AREANA

AVIATION RESEARCH ECOSYSTEM ADVANCED NOVEL APPROACH

D3.2 – Report focusing on the current state and planned R&I for hydrogen and electric aviation technology in Europe and associated countries

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This project received funding from the European Union´s Horizon Europe Coordination and Support action under Grant agreement No. 101137574.

Document General Information

Project Title	AVIATION RESEARCH ECOSYSTEM ADVANCED NOVEL APPROACH
Project Acronym	AREANA
HE Call Topic ID Code	HORIZON-CL5-2023-D5-01-10
Grant Agreement	101137574
Project Coordinator	VZLU AEROSPACE, A.S.
Deliverable ID	D3.2 - Report focusing on the current state and planned R&I for hydrogen and electric aviation technology in Europe and associated countries
Lead Beneficiary	VZLU
Contributing Beneficiary	
Work Package Number	WP3
Task Number	
Due Date	M13 [31.1.2025]
Actual Submission Date	M13 [15.1.2025]
Deliverable Type	Report
Dissemination Level	Public
Export Control	No

Document Author(s) and Reviewer(s)

Lead Beneficiary		
Partner Name	**Name**	**Signature**
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VZLU	Pavlina Lobpreisova	Pavlína Lobpreisová Digitálně podepsal Pavlína Lobpreisová Datum: 2025.01.29 07:35:33 +01'00'

Contributing Beneficiary		
Partner Name	**Name**	**Signature**

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Partner Name	**Name**	**Signature**
VZLU	Pavlina Lobpreisova	Pavlína Lobpreisová Digitálně podepsal Pavlína Lobpreisová Datum: 2025.01.29 07:36:01 +01'00'

Version Control

Version	Date	Made by	Short Description of Changes
V1	16.1.2025	Jan Kubata	First draft

Abstract

This report summarizes the status and prospects of hydrogen and electric aviation technology in Europe and associated countries. Guided by the European Green Deal’s ambition for net-zero emissions, major R&I efforts center on hydrogen combustion and fuel cells, as well as battery-electric and hybrid-electric propulsion. Recent demonstrations (e.g., ZEROe concepts, H2Fly, ZeroAvia, Pipistrel Velis Electro) highlight technical feasibility but also reveal challenges in infrastructure, safety standards, and certification. Innovative funding mechanisms and public-private partnerships are accelerating progress, aiming for short-haul zero-emission flights in the near term. With robust policies and concerted stakeholder collaboration, Europe is poised to lead the global transition toward climate-neutral aviation.

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1. Glossary

- **Cryogenic:** Relating to very low temperatures, often referring to liquid hydrogen storage below -250°C.
- **Fuel Cell:** A device that converts chemical energy (e.g., from hydrogen) into electricity through electrochemical reactions.
- **Energy Density:** Amount of energy stored per unit mass or volume, critical for comparing hydrogen vs. batteries.
- **NOx:** Nitrogen oxides, pollutants formed at high combustion temperatures, contributing to smog and acid rain.
- **Power Electronics:** Systems managing electrical energy flow (e.g., inverters, converters) in electric and hybrid aircraft.

2. Executive Summary

This report provides a comprehensive overview of ongoing research and innovation (R&I) in hydrogen and electric aviation technology across Europe and associated countries. In line with the European Green Deal's ambition for climate neutrality by 2050, the aviation industry is undergoing a transformative shift toward zero-emission propulsion systems. Key highlights include:

- **Hydrogen Propulsion:** Multiple pathways—hydrogen combustion in modified gas turbines and hydrogen fuel cells—show strong promise for reducing carbon dioxide (CO_2) emissions drastically. However, cryogenic storage challenges, infrastructure development, and safety considerations require focused R&I efforts.

- **Electric Aviation:** Battery-electric aircraft are already flying in limited capacities (small commuter planes and demonstrators). Hybrid-electric systems, combining conventional turbines with electric drives, can reduce emissions by up to 30–40% for regional flights. Advances in battery technology, especially solid-state batteries, are critical for scaling up.

- **Supporting Policies:** Funding through the Clean Aviation Joint Undertaking, Horizon Europe, and various national programs underpins the rapid acceleration of zero-emission aviation. Collaboration between industry, research institutions, and policymakers ensures a broad knowledge base and shared resources.

- **Challenges and Opportunities:** While both hydrogen- and electric-powered aircraft face specific hurdles (from technological maturity to infrastructure requirements), Europe's integrated approach may yield synergistic benefits. The push for greener aviation aligns with a broader hydrogen economy and battery manufacturing initiatives, potentially creating new jobs and spurring economic growth.

By examining the state of the art, planned projects, and infrastructural needs, this report serves as a roadmap for stakeholders intending to advance zero-emission aviation and meet EU Green Deal targets.

3. Introduction

3.1 Background and Rationale

Aviation remains indispensable for global mobility, yet it poses a significant challenge for climate change mitigation. The Intergovernmental Panel on Climate Change (IPCC) reports that aviation accounts for approximately 2.5% of global CO_2 emissions, alongside non-CO_2 impacts such as contrails and NO_x emissions, which further exacerbate atmospheric warming. The European Green Deal, introduced in December 2019, underscores the need to decarbonize transport, aiming for climate neutrality by 2050. Given the limited success of alternative fuels and offsets in the aviation sector thus far, novel propulsion systems—particularly hydrogen and electric—are being explored more aggressively than ever before.

3.2 Scope of the Report

This study focuses on hydrogen and electric aviation technologies within the European Union and associated countries (e.g., Norway, the United Kingdom, Switzerland). Its scope includes:

- Assessing the current state of hydrogen and electric aircraft prototypes and demonstrations.
- Evaluating the overarching R&I programs and funding mechanisms that support zero-emission aviation.
- Identifying challenges, opportunities, and pathways for widespread adoption and market entry.
- Offering a roadmap aligned with the EU Green Deal targets, providing stakeholders with strategic insights into technology development and infrastructural investments.

3.3 Methodology and Data Sources

Information was gathered via:

- **Desk Research:** Official policy documents, scientific literature, and reports from the European Commission, Clean Aviation, and other industry bodies.

- **Published Interviews and Workshops:** Insights from aerospace researchers and engineers involved in ongoing hydrogen and electric aviation projects.

- **Case Studies:** In-depth examination of major demonstration programs (e.g., Airbus ZEROe, H2Fly, Pipistrel, ZeroAvia) to exemplify practical progress.

Wherever possible, data is cross validated through multiple sources to ensure reliability.

4. Policy Framework and Industry Context

4.1 The European Green Deal and Its Aviation Impact

The European Green Deal, introduced in December 2019, set forth a transformative vision for making the European Union climate-neutral by 2050. Although it addresses multiple sectors, from energy to agriculture to construction, transportation is a critical component, accounting for approximately one-quarter of the EU’s greenhouse gas (GHG) emissions. Aviation is recognized as a hard-to-abate sector owing to the high energy density requirements of flight and the logistical challenges of adopting alternative fuels.

Within the scope of the Green Deal, the aviation industry is under pressure to reassess its reliance on traditional kerosene-based propulsion. The EU has therefore launched several initiatives that encourage or mandate reductions in aviation emissions. These measures include incentives for research into fuel cells and hydrogen combustion engines, support for building a robust hydrogen economy in Europe, and the development of large-scale battery manufacturing capacity under the European Battery Alliance. Through these mechanisms, the European Commission aims to position Europe as a global leader in sustainable aviation technology, intending not only to meet domestic climate goals but also to export greener aircraft solutions to the rest of the world.

The funding support tied to the Green Deal is substantial. Projects that propose radical emission-cutting solutions are prioritized for grants and partnerships. The synergy with other policy instruments, such as the Emissions Trading System (EU ETS) and initiatives designed to foster renewable energy uptake, further underlines the centrality of the Green Deal in guiding Europe’s aviation transition. In combination with a push toward system-wide efficiency improvements, these measures underscore the importance of integrating hydrogen and battery technologies into the mainstream production pipelines of large aerospace firms.

4.2 Sustainable and Smart Mobility Strategy

The European Commission’s Sustainable and Smart Mobility Strategy, officially presented in December 2020, sets out a sweeping vision for a greener, more efficient, and technologically advanced transport sector. Building on the overarching framework of the European Green Deal, the Strategy seeks a 90% reduction in transport-related greenhouse gas (GHG) emissions by 2050 compared to 1990 levels. Although it addresses multiple transport modes—ranging from road vehicles and rail systems to inland waterways and maritime shipping—aviation is a key component given its distinctive emissions profile and the sector’s rapid growth over recent decades.

A central feature of the Strategy is its emphasis on modernizing air traffic management (ATM) and promoting integrated mobility solutions that cut across national borders, thereby reducing operational inefficiencies and flight delays that waste fuel. This objective complemented the Commission's ambition to introduce next-generation propulsion systems, such as hydrogen fuel cells, battery-electric powertrains, and hybrid-electric architectures, into the commercial aviation market. By encouraging both incremental improvements (e.g., improved airspace usage) and disruptive innovations (e.g., zero-emission aircraft), the Strategy aims to make air travel cleaner and more accessible over the coming decades.

Key Pillars of the Strategy Affecting Aviation

Several pillars of the Sustainable and Smart Mobility Strategy directly influence how European aviation will evolve:

1. **Decarbonizing Short-Haul Travel:** Short-haul routes often have viable alternatives such as rail or bus, but air travel remains vital for remote regions or island communities. The Strategy advocates for shifting more short-distance flights to rail where feasible, while simultaneously investing in new aviation technologies that enable zero- or low-emission short-haul services. Over time, this approach aims to ensure that aviation's environmental footprint is minimized for routes that are less easily served by ground transport.

2. **Facilitating the Rollout of Zero-Emission Aircraft:** The Commission foresees the market readiness of zero-emission commercial aircraft (powered by hydrogen or electric technologies) by 2035–2040. In support of this timeline, the Strategy promotes research and innovation funding—channeled through Horizon Europe, the Clean Aviation Joint Undertaking, and other EU instruments—to drive breakthroughs in propulsion, materials, and energy storage. Airports are similarly encouraged to prepare for new fueling and charging requirements, thus de-risking the introduction of alternative propulsion aircraft in regular operations.

3. **Promoting Sustainable Aviation Fuels (SAFs):** While the Strategy champions hydrogen and electric propulsion in the longer term, it also recognizes SAFs as an essential bridging solution—particularly for long-haul flights where hydrogen or battery-electric systems may remain technically unfeasible for many years. Measures such as blending mandates, incentives for SAF production, and the creation of a robust EU-wide SAF market support a gradual decrease in net aviation emissions even before fully zero-emission aircraft become widespread.

4. **Strengthening Intermodal Connections:** The Strategy addresses the broader context of travel and logistics, encouraging airports, rail operators, and maritime ports to work together to optimize passenger flows and reduce overall carbon impact. By improving connectivity—such as seamless transfers between flights and high-speed trains—the Commission envisions that consumers will have convenient, lower-emission travel options, thus contributing to overall decarbonization goals.

5. **Leveraging Digital Technologies and Innovation:** Automation, digital platforms, and data-driven solutions are identified as drivers for efficiency. In aviation, this might translate into improved route planning, reduced congestion near airports, and real-

time data sharing between air traffic control systems. The Commission expects that such innovations will reduce fuel burns in the short term (by cutting unnecessary holding patterns or ground delays) and facilitate integration with future hydrogen or electric propulsion systems.

Funding, Governance, and Stakeholder Engagement

The Sustainable and Smart Mobility Strategy is backed by substantial EU funding mechanisms aimed at both infrastructure and technological development. Programs such as Connecting Europe Facility (CEF) co-fund trans-European transport networks, including the modernization of aviation infrastructure and the introduction of greener refueling or charging systems at key hubs. Horizon Europe, meanwhile, targets advanced R&I, bridging the gap between laboratory research and commercial demonstrations in zero-emission propulsion.

Governance of the Strategy involves close coordination between the European Commission, member states, and key stakeholders across the private sector. Aviation manufacturers, airlines, airport operators, energy providers, and research organizations cooperate in consortia tasked with pilot programs, demonstrations, and knowledge exchange. This multi-actor approach ensures that different perspectives—economic, technical, logistical, and social—inform policymaking and project implementation.

Implications for European Aviation

By linking climate objectives with economic opportunities, the Sustainable and Smart Mobility Strategy reinforces the idea that aviation's future in Europe hinges on adopting innovative, cleaner propulsion methods. It contends that a supportive policy environment, adequate infrastructure investments, and robust cooperation among stakeholders will propel the sector toward net-zero emissions by the mid-century mark. In doing so, the Strategy anticipates:

- A more rapid introduction of hydrogen-fueled and electric aircraft for regional routes.
- Deeper integration of renewable energy sources into airport operations, enabling green hydrogen production and high-capacity charging for electric planes.
- Active engagement with global aviation bodies (e.g., ICAO) to harmonize emission reduction targets, certification standards, and best practices.
- Heightened competitiveness of the European aviation industry, which could become a global leader in designing and manufacturing next-generation aircraft and propulsion systems.

Strategy remains ambitious and faces challenges in orchestrating the systemic transitions needed across multiple layers of aviation operations. Hydrogen and electric propulsion technologies still require significant R&I to meet commercial viability thresholds, while the logistics of installing new infrastructure at airports—in parallel with meeting ongoing operational demands—can be complicated and costly. Moreover, the success of the Strategy depends on member states' willingness to harmonize regulations, co-finance major infrastructure projects, and align national initiatives with broader EU-level goals.

Nevertheless, the Sustainable and Smart Mobility Strategy serves as a roadmap that unifies different policy threads under a single banner of climate action, digitalization, and innovation. It positions the European Union to lead the charge in ushering aviation into a post-carbon era, balancing growth in passenger demand with responsible resource use and a concerted effort to reach net-zero emissions by 2050.

4.3 Role of Associated Countries in EU-Funded Research

Although the European Union is the primary driver of these policy initiatives, several associated nations, notably Norway, the United Kingdom, and Switzerland, actively participate in EU-funded aviation research. Norway has taken a pronounced stance by announcing an ambition for all domestic flights to become zero-emission by 2040, leveraging government-owned airports and the support of Avinor to test hydrogen and electric aircraft. The United Kingdom has established the Jet Zero Council, aiming to coordinate efforts between industry and government to deliver zero-emission commercial aviation through support for hydrogen propulsion, electric aircraft, and sustainable fuels. Switzerland, with its world-class universities and research centers, contributes advanced R&D in hydrogen production and storage, as well as specialized battery technologies.

This collaborative approach extends beyond Europe's borders. Many multinational corporations, particularly major aircraft engine manufacturers, also have research facilities that are partnered with EU-funded consortia. These shared research undertakings serve to expand the knowledge base and spur faster innovation cycles. Consequently, Europe can harness diverse expertise, spread the risk of large-scale ventures, and unify regulatory frameworks that may eventually become global standards for zero-emission aviation certification.

4.4 The Broader Global Context of Green Aviation

Although this report emphasizes Europe and its associated countries, hydrogen and electric aviation represent a global trend. Countries like the United States, Canada, Japan, and some Middle Eastern nations are making parallel investments in carbon-free flight. NASA, for instance, has been investigating novel aircraft concepts under its Electrified Aircraft Propulsion initiative, while various start-ups in California's technology hubs are pursuing advanced battery chemistries or zero-emission flight platforms. In Asia, countries such as Japan and South Korea are developing hydrogen roadmaps that include hydrogen-fueled aircraft and airport infrastructure.

Global alliances, including the International Civil Aviation Organization's (ICAO) initiatives, are attempting to forge a worldwide consensus on emissions reductions in aviation, culminating in programs like the Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA). While offsets and sustainable aviation fuels remain part of the broader strategy, the pursuit of hydrogen and electric propulsion is expected to become more pronounced as technical maturity grows. With Europe's strong regulatory frameworks and targeted R&I investments, it is well-positioned to influence the trajectory of the global aviation industry and potentially export its zero-emission solutions worldwide.

5. Hydrogen Aviation Technology

5.1 Foundations of Hydrogen Propulsion

Hydrogen offers an intriguing proposition for aviation due to its high specific energy and zero carbon emissions at the point of use. Two principal avenues dominate hydrogen propulsion research: hydrogen combustion in modified gas turbines and hydrogen fuel cells that generate electric power. The theoretical and applied underpinnings of both approaches trace back decades, with NASA's early experiments in hydrogen flight and Soviet-era tests of liquid hydrogen on experimental aircraft demonstrating the fuel's basic feasibility.

Modern interests in hydrogen aviation leverage improved materials science, cryogenic handling, and fuel cell technology. Developments in tank insulation, high-temperature alloys, and composite materials allow the storage of liquid hydrogen at -253°C with less boil-off and lower mass penalties. Furthermore, the falling cost of renewable electricity supports the production of green hydrogen via electrolysis, an important factor in ensuring that hydrogen remains carbon-neutral over its lifecycle. By combining these elements, the aviation sector hopes to exploit hydrogen's significant energy-per-unit-mass advantage, which theoretically can exceed that of conventional jet fuel when stored cryogenically.

Yet, hydrogen's low volumetric density means larger storage tanks are needed, driving new aircraft designs that integrate novel fuselage geometries or incorporate dedicated tank compartments. Some design concepts shift away from the classic tube-and-wing approach to accommodate cryogenic tanks in the fuselage or inside extended aerodynamic fairings. These structural adaptations open the door to blended wing body aircraft, rethinking overall aerodynamic efficiency. As hydrogen is extremely light per unit of energy, the trade-off between tank volume and aerodynamic drag is at the forefront of engineering considerations.

Research labs and major manufacturers are also exploring catalytic combustion pathways that can minimize NO_x generation, pushing hydrogen combustion toward near-zero local pollutants. This typically involves optimizing burner design, introducing staged combustion, or employing specialized catalytic coating. Such deep-level propulsion research integrates fluid dynamics, combustion physics, and materials engineering to address the complexities of burning hydrogen in a turbine environment originally designed for kerosene.

5.2 Current State of Hydrogen Aircraft Development

Hydrogen aircraft have progressed from small-scale demonstrations to a pipeline of planned regional and even single-aisle concepts. Airbus's ZEROe initiative commands global attention, with conceptual designs for turboprop, turbofan, and blended wing body configurations. The turboprop prototype envisions propelling around 100 passengers up to a few thousand kilometers, placing it squarely in the short-haul regional market. Airbus’s turbofan concept is aimed at short- to medium-haul routes of 1,000–2,000 km, currently the largest segment of intra-European travel. The blended wing body design, although the most radical, promises enhanced aerodynamic efficiency and better internal space for hydrogen tanks.

Start-ups and research consortia add diversity to this landscape. Germany’s H2Fly successfully flew a four-seater test plane that used fuel cells, demonstrating the possibility of small-scale hydrogen-electric propulsion. ZeroAvia, a UK and US-based venture, has converted conventional turboprops into hydrogen-electric demonstrators, inching toward 19–50-seat capacities. These smaller efforts, though limited in range and payload, are invaluable for tackling the near-term engineering hurdles: reliable liquid hydrogen storage, optimizing fuel cell stacks for aviation, and ensuring stable system integration within existing airframes.

Another active R&I field involves retrofitting existing gas turbines to burn hydrogen. Rolls-Royce and other engine specialists are adapting turbine combustor sections to handle hydrogen’s different flame characteristics, with an eye toward eventually replacing or complementing kerosene. This approach could, in theory, expedite the arrival of hydrogen-powered flight by leveraging much of the existing jet engine manufacturing base, though cryogenic storage integration still demands substantial modifications to the aircraft structure.

5.3 Fuel Cell Systems and Technological Gaps

Fuel cell systems are critical for the most advanced zero-emission scenarios, generating electrical power onboard instead of relying on combustion. Proton-exchange membrane (PEM) fuel cells dominate near-term aviation research because of their relatively high-power density and responsiveness. However, sustaining these power outputs under varying altitude and temperature conditions remains challenging. Researchers investigate new membrane materials with improved stability at reduced pressure, advanced bipolar plates for enhanced thermal conduction, and catalysts that minimize platinum usage without sacrificing performance.

Hybridized systems that combine fuel cells and batteries are emerging as particularly promising. In these architectures, the fuel cells supply a steady-state power requirement, while the batteries provide peak power during takeoff and climb, allowing for a smaller—and lighter—fuel cell stack. Thermal management becomes a prime concern: fuel cells generate heat, batteries need to avoid overheating, and high-altitude, low-temperature environments present their own set of complexities. Engineers explore novel cooling loops, using cryogenic hydrogen as a heat sink in some designs, or developing specialized radiators that can function effectively in thin air.

Longevity is equally pivotal; commercial airline operations demand thousands of flight cycles without excessive degradation in the power system. Breakthroughs in electrolyte chemistry, electrode design, and system packaging will be needed to ensure consistent performance over many years. Furthermore, the rigors of certification (e.g., vibration, rapid pressure changes, potential exposure to moisture and dust) place strict reliability conditions on fuel cell stacks. Overcoming these hurdles will be essential for moving from small prototypes to robust regional or even single-aisle aircraft that rely primarily on fuel cell power.

5.4 Cryogenic Storage, Infrastructure, and Airport Adaptations

Storing hydrogen in liquid form remains the central technical barrier to widespread adoption. Liquid hydrogen, while offering superior energy density by mass, occupies significantly more volume than kerosene. Tanks must maintain cryogenic conditions (-253°C) for extended periods, which involve specialized insulation systems that minimize boil-off. Multi-layer vacuum insulation, advanced foam layers, and other proprietary materials are under continuous development to reduce the rate at which hydrogen transitions back to gas form. Even minimal boil-off can complicate fueling logistics and require venting protocols.

Infrastructure at airports will also need a substantial overhaul. Traditional kerosene-based fueling trucks cannot handle cryogenic hydrogen, implying an investment in new tanker designs or fixed pipelines linking centralized hydrogen storage tanks to parked aircraft. On-site electrolysis powered by renewables could supply green hydrogen directly, sidestepping some transportation steps, but it necessitates ensuring a steady supply of electricity, water, and liquefaction capabilities. Large-scale liquefaction units are capital-intensive and energy-demanding, although economies of scale may emerge if hydrogen is also used for ground service vehicles or other industries around the airport.

In parallel, training airport personnel to handle cryogenic fuels, implementing hydrogen leak detection systems, and adapting fire-suppression capabilities all form part of the broader operational shift. These new protocols, once standardized, will likely become part of an international infrastructure blueprint. Some forward-thinking airports in Scandinavia and the UK are already experimenting with small hydrogen production facilities, partly to gain real-world experience in safe handling and to prepare for scheduled commercial test flights in the late 2020s.

5.5 Safety and Regulatory Aspects of Hydrogen-Powered Flight (Unchanged)

Safety is paramount in aviation, and hydrogen's properties introduce unique considerations. Although hydrogen is not inherently more dangerous than kerosene, its wider flammability range and cryogenic handling requirements demand specialized procedures. Regulators such as EASA (European Union Aviation Safety Agency) and national aviation authorities are working to update standards to address the risks of hydrogen leaks, cryogenic tank structural integrity, and high-pressure systems. Certification processes must encompass not only the propulsion system but also the ground handling infrastructure. Despite these challenges, hydrogen's safety record in industrial settings suggests that with the right protocols and engineering rigor, safe operation is achievable. Demonstration projects and test flights over the next decade will clarify and refine these standards, ultimately laying the regulatory foundation for mainstream hydrogen commercial aviation.

5.6 Planned R&I Initiatives and Industry Collaborations (Expanded)

Research on hydrogen aviation is boosted by multiple large-scale initiatives within the EU, notably the Clean Aviation Joint Undertaking, which allocates substantial funding to zero- and low-emission propulsion demonstrations. This framework fosters partnerships among major manufacturers (Airbus, Safran, Rolls-Royce), research entities (DLR, ONERA, universities), and airport operators. The aim is to develop technology demonstrators capable of flying 20–50 passengers using hydrogen propulsion, with hopes of scaling to 100+ passengers by the mid-2030s.

Projects under Horizon Europe also fund interdisciplinary research in areas such as new tank materials, advanced fuel cell stacks, and hydrogen combustion turbines. Complementary national programs support technology testbeds: Norway’s Avinor invests in airport-based hydrogen fueling infrastructure, while the Aerospace Technology Institute (ATI) in the UK has launched the FlyZero initiative, investigating liquid hydrogen aircraft concepts for commercial service in the 2030s. Through these consortia, researchers and industry stakeholders share findings on aerodynamic performance, system integration, and manufacturing processes, accelerating the technology’s journey toward commercialization.

Internationally, collaborations with NASA, Japan’s hydrogen consortia, and private aerospace ventures in North America further enrich the European knowledge base, sometimes via direct co-funding agreements or data-sharing protocols. These initiatives collectively de-risk ambitious goals by distributing costs and consolidating expertise. If they meet their milestones, the result could be a leap from today’s experimental hydrogen aircraft to viable, certified planes crisscrossing European skies with minimal climate impact.

6. Electric Aviation Technology

6.1 Background on Battery-Electric and Hybrid-Electric Concepts

Electric propulsion in aviation encompasses both purely battery-electric aircraft and hybrid-electric systems. Battery-electric planes rely on electricity stored in onboard batteries to power one or more electric motors driving propellers or fans. Their appeal lies in straightforward zero operational emissions, lower noise, and reduced mechanical complexity, as electric motors require fewer moving parts than internal combustion engines.

Hybrid-electric configurations, by contrast, integrate an electric motor with a conventional turbine or piston engine. The engine may run on kerosene, Sustainable Aviation Fuel (SAF), or potentially hydrogen in the future, while the electric system handles partial loads, regenerative braking on descent, or peak power demands during takeoff. This approach can significantly cut fuel burn and carbon output for regional and short-haul flights, serving as a bridge technology until battery energy densities reach levels sufficient for all-electric larger aircraft.

European research programs consider electric aviation a strategic area for achieving near-term reductions in aviation emissions. Although battery energy densities currently constrain fully electric aircraft to short-hop missions under a few hundred kilometers, ongoing progress in advanced chemistries (lithium-sulfur, lithium-metal, and solid-state cells) could push that range upward. Combined with improved aerodynamic designs and lighter airframes using composites, new prototypes aim to stretch flight durations enough to cover valuable intercity or commuter routes.

6.2 Current State of Battery-Electric Aircraft

Numerous battery-electric aircraft projects have reached flight test phases, illustrating that the core idea of electric propulsion is both technically feasible and certifiable for small-scale operations. The Pipistrel Velis Electro remains a hallmark achievement as the first EASA type-certified electric aircraft, suitable for flight training. Its battery pack, motor, and power management system demonstrate the practicality of zero-emission flight for limited distances, typically under one hour. While range limitations prevent it from competing with conventional small trainers in all conditions, it nonetheless validates essential elements: battery containment, cooling, and integration with flight controls.

Beyond Pipistrel, Eviation’s Alice prototype has garnered attention for its aim to carry nine passengers at ranges of several hundred kilometers. Although still under development, Alice could pioneer the commuter category, allowing short regional routes with minimal noise and direct emissions. MagniX, an electric powertrain provider, collaborates with various operators to retrofit existing planes with high-power electric motors for cargo or passenger use. These conversions highlight the potential for reducing emissions in remote areas or specialized services—like seaplanes or island-hopping routes—where flight distances are naturally shorter.

Efforts are also underway to scale up beyond nine or nineteen seats. Heart Aerospace, based in Sweden, initially announced a 19-seat electric aircraft and later revised its design to a 30-seat hybrid-electric configuration. This evolution underscores the ongoing challenge of balancing battery weight, passenger capacity, and range. New designs emphasize aerodynamic refinements, such as high-aspect-ratio wings and distributed propulsion (placing multiple smaller electric motors along the wing), to enhance lift-to-drag ratios and optimize aircraft performance despite the weight penalty of batteries.

6.3 Advances in Battery Chemistry, Manufacturing, and Recycling

The pace of innovation in battery technology largely dictates how quickly electric aviation can scale. Lithium-ion cells dominate today’s aircraft applications, but next-generation chemistries promise leaps in energy density, improved cycle life, and enhanced safety. Solid-state batteries replace the liquid electrolyte with a solid one, enabling higher energy per kg, reducing fire risk, and potential for faster charging. Lithium-sulfur and lithium-metal anodes further boost theoretical energy densities, although challenges like short cycle life or dendrite formation must still be resolved.

From a manufacturing perspective, Europe’s industrial policy aims to bolster domestic battery cell production through the European Battery Alliance, seeking to reduce reliance on external sources. Gigafactories dedicated to aviation-grade batteries could implement tighter quality controls than automotive lines, optimizing cells for the power and thermal demands of flight. These efforts also promote sustainability in raw materials sourcing, with an eye on ethical mining, responsible supply chains, and end-of-life strategies.

Recycling forms the final pillar of a circular battery economy. As aviation-grade batteries degrade over time, they may still find secondary uses in stationary energy storage before being dismantled to reclaim lithium, cobalt, nickel, and other metals. Closing the loop is essential to reducing the overall environmental footprint of electric planes, ensuring that resource-intensive materials remain in circulation and that the net carbon gains from zero-emission flight are not offset by upstream impacts of mining and disposal.

6.4 Hybrid-Electric Systems: Opportunities and Challenges

Hybrid-electric architecture occupies a crucial middle ground, capturing benefits of electrification while sidestepping the energy density shortfall of current batteries. In many designs, a gas turbine in one wing drives a generator that feeds electric motors on both wings, supplemented by a battery pack to supply extra thrust during takeoff or climb. Alternatively, a smaller turbine combined with a battery might reduce overall fuel burn and lower emissions by 30–40% relative to a standard turboprop.

The E-Fan X project, though concluded, provided a wealth of data on integrating a 2MW electric motor into an existing regional jet airframe. Rolls-Royce, Siemens, and Airbus all contributed to developing high-voltage power electronics, liquid cooling circuits, and control systems capable of shifting between turbine power and electric thrust seamlessly. This synergy points to a future in which multiple power sources can be orchestrated for optimal performance, noise reduction, and operational flexibility.

However, hybrid systems often suffer from complexity and weight penalties. Balancing the mass of a conventional engine, a generator, batteries, and electric motors require advanced structural and aerodynamic solutions. Additionally, reliability and maintenance protocols have become more complex, as multiple power sources must be monitored and serviced. Even so, hybrid-electric designs may be the near-term solution for routes of 500–1,000 km, offering lower emissions than purely fossil-fuel-based aircraft while technology for fully electric flight matures.

6.5 Key Ongoing Electric Aviation Projects and Demonstrators

Electric aviation research is characterized by a mix of start-ups, established OEMs, and collaborative research consortia. Some prominent endeavors include:

- **Eviation Alice:** A nine-passenger, fully electric commuter plane aiming to enter service soon. Its design employs an all-composite airframe and twin electric motors, with an ambitious target range above 400 km, pending further battery improvements.
- **Heart Aerospace’s ES-30:** This revised design accommodates around 30 seats in a hybrid-electric configuration, balancing a smaller battery pack with a range-extending generator. By aligning seat capacity with real regional demands, Heart Aerospace seeks to make electric flight economically viable for typical commuter routes.
- **MagniX Retrofits:** MagniX, headquartered partly in the Pacific Northwest, has partnered with operators to electrify seaplanes and short-haul commuter planes. The company’s high-power electric propulsion units aim at 375–750 kW per motor, scalable to multiple configurations.

- **Rolls-Royce Electric Ventures:** Rolls-Royce has invested heavily in electric propulsion, building on the E-Fan X experience and acquisitions of smaller electric specialists. Projects include advanced integrated propulsors and energy management systems for future regional aircraft.
- **Pipistrel's Evolution:** Following the success of the Velis Electro, Pipistrel continues to refine electric trainer aircraft. Ongoing R&D includes larger capacity planes and more robust battery systems suited for flight schools and aerial tourism, capitalizing on the reduced noise footprint of electric power.

These initiatives, supported by grants from EU programs like Horizon Europe or national agencies, conduct rigorous testing of motors, inverters, battery packs, cooling systems, and flight control software. Many also include airline partners or flight training organizations eager to adopt greener fleets. The combined outcome is a multilayered ecosystem that fosters competition, speeds up innovation, and steadily raises the technology readiness level of electric aircraft.

6.6 Planned R&I Initiatives in Electric Aviation

Under Horizon Europe, dedicated calls for "Disruptive Technologies in Aviation" fund electric propulsion research, focusing on:

- **High-Energy Batteries:** Improving energy density to surpass 500 Wh/kg.
- **Lightweight Materials:** Reducing the overall weight of the aircraft's structure and powertrain components.
- **Grid and Charging Infrastructure:** Implementing high-capacity charging stations at airports, plus exploring battery swapping systems for quick turnaround times.

The Clean Aviation program also funds large-scale demonstrators for hybrid-electric regional aircraft, aiming to secure certification by the early 2030s.

7. Synergies: Hydrogen vs. Electric Propulsion

7.1 Comparative Overview

Hydrogen-based and battery-electric solutions each offer distinct benefits and hurdles. Table 1 highlights key points:

Parameter	**Hydrogen (Fuel Cell or Combustion)**	**Battery-Electric/Hybrid-Electric**
Technical Feasibility	Demonstrators exist (H2Fly, ZeroAvia); Airbus concept for 2035	Pipistrel Velis certified; hybrid demos (E-Fan X) for larger aircraft
Infrastructure Requirements	Large-scale hydrogen production, liquefaction, and refueling	High-capacity charging stations, possible battery swapping facilities
Energy Density	Hydrogen: High per kg, but cryogenic storage complexities	Battery: Limited by current technology, but advances in solid-state likely
Emission Reduction	Potential for zero CO_2; some NOx if combusted	Zero CO_2 in operation; lifecycle emissions tied to battery production
Timeline	Possible regional use by mid-2030s; scaled adoption by 2040+	Small-scale electric in use now; larger hybrid-electric in next decade

Table 1. Key comparisons between hydrogen and battery-electric pathways (Source: Clean Aviation, 2024).

7.2 Infrastructure Requirements and Energy Considerations

Hydrogen and electric aircraft both require substantial infrastructural investments, but their needs differ markedly. Hydrogen aviation depends on robust supply chains for producing and transporting liquid hydrogen at cryogenic temperatures. This can involve on-site electrolyzes powered by renewable electricity, liquefaction facilities, and specialized refueling equipment at airports. Conversely, electric aviation relies on the electrical grid capacity to deliver high-power charging, potentially in the multi-megawatt range for larger aircraft. Since battery-electric planes might only be suitable for shorter routes under current energy density constraints, many airports may be able to manage the charging demand without extensive grid upgrades, at least in the early phases.

In some scenarios, a combined approach using both hydrogen production and electric charging infrastructure could offer synergies. Airports may produce green hydrogen via electrolysis for hydrogen aircraft while also deploying battery charging stations, possibly leading to shared renewable energy assets and complementary revenue streams. Over time, the co-location of hydrogen refueling and electric charging could serve a diversified fleet, although managing complexity and safety for two different zero-emission fuels will demand rigorous planning and regulatory oversight.

7.3 Life Cycle Emissions and Environmental Impact

While both hydrogen and battery-electric propulsion offer zero operational CO_2 emissions during flight, their total life cycle emissions vary depending on how the hydrogen is produced or how the batteries are manufactured and recycled. Green hydrogen produced by renewable-powered electrolysis has the lowest carbon footprint, but gray or blue hydrogen derived from fossil fuels can undermine the climate benefits if carbon capture and storage is not effectively deployed. Battery-electric aircraft similarly need low-carbon grids for charging maximizing emission reductions, and they also rely on responsible sourcing of battery materials and robust recycling programs.

Non-CO_2 emissions, such as NO_x from hydrogen combustion or the life cycle impacts of materials extraction for batteries, must also be carefully evaluated. In principle, hydrogen fuel cells avoid NO_x emissions altogether, but hydrogen combustion in a gas turbine can still produce NO_x if not controlled adequately. Battery production generates environmental concerns related to mining operations for lithium, cobalt, and other metals. Consequently, true climate and environmental benefits rest upon the entire supply chain being decarbonized, from raw material extraction to end-of-life disposal or recycling.

7.4 Market Adoption and Commercial Viability

Market adoption of hydrogen and electric aircraft will depend on multiple factors. Airlines prioritize total cost of ownership, which includes capital expenditure, operational costs, maintenance, training, and infrastructure considerations. Early estimates suggest that if hydrogen can be produced at scale using renewable energy, it could become a competitive fuel option by the late 2030s or 2040s. Electric aviation’s cost trajectory is also predicted to drop over time, driven by improvements in battery manufacturing and economies of scale.

Passenger acceptance can influence adoption as well, particularly in an era of heightened environmental awareness. Zero-emission aircraft stand to benefit from supportive policies, such as carbon taxes on conventional fuels or environmental regulations that restrict high-emission aircraft. Nonetheless, airlines remain cautious about technology risk, maintenance complexities, and the availability of suitable airports with the necessary refueling or recharging capacity. Demonstrations of operational reliability, safety, and favorable economics will be essential to drive a wider commercial uptake, likely beginning with short regional routes or niche operations.

8. Key Challenges and Barriers

8.1 Regulatory Hurdles and Certification Pathways

One of the most substantial barriers to introducing hydrogen and electric aircraft is the regulatory environment. Aviation is heavily regulated at both national and international levels, ensuring uniform safety standards. Current regulations revolve around kerosene-based propulsion systems, and they do not yet fully address the unique attributes of hydrogen and electric flight. EASA, the FAA in the United States, and other bodies must revise or expand their certification criteria to consider cryogenic hydrogen storage, high-voltage battery systems, and novel airframe designs. This process can be time-consuming, yet it is essential to guarantee public safety and maintain the overall reputation of commercial aviation.

Revision of regulations requires close coordination with technology developers so that test data, risk assessments, and engineering analyses inform the new standards. Many advanced aviation projects already involve parallel processes of design and regulatory consultation, ensuring alignment from the early conceptual stages. Nonetheless, this interplay between innovation and regulation can introduce delays. Companies that are first to market with radical technology face a steeper regulatory learning curve, though this can also lead to competitive advantages once certification is secured.

8.2 Supply Chain and Industrial Capacity Constraints

Transitioning to hydrogen or electric aircraft requires new supply chains and industrial capacities. In the hydrogen realm, the production, distribution, and storage infrastructure must be built up significantly. Electrolyze manufacturing must expand, and liquefaction facilities must scale to handle increasing volumes. In parallel, advanced cryogenic tanks, fuel cell stacks, and specialized materials for hydrogen embrittlement resistance must be produced in large quantities. Supply chain bottlenecks in any of these areas can slow aircraft production and raise costs.

Electric aviation faces similar constraints, especially when it comes to battery cell production. The automotive sector’s burgeoning demand for high-performance batteries has already led to competition for critical minerals like lithium, cobalt, and nickel. Ensuring that these resources are available for aviation demands strategic partnerships, potential exploration of alternative battery chemistries, and robust recycling infrastructures to reclaim valuable materials. Scaling up to meet the demands of a significant portion of the aviation market is not trivial and may require multiple gigafactories dedicated to aviation-grade battery production.

8.3 Public Perception, Community Acceptance, and Airline Adoption

Despite a rising global focus on sustainability, public perception of flying with hydrogen or electric propulsion may present a short-term obstacle. Many people associate hydrogen with the Hindenburg disaster, despite the distinct difference between hydrogen used in a rigid airship and hydrogen stored in modern cryogenic tanks under strict safety standards. Furthermore, battery fires in consumer electronics might lead to public concerns about electric aircraft safety. Clear communication by manufacturers, airlines, and regulators is crucial to dispel misconceptions and highlight the robust safety measures embedded in modern zero-emission designs.

Airlines themselves need to be convinced of the commercial viability of hydrogen or electric fleets. This requires compelling evidence of operational reliability, maintenance cost savings, and potential regulatory or market incentives that make early adoption beneficial. Demonstration flights can serve as public showcases, and pilot programs with small hydrogen or electric fleets can help airlines assess real-world performance data, train crews, and refine operational guidelines. As public awareness of climate issues grows, airlines that pioneer zero-emission fleets may also enjoy reputational advantages, attracting environmentally conscious passengers.

8.4 Technical Risks and Safety Concerns in Zero-Emission Aviation

Both hydrogen and electric propulsion systems introduce technical complexities that demand careful risk management. Hydrogen’s cryogenic handling, while not fundamentally more dangerous than kerosene if done properly, does require specialized knowledge to ensure the integrity of cooling systems, tanks, and transfer lines. Temperature fluctuations can lead to metal embrittlement, and controlling hydrogen leaks is paramount to prevent the formation of flammable mixtures.

Electric aircraft carry risks related to high-voltage systems and potential battery thermal runaway. If a battery cell is punctured or experiences an internal short-circuit, the heat and gases generated can propagate quickly through the battery pack. Designing battery casings, insulation, and ventilation systems to mitigate these risks remains a critical focus area for developers. Ongoing improvements in battery chemistry, such as solid-state electrolytes, may reduce the likelihood of catastrophic failures, but these are still in relatively early stages of commercial readiness. In both cases, comprehensive safety protocols and redundancy measures must be in place to preserve aviation’s strong safety culture.

9. Opportunities for Stakeholders

9.1 Role of Airlines

Airlines find themselves in a unique position to influence the trajectory of zero-emission flight. By placing early orders or signing letters of intent with manufacturers, airlines can bolster investor confidence in emerging hydrogen or electric solutions. They can also partner directly with technology providers to refine designs based on real-world operational considerations, such as flight scheduling, ground handling, and maintenance logistics. Airlines that demonstrate a willingness to adopt greener fleets may also benefit from marketing advantages and possibly from preferential slots or reduced fees at airports that encourage low-noise and zero-emission operations.

Furthermore, airlines can contribute significantly to the development of industry-wide best practices in pilot training, cabin crew procedures, and emergency protocols for zero-emission aircraft. Collaboration between airlines, aviation authorities, and aircraft manufacturers helps shape regulations that are not only safe but also practical and cost-effective for operators.

9.2 Role of Airports and Infrastructure Providers

Airport operators stand at the front line supporting the transition to zero-emission aviation. Installing hydrogen refueling stations, cryogenic storage facilities, and high-capacity charging infrastructure for electric aircraft requires significant capital investment. Yet, airports that proactively implement these solutions may gain a competitive edge, attracting airlines looking to operate zero-emission flights and showcasing environmental leadership to local communities. The synergy between ground vehicle electrification (airport buses, baggage tugs, and other service vehicles) and emerging hydrogen or electric aircraft can further justify investments in renewable energy production on or near airport premises.

Airports can coordinate with regional energy providers to ensure that their electricity supply is green, thereby maximizing the climate benefits of electric aviation. They can also form consortia with neighboring airports to share best practices in hydrogen or electric infrastructure, creating network effects that can quickly scale up zero-emission flight routes.

9.3 Role of Governments, Policymakers, and Regulators

National and regional governments have at their disposal a range of policy instruments that can accelerate zero-emission aviation. These may include research and development grants, loan guarantees, tax credits for hydrogen production, or subsidies for installing necessary refueling and charging infrastructure. Regulatory frameworks can be tailored to encourage airlines to adopt lower-emission aircraft, such as through carbon taxes on kerosene-based flights or noise and emission fees at airports. Moreover, governments can enhance crossborder coordination to harmonize standards for hydrogen handling, electric charging interfaces, and pilot certification, streamlining the rollout of zero-emission fleets.

Collaboration with international bodies is equally pivotal. Governments in Europe, for example, can push for global adoption of stringent emissions targets through ICAO and other forums, thereby leveling the playing field for zero-emission propulsion and boosting the competitiveness of European-developed solutions.

9.4 Role of Research Institutions, Academia, and Collaborations

Research institutions and universities are the engines of innovation in hydrogen and electric aviation. Their focus on fundamental science, whether it be in the electrochemistry of high-capacity batteries, the materials science of cryogenic tanks, or computational fluid dynamics for more efficient propulsion, underpins the industry's ability to progress. Collaborative research projects, often co-funded by the EU or national agencies, allow academic and industrial researchers to pool expertise, share testing facilities, and reduce duplication of efforts. This joint approach not only speeds up development but also creates a pipeline of skilled graduates trained in emerging aerospace and clean energy technologies.

Spin-off companies from academic labs can play a crucial role in commercializing breakthroughs that might otherwise remain confined to theoretical papers or prototypes. Institutions like DLR in Germany, ONERA in France, and universities across Europe have become key players in bridging the gap between early-stage research and industrial application. In many cases, they also offer specialized test beds, wind tunnels, or pilot plants for hydrogen production, providing tangible benefits to both established aerospace companies and start-ups.

10. Case Studies

10.1 Airbus ZEROe

Airbus's ZEROe initiative stands as one of the most high-profile undertakings in hydrogen aviation. In 2020, Airbus revealed three conceptual designs intended to demonstrate how hydrogen could power commercial aircraft by 2035. These concepts include a turboprop, a turbofan, and a blended wing body design. The turboprop layout focuses on short-haul operations, with capacity for up to 100 passengers. The turbofan concept targets the short-to-medium haul segment, promising seating for 120–200 passengers and the potential to serve most intra-European routes. The blended wing body offers a more radical departure from conventional tube-and-wing designs by embedding hydrogen tanks in a thick, wide fuselage area.

Each of these concepts highlights unique engineering challenges, particularly regarding liquid hydrogen storage, aerodynamic performance, and system integration. Airbus is leveraging internal R&D resources and collaborating with external partners, including engine manufacturers and research institutes, to validate the feasibility of each concept. Although the 2035 timeline is ambitious, its very announcement has galvanized significant interest and investment in hydrogen aviation, potentially accelerating the broader zero-emission aircraft ecosystem.

Figure 1 Airbus ZeroE blended wing and turbofan (source:Airbus)

10.2 H2Fly Demonstrations

H2Fly, a German venture centered at the DLR (German Aerospace Center) and the University of Ulm, has achieved several milestones in flight testing a four-seater aircraft powered by hydrogen fuel cells. These demonstrations serve to underscore hydrogen's viability at small scales, laying the groundwork for eventual scaling to larger regional commuter planes. H2Fly's aircraft incorporate lightweight composite hydrogen tanks and an electric drivetrain, which together deliver propulsion without producing CO_2 or NO_x. Test flights have revealed insights into system efficiency, durability, and the unique flight profiles associated with hydrogen-electric aircraft.

Figure 2 The hydrogen-electric 'HY4' demonstrator aircraft took off from Maribor, Slovenia (source: H2Fly)

By incrementally pushing the boundaries of endurance, altitude, and payload capacity, H2Fly provides a valuable testbed for hardware suppliers and researchers investigating how components such as compressors, fuel cell membranes, and thermal management systems operate under real flight conditions. The project's results feed into the design of next-generation fuel cells for aeronautical applications, with the long-term goal of enabling 19-seat or larger hydrogen commuter planes suitable for short-hop regional flights.

10.3 Pipistrel Velis Electro

The Pipistrel Velis Electro, certified by EASA in 2020, serves as a leading example of a fully electric, battery-powered aircraft that is already operational. Though its applications are currently limited to flight training and recreational flying, Velis Electro's significance lies in its regulatory certification, which paved the way for future electric aircraft designs. The aircraft features a modest range of around 50 minutes and can seat two people, but its low noise signature and zero emissions make it attractive for environmentally sensitive areas and flight schools that prioritize green credentials.

Importantly, Pipistrel's certification journey with EASA has provided valuable lessons on how to test and validate battery packs, manage thermal issues, and ensure that electronic control systems meet stringent aviation standards. The knowledge gained can be extended to larger electric aircraft projects, helping reduce certification risk and accelerate subsequent product development cycles. Pipistrel has also expanded its range of electric aircraft concepts, aiming to target higher payloads and longer ranges as battery technology matures.

Figure 3 Pipistrel Velis Electro (source: Pipistrel)

10.4 E-Fan X and Hybrid-Electric Milestones

The E-Fan X project was a collaboration between Airbus, Rolls-Royce, and Siemens that sought to demonstrate the feasibility of a hybrid-electric powertrain in a BAe 146 test aircraft. Though it ended in 2020, the project achieved significant progress, including the integration of a 2MW electric motor into one of the aircraft’s four engines. This motor was powered by a combination of a battery system and a generator linked to a conventional turbine. The effort yielded critical data on power electronics, thermal management, and the interactions between electric and mechanical components at high altitudes.

Although the project was discontinued before full flight tests, it left a legacy of engineering know-how and hardware development that continues to inform ongoing hybrid-electric initiatives. Rolls-Royce, for instance, has leveraged lessons from E-Fan X to enhance its expertise in high-power electrical systems, which could eventually be applied to partial or fully electric regional aircraft. The partnership also underscored the value of interdisciplinary collaborations, bringing together engine manufacturers, airframe designers, and electrical system experts to tackle a complex new propulsion paradigm.

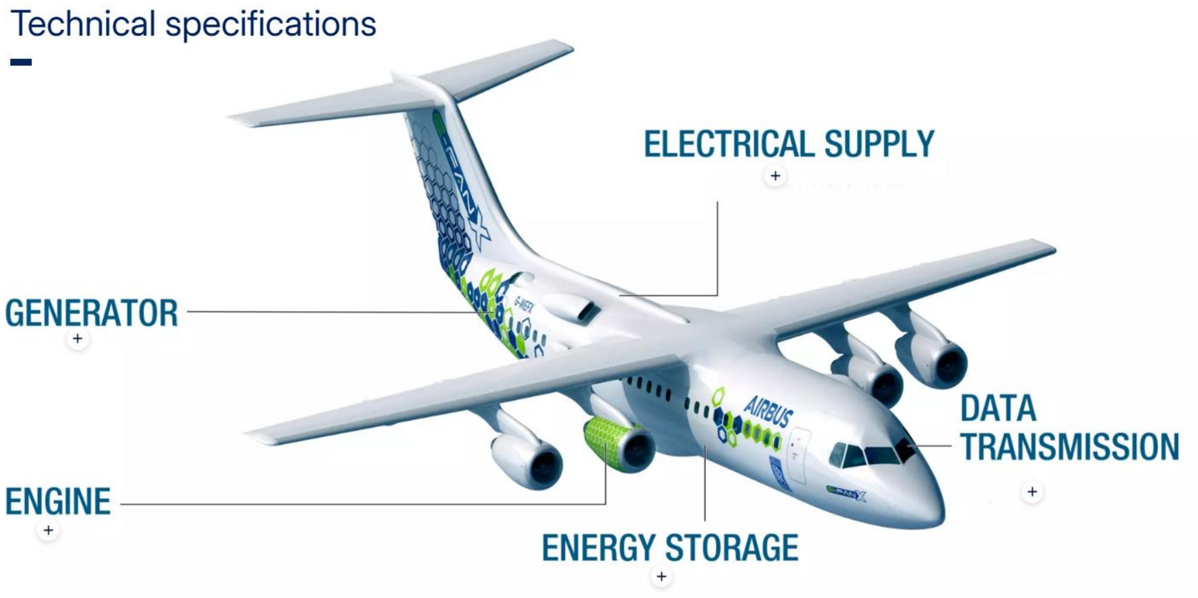

Figure 4 E-FanX demonstrator (source: Airbus)

10.5 ZeroAvia's Hydrogen Powertrain

ZeroAvia, with headquarters in the United Kingdom and operations in the United States, has been a pioneer in demonstrating hydrogen-electric propulsion in retrofitted aircraft. Its flight tests have included modifying a Piper Malibu to run on a hydrogen fuel cell powertrain, enabling short flights that showcase reduced noise and zero CO_2 emissions. The company is working on scaling this technology to 19-seat and even 50-seat regional planes, targeting commercial entry in the late 2020s.

ZeroAvia's approach to retrofitting existing airframes, rather than designing an entirely new aircraft from scratch, offers a faster pathway to market, although the resulting aircraft may not be as optimized for hydrogen as a purpose-built design. Still, the demonstration flights capture global attention, reinforcing confidence among airlines, regulators, and investors. The company has also been forging partnerships with major airlines, energy providers, and aircraft lessors, suggesting that the path to commercial operations could accelerate rapidly if technology and certification challenges are sufficiently resolved.

Figure 5 Retrofitted Do228 equipped with ZA 600 hydrogen-electric engine during flight test campaign (source:ZeroAvia)

10.6 Heart Aerospace and Other Noteworthy Initiatives

Heart Aerospace is a Swedish company that has received significant investment and recognition for its regional electric aircraft concepts. The firm aims to develop a 30-seat hybrid-electric or fully electric aircraft capable of operating on routes typically served by small turboprops today. The concept centers on improving commuter air transport, particularly in regions where short-to-medium routes predominate and where electric aviation can provide substantial cost and emission benefits.

Several other noteworthy initiatives exist across Europe, including university-driven research projects in advanced battery chemistries, airport-led pilot programs for hydrogen production, and start-ups focusing on specialized components such as high-power inverters or cryogenic valves. These decentralized efforts contribute to a dynamic ecosystem in which knowledge transfer and competition drive the rapid evolution of hydrogen and electric aviation technologies.

11. Financing and Funding Mechanisms

11.1 EU-Level Funding: Horizon Europe, Clean Aviation Joint Undertaking

Horizon Europe, the EU's flagship research and innovation program for the period 2021–2027, plays a pivotal role in financing disruptive aviation projects, including hydrogen and electric propulsion endeavors. Horizon Europe builds on the success of its predecessor, Horizon 2020, by expanding thematic clusters dedicated to climate, energy, mobility, and digital technologies. Consortia is composed of industry players, research organizations, and public agencies that can apply for competitive grants, often matched by private investment.

Within this framework, the Clean Aviation Joint Undertaking has become the main forum for large-scale demonstrators and collaborative research on sustainable aircraft. As a public-private partnership, it unites the European Commission, major aerospace manufacturers, SMEs, and research institutions to tackle ambitious goals such as developing full-scale hydrogen propulsion systems or refining high-power electric drivetrains. The Joint Undertaking provides significant funding—potentially amounting to billions of euros over a decade—and orchestrates integrated roadmaps for technology validation, certification, and market entry.

11.2 National and Regional Funding Schemes

Individual EU member states and associated countries also allocate substantial resources to zero-emission aviation. Germany, for example, operates the Luftfahrtforschungsprogramm (LuFo), which supports a range of aviation R&D activities with a specific emphasis on reducing emissions. France channels funds through agencies like Bpifrance and invests in national champions such as Airbus and Safran, while the United Kingdom has earmarked investments in the Aerospace Technology Institute (ATI) to catalyze innovation in hydrogen propulsion, advanced materials, and hybrid-electric systems. Scandinavian countries such as Norway and Sweden leverage strong public support for climate action to finance airport hydrogen facilities and early commercial routes for electric planes.

Often, regional authorities and city councils contribute grants or subsidies to test zero-emission aircraft solutions in local contexts, like short island-hopping routes or mountainous areas where road travel is comparatively difficult. These smaller-scale public investments can yield disproportionate benefits, serving as tangible examples for other regions and collecting operational data that shapes future technical designs.

11.3 Public-Private Partnerships

Public-private partnerships have emerged as a cornerstone of zero-emission aviation research. The cost and risk associated with developing an entirely new type of aircraft propulsion system is too high for many companies to shoulder alone, especially when the timeframe to profitability can extend well over a decade. By pooling resources, expertise, and infrastructure, public agencies and private corporations can share both the rewards and the risks. Governments benefit from accelerating the development of technologies that align with national and international climate goals, while companies gain access to funding and regulatory pathways that might otherwise be out of reach.

Examples of such collaborations include entire ecosystems built around test airports where hydrogen production, fuel cell integration, and pilot training are co-located. In many cases, these hubs form part of a broader industrial policy that envisions a leading role for Europe in clean energy industries like hydrogen electrolysis, battery gigafactories, and smart grids, all of which can feed into or benefit from zero-emission aviation.

11.4 Private Investment and Venture Capital

Alongside public sources, venture capital and private equity firms have shown mounting interest in hydrogen and electric aviation. The success of certain high-profile start-ups in raising large funding rounds illustrates the willingness of investors to support cutting-edge aerospace projects, particularly when there is an obvious alignment with broader climate-focused policies and consumer sentiment. Corporate venture arms of established aerospace and energy companies, such as Boeing's HorizonX or Shell Ventures, also participate, providing strategic capital, technical expertise, and market access.

Private investment, however, often comes with an expectation of more immediate returns than can be achieved through government-backed research. To bridge this gap, some companies adopt a phased approach, targeting smaller, less-regulated markets (like cargo drones or eVTOL air taxis) that can generate revenue and de-risk technology before moving on to larger, fully certified aircraft. Over time, these entrepreneurial approaches can inject fresh ideas into the traditional aerospace sector, fueling innovation and cross-pollination of expertise.

12. Infrastructural Requirements and Development

12.1 Hydrogen Production, Distribution, and Storage

Hydrogen production lies at the heart of any widespread deployment of hydrogen-powered aircraft. Green hydrogen, produced through electrolysis driven by renewable energy sources like wind or solar, yields the greatest climate benefits. Yet, for hydrogen to become a mainstream aviation fuel, significant capacity expansion and cost reduction in electrolyze technology is necessary. The process of liquefying hydrogen also consumes considerable energy, and infrastructure for transporting liquid hydrogen (LH_2) at -253°C remains limited. Dedicated pipelines, tanker trucks, or rail containers can be used, each bringing its own set of technical and safety considerations.

Storage terminals at airports must include cryogenic tank farms that can hold sufficient LH_2 to refuel multiple flights. These tanks generally require advanced insulation and safety systems to manage boil-off gas and pressure changes, particularly under fluctuating demand profiles. While some airports may choose to generate hydrogen on-site through electrolysis, others might rely on centralized production and distribution networks. Collaborative planning among airport authorities, energy utilities, and hydrogen suppliers is critical to avoid bottlenecks and ensure steady supply. Such infrastructure projects require large upfront investments, but they can also serve additional industries, including ground vehicles, maritime transport, or local energy grids, thereby distributing costs more broadly.

Figure 6 The world's largest facility for producing hydrogen using renewable energy is the Fukushima Hydrogen Energy Research Field (FH2R) (Source: Government of Japan)

12.2 Adaptations for Airports Handling Hydrogen and Electric Fleets

Airports of the future will likely need to accommodate a mix of hydrogen and battery-electric aircraft. This dual transition demands detailed planning to avoid operational disruptions and safety risks. Airports handling hydrogen aircraft must set aside specific zones for cryogenic refueling, supported by leak detection and firefighting systems designed for hydrogen's unique properties. Staff training and robust operational procedures will be essential to prevent mishaps and reassure flight crews and passengers of the safety of these new technologies.

Meanwhile, airports serving electric aircraft need to install charging stations with the capability to deliver large amounts of power rapidly, especially if quick turnarounds are desired. The location of these stations must be strategically arranged to fit within existing gate layouts, baggage handling logistics, and passenger boarding processes. In areas where space is constrained, alternative models like battery swapping may be tested. Each airport must assess the local grid capacity, working with power utilities to ensure that electric loads for charging do not exceed available infrastructure. In some cases, microgrids or local renewable energy generation may supplement the broader electrical grid, providing added resilience and reduced carbon footprints.

12.3 Electric Charging Stations, Battery Swapping, and Power Grids

Electric aircraft charging requirements can reach multiple megawatts, potentially surpassing what many airports can currently supply without significant upgrades. Although short-haul electric planes typically have smaller battery packs, scaling up to aircraft that seat dozens of passengers and require rapid recharging between flights becomes a logistical challenge. Battery swapping is one potential solution, wherein an aircraft's depleted battery pack is quickly exchanged for a fully charged one, minimizing ground time. However, this approach necessitates modular battery designs, automated swapping machinery, and substantial capital outlay for spare battery packs.

Power grid upgrades and the incorporation of renewable energy sources into airport operations can help spread the load while enhancing sustainability. Some airports have begun installing large solar arrays on terminal roofs or nearby land to feed dedicated charging networks. Others are exploring direct connections to wind farms or geothermal plants. Partnerships with local utilities are often necessary to coordinate capacity expansions, tariff structures, and load management strategies such as demand response or on-site energy storage (e.g., large stationary battery banks). As for electric aviation scales, these grid-related considerations will play an increasingly prominent role in the discussions surrounding sustainable transport.

12.4 Timeline for Infrastructure Readiness and Implementation

Infrastructure expansion tends to follow technological feasibility. Early adoption efforts, focused on small commuters or regional aircraft, will guide the pace of infrastructure deployment at selected pilot airports. From 2025 through 2030, many projects are likely to remain in demonstration mode, testing various configurations of hydrogen production, distribution, and electric charging. This period will allow airports and operators to develop the best practices and ascertain cost-effectiveness.

Between 2030 and 2040, if zero-emission aircraft demonstrate clear commercial viability, an increasing number of airports will adopt hydrogen and electric infrastructure, often prioritizing short-haul and inter-regional routes. By 2040 to 2050, large-scale implementations at major hubs could become standard, especially if regulatory mandates or carbon pricing strongly incentivize zero-emission operations. However, the exact timeline will depend on the speed of technological breakthroughs, the willingness of public and private stakeholders to invest, and the evolution of global energy markets.

13. Roadmap to 2050

13.1 Short-Term Goals (2025–2030)

In the immediate term leading to 2030, the focus will likely remain on proving the technical and economic feasibility of hydrogen and electric aviation in practical, real-world contexts. Demonstration projects with small to mid-sized aircraft, whether fully electric or hydrogen-fueled, are expected to proliferate. Airport infrastructures in pilot regions, such as Scandinavia or selected UK airports, will begin integrating hydrogen production facilities and high-power charging stations. Regulators will lay the groundwork for new certification standards by engaging manufacturers in iterative testing processes. This phase should see the first limited commercial services of zero-emission aircraft, primarily on short regional routes of up to about 500 kilometers.

During this period, cost-reduction strategies for key technologies—such as electrolyzes, fuel cells, or battery packs—will be a top priority. Investments made via Horizon Europe and national programs will validate the performance, reliability, and safety of these new propulsion systems. Collaboration among manufacturers, airlines, airports, and public agencies will help align technology deployment with realistic operational frameworks, ensuring that aircraft designs are guided by user needs rather than mere technological possibility.

13.2 Medium-Term Goals (2030–2040)

From 2030 to 2040, the emphasis should shift to scaling up and diversifying the range of zero-emission aircraft in commercial service. Airlines could start deploying hydrogen or electric planes on a wider network of short to medium-haul routes. Fleets could expand to encompass 50- to 100-seat regional jets, assuming continuous improvements in power density for fuel cells or batteries. As more airports adopt suitable refueling and recharging capabilities, route planning flexibility will increase, making zero-emission flights a routine occurrence in select corridors. Heightened competition among manufacturers might reduce aircraft costs and spur design innovations, potentially leading to improved range and payload capacities.

At the infrastructure level, major international airports will begin to incorporate hydrogen or electric servicing for certain gates, while smaller airports in remote or island communities might fully transition to zero-emission aircraft if their route structures remain short. Standards and certifications will solidify during this period, fostering an environment that encourages private investment. Meanwhile, the costs of green hydrogen and renewable electricity should continue falling, aided by parallel decarbonization efforts in other sectors like industry and heavy transport, improving the overall economics of zero-emission aviation.

13.3 Long-Term Goals (2040–2050)

The final decade leading up to 2050 is expected to see widespread adoption of hydrogen and electric aircraft for a significant portion of short to medium-haul flights within Europe. By this point, major aerospace manufacturers such as Airbus, Boeing, and regional OEMs could offer certified hydrogen or electric models across multiple market segments. Advances in cryogenic tank design, fuel cell power density, solid-state batteries, and system integration could enable aircraft with ranges exceeding 1,500 kilometers, further challenging the dominance of conventional kerosene propulsion.

Infrastructure upgrades at airports worldwide will likely be standard procedure, incorporating hydrogen fueling stations and robust high-power charging networks. If global climate regulations tighten, zero-emission aircraft might become a preferred choice for many airlines, accelerating fleet turnover. By achieving these milestones, the aviation sector can significantly align with the overarching net-zero goal championed by the European Green Deal, mitigating the climate impact of air travel and cementing Europe’s leadership role in sustainable aerospace innovation.

14. Outlook and Conclusions

The transition to zero-emission aviation in Europe and associated countries is no longer a speculative exercise but an active, multi-pronged effort intertwined with bold climate commitments and tangible industrial progress. Hydrogen propulsion—via combustion in modified gas turbines or through fuel cell systems—presents a compelling route for addressing the high-energy needs of commercial flights while eliminating direct CO_2 emissions. Electric aircraft, whether pure battery-electric or hybrid-electric, offer a parallel solution with immediate applicability in smaller markets and the potential for incremental scaling as battery technology improves.

Both pathways present distinct infrastructural and technical challenges. Hydrogen requires robust cryogenic systems, specialized refueling networks, and carefully adapted airport facilities. Electric aviation demands expanded grid capacity, large-scale battery manufacturing, and advanced charging or swapping systems. Regulatory bodies, such as EASA, are grappling with how best to certify new propulsion architectures without compromising safety. Stakeholders, including airlines, airports, government agencies, and research institutions, each have a role to play in advancing or hindering progress.

Despite the complexities, Europe’s policy environment—anchored by the European Green Deal and the Sustainable and Smart Mobility Strategy—creates fertile ground for innovative research and commercialization. Programs like Horizon Europe and the Clean Aviation Joint Undertaking accelerate investment, de-risk technology demonstrations, and catalyze partnerships. Meanwhile, associated countries such as Norway, Switzerland, and the UK contribute their own ambitious targets, intensifying a sense of collective effort.

Achieving widespread zero-emission aviation by 2050 will demand sustained momentum. It calls for ongoing breakthroughs in materials science, propulsion engineering, and cost-effective manufacturing. It requires major airport transformations, sweeping infrastructure deployments, and consistent, supportive regulatory frameworks. Public confidence in the safety and reliability of these new aircraft technologies will also be vital. If successfully coordinated, the transformative shift to hydrogen and electric propulsion stands to deliver significant climate benefits, economic growth in nascent green industries, and an improved public image for air travel in an era of climate consciousness. Europe's leadership in this domain could prove decisive not just for its own emissions trajectory, but also for setting global precedents in the race to decarbonize aviation.

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This project received funding from the European Union´s Horizon Europe Coordination and Support action under a Grant agreement No. 101137574.