Embraer 190	BiC	2018	FA	2030	FA	2030	FA	2035	FA	2035
110-129	A319	BiC	2016	FA	2037	TTWB	2037	H2	2035	BiC	2035
130-159	A320	BiC	2016	FA	2037	TTWB	2037	0.5H2	2037	BiC	2037
160-199	B737-800	BiC	2017	FA	2037	TTWB	2037	0.5H2	2040	BiC	2040
200-249	B787-800	BiC	2011	FA	2038	FA	2038	FA	2035	FA	2035
259-299	A330-300	BiC	2018	FA	2040	FA	2040	FA	2036	FA	2036
300-399	B777-300ER	BiC	2025	FA	2042	FA	2042	FA	2040	FA	2040
400+	A380-800	–	–	–	–	–	–	–	–	–	–

For example, scenario BL+S2 assumes that all aircraft get progressively replaced by the best in class available today (this replacement has already begun), with initial entry-into-service dates prior to the publication of this report. This progressive replacement continues in all scenarios. In 2030 new aircraft become available for the 30-69 and 70-109 seat categories. The 30-69 category is assumed to be replaced progressively by zero-emissions concepts while all the rest get replaced by their Future Aircraft option, which still relies on hydrocarbon fuels but have efficiency gains in line with table A2. The dates displayed in the table are the dates at which this replacement starts to take place, and it follows a normal "S" product adoption curve. Scenario BL+S4 is a very aggressive hydrogen uptake scenario, in which hydrogen aircraft are assumed to appear in the 110-199 seat category as well. The 0.5H2 means that only 50% of the market adopts these technologies for the specific seat category in which they become available. The production ramp-up period for hydrogen aircraft is assumed to be 10 years.

The following chart shows the resulting emissions by 2050 of 5 out of the 10 scenarios modeled (production ramp-up time of 5 years for kerosene aircraft and 10 years for hydrogen and TTWB). The reductions quoted in the main text are bounded by these scenarios.



Description of roadmap milestones

#	Timeline	Reducing in-flight energy: Milestone	Reducing in-flight energy: Description	SAF & hydrogen aircraft: Milestone	SAF & hydrogen aircraft: Description	Batteries & hybrid aircraft: Milestone	Batteries & hybrid aircraft: Description
1	Before 2023	Engine BPR of 10+ in service Geared turbofan in service thrust class: 150kN.	BPR: By Pass Ratio. Geared turbofan refers to Pratt and Whitney PW1000 engine in service in A220 and some A320 neos.	Flight test of 19-seater retrofit sub-MW HFC aircraft.	Zero Avia- HiFLyer 2, Dornier 228.	Longest hybrid-electric flight on record: 1,135 miles.	Ampire EEL aircraft (Cessna 337 modified).
2	Before 2023	Laminar flow control in service on some aircraft and selected surfaces.	B787 has laminar flow control on the tail.	Flight test of 40-seater retrofit sub-MW HFC aircraft.	Universal Hydrogen's Flying Mc Clean, Dash8-300.	Electric flight speed record broken: 532 km/h.	Rolls Royce ACCEL.
3	Before 2023	More electric aircraft in service (electric actuation of control surfaces).	B787 is a more electric aircraft, actuators and other functions are electrical instead of hydraulic. The 787's engines have a near 0.5MW electric power offtake.	Major manufacturer announces exploring clean-sheet narrow body H_2 aircraft.	Airbus announcement for the ZEROe project.	Battery energy storage: <200 Wh/kg.	Current energy storage capacity for best-in-class batteries.
4	Before 2023	Composite material wings and fuselage sections in service.	Examples are the 787, A350, A380, A220 with composite wings and some fuselage parts.	Flight & ground tests on blended and unblended SAF.	For example Airbus A320 & A350 test campaign, Emirate's flight with a 777-300ER, or ATR72-600 prototype test flight.		
5	2023 – 2030	High power density small core demo.	Demonstrators of small engine cores like Hytec.	100% SAF compatible seals and metering validated.	Seals and metering systems identified as a critical technology milestone to enable 100% paraffinic SAF.	Reg + sub-regional hybrid.	
6	2023 – 2030	UHBPR: low NO_x engine flight test.	Ultra High By-Pass Ratio engines- Engines with a much larger fan,- increase propulsive efficiency. Low NO_x combustors, example: RR Ultrafan.	EIS retrofitted regional TP HFC aircraft.	Entry Into Service of retrofitted sub-regional aircraft, like ZeroAvia or UniversalH2.	Urban air mobility (fixed & rotating wing. VTOL).	Flight tests of different UAM concepts. Numerous examples of this around the world.
7	2023 – 2030	Continuation of more electric control surfaces into all aircraft classes.	Systems similar to the 787 more-electric architecture could be implemented on other aircraft classes too.	Advanced fuel cell cryogenic flight test.	Flight tests of next generation of fuel cells, with liquid hydrogen tanks as storage medium. For example, Air Liquide and H_2 Fly or, ZeroAvia.	Distributed propulsion for commuter aircraft/UAM demonstrator.	Examples: Project Whisk – but also Vertical Aerospace, Lilium, etc.
8	2023 – 2030	Open rotor flight demonstrator.	This refers to SAFRAN's program – RISE, To test an open rotor engine on a A380 test bed.	EIS retrofitted regional TP HFC aircraft.	Larger aircraft retrofits on the regional market sized aircraft likely to be Turboprop.	1-2 MW electric motor flight demonstrator.	General Electric and NASA's program to demonstrate high power motors. Also Wright Electric and MagniX are examples of electric power train companies.
9	2023 – 2030	UHAR wing demonstrator.	UHAR: Ultra-High Aspect Ratio wings demonstrated in wing tunnels and flight tests.	Aviation compatible fuel cell stacks 4 kW/kg.	Fuel cells at the moment exist for cars, but don't have the energy density required for large aircraft. 4 kW/kg is estimated as an initial usable power density.	Flight test: hybrid-electric aircraft.	Likely flight test of a regional turboprop hybrid aircraft in the 75+ seater category.

Aircraft Technology Net Zero Roadmap

#	Timeline	Reducing in-flight energy		SAF & hydrogen aircraft		Batteries & hybrid aircraft	
		Milestone	Description	Milestone	Description	Milestone	Description
10	2023 – 2030	Flight test: revolutionary aircraft architecture – UHAR.	Boeing and NASA Sustainable Flight Demo: truss-braced wing aircraft.	Flight test: gH_2 storage tank Regional – commuter (GI: 15-20%).	GI: Gravimetric index – measure of the weight of the tank vs weight of tank and fuel. Initial tests to be done on tanks with gaseous hydrogen and relatively low GI.	EIS of all electric aircraft 30 pax/100 NM.	EIS of an all-electric regional aircraft as announced by Heart Aerospace. With the option of range extension with SAF.
11		Hybrid or blended wing body demonstrator.	Demonstrator of the full-scale Bombardier EcoJet or the US DOF military application blended wing body.	Decision point: size & propulsion system definition for clean sheet H_2 aircraft.	A decision point around this time will have to be made on whether the clean-sheet aircraft is regional or narrow body aircraft.		
12				Flight test: hydrogen engine, tanks and fuel systems.	Flight test scheduled by Airbus and CFM. One H_2 powered engine with tanks and fuel systems on an A380 test bed.		
13				All new delivered aircraft compatible with 100% unblended SAF.	As announced by Airbus and Boeing, all aircraft compatible with SAF after 2030.		
14	2030 – 2035	Multi-function structures demonstrated.	Multi-function structures are structural elements that have more than one function: for example, antennas embedded in the fuselage. Or structures that are also dissipating heat, or storing fuel.	H_2 gas turbine powered aircraft flight test.	This is a flight test of a fully integrated hydrogen-powered airplane with gas turbines (not fuel cells).	EIS urban & metropolitan VTOL battery powered aircraft.	EIS of platforms like Lilium, Vertical Aerospace, Bell, etc. VTOL= Vertical Take-Off and Landing.
15		EIS of mild hybrid-turboprop regional aircraft.	Potentially ATR, as suggested by project EVO.	Large heat management system demonstrator.	Heat management are systems that get rid of wasted heat for example from fuel cells, and use it for something else. Also applies to warming the liquid hydrogen to make it into a gas before injecting it in the engine.	Improved specific energy of batteries for 2nd generation electric aircraft ~225 Wh/kg.	Improved battery technology enables higher specific energy, unlocking larger payloads or longer ranges for battery aircraft.
16				High gravimetric index of LH_2 tanks demonstrated (GI > 30%).	Light liquid hydrogen storage tanks demonstrated.		
17				EIS of clean sheet short to medium-range H_2 aircraft.	Characteristics as described by Airbus on ZEROe for the regional clean sheet (new design) aircraft. Ambitions also for clean-sheets from start-ups.		

Aircraft Technology Net Zero Roadmap								
#	Timeline	Reducing in-flight energy		SAF & hydrogen aircraft		Batteries & hybrid aircraft		
		Milestone	Description	Milestone	Description	Milestone	Description	
18	2035 – 2040	EIS of revolutionary narrow body aircraft.	EIS – Entry Into Service. Refers to the aircraft demonstrated by Boeing and NASA – possibly TTWB.	Increased fuel cell stack specific power for future aircraft platforms (8k W/kg).	Next generation of high temperature fuel cells, enabling longer ranges or larger payloads for HFC aircraft.	New battery chemistries enable higher specific energy for batteries > 350 Wh/kg.	Third generation of batteries, considerably increasing specific energy, improving applicability of battery aircraft.	
19	2035 – 2040	EIS of next-get wide body aircraft (aspirational).	Speculative EIS for next-gen wide body aircraft, not announced yet, so purely aspirational.	EIS of clean sheet NB H_2 aircraft – 200 pax/2000 NM.	Airbus ZEROe aircraft narrow-body market. Range and pax from Airbus website.			
20	2040 – 2050			EIS of wide body aircraft – H_2 combustion (aspirational).	This model is not announced, nor included in the IATA modelling but it is an aspirational concept based on publications like ATI FlyZero Mid sized, or Cranfield University's wide body concepts.			

References

[1] **ISABE**, International Society of Air Breathing Engines
"**Presentations displayed by OEMs: Airbus, Boeing, Pratt & Whitney, Bombardier, General Electric, Rolls Royce, NASA**"
Ottawa, Canada, 2022.

[2] **ATI**, Aerospace Technology Institute
"**Destination Zero: The technology journey to 2050**"
https://www.ati.org.uk/wp-content/uploads/2022/04/ATI-Tech-Strategy-2022-Destination-Zero.pdf, 2022.

[3] **DLR**, Deutsches Zentrum fur Luft- un Raumfahrt- German Aerospace Centre
"**Towards zero – emission aviation – DLRs new aviation strategy**"
https://www.dlr.de/content/en/articles/news/2021/04/20211215_towards-zero-emission-aviation.html, 2021.

[4] **TU Delft,** Technische Universitat Braunschewig
"**Accelerating the path towards carbon-free aviation**"
https://d2k0ddhflgrk1i.cloudfront.net/LR/Actueel/News/2022/Q3/Accelerating%20the%20path%20towards%20carbon-free%20aviation%20%28002%29.pdf.

[5] **Airbus**
"**New Energy Ecosystem – Accelerating high-potential pathways through impactful partnerships**"
https://www.airbus.com/en/sustainability/environment/climate-change/new-energy-ecosystem, [Accessed 23.11.2022].

[6] **ICAO**, International Civil Aviation Organization
"**Report on the feasibility of a Long-Term Aspirational Goal (LTAG) for international civil aviation CO_2 emissions, Appendix M3**"
https://www.icao.int/environmental-protection/LTAG/Pages/LTAGreport.aspx, 2022.

[7] **ICAO**, International Civil Aviation Organization
"**Independent Expert Integrated Technology Goals Assessment and Review for Engines and Aircraft**"
https://store.icao.int/en/independent-expert-integrated-technology-goals-assessment-and-review-for-engines-and-aircraft-english-printed, 2019.

[8] **ATAG**, Air Action Transport Group
"**Waypoint 2050, second edition**"
https://aviationbenefits.org/media/167417/w2050_v2021_27sept_full.pdf, 2021.

[9] **ATA**, Air Transport Analytics, **Ellondee Ltd**
"**Understanding the potential and costs for reducing UK aviation emissions – Report to the committee on climate change and the Department for transport**"
https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/785685/ata-potential-and-costs-reducting-emissions.pdf, 2018.

[10] **EIA**, Energy Information Administration (USA)
"**International electricity consumption**"
https://www.eia.gov/international/data/world/electricity/electricity-consumption?pd=2&p=0000002&u=0&f=A&v=mapbubble&a=-&i=none&vo=value&t=C&g=00000000000000000000000000000000000000000000000001&l=249-ruvvvvvfvtvnvv1vrvvvvfvvvvvvfvvvou20evvvvvvvvvvvnvvvs0008, 2019.

[11] **Rolls Royce**
"**UltraFan, The Ultimate TurboFan**"
https://www.rolls-royce.com/innovation/ultrafan.aspx, [Accessed 23.11.2022].

[12] **Rolls Royce**
"**Rolls Royce XWB**"
https://www.rolls-royce.com/~/media/Files/R/Rolls-Royce/documents/civil-aerospace-downloads/trent-xwb-infographic.pdf, 2018.

[13] **NASA**, National Aeronautics and Space Administration
"**Hybrid Thermally Efficient Core Project (HyTEC) Project**"
https://www.nasa.gov/aeroresearch/programs/hytec/, [Accessed 23.11.2022].

[14] **SAFRAN**
"**CFM Rise Program: Revolutionary innovation for sustainable engines**"
https://www.cfmaeroengines.com/wp-content/uploads/2021/07/CFM_RISE_Whitepaper_Media.pdf, 2022.

[15] **Boeing**
"**Meet the 777x**"
https://www.boeing.com/commercial/777x/, [Accessed 23.11.2022].

[16] **Airbus**
"**Airbus begins assembly of first future "eco-wing" prototype**"
https://www.airbus.com/en/newsroom/press-releases/2021-09-airbus-begins-assembly-of-first-future-eco-wing-prototype, [Accessed 23.11.2022].

[17] **Boeing**
"**787 No – Bleed systems: saving fuel and enhancing operational efficiencies**", Mike Sinnett
https://www.boeing.com/commercial/aeromagazine/articles/qtr_4_07/article_02_1.html.

[18] **IPCC**, International Panel on Climate Change
"**Aviation and the global atmosphere**", Cambridge University Press
https://archive.ipcc.ch/ipccreports/sres/aviation/index.php?idp=0, 1999.

[19] **NASA**, National Aeronautics and Space Administration
"**Blended Wing Body – A potential new aircraft design**"
https://www.nasa.gov/centers/langley/news/factsheets/FS-2003-11-81-LaRC.html, [Accessed 23.11.2022].

[20] **Flight Global**
"**US Air Force to test blended-wing logistics aircraft by 2027**"
https://www.flightglobal.com/fixed-wing/us-air-force-to-test-blended-wing-logistics-aircraft-by-2027/150501.article#:~:text=A%20blended%2Dwing%2Dbody%20design,environment%E2%80%9D%2C%20the%20report%20says, [Accessed 23.11. 2022].

[21] **Bombardier**
"**Bombardier's Ecojet: Developing the future of buisiness aviation**"
https://bombardier.com/en/ecojet, [Accessed 23.11.2022].

[22] **NASA**, National Aeronautics and Space Administration
"**Sustainable Flight Demonstrato**r"
https://www.nasa.gov/aeroresearch/programs/iasp/sfd, [Accessed 23.11.2022].

[23] **ATI**, Aerospace Technology Institute, **ACI**, Airports Council International
"**Integration of Sustainable Aviation Fuels into the Air Transport System**"
https://www.ati.org.uk/wp-content/uploads/2022/06/saf-integration.pdf, 2022.

[24] **EI**, Energy Institute
"**EI 1533 Quality assurance requirements for semi-synthetic jet fuel and synthetic blending components (SBC)**"
ISBN: 9781787253513
https://publishing.energyinst.org/topics/aviation/aviation-fuel-handling/1533, 2022.

[25] **IATA**, International Air Transport Association
"**ABC of Environment & Aviation – Hydrogen: A decarbonization solution of the future**"
https://flyaware.iata.org/documents/abc-of-hydrogen-aviation, 2022.

[26] **ZeroAvia**
"**Powertrain timeline**"
https://www.zeroavia.com/, [Accessed 23.11.2022].

[27] **Universal Hydrogen**
"**Landing page**"
https://hydrogen.aero/product/, [Accessed 23.11.2022].

[28] **Stralis**
"**Stralis – Fly Sustainably withough compromise**"
https://stralis.aero/, [Accessed 22.11.2022].

[31] **FlightGlobal**
"**GKN confident fuel cells could power 96-seat aircraft as H2GEAR project advances**"
https://www.flightglobal.com/aerospace/gkn-confident-fuel-cells-could-power-96-seat-aircraft-as-h2gear-project-advances/149046.article, [Accessed 21.11.2022].

[32] **Airbus**
"**How Blue Condor will accelerate Airbus' first hydrogen-powered test flights**"
https://www.airbus.com/en/newsroom/stories/2022-07-how-blue-condor-will-accelerate-airbus-first-hydrogen-powered-test-flights, [Accessed 3.11.2022].

[33] **Airbus**
"**Airbus and CFM International to pioneer hydrogen combustion technology**"
https://www.airbus.com/en/newsroom/press-releases/2022-02-airbus-and-cfm-international-to-pioneer-hydrogen-combustion, [Accessed 4.10.2022].

[34] **Airbus**
"**Airbus increases its UK innovation footprint to develop new hydrogen technologies**"
https://www.airbus.com/en/newsroom/press-releases/2022-05-airbus-increases-its-uk-innovation-footprint-to-develop-new, [Accessed 6.07.2022].

[35] **ATI**, Aerospace Technology Institute, **FlyZero**
"**FlyZero Executive Summary**"
https://www.ati.org.uk/wp-content/uploads/2022/03/FZO-ALL-REP-0003-FlyZero-Executive-Summary.pdf, 2022.

[36] **MagniX**
"**MagniX Leading the Electrification of Aviation**"
https://www.magnix.aero/, [Accessed 8.11.2022].

[37] **WrightElectric**
"**The Wright Spirit: All short flights can be zero emissions starting 2026**"
https://www.weflywright.com/, [Accessed 23.11.2022].

[38] **GE Aerospace**
"**GE Aviation selected by NASA for hybrid electric technology demonstrator**"
https://www.geaerospace.com/press-release/other-news-information/ge-aviation-selected-nasa-hybrid-electric-technology, [Accessed 5.11.2022].

[39] **FlightGlobal**
"**GKN confident fuel cells could power 96-seat aircraft as H2GEAR project advances**"
https://www.flightglobal.com/aerospace/gkn-confident-fuel-cells-could-power-96-seat-aircraft-as-h2gear-project-advances/149046.article, [Accessed 23.11.2022].

[40] **GKN**
"**GKN Aaerospace leades development of ground breaking hydrogen propulsion system for aircraft**"
https://www.gknaerospace.com/en/newsroom/news-releases/2021/gkn-aerospace-leads-development-of-ground-breaking-hydrogen-propulsion-system-for-aircraft2/, [Accessed 23.11.2022].

[41] **ATI**, Aerospace Technology Institute, **FlyZero**
"**Regional Aircraft Concept Report FZO-AIN-REP-0008**"
https://www.ati.org.uk/flyzero-reports/#, 2022.

[42] **Overleaf**
"**Overleaf: Novel low-pressure cryogenic liquid hydrogen storage for aviation**"
https://overleaf-project.eu/news/overleaf-novel-low-pressure-cryogenic-liquid-hydrogen-storage-for-aviation-2/, [Accessed 1.11.2022].

[43] **ATI**, Aerospace Technology Institute, **FlyZero**
"**FlyZero Sustainability Report – The lifecycle impact of hydrogen-powered aircraft**"
https://www.ati.org.uk/wp-content/uploads/2022/03/FZO-STY-REP-0005-FlyZero-Sustainability-Report.pdf, 2022.

[44] **EnableH2**
https://www.enableh2.eu/, [Accessed 7.7.2022].

[45] **Dray, et al.**
"**Cost and emission pathways towards net-zero climate impacts in aviation**", Nature Climate Change, Vol. 12
https://doi.org/10.1038/s41558-022-01485-4, p. 956-976, 2022.

[46] **NLR**, Netherlands Aerospace Centre
"**Novel aircraft propulsion and availability of alternative, sustainable aviation fuels**"
https://reports.nlr.nl/server/api/core/bitstreams/4b0c1993-4b41-498a-9f08-490f12ded575/content, 2022.

[47] **Mission Possible Partnership**
"**Making Net-Zero Aviation Possible – An indusry backed 1.5 C aligned transition strategy**"
https://missionpossiblepartnership.org/wp-content/uploads/2022/07/Making-Net-Zero-Aviation-possible.pdf, 2022.

[48] **ICF**
"**Fueling Net zero: How the aviation indsutry can deploy sufficient sustainable aviation fuel to meet climate ambitions**"
https://www.icf.com/insights/transportation/deploying-sustainable-aviation-fuel-to-meet-climate-ambition, 2022.

[49] **ATI**, Aerospace Technology Institute, **ACI**, Airports Council
"**Integration of hydrogen aircraft into the air transport system: An airport operations and infrastructure review**"
https://www.ati.org.uk/wp-content/uploads/2021/08/aci-ati-hydrogen-report-1.pdf, 2021.

[50] **ATI**, Aerospace Technology Institute, **FlyZero**
"**Hydrogen infrastructure and operations: Airports, Airlines and Airspace**"
https://www.ati.org.uk/wp-content/uploads/2022/03/FZO-CST-POS-0035-Airports-Airlines-Airspace-Operations-and-Hydrogen-Infrastructure.pdf, 2022.

[51] **DNV**
"**Hydrogen supply to Norwegian Airports, Avinor, AS**"
https://avinor.no/globalassets/_konsern/miljo-lokal/miljorapporter/hydrogen-supply-to-norwegian-airports.pdf, 2022.

[52] **Hoelzen, et al.**
"**H2-powered aviation at airports – Design and economics of LH2 refueling systems**"
Energy conversion and management, vol. 14
https://www.sciencedirect.com/science/article/pii/S2590174522000290, p. 100206, 2022.

[53] **CPC**, Connected Places Catapult
"**Zero Emission Flight Infrastructure Standard Gap Analysis**"
https://cp.catapult.org.uk/news/zero-emissions-flight-infrastructure-standards-gap-analysis/, 2021.

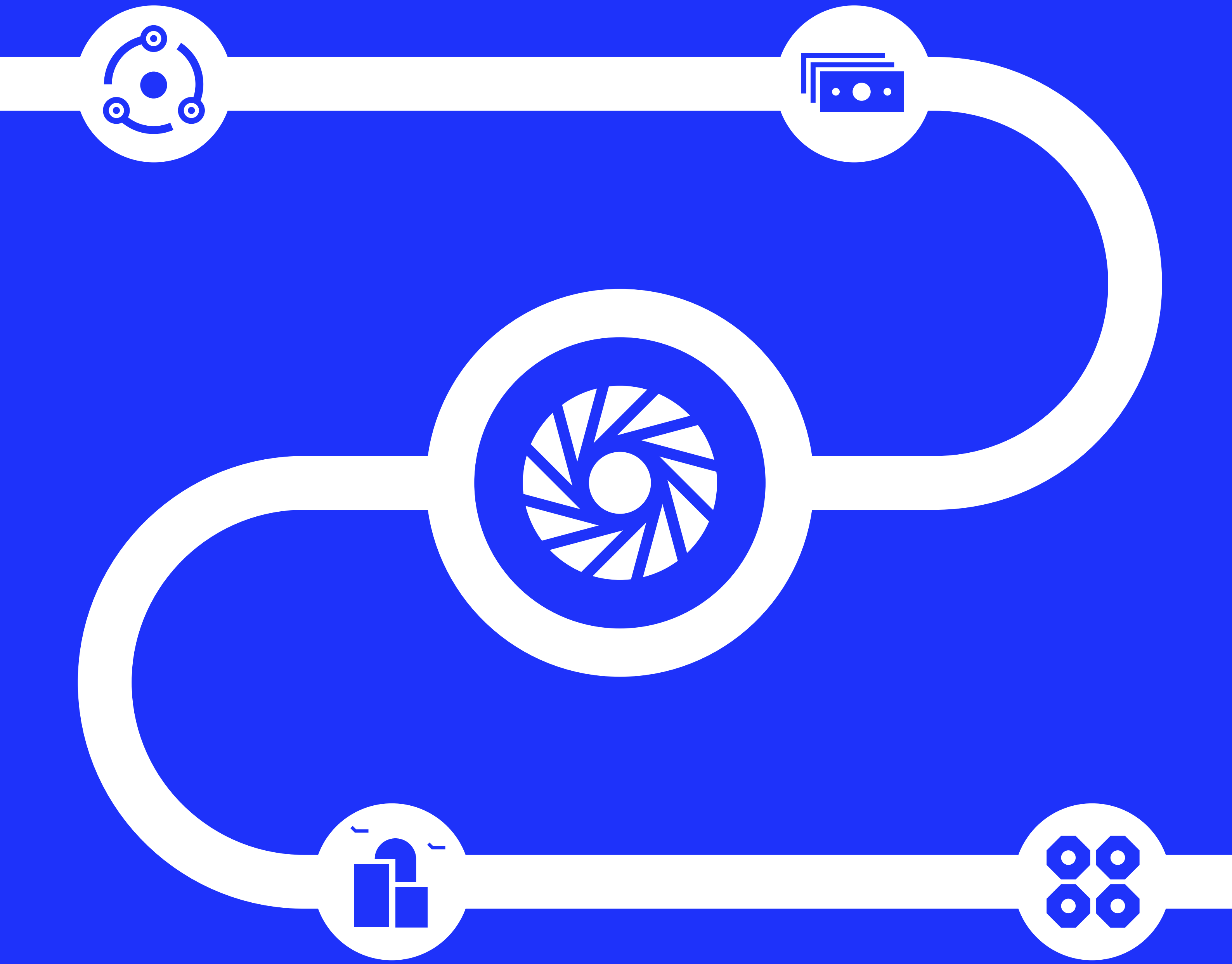
[54] **CPC**, Connected Places Catapult
"**Zero Emission Flight Infrastructure white paper**"
https://cp.catapult.org.uk/news/zero-emission-flight-infrastructure-white-paper/, 2022.

[55] **IEA**, International Energy Agency
"**Outlook for electricity**"
https://www.iea.org/reports/world-energy-outlook-2022/outlook-for-electricity, 2022.

[56] **IATA**, International Air Transport Association
"**Direct Air Capture (DAC) and Storage (DAC+S): Essential Components to Achieve Net Zero Carbon in Aviation**"
https://flyaware.iata.org/documents/direct-air-capture-and-storage-essential-components-to-achieve-net-zero-carbon-in-aviation, 2023.

[57] **ICAO**, International Civil Aviation Organization
"**Report on the feasibility of a Long-Term Aspirational Goal (LTAG) for international civil aviation CO_2 emissions, Appendix M5**"
https://www.icao.int/environmental-protection/LTAG/Pages/LTAGreport.aspx, 2022.

[58] **Boeing**
"**Boeing breakthrough in all-composite cryogenic propellant tank advances technology readiness**"
https://boeing.mediaroom.com/news-releases-statements?item=130996, 2022.



International Air Transport Association
800 Place Victoria, PO Box 113
Montreal, Quebec, Canada H4Z 1M1
Tel +1 (514) 874 0202

iata.org

IATA