A-to-B flight demonstration

Executive Summary

The goal of this project was to showcase the end-to-end electrolytic hydrogen supply chain aimed at provisioning low carbon hydrogen supply to a hydrogen-electric aircraft thus supporting the advancement of decarbonised aviation in the UK. The following four objectives were derived from the overarching goal:

- Demonstrate the technological feasibility of gaseous hydrogen delivery to aircraft from end-to-end including electrolytic hydrogen production, conditioning, compression, transportation and dispensing and end use in flight.
- Test the concept of operations for hydrogen-electric aircraft in a commercial airport environment.
- Measure the effective levelised cost of hydrogen for this use case and develop a clear understanding of the key commercial metrics and challenges to be overcome as a first step to reach commerciality threshold by Q4 2025.
- Lead contributions to the development of protocols, regulations and standards for hydrogen use at airports in collaboration with appropriate entities.

This work was supported by funding from the UK Department for Transport in the 2023-2024 financial year however the opinions expressed within the report are solely those of ZeroAvia.

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1. Introduction and project overview

1.1. Background and rationale for the project

Aviation is fundamental to the global economy and keeping people connected. Today more than ever, it plays a vital role in expanding horizons and broadening opportunities to work, live and learn, for people all around the world. If even more people, communities, and businesses are to enjoy these benefits, the aviation sector must grow responsibly and play its part in a net-zero future. Before the COVID-19 pandemic, aviation produced around one billion tonnes of carbon emissions in 2019, accounting for 3% of total emissions released into the atmosphere globally. And this is predicted to reach 22% according to the International Coalition for Sustainable Aviation (ICSA) as other sectors abate and aviation demand grows.

Aviation is traditionally recognised as a difficult-to-decarbonise sector and faces significant public pressure. The "shame of flying" (flyskam in Swedish) is an anti-flying social movement aimed at reducing aviation's environmental impact. It has gained considerable attention in the media in recent years. However, the scale of the challenge is, if anything, underestimated. Non-CO2 combustion impacts are thought to be up to two-thirds of the climate warming effect, and solutions like Sustainable Aviation Fuel (SAF) cannot tackle the full environmental impact, and will also be stymied by cost and scalability. The industry desperately needs technological advances to deliver sustainable flight.

Many stakeholders in the aviation value chain have committed to various sustainability goals, including emission-reduction targets, SAF targets, targets that include compensation, and membership in coalitions. In addition to the defined paths to reduce emissions that are in line with the Paris Agreement, the Science Based Targets initiative (SBTi) has emerged as one of the leading standards. As of April 2023, 25 airlines — mostly based in the Americas and Europe — have set or have committed to setting science-based targets. According to McKinsey analysis, this group represents more than 30% of global passenger traffic. On the OEM (original equipment manufacturer) side, aerospace, and defence companies, representing about 20% of the global value pool, have also committed to goals aligned with SBTi.

1.2. Overview of hydrogen-electric technology in aviation

ZeroAvia (ZA) is pioneering zero emission aviation by building a hydrogen-electric powertrain (used interchangeably with “engine” and “drivetrain”) to replace conventional jet-fuelled engines in existing aircraft models. This approach maximises the climate impact of the solution because the addressable market covers existing airframes (retrofit) and new airframes (line fit), and also optimises time to market because changes to airframe design are minimised, thus shortening the product development and certification timelines.

According to independent studies (https://www.clean-aviation.eu/media/publications/hydrogen-powered-aviation), hydrogen-electric is the most environmentally friendly approach of all practical sustainable aviation solutions, as the only emission is water vapour. Hydrogen fuel cells can deliver electrification in aviation where battery-electric systems are prohibitive due to poor gravimetric energy density, high costs and battery life impacts of cycling the batteries.

ZeroAvia was founded in 2017 in Hollister, CA and since then has opened additional offices in Seattle, WA, and the UK, where the company has significant R&D operations. ZeroAvia completed the development, production and testing of our first prototype engine, ZA250 (a 250kW powertrain for 6 seat aircraft), and conducted c.20 hours of flight tests, beginning with a major milestone when ZeroAvia flew for the first time the Piper Malibu - the World's largest commercial hydrogen-electric aircraft in the UK in September 2020.

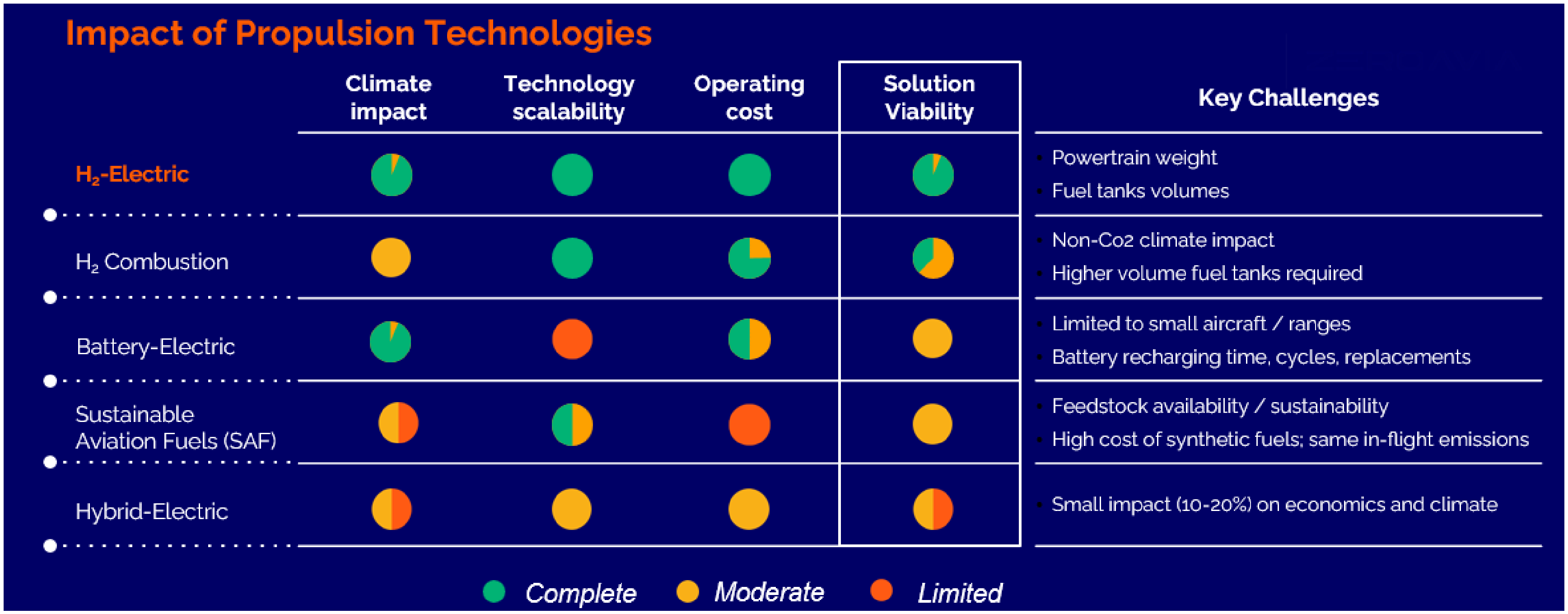


Chart comparing various technologies currently under development and aimed to decarbonise aviation: hydrogen-electric, hydrogen combustion, Sustainable Aviation Fuels (SAFs) and hybrid electric.

The above chart compares various technologies currently under development and aimed to decarbonise aviation: hydrogen-electric, hydrogen combustion, Sustainable Aviation Fuels (SAFs) and hybrid electric. The contemplated criteria are (i) the reduction potential in climate impact (including CO2 and non-CO2 emissions) and (ii) technology scalability. The hydrogen-electric pathway is the only viable option when adopting a holistic approach.

Each technology has its own challenges. The hydrogen-electric solution faces the problem of the weight of the powertrain as well as the higher volume taken by fuel tanks. The hydrogen combustion technology solves the problem related to CO2 emissions but not the one of NOx, particles and sulfates. Also, the efficiency of the engine being lower vs. the hydrogen-electric technology, it requires even larger fuel tanks. Sustainable Aviation Fuels face several challenges including (i) the feedstock sustainability, (ii) the quantity of electricity and cost thereof to produce Power-to-Liquid fuels and (iii) flight emission will remain unchanged (including non-CO2. Finally, the hybrid-electric technology only partially addresses the problem with a reduction of c.10-20% maximum.

This project was emulated with the testing of a 600kW prototype in a 19-seat testbed aircraft in January 2023. From late 2025, the company will offer a certified commercial 600kW powertrain system (ZA600) that can replace conventional engines in sub-regional 20-seat aircraft flying up to 300 nautical miles, which is currently in final development.

ZeroAvia has ambitious plans to scale this technology to 50+ seat regional aircraft by 2027 (with ZA2000 product family, a 2-5MW powertrain), and 100+ seat aircraft by 2030 (with ZA10,000 product family, a 10MW+ powertrain). ZeroAvia's engines will be supported by its practical and optimised approach to fuel infrastructure, including distributed hydrogen production systems that will minimise the cost of hydrogen and ensure low-emission content. This approach has quickly earned the interest of many airlines, who have placed nearly 2,000 engine pre-orders with ZeroAvia. This project could be a game-changer for the industry by helping solve the chicken and egg dilemma at an airport scale and deliver deep-decarbonisation of aircraft via ZeroAvia's own engines and through other system integrators, with the potential to catalyse the displacement of over 1.5 GtCO2e by 2040.

1.3. Infrastructure challenge

ZeroAvia's primary customers are airline operators. In the commercial conversations ZeroAvia currently has, one of the main concerns airline operators have is the reliable and cost-effective provision of hydrogen on airports. This project will prove the empirical feasibility of delivering gaseous hydrogen to an aircraft at a commercial airport. Additionally, the cost of green H2 is key to cheaper aviation, and the cost of "last mile" delivery from production to aircraft will be addressed directly by this project. These arguments will be quite instrumental in showing developments in hydrogen infrastructure and convincing airlines to adopt the technology.

ZeroAvia's vision is that the last mile delivery of hydrogen fuel to aircraft will be performed by refuelling trucks, capable of picking up hydrogen (c.1,000 kilograms) from sources and transport them to the apron to then refuel hydrogen-electric powered aircraft. These refuelling units will be monetised as part of ZeroAvia's "wet" power-by-the-hour offering, consisting of offering the engine, the fuel (hydrogen) as well as maintenance services. Such refuelling technology does not exist today and we expect this project to include novel technology, therefore leading to the development of intellectual property including patents and potentially technology licensing. The product will then be manufactured in the UK either by subcontractors or ZeroAvia themselves.

This project is poised to make a substantial positive impact on the industry. It will accelerate comprehension of gaseous refuelling, highlighting its advantages and effectively addressing associated risks, particularly those concerning health and safety. Consequently, it will facilitate ZeroAvia's discussions with customers and encourage their adoption of the technology. This progression will contribute to transitioning towards a more sustainable aviation sector, both within the UK and on an international scale.

1.4. Project timeline

At the time of the application submission, the intent was to fly before the end of 2023. Unfortunately, due to unforeseen circumstances, the process to obtain the Permit to Fly (PtF) has taken longer than planned initially. The delay was mainly driven by available resourcing with the CAA. The team supporting ZA at CAA have a lot of ongoing projects that need to be supported. Although our project was escalated to highest priority, we were still experiencing delays. This feedback has been communicated to CAA on multiple levels and it has been acknowledged by the CAA. We have worked with the CAA team to understand what ZeroAvia can do going forward to improve efficiency. These actions have been taken onboard for future permit to fly (PtF) projects (e.g. clearer, more detailed project plans presented to CAA and ZeroAvia sticking to project plan).

The below image shows the proposed timeline as of March 24th. Given the nature of the experimental aircraft, the timeline is extremely dependent on the weather. Both flight and refuelling is only viable in dry conditions.

	2024											
Activity	**Jan**	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**
Determination of Location	x	x										
Recce to chose location			o									
Fire Crew Training				x	x							
Extended A to A Flights				x	x							
Development of "Landaway ConOps"				x	x	x						
PtF						o						
A to B Mobilisations						x						
A to B Flight						o						
Return Flight						x						
Flight Test Report						x	x					
A to B Flight Report						o (v1)	o (v2)					

x	Task
o	Milestone

The Gantt chart above shows the tasks and milestones of the project. The Permit-to Fly process taking longer than expected, at the time of writing the flight is expected to happen in June 2024. This document is the first version of the final flight report.

1.5. Purpose of the A-to-B flight

This A-to-B flight serves as a blueprint for future aircraft deployments and sets the tone for ZeroAvia's ambitions by completing the first A-to-B hydrogen-electric flight in the UK. It effectively illustrates the lifecycle of hydrogen molecules, from generation to production, compression, and distribution.

For the Office of Airworthiness, the A-to-B flight presents an opportunity to continue the collaborative partnership between the CAA and ZeroAvia. It also underscores the growth and reliance on the OOA team, transitioning from E-Conditions on the Piper to an Experimental PtF (A-to-A), through to A-to-B on their journey to a certifiable product. This further solidifies the trust the regulator has demonstrated in ZeroAvia to date, along with their ongoing support for aviation decarbonisation. This latest extension of flight conditions marks the regulator's first certification of a hydrogen-powered flight to a destination away from base.

For the aircraft, it represents another opportunity to showcase to the world that Hydrogen-Electric powertrains are not merely futuristic concepts. It serves as a flagship in aviation, positioning the UK aviation industry at the forefront of new technology development. The A-to-B flight also contributes to raising awareness of aviation industry support functions, including ground support crews, air traffic control, and airfield fire departments.

For the hydrogen Infrastructure team, it tests our adaptable approach to supplying fuel to support powertrain development, combining onsite hydrogen production with third-party hydrogen supply. Despite extensive use at its parent unit at Cotswold Airport, the current hydrogen equipment has yet to undergo testing in a real-world scenario. This enables the team to evaluate its capability to ensure the safe road transport of hydrogen (an aspect yet to be addressed), as well as real-world upskilling of supporting teams, such as fire and ground crews, at a destination away from base.

The objective is to develop a checklist of requirements for land away locations, facilitating continued rollout as the A-to-B campaign progresses and boundaries are pushed further.

2. Infrastructure operations

2.1. General concept

ZeroAvia Infrastructure is a dedicated team of engineers and strategists working towards the development of the end-to-end Hydrogen Ecosystem required to support Hydrogen-Electric aviation. Through strategic partnerships and onsite Hydrogen production, ZeroAvia Infrastructure will develop the blueprint for the successful roll out of Hydrogen Infrastructure at airports in order to supply our customers.

A large part of developing the protocol and standards required to see a successful roll out of the powertrain technology is the real-world demonstration and validation of the full end-to-end hydrogen molecule delivery. ZeroAvia Infrastructure has, to date, supported the demonstration flights of the Piper Malibu and Dornier-228 through government funded projects such as HyFlyer I & II. In these projects, ZeroAvia has partnered with the European Marine Energy Centre (EMEC) to provide the hydrogen production, compression and refuelling assets required to get the demonstrator aircraft in the air.

The process starts with on-site electrolysis, utilising Enapter Electrolyser units to produce the hydrogen required, which subsequently has the moisture removed from the hydrogen through Drying Units. The hydrogen is then stored in a low-pressure buffer storage vessel, before being distributed to a Fuel Cell Systems HyQube. From here, the hydrogen is compressed up to 425barg and filled into the Nanosun Pioneer 145 refueller. The Nanosun Pioneer is a 20' ISO container integrated on to a 40' trailer to act as a mobile refueler. The refueler itself is ADR (the transportation of dangerous goods regulations) compliant, meaning it can be transported on public roads across the UK and Europe. The Nanosun is capable of holding up to 416kg of compressed hydrogen. This hydrogen is then refuelled into the aircraft using a cascade fill methodology, utilising the SAE J2601 (Fuelling Protocols for Light Duty Gaseous Hydrogen Surface Vehicles) non-communications based refuel protocol, this protocol uses pre-programmed look up tables, ambient temperature and sensed refuelling line pressure to refuel the aircraft vessel to >80% state of charge (SOC).

Typically, refuelling operations are carried out outdoors away from all ignition sources, to ensure adequate ventilation. During refuelling it is important to ensure that the minimum number of operators is present and that entry into the area is controlled. This is to ensure that anyone operating the equipment has the correct PPE, and refuelling occurs away from all potential sources of ignition (phones and smart watches). These rules apply only to the people operating the equipment. For commercial operations, ATEX zones will be designated where public access is prohibited.

2.2. Choice of B location

2.2.1. Choosing the B Airport

When considering a location to carry out the very first A-to-B flight for the Dornier-228, the first criteria was to find an airfield close to the A location, i.e. the Kemble airport where ZeroAvia has their R&D centre. It was also important that the location had experience dealing with experimental aircraft, had an advanced level of safety cover (fire and experienced ground crew, and was not a heavily trafficked airport. When looking at all of the above, MOD Boscombe Down was selected due to its experimental aircraft and alternative fuels experience. From an infrastructure perspective, the team at Boscombe have previous experience dealing with hydrogen in aviation, have the space available for safe hydrogen refuelling operations and storage area.

2.2.2. Decision matrix

As the ZeroAvia Infrastructure team prepares for the A-to-B flight, determining a safe location for refuelling is crucial, as well as the storage location of the aircraft. To do this the team has carried out a number of reconnaissance visits to locations on Boscombe Down Airport (the preferred B destination) and after this visit a decision matrix was created to score both possible locations suitability, this includes the ability to refuel safely and practically.

Boscombe Down is a well-equipped airport with ample room to carry out hydrogen operations. When visiting Boscombe, ZeroAvia was presented with a number of available locations for where the aircraft could be stored, and hydrogen refuelling could take place. These locations were narrowed down to 2 sites:

Site 1: Maintenance Hangar
The hangar at Boscombe down is spacious and split into quadrants for various different maintenance activities on multiple aircraft. The tall ceilings and active ventilation system provide room for hydrogen dispersion in the event of a hydrogen venting incident. It has good accessibility to GSE, ground power is readily available for both the aircraft and refueler and is manned 24 hours. However, the close proximity to both Boscombe personnel and other aircraft provides a higher risk than other locations in the event of an emergency. The operating area to the front of the hangar offers ample room to carry out hydrogen refuelling, however the area would need cordoning off preventing access to the taxiway/runway to airfield vehicles entering from “landside”.

Site 2: Hardened Aircraft Shelter (HAS)
Boscombe is equipped with over 15 HAS’ onsite, all having access to the taxi way. The HAS’ shelter proposed to ZeroAvia was one which has previously been used for hydrogen operations. The secluded nature of the HAS offers good separation from Boscombe personnel and other aircraft but isolates the ZeroAvia ground crew. The lower ceiling heights of the HAS’s and “ribbed” roof construction offer more areas for Hydrogen to pool in the event of an unforeseen system vent. The operating area to the front of the HAS offers the required room for the aircraft operations, the positioning of the Hydrogen refueler would prove challenging as the exit route in the event of an emergency would be blocked.

Both options showed promise, with both the Hangar and HAS proving more than suitable locations with some risk associated with either site. A decision matrix session was carried out with both locations being scored against a number of different criteria, weighted based on importance. The results can be seen below:

Boscombe Down - Location		Hangar			HAS		
Criteria #	Criteria	Criteria Score	Criteria Weight	Final Score	Criteria Score	Criteria Weight	Final Score
1	Access to GSE	10.0	0.8	7.5	4.7	0.8	3.5
2	Power availability	10.0	1.0	10.0	9.0	1.0	9.0
3	Ability to refuel	8.0	1.0	8.0	6.0	1.0	6.0
4	Safety/DSEAR	6.8	1.0	6.8	5.2	1.0	5.2
5	Welfare	5.5	1.0	5.5	5.3	1.0	5.3
6	Maintenance	10.0	0.3	2.5	3.5	0.3	0.9
7	Secruity	6.3	1.0	6.3	10.0	1.0	10.0
8	A/C Movements	9.5	0.8	7.1	6.5	0.8	4.9
	Total Scores	66.1		53.7	50.1		44.7

The above decision matrix compares the maintenance hangar and the hardened aircraft shelter across 8 criteria, including (i) access to GSE, (ii) power availability, (iii) ability to refuel, (iv) safety and considerations around Dangerous Substances and Explosive Atmospheres Regulations (DSEAR), (v) Welfare, (vi) maintenance, (vii) security and (viii) aircraft movements.

Final scores amount to 53.7 and 44.7 for the hangar and the hardened aircraft shelter respectively.

Criteria explained below:

1. Access to Ground Support Equipment (GSE): How accessible is the site to aircraft tugs, tow bars and electrical ground power units?
2. Power Availability: The batteries on the aircraft require an overnight charge, is there good access to power in the location? Is there 16A 230V power available for the refueler outside?
3. Ability to Refuel: Is there space in the location to refuel the aircraft? Is there enough separation from potential ignition sources? Is the area away from non-authorised personnel?
4. Safety/Dangerous Substances and Explosive Atmospheres Regulations (DSEAR): Does the location have enough ventilation? Is there ATEX rated equipment in the location? Is there adequate lighting at the location?
5. Welfare: Are the facilities suitable for the ZeroAvia ground crew?
6. Maintenance: How suitable is the location in the event the aircraft needs reactive maintenance?
7. Security: How safe is the aircraft in the location? How visible will the aircraft be to Boscombe personnel?
8. A/C Movements: Suitable space for taxi and towing of the aircraft?

Based on the decision matrix, the hangar came out as the preferred location to store the aircraft. But during the conversations with Boscombe, the “arming bay” was offered as a refuelling location. The Boscombe down arming bay is the preferred choice of refuelling location due to its distance from other airport activities. Boscombe have been supportive of the utilisation of this location while the aircraft is on landaway and will be the primary refuelling location. Should this location not be available during landaway, then the apron of the hardened aircraft shelter will act as a back-up option. The image below is an aerial view of the Boscombe Down airfield showing the hangars, the runway and the arming bay.

2.2.3. Required documentation

In order to refuel at a secondary location the following items need to be shared:

- DSEAR Report
    - Hazardous Area Classification
    - Emergency Response Plan
- Standard Operations Procedure
- Refuelling procedure
- Risk Assessments and Risk Registers

2.3. Safety and airport coordination

2.3.1. Risk assessment

Boscombe Down is no stranger to experimental aircraft, but when considering operating a Hydrogen Electric engine in a new location for the first time, there are a number of safety considerations that need to be accounted for:

HAZOP: HAZOP stands for hazard and operability study. A full HAZOP is conducted on Hydrogen refuelling activity and the concept of operations in a more commercial setting. The purpose of the HAZOP is to systematically examine the operation of both Hydrogen Refuelling and aircraft operations at its land away location, and essentially catastrophise problems and risks that may arise to ensure the right control measures and mitigations are in place. The HAZOP will also recommend any additional risk mitigations or operational controls as part of the study.

DSEAR Assessment: Dangerous Substances and Explosive Atmosphere Regulations (DSEAR) is a Health and Safety Executive (HSE) directive that requires employers to identify dangerous substances or hazardous areas caused by explosive materials in the workplace and the controls put in place to remove/control them. Both the aircraft and refueller are subject to a DSEAR assessments, both of which will be passed to Boscombe to form part of their site wide DSEAR Report. A DSEAR report will contain the following:

- Hazardous Area Classification drawings: The purpose of this to highlight atmospheres around the equipment that contain, or may contain in sufficient quantities, flammable or explosive gas, in ZeroAvia's case, hydrogen. This drawing can be used to educate emergency services so that, in the event of an emergency, they are aware of the hazardous areas.
- Emergency Response Plan: A detailed plan highlighting the actions required in the event of an emergency on the equipment at the land away location.
- PPE Requirements: This states what safety equipment is required when working in or around the equipment. For the case of the refueler and aircraft, all authorised crew are required to wear anti-static clothing and a personal gas detector when operating in, or around Hazardous Areas.
- Training Requirements: This is designed to inform the reader what training requirements are needed to operate on, or near the equipment.

Risk Assessment: On top of the above documentation, a full risk assessment is completed in the presence of all stakeholders. This includes personnel from Boscombe Down. This joint risk assessment ensures there is full alignment across all parties involved in the A to B flight. All identified risks are stored on a risk registry held by the ZeroAvia safety team, and periodically tracked.

2.4. Hydrogen production and conditioning

2.4.1. Technology and process

The cornerstone of our hydrogen production facility at Kemble is the electrolysis process, a clean and efficient method of splitting water (H2O) into its constituent elements—hydrogen (H2) and oxygen (O2)—using electrical energy. This process is pivotal for generating the zero-emission fuel necessary for our Research & Development activities as well as our hydrogen-powered aviation trials. The following outlines the technology and processes involved at a small-scale setup designed for our project needs.

- <u>Water Input Quality and Pre-treatment:</u> The electrolysis process begins with water—typically requiring high purity to prevent electrolyser damage and ensure efficient operation. The pre-treatment stage involves filtering and deionizing water to remove impurities and ions that could hinder the electrolysis efficiency or damage the electrolyser components.

- Electrolyser Technology: At the heart of our hydrogen production is a Proton Exchange Membrane (PEM) electrolyser, from Enapter. This technology is ideal for small-scale operations at the airport, where space is at a premium and we may want to make hydrogen production as flexible as possible.
- The Electrolysis Process: Within the electrolyser, water is introduced to the anode side of the unit. When electrical current is applied, water molecules are split into oxygen, protons, and electrons through the process of oxidation. The protons then pass through the PEM to the cathode side, where they combine with electrons (supplied by the external circuit) to form hydrogen gas, a process known as reduction.
- Hydrogen and Oxygen Separation: The electrolysis process inherently produces hydrogen and oxygen gases. These gases are separated within the electrolyser; hydrogen is collected at the cathode side, and oxygen is collected at the anode side. Each gas is then vented from the system through separate channels, ensuring no cross-contamination and maintaining high purity levels of the produced hydrogen.
- Hydrogen Conditioning: Post-electrolysis, the hydrogen gas undergoes conditioning to ensure it meets the specific requirements for aviation use. This includes compression to the desired storage pressure (500 barg), cooling to remove any excess heat generated during electrolysis and compression, and purification to remove any residual moisture or other impurities. The result is high-purity, compressed hydrogen ready for use as a clean aviation fuel.

2.5. Transportation and dispensing infrastructure

2.5.1. Mobile Storage and Dispensing Unit

In the context of this project, ZeroAvia will rely on the NanoSUN Pioneer to perform aircraft refuelling operations. It is worth noting that ZeroAvia's Infrastructure team is currently developing its own solution to cover the last mile delivery of hydrogen fuel to aircraft. This Mobile Storage and Dispensing Unit will include the following innovative capabilities:

- A chassis which is airside, meets road legality requirements, as well as ATEX safety zone requirements and is therefore allowed to go landside pick up hydrogen at any supply point around the airport and move around airside to perform refuelling activities.
- Compressed gaseous hydrogen storage cylinders capable of storing 700 kilograms of hydrogen at a pressure of c.500 bar.
- An advanced pressurisation system integrating a booster/compressor onboard the truck. This allows the refuelling unit to be agnostic to hydrogen sources between 20 and 500 bar. In addition, the truck integrates bidirectional headers to allow for inter-banks transfers to consolidate pressure, thus decreasing the ullage to c.10% of the total hydrogen capacity.

- a control system and human machine interface (HMI) which includes protocols for (i) refilling (hydrogen source to truck), (ii) re-consolidation of un-useable Hydrogen and (iii) refuelling (truck to aircraft).

The first two images below are computer-aided designs (CAD) of the Mobile Storage and Dispensing unit developed by ZeroAvia. They are side views of the trailer. It is open on the side and hence shows the load: six banks of hydrogen vessels. The last image is an actual picture of the MSD system in Kemble.

Mobile Storage and Dispensing unit developed by ZeroAvia

Mobile Storage and Dispensing unit developed by ZeroAvia

Mobile Storage and Dispensing unit developed by ZeroAvia

2.5.2. Logistics

In order to transport Hydrogen on UK public roads, your vehicle needs to be ADR compliant, which enables the transport of dangerous substances by road. When looking at the Nanosun Pioneer and ZeroAvia refueler, the trailer itself needs to be ADR compliant, as the does the tractor unit. It also requires an ADR trained driver.

2.5.3. Refuelling process, procedures and turnaround times

3. Flight Operations

3.1. Safety

A Flight Test Risk Assessment was conducted and is detailed in the Test Risk Assessment (TRA). During flight testing, system failures, observations, malfunctions, and defects were logged by ZA Airworthiness department. A record of this log is saved electronically on the ZeroAvia server. The airworthiness and safety impact of each item was classified by the Head of Airworthiness after each test. For each item and where applicable, mitigations or solutions were actioned, and the appropriate change control document or problem report number was recorded.

3.2. CAA permit to fly process

ZeroAvia does not hold a CAA Design Organisation Approval. As such the Approval of Flight Conditions and resultant Permit to Fly are both issued by the CAA on application from ZeroAvia.

3.3. Aircraft under test

The maiden flight of the ZA600 on G-HFZA was on January 19th 2023, which ran through to a test campaign of 10 flights, concluding July 13th 2023. The primary test objectives of the flights were met, with no handling qualities that caused the pilot undue concern. The aircraft exhibited no signs of undamped oscillations due to the new engine installation through the tested speed range and the flight altitude of 5,000ft was reached on the penultimate flight.

The Dornier DO-228-200 (aircraft constructor No. 8046) is used for the ZA600 development programme. The aircraft was operated by Aurigny Air Services Ltd from 2015 to 2021 and prior to this, two other EASA AOC organisations. It has circa 21,000 airframe hours and 40,000 cycles. The ZA600 powertrain installed on the aircraft has a reduced power profile in comparison with the engine it is replacing. It is fitted with a 5-blade fixed pitch propeller that operates at a different optimum RPM to the installed engine on the RHS.

Dornier 228 Demonstration flight to a UK commercial airport

3.4. Flight methodology and data capture

An assessment of aircraft performance will be made throughout the test programme as was completed in Phase 1 (A-A flight at Kemble) - with no changes to test techniques employed.

For level flight performance for normal operation (AEOP) will be established (if possible, across the wind) within the constraints of the limited geographical envelope. Cruise endurance test points will be conducted at a range of throttle settings at 120KIAS to determine optimum power setting for A-B flights. For flight performance for one engine inoperative (OEI) the aircraft will be configured to simulate a failed engine with the respective engine set to simulate zero thrust.

The ZA600 has a digital readout for battery and H2 usage that can be analysed against feedback power and Torque – this is also recorded automatically for review post flight. The turbine engine parameters are not recorded automatically, and fuel flow gauges are used as a rough estimate in stable conditions. A fuel counter in the aircraft can be used to estimate fuel usage over stable runs. Level flight performance will be normalised for temperature and altitude as recorded on the days conditions by the flight crew using a stabilised point technique.

Flight Test Instrumentation (FTI) is split between two categories. Category one is voice and video data capture. This is achieved with cabin mounted cameras attached to suitable, stable vertical surfaces within the cabin.

The second category is monitoring of the ZA600 powertrain. This uses a CANbus communication system to transmit critical parameters for its own operation and these are relayed to a cockpit mounted display for the FTE to enable monitoring. Additional cabin mounted displays are present for ground use that also record all data internally for subsequent download. CANbus data is additionally fed to the ground via a radio telemetry link installed on the aircraft. A ground station receives and monitors this data - supporting the flight test crew in monitoring of critical parameters.

4. Commercial and Economic Assessment

This project has been an occasion to rely on a real-life example to simulate the economics of a full hydrogen supply chain. ZeroAvia hence improved their financial model and their end-to-end analysis of the levelised cost of hydrogen, including hydrogen production, processing, storage, transport and refuelling to support commercial flight. The various cost components are the following:

- Capex: grid connection, electrolyser, compressor, storage, mobile storage and dispensing refueller and tractor unit
- Opex: grid fees (non-commodity charges), power costs (commodity charges), asset maintenance, fuel costs (transport), labour costs

ZeroAvia's hydrogen infrastructure model calculates the levelised cost of hydrogen under a variety of sensitivities and scenarios. An example output of this model is included below, it shows a sensitivity table of the levelised cost of hydrogen (LCOH) determined by variables such as the electrolyser capacity (in megawatts) and the price of electricity (in $).

Gaseous H2 - LCOH ($/kg)

Year Selector (2023-2050) 2023

Electrolyser Capacity (MW)	H2 Produced (Tonnes per Year)	Power Price ($/MWh) 200	175	150	125	100	75	50	25
0.3	35	26.1	24.3	22.6	20.8	19.1	17.3	15.6	13.8
1	136	17.1	15.6	14.1	12.5	11.0	9.5	8.0	6.4
5	707	14.4	12.9	11.4	9.9	8.5	7.0	5.5	4.0
10	1,471	13.4	11.9	10.5	9.1	7.7	6.3	4.9	3.4
15	2,206	13.3	11.8	10.4	9.0	7.6	6.2	4.7	3.3
20	2,941	13.2	11.8	10.4	8.9	7.5	6.1	4.7	3.3
50	7,636	12.9	11.5	10.1	8.8	7.4	6.1	4.7	3.3
100	15,272	12.3	10.9	9.6	8.2	6.9	5.5	4.2	2.9

Liquid H2 - LCOH ($/kg)

Year Selector (2023-2050) 2023

Electrolyser Capacity (MW)	H2 Produced (Tonnes per Year)	Power Price ($/MWh) 200	175	150	125	100	75	50	25
0.3	35	33.4	31.4	29.4	27.5	25.5	23.6	21.6	19.6
1	136	20.7	19.0	17.3	15.6	14.0	12.3	10.6	9.0
5	707	17.1	15.4	13.8	12.2	10.6	9.0	7.3	5.7
10	1,471	15.3	13.8	12.2	10.7	9.1	7.6	6.0	4.5
15	2,206	15.2	13.6	12.1	10.6	9.0	7.5	5.9	4.4
20	2,941	15.1	13.6	12.0	10.5	8.9	7.4	5.8	4.3
50	7,636	14.4	12.9	11.4	9.9	8.5	7.0	5.5	4.1
100	15,272	13.4	12.0	10.6	9.1	7.7	6.2	4.8	3.3

ZeroAvia's hydrogen infrastructure model calculates the levelised cost of hydrogen determined by variables such as the electrolyser capacity (in megawatts) and the price of electricity (in $).

At the end of the project, we will be in a position to compute actual financials based on a real-life example. It will allow ZeroAvia to showcase achievable levelised cost to support small aircraft demand use cases. The team will also perform a full well-to-wake lifecycle analysis comparison of hydrogen-electric flight versus incumbent jet fuel, in turn revealing an economic gap. The materials be used to promote policies and funding schemes targeted towards the development of hydrogen aviation.

ZeroAvia's life-cycle emissions model calculates the emissions produced from production to end use (well-to-wake) for jet fuel vs H2, showcasing the CO2e savings that hydrogen aviation can bring. An output of this model for a Cessna Caravan C208B is shown below. The bar chart compares the CO2-equivalent emissions across jet fuel (821 kgCO2e), hydrogen-electric flight with hydrogen being produced with solar energy (70 kgCO2e), hydrogen electric flight with hydrogen being produced with wind energy (35 kgCO2e) and hydrogen-electric flight with hydrogen being produced with electricity from the grid (409 kgCO2e).

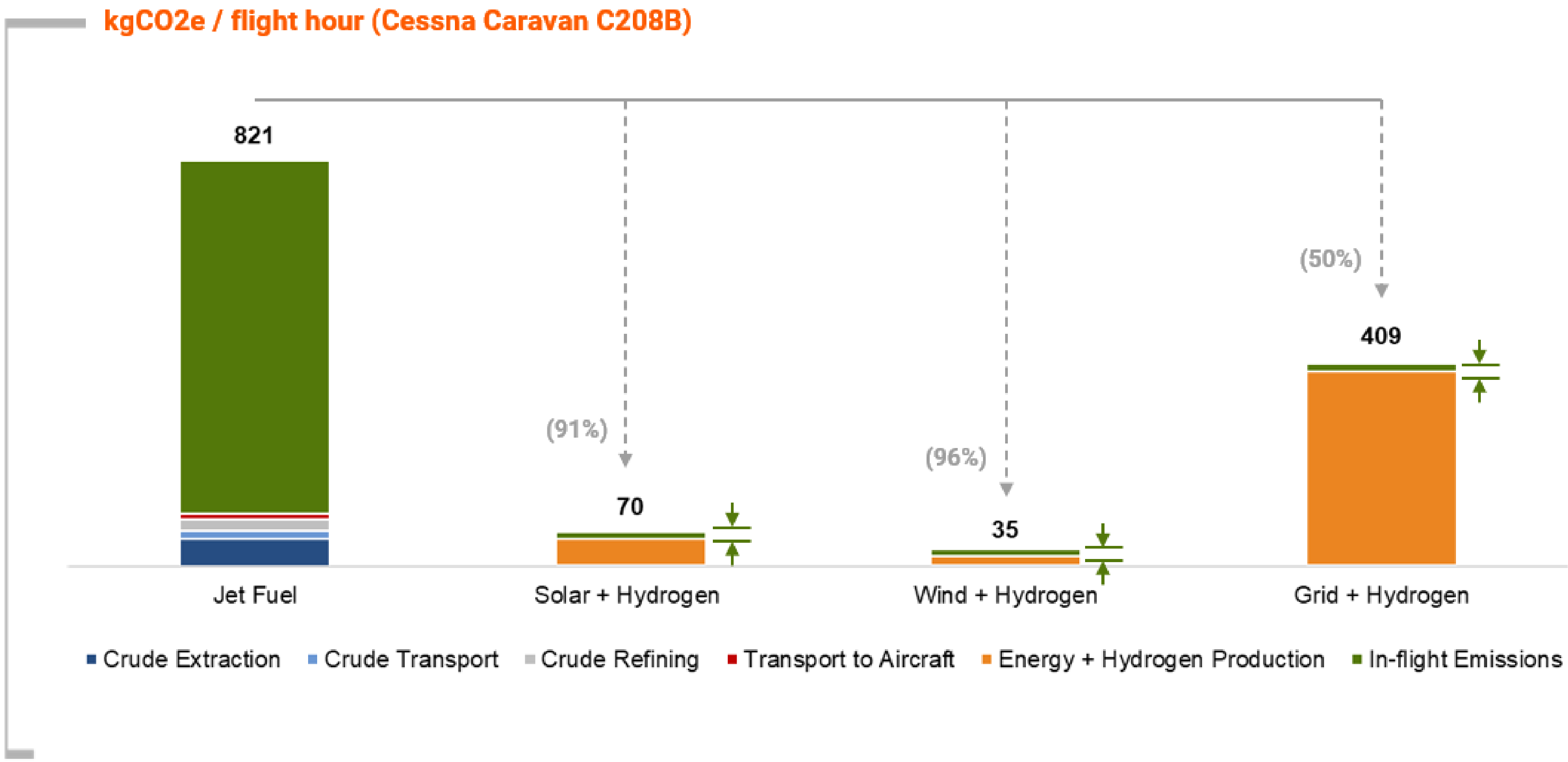
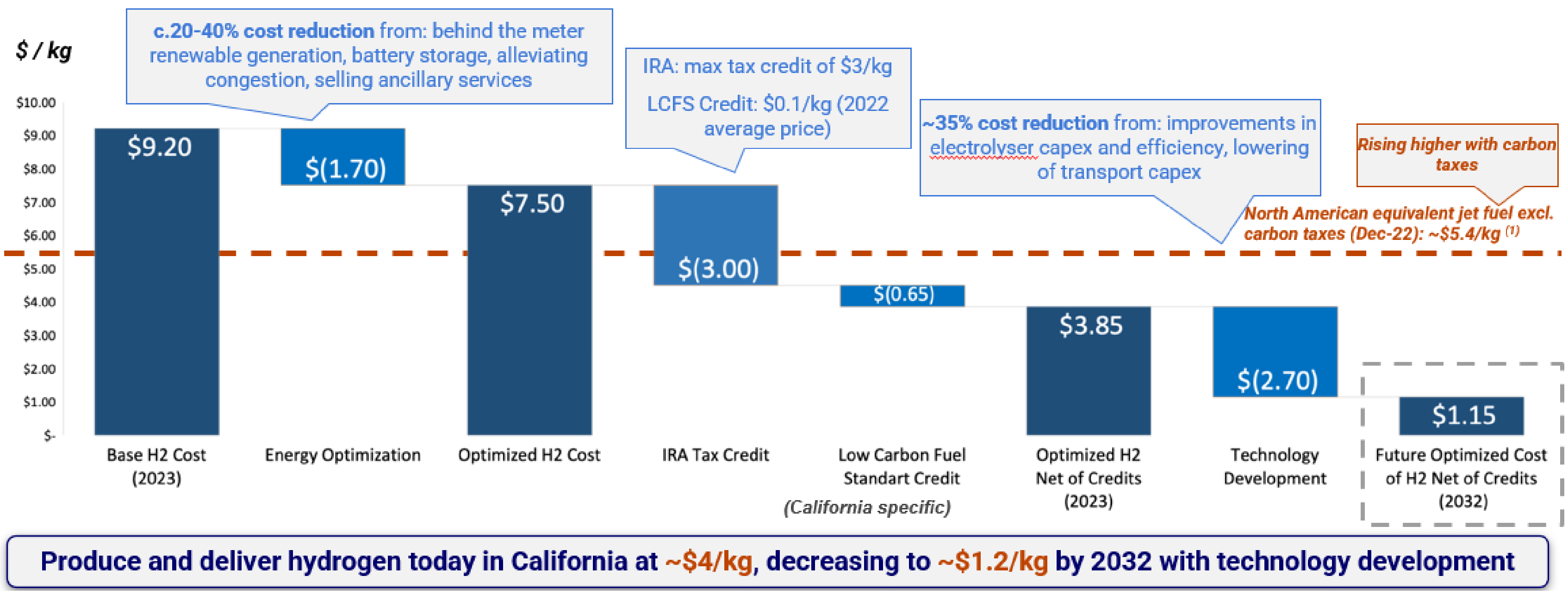


Chart comparing the CO2-equivalent emissions across jet fuel, hydrogen-electric flight with hydrogen being produced with solar energy, wind energy, and electricity from the grid.

- The levelised cost of hydrogen (LCOH) can be lowered by implementing the following recommendations:
    - Optimise asset utilisation by minimising downtime and limiting the number of shutdowns and ramp-ups, which will extend the electrolyser's lifetime and enhance its efficiency.
    - Secure grant, incentives and credits to offset green premiums.
    - Access low-cost power. Since power constitutes a significant portion of electrolysis costs, any savings on energy procurement will reduce the overall cost of the fuel.
    - Reduce effective power costs by implementing ZeroAvia's Smart Energy Management software (smart grid solutions). ZA's proprietary software optimises hydrogen production by generating hydrogen when electricity is cheapest and selling electricity to the grid when power is scarce or expensive.
    - Assess the advantages of economies of scale for hydrogen production and logistics. Economies of scale can be achieved by expanding the scope of hydrogen offtakers for a given production facility, serving multiple hydrogen applications such as ground support equipment at airports, buses, and heavy-duty transport.
    - Co-locate with renewable energy sources to reduce non-commodity grid charges and the overall levelised cost of production. By connecting directly to renewable power assets, you can indeed avoid grid connection and related taxes.

ZeroAvia's hydrogen infrastructure projects will look to minimise the levelised cost of hydrogen by optimising energy management, securing available tax and hydrogen credits, optimising project scale and leveraging technology developments. An output of this model, highlighting some of the cost reduction opportunities, is shown below for an illustrative project in the US. The bar chart starts with a base H2 cost and then shows a waterfall of various levers to optimise the cost. These levers include (i) energy optimisation (via behind-the-meter renewable generation, battery storage, congestion alleviation and sale of ancillary services), (ii) tax credits (Inflation Reduction Act in the US and Low Carbon Fuel Standard Credit and (iii) various expected technology developments (improvements in electrolyser capex and efficiency, as well as the reduction in capex related to hydrogen transport).

ZeroAvia analysis - H2 delivered cost to aircraft in California, USA (14 ton/day facility)



Key Assumptions: California location; gaseous hydrogen (no liquefaction); electrolyser size of 32 MW; mean electrolyser utilisation is about 82% and dynamically adjusted based on the grid conditions; electrolyser efficiency of 65%; project lifetime of 15 years; electrolyser capex of $1.6m/MW, flat wholesale power price of $88/MWh escalating at 2.1% CPI; mobile storage and dispensing truck transportation method (no pipeline); average round road trip of 300km

Note: (1) North American Jet-A fuel price of $0.97/kg pre-adjustment, corresponding to H2 breakeven price of ~$2.8/kg when adjusting for energy equivalence, and ~$5.4/kg when adjusting for improved engine efficiency (use more jet fuel for given output); assumes no carbon tax on jet fuel. Source: (1) IATA as of 02 December 2022.

5. Summary and next steps

The project aimed to showcase the end-to-end electrolytic hydrogen supply chain to support hydrogen-electric aircraft, thereby advancing decarbonised aviation in the UK. Despite the delay in obtaining the permit to fly from the Civil Aviation Authority, significant progress was made towards achieving the project's objectives.

We have completed all the preparatory work to provide hydrogen to the aircraft at an airfield other than ZeroAvia's R&D centre for the first time in the company's history. This established a robust foundation for the practical application of hydrogen in aviation. The project undertook a detailed analysis of the effective levelised cost of hydrogen for aviation use. This analysis identified key commercial metrics and challenges, setting the stage for achieving commercial viability by Q4 2025. The findings from this analysis are critical for informing future investment and development strategies. They will be complemented by actual data upon the performance of the flight.

Regarding the next steps, ZeroAvia expects to obtain the permit to fly from the Civil Aviation Authority shortly. We will then be able to proceed with the experimental flight, which is an important milestone to further enhance and validate aircraft performance, as well as the hydrogen supply chain in real-world conditions.

It is also important to note that the project will result in other achievements and knock-on effects. It will further enrich our internal techno-economic analysis and help us optimise the levelised cost of hydrogen. The project will raise awareness among the general public and attract interest from various stakeholders such as industry partners, airline customers, and regulatory bodies, thus helping to advance hydrogen-electric technology and the development of a supportive ecosystem.

By following these steps, we aim to continue advancing the hydrogen-electric aviation sector, contributing to a sustainable and decarbonised future for the aviation industry.