Blueprint for Zero Emission Flight Infrastructure

START

CATAPULT Connected Places

Funded by Department for Transport

EXECUTIVE SUMMARY

Airport and airfield infrastructure must rapidly evolve to enable net zero aviation and ensure the UK leads in zero emission aviation systems. Widespread adoption of Sustainable Aviation Fuel, hydrogen-powered and battery electric aircraft is critical to achieving the UK's goal of reaching net zero in aviation by 2050. These aircraft are expected to be operational in this decade. Planning the airport and airfield infrastructure for our net zero future must start now.

This mixed economy with electric and hydrogen-powered aviation operating alongside kerosene, jet fuels (of various types) and Sustainable Aviation Fuel (SAF) will increase the complexity of airport and airfield operations. New technologies will work in parallel, replacing the mature aviation fuel infrastructure over time. This parallel operation will require multiple infrastructures, policies, procedures and teams to coexist.

The Zero Emission Flight Infrastructure (ZEFI) programme, commissioned by the Department for Transport, is bringing together government, industry, regulators and academia to understand better the infrastructure changes required at airports and airfields to prepare for hydrogen-powered and battery electric aircraft.

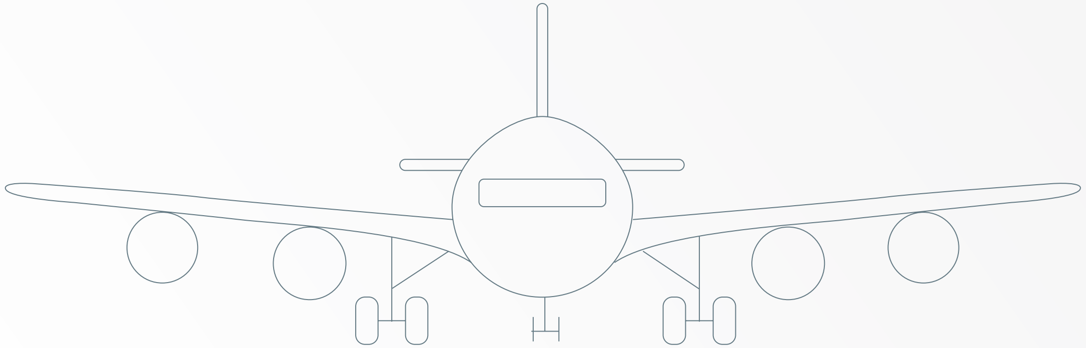
This work is part of the Government's commitment in the Ten Point Plan for a Green Industrial Revolution to invest in Research and Development (R&D) on the infrastructure upgrades required at UK airports to transition to hydrogen-powered and battery electric aircraft. General Aviation (GA) airfields, medium-sized regional and major commercial airports will need to service different aircraft technologies. ZEFI examines the resulting variety of infrastructure requirements.

The introduction of new infrastructure to prepare for net zero aviation presents challenges for airport and airfield operators, including:

- significant timescales from conception to operation of new airport and airfield infrastructure compared with the urgency to achieve net zero.
- various maturities of aircraft and infrastructure technologies and their interdependencies.
- construction and operation of new infrastructure while operating and maintaining existing infrastructure.
- funding in a challenging operating environment.
- few available standards, policies, procedures and training for the new infrastructure.

To ensure there is the necessary airport and airfield infrastructure to support net zero aviation in a timely and efficient manner, we propose the following interventions:

- Build a culture supporting the net zero transition, encouraging airports, airfields, and airlines to articulate their net zero needs through initiatives such as ZEFI.
- Technology developers and the aviation industry to work closely in collaborative research and development projects, and knowledge sharing initiatives.
- Government support with a particular focus on promoting research, encouraging investment, defining standards and regulations, and developing training.
- Aviation industry involvement in megawatt charging standards development and the Hydrogen Advisory Council.
- International and national coordination for cross-border operations, ensuring the most effective use of resources and coordinated delivery of net zero aviation.
- Cultivate a market for zero emission aviation with targeted financial support and incentivisation of net zero technologies and operations.



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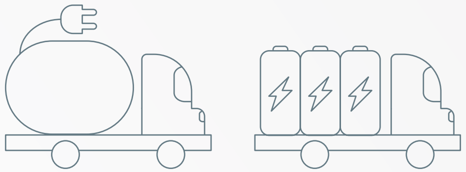

FOREWORD

KAREN DEE
Chief Executive
Airport Operators Association (AOA)

The climate emergency has not gone away during the COVID-19 pandemic and remains one of the pressing issues of our time. Air travel has delivered untold benefits to individuals, society, and our economy. Climate change now puts much of what we have built as a country at risk. We must therefore act to reduce our climate impacts in a way that preserves the benefits of air travel.

Our recovery from COVID-19 offers us an opportunity to change: the chance to return our passenger numbers to pre-pandemic levels without pre-pandemic climate impacts. UK airports and airfields are well-placed to do so. Through the Sustainable Aviation coalition, UK aviation was the first national aviation industry in the world to commit to net zero by 2050. We want to maintain our global leadership role in aviation's transition to net zero. This will benefit our climate, create green aviation jobs, and build expertise we can export.

Airports and airfields facilitate air travel, and we have our own unique role to play in aviation's decarbonisation. As aerospace manufacturers develop the propulsion technologies of the future and airlines work on increasing the uptake of sustainable aviation fuels, our ground-based infrastructure must be ready to support those steps towards net zero.

Ensuring our infrastructure is future-proof requires a vision for our future and cross-sector collaboration alongside close cooperation with the UK and devolved governments to deliver it. This Blueprint for Zero Emission Flight Infrastructure report is an excellent starting point for that journey towards net zero airport infrastructure. We are grateful for Connected Places Catapult's work in creating it.

As the AOA, our members and we are committed to delivering on the call to action this report represents. Now is our chance to build back better, and we must seize it.

RACHEL GARDNER-POOLE
Chief Operating Officer
Connected Places Catapult

The Department for Transport (DfT) has commissioned Connected Places Catapult to engage with industry to understand how airports and airfields can support the zero emission aircraft of the future. This work is critical to inform and prepare the sector for urgently developing and delivering the innovations and systems that will make net zero aviation a reality. The Zero Emission Flight Infrastructure (ZEFI) programme is focused on the integrated infrastructure required for net zero aircraft operations. The programme complements the research being conducted by FlyZero which focuses on conceptual aircraft, including the design, market conditions, and the key requirements to achieve commercial zero emission aircraft by 2030.

Connected Places Catapult has released a White Paper providing an overview of the available technology options and highlighting the key challenges needing to be solved. This Blueprint for Zero Emission Flight Infrastructure provides a detailed Operational Concept for the future aviation infrastructure required at airports and airfields to prepare for hydrogen-powered and electric aircraft. It presents a range of stakeholder views and challenges faced across the sector and recommends key interventions that should kick-start industry action and provide clear 'Jet Zero' objectives for aviation. This publication further supports the call to action for airports, airfields, and service providers to start considering their own requirements, and we invite you to engage with Connected Places Catapult as an independent body to help inform future research and development.

Decisive action is crucial to enable zero emission aviation to preserve the benefits of air travel and maximise the opportunities that decarbonisation can bring.

INTRODUCTION

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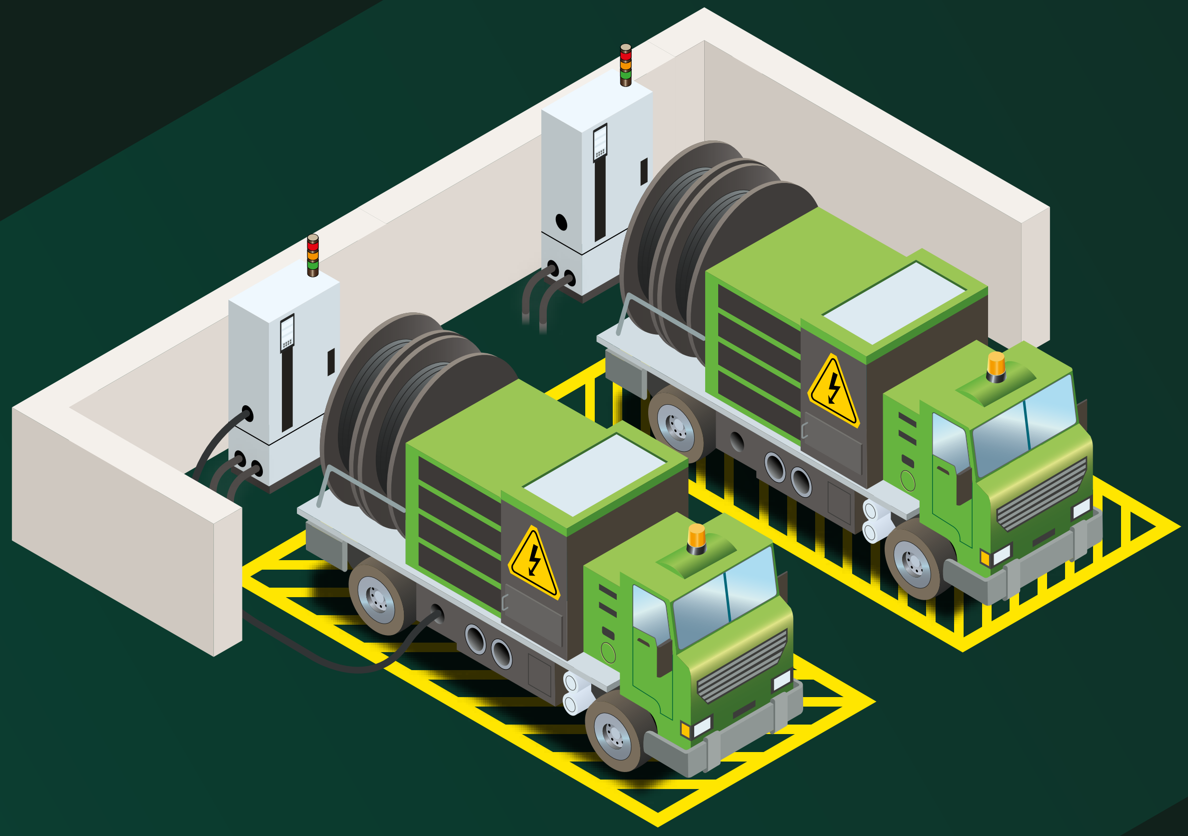


Introducing new hydrogen-powered and battery electric aircraft to reach net zero aviation will require significant infrastructure changes. This report outlines the options for these fundamental infrastructure changes and provides essential information to airport and airfield operators, and the broader aviation ecosystem. We present the technologies and subsystems that make up different options for infrastructure changes along with supporting systems and other aspects for airport and airfield operators to consider in their planning. The report also highlights the graduated transition for airport and airfield infrastructure to support net zero aircraft with key challenges and interventions for operators, the wider aviation industry, government, and regulators.

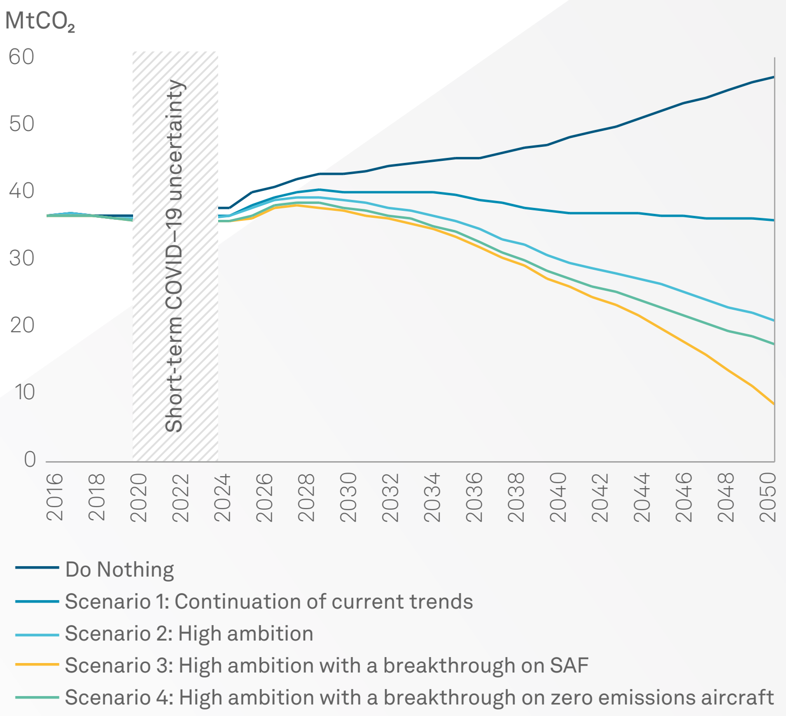
The domestic Greenhouse Gas emissions from transport amounted to 27%, totalling 122 $MtCO_2e$ (million tonnes of carbon dioxide equivalent), of the UK's emissions in 2019 [1]. UK domestic and international aviation emissions combined caused 38 $MtCO_2e$ emissions, contributing to 23% of the UK's total emissions from all transport modes. In the past three decades, the emissions from most transport modes have been stable. However, international aviation emissions have more than doubled from 16 $MtCO_2e$ to 37 $MtCO_2e$ [2]. While the drive to net zero cuts across all industries, aviation plays a critical role in decarbonisation.

Background

The UK government committed in 2019 to "ensure that the net UK carbon account for the year 2050 is at least 100% lower than the 1990 baseline" [3], and in 2021 this was extended to include the UK's share of international aviation emissions. In 1999, the Intergovernmental Panel on Climate Change (IPCC) stated that the gases and particles emitted by aircraft "alter the concentration of atmospheric greenhouse gases, including carbon dioxide (CO_2), ozone (O_3), and methane (CH_4); trigger formation of condensation trails (contrails); and may increase cirrus cloudiness – all of which contribute to climate change" [4].

The UK Government's Net Zero Strategy states, "We will address aviation emissions through new technology such as electric and hydrogen aircraft, [and] the commercialisation of sustainable aviation fuels [SAF]…" [5]. The substantial adoption of SAF, hydrogen-powered and battery electric aircraft will be critical to achieving the UK's net zero goals. The different scenarios for UK aviation decarbonisation are shown in Figure 1. Additional infrastructure, supporting systems and operations will be required at airports and airfields to realise the full potential of the opportunity.

Figure 1: Aviation decarbonisation scenarios reproduced from the Department for Transport Jet Zero Consultation [6] under the Open Government Licence v3.0



Air traffic is expected to continue to grow by 2050; the Balanced Net Zero Pathway from the Committee on Climate Change (CCC) assumes 25% growth by 2050 compared to 2018 [7]. This growth intensifies the need to significantly reduce greenhouse gas emissions per flight to achieve net zero aviation.

There are also commercial and geopolitical reasons to ensure air travel is less vulnerable to disruption from global fuel supply and price dynamics. Fuel is often cited as a significant element of airline operating costs, and managing the risk of fuel price increases is an important activity for most airlines.

The Sustainable Aviation organisation representing the aviation industry in the UK has committed to achieving net zero emissions by 2050 [8], and pressure from national governments, intergovernmental organisations, and regulators is being applied via schemes such as the International Civil Aviation Organisation (ICAO) Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA).

There are opportunities to reduce carbon emissions associated with the aviation industry by reducing demand with market interventions and influencing consumers, improving airport and airfield operations, airspace design and air traffic management. However, significant reductions are predicted to come from improvements to aircraft and propulsion system technology [9]. These interventions are also highlighted in the 'Jet Zero' Consultation [10] on the government's vision and strategy for net zero aviation.

Programme scope

The Zero Emission Flight Infrastructure (ZEFI) programme, led by Connected Places Catapult for the DfT, aims to understand the airport and airfield infrastructure required to support hydrogen-powered and battery electric aircraft.

ZEFI focuses on systems and technology for fixed-wing aircraft use, which emit zero greenhouse gases. We acknowledge that future airport and airfield environments will contain a spectrum of other aircraft technologies. These include partly greenhouse gas emitting solutions such as hybrid-electric and net-zero technologies such as Electric Vertical Take-Off and Landing (eVTOL) aircraft, rotorcraft and airships. Whilst these were not explicitly considered by this report, much of the infrastructure discussed will also support these solutions.

The report considers the fuel or energy flow from arrival at the airport or airfield to the connection to the aircraft. The electric and hydrogen supply chain outside the physical site boundary and the design of zero emission aircraft provide context for the report but fall outside the direct scope. Other parallel projects are researching these areas.

Figure 2: ZEFI work packages

Work package					
Programme Inception	Literature review	Stakeholder identification	Existing review infrastructure	Airport and airfield categorisation	TRIG:ZEF grant package definition
Operational Concept	Electric	Hydrogen	SAF		
Systems Analysis	Major Commercial Airport: Hydrogen	Medium Sized Airport: Hydrogen and Electric	Small GA Airfield/Airport: Hydrogen and Electric		
Technology Roadmapping	Electric	Hydrogen			
Standards Gap Analysis	Electric	Hydrogen			
Dissemination	Demos and events support	Reports and case studies	Showcase event		

← Demonstration programme →

← TRIG:ZEF →

Figure 2 shows the ZEFI programme structure linking stakeholder insights, analysis, and outputs. The study summarises the broad range of required changes to infrastructure, technology, operations, and skills across the aviation industry to support the transition to zero emission aircraft at UK airports and airfields.

This Operational Concept Blueprint Report was developed, taking input from a wide range of sources and stakeholders and condensing them into a vision for the options available for future airport and airfield infrastructure. This report highlights the similarities and differences between the existing fuels, SAF, hydrogen, and electrically powered aviation systems. Each airport or airfield may only implement a subset of the available technologies, depending on the aircraft and routes supported and their specific constraints and requirements.

This Blueprint document presents the systems as a 'menu' of options focussing on the technical features of each technology or system. We investigate the technologies' impact on operations, people, safety and supporting systems. In doing so, we describe the systems functionally, irrespective of the airport or airfield size and routes serviced, showing the constraints and requirements imposed by these different environments.

Our case study and system analysis work showcases the scale of progress and the spectrum of strategies taken by airports and airfields to prepare and plan for the transition to new zero emission technology. The case studies will share insights into the different approaches being taken by UK airports and airfields to plan for the transition by considering the following:

- Changes needed to the infrastructure and operations.
- Benefits and risks associated with zero emission technology.
- Maturity and readiness levels of airfields and airports.
- Future players in hydrogen refuelling and electric charging.

After this operational concept and the case study work package, the next step in the progamme will develop a technology and standards roadmap for the transition to hydrogen-powered and battery electric infrastructure. The roadmap outputs will present a phased approach to commercialising and implementing new technology that addresses the urgent challenges that airports and airfields face. The roadmap will provide a timeline and guidance on how airports and airfields may reduce their risk exposure and unlock the opportunities offered by the new and exciting systems becoming available during this critical transition.

The ZEFI Programme also supports demonstrations to showcase UK technology and innovation and build our understanding of hydrogen and battery technologies in airside environments. Finally, the programme also hosts the Transport Research and Innovation Grant: Zero Emission Flight (TRIG:ZEF) competition to support UK research and development related to zero emission flight infrastructure. The competition has offered grants of up to £50,000 to fund 15 innovative technology development projects, and the winners have been announced.

Target audience

From large international hub airports to General Aviation airfields, all types of aerodromes need to make infrastructure changes to support future aircraft. To encourage and support the preparation for this change, the operators of airports and airfields are the primary audience for this report. As well as airport and airfield operators, this report also targets the broader aviation ecosystem, airlines, technology developers, the energy sector, government and regulators to inform, engage and ensure the goal of net zero aviation is achieved.

SYSTEM DEFINITION

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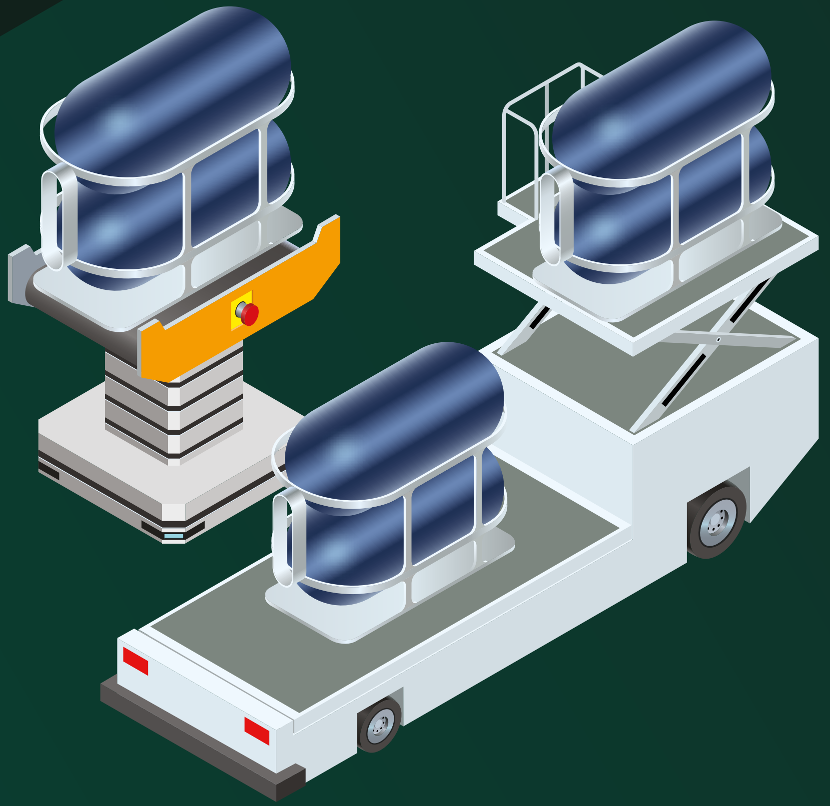


System boundary

This report focuses on the infrastructure, operations and human factors within an airport or airfield environment. The supply and production of fuel and electricity are out of scope and assumed to scale up in line with the demand from changes to airport and airfield infrastructure. Similarly, the aircraft fleet and accompanying maintenance and inspection activities are out of scope. This study will not explore potential changes and impacts on airframes and aircraft design caused by new technology and fuel types.

It is essential to understand the external environment where the system resides. It provides context to the future zero emission aviation system and the projected changes required. The external environment includes fuel, hydrogen and electricity supply and production.

At present, SAF and hydrogen production in the UK is limited and may involve long transport connections for delivery to the airports and airfields. However, this is expected to move closer to airports and airfields over time, for instance, hydrogen hubs providing local storage outside the airport or airfield. Likewise, locations near waterways or railway lines may utilise those connections for delivery. More detail is set out in the UK Government's Hydrogen Strategy [11].

The electrical demand at airports and airfields will increase significantly. Current production is primarily external to the site, with only some operators starting to introduce their own renewable generation. Zero emission aviation, combined with growing domestic demand (e.g. electric vehicles), will necessitate power distribution changes and significant increases in power network capacity.

At the upstream end, the system boundary sits at the threshold where electricity, fuel or hydrogen (in various formats) enters the airport or airfield. For the electrical system, the boundary is physically at the incoming feed from the electricity distribution network into the on or near- site sub-station and transformer. For the fuel and hydrogen systems, the boundary sits at the point where fuel is measured and its custody transferred from either a pipeline or a road or rail delivery method to the airport or airfield's fuel handling.

On-site generation of electricity is included within the scope of ZEFI but will not be explored in detail as the technology is already mature. It delivers an optional solution to decarbonise the electricity supply for the airport or airfield, which can be used for the electrolysis of hydrogen or other electrical applications.

At the downstream end of our system, we consider the point of connection to the aircraft. Our system of interest includes the plug connectors and hose connectors used to charge or refuel the aircraft but is not concerned with any aircraft design or internal systems. This includes conceptual technologies such as those used for battery electric, hydrogen tank or fuel cell swapping. For these technologies, we have interest in system interoperability (e.g. size, interfaces and couplings), but are not concerned with airframe integration.

System overview

The system is conceptually divided into three principal areas (shown in Figure 3):

1. **Core Functional Systems** – These systems take primarily physical forms and perform discrete functions in the end-to-end conveyance of either electrical charge, fuel or hydrogen from the point of entry into the airport or airfield domain until the point of entry into the aircraft. We have grouped these systems into four process zones:

   a. Arrival and On-site Generation
   This grouping includes the delivery of either electrical charge or hydrogen and fuel into the airport or airfield site. It includes the transfer of the fuel from the delivery vehicle or the voltage conversion from national networks or distribution systems into an appropriate voltage for use in the airport and airfield environment. On-site electricity generation is included in this process grouping but will be considered a black box due to the maturity of commercial solar and renewable technology. For this study, the on-site production of hydrogen is limited to 'green' hydrogen electrolysis from either renewable or grid sourced energy. This process is currently the most easily scalable in an airport or airfield setting and lowest CO_2 equivalent emissions per unit (for renewable electrolysis) modelled in the UK's Hydrogen Strategy.

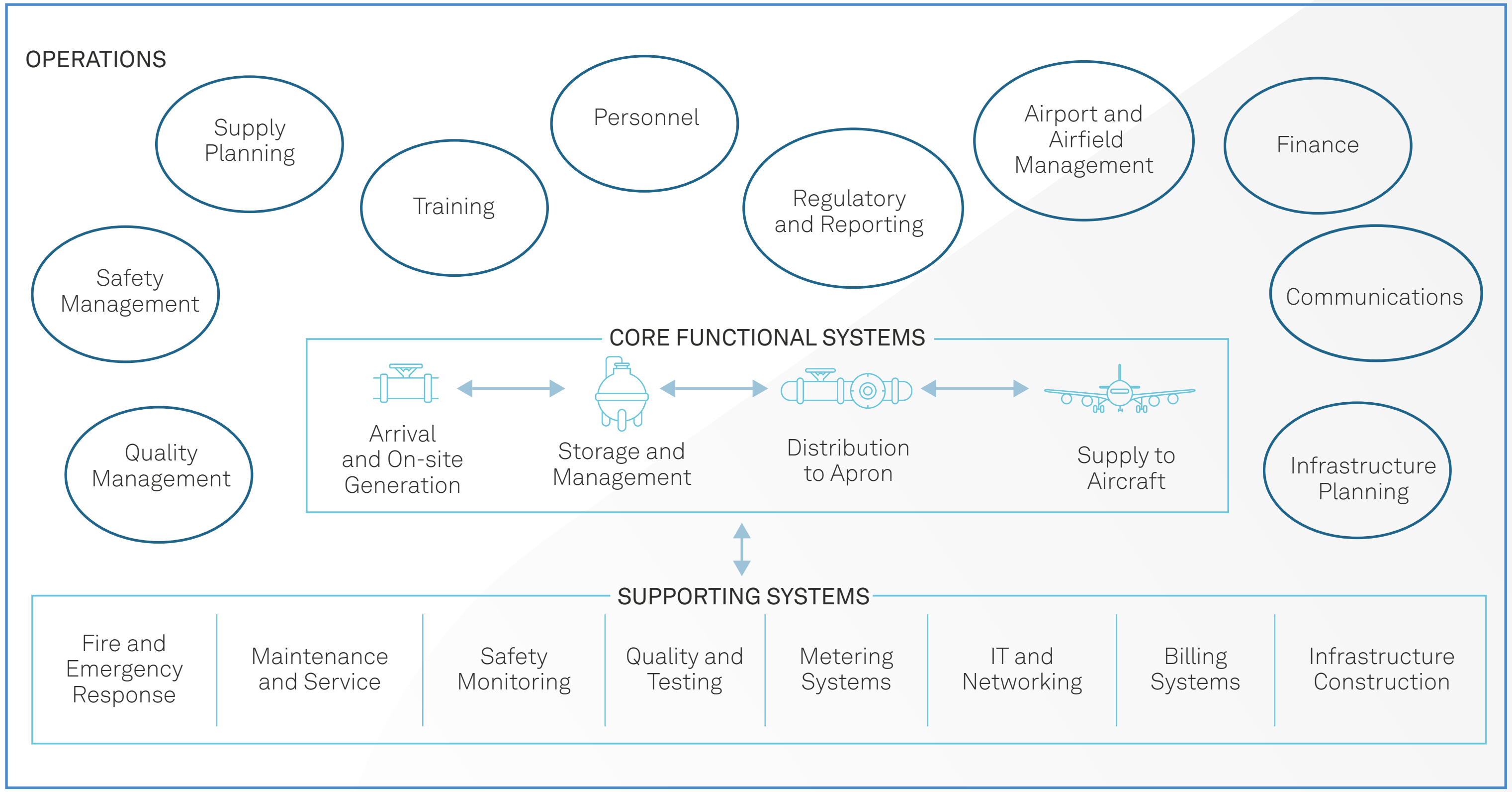
b. Storage and Management
This group of functional subsystems includes the on-site storage and management of the electricity, fuel or hydrogen. These systems are there to provide a buffer capacity to fulfil fuelling requirements and control the flow of fuel and electricity where required.

c. Distribution to Apron
This group of subsystems act to transfer the electricity or fuel commodities via either fixed or mobile systems from their storage locations to the apron, and onto the aircraft stands, ready to supply the aircraft.

d. Supply to Aircraft (fuelling, charging and swapping)
The final grouping includes the subsystems to interface directly with the aircraft for charging, battery swapping, hydrogen fuel cell or tank swapping, or aircraft refuelling.

2. **Supporting Systems** – These systems either provide functions in degraded or emergency operating conditions or support the Core Functional Systems in a way that isn't directly required to convey fuel, hydrogen, or electrical charge.
3. **Operations** – These aspects describe the organisational and operational environment within which the Core Functional and Supporting Systems exist.

Figure 3: System overview diagram showing the three areas considered within this Blueprint for Zero Emission Flight Infrastructure Report.



EXISTING SYSTEM

03

New sustainable aviation fuels will be a crucial piece of the puzzle in supporting the managed transition to zero emission flight.

Introduction to Sustainable Aviation Fuel

Sustainable Aviation Fuels (SAF) are one important element required to drive the decarbonisation of aviation and reach the 2050 net zero target. They provide a sustainable alternative to conventional aviation fuel that is compatible with existing aircraft. As electric, hydrogen and hybrid-powered propulsion systems develop in maturity, SAF provides an interim solution now to reduce life-cycle greenhouse gas emissions. In the longer term, SAF is expected to remain in place for long-haul flights where battery electric technology does not provide the performance required [12].

The production of SAF utilises a wide range of recycled carbon and biomass-based source materials. SAF is currently blended with conventional fuels to achieve drop-in compatibility, ensuring sufficient aromatic hydrocarbons in the blend for optimal engine operation. The currently qualified blends contain between 5% and 50% SAF (most are certified at 50%) with a goal to increase this to 100% in the future. New blends and production methods are an active area of industry development, but investigation of this topic is outside the scope of the ZEFI programme. SAF is already in use by UK airports and airfields where it is commingled with conventional aviation fuels within the storage tanks. SAF blending is expected to remain external to the airport or airfield. The SAF supply chain is developing, and availability is therefore limited; growth is required in domestic and international supplies to meet the predicted demand from aviation. Much of the SAF in use travels significant distances by road due to the low levels of UK production at present.

Sustainable Aviation Fuel infrastructure

SAF utilises the existing aviation fuel infrastructure. There are no anticipated changes unless compatibility issues require the separate storage of alternative blends.

Aviation fuel arrives at the airport by road, rail or pipeline. Large airports are typically served by dedicated pipelines supplying jet fuel to the on-site storage system through a series of valves, meters and filters. Receipt of fuel occurs before the custody transfer meter on the airport receiving system. In the case of road and rail, quality checks are carried out on the fuel at the receiving and unloading station.

The jet fuel received is processed through a series of filters to remove contaminants and water. The fuel is then pumped into the storage tanks at the airport to allow for settling and further checks. The stored fuel is recertified before being distributed to the apron via either a hydrant system or loaded into bowser vehicles.

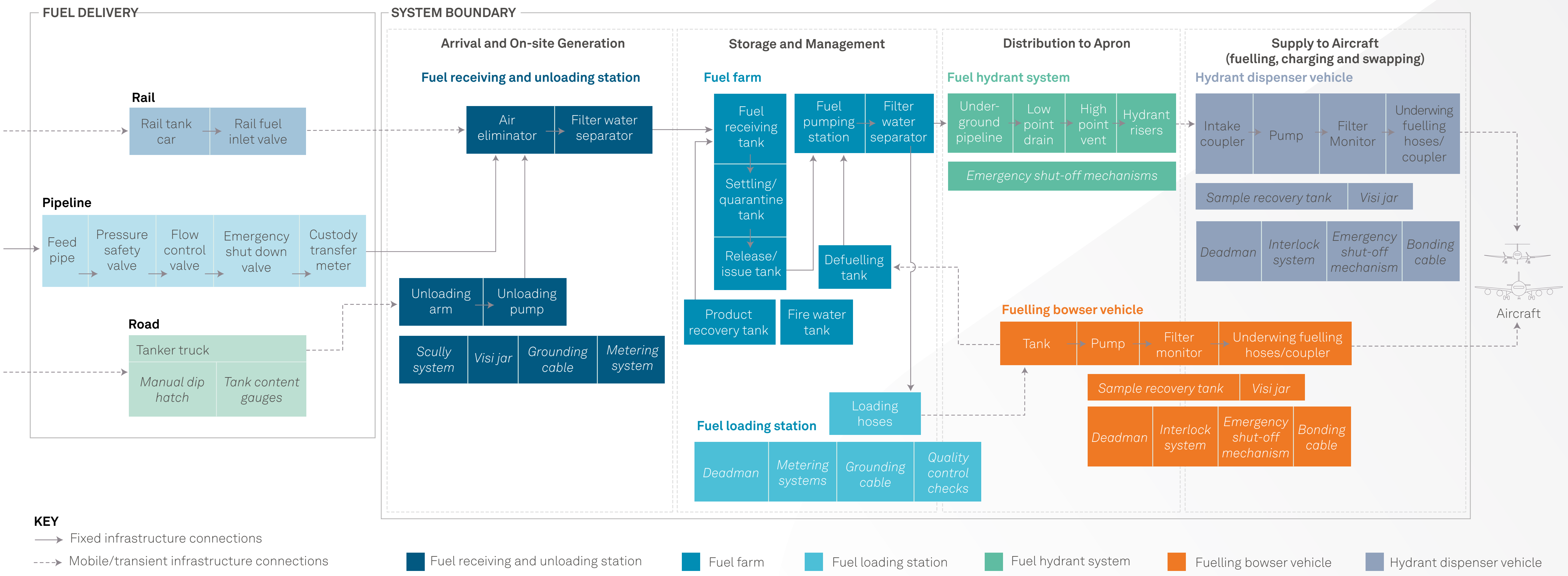
For bowser delivery, quality checks are also performed at the fuel loading station on the fuel provided. The bowser will be used to fuel the aircraft at a stand or parking location on the apron by pumping fuel through hoses into an underwing connection. The bowser can also be used to defuel an aircraft and return fuel to a defuelling tank in the fuel farm. The returned fuel can be checked and released back into the fuel system or disposed of.

The hydrant system consists of primarily underground pipework delivering fuel to stands and the apron. When a hydrant system is used, a dispenser vehicle is connected between the hydrant system riser and the underwing aircraft fuelling points. The dispenser controls the flow of fuel into the aircraft, the volume delivered and ensures fuel quality.

Both dispenser vehicles and bowsers feature multiple systems to ensure safety including earth bonding, deadman systems and interlocks.

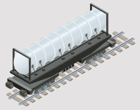
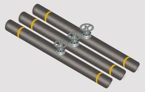
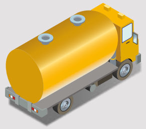
The location of the fuel farm may be either airside, landside or split depending on the airport security arrangements and design. This can cause significant challenges where vehicles have to regularly transit through the security points at the boundary fence. In some cases, at busy times, additional bowsers are required to be filled and staffed airside to prevent bottlenecks through security.

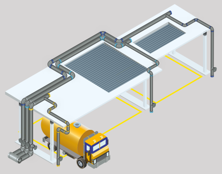
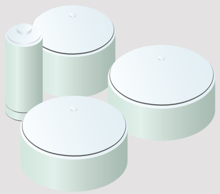
Figure 4: Existing fuel and SAF system architecture

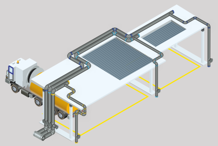
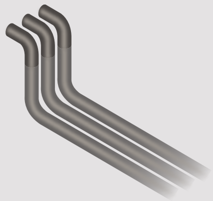


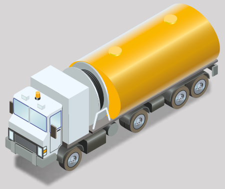
Subsystem breakdown

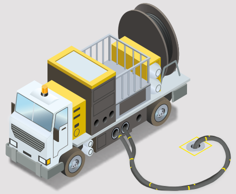
Table 1: Existing fuel and SAF subsystems and components

Subsystem		Description	Components	System data, thresholds, and constraints
Fuel delivery	Rail 	Fuel arrives in rail fuel wagons.	• Rail fuel wagon. • Rail fuel inlet valve.	
	Pipeline 	Fuel arrives at the fuel farm via pipeline from the refinery/terminal.	• Feed pipe. • Pressure safety valves. • Flow control valves. • Emergency shut down valves. • Custody transfer meter.	• Single source supply of fuel to the airport. • Pipeline maintenance or repair can create a shortage of fuel supply. • Off-specification product is difficult to drain from the pipeline. • A closed system is created between the refinery/terminal and the airport whereby the blending of fuel is restricted. • Length of pipelines can impact the properties of the fuel. • Pipeline delivery flow rate is ~25,000 L/min.
	Road 	Fuel arrives at the fuel farm via truck from the refinery/terminal.	• Tanker truck. • Manual dip hatch (hatches can be opened when required to carry out dipping or sampling). • Tank content gauges.	• Road banned schedule of heavy vehicles impacts the delivery of fuel on time.

Subsystem	Description	Components	System data, thresholds, and constraints
Fuel receiving and unloading station 	Fuel arrives via tanker trucks and offloads the fuel at the unloading station into the storage tanks.	• Unloading arm. • Unloading pump. • Air eliminator. • Filter water separator. • Scully system (overfill prevention system). • Visi jar (closed sampling jars for visual examination and aviation fuel quality control). • Grounding cable. • Metering system (measurement of quantity unloaded).	• A low flow rate can impact the time to offload the fuel. Causes include: – an inadequate pump – inadequate piping size • Usually rated for ~1,100 L/min of flow capacity each, taking approximately 30 minutes to empty a truck.
Fuel farm 	Storage of fuel on-site. Inventory management, quality management, and recertification of fuel.	• Three main storage tanks: – Receiving tank. – Settling/quarantine tank. – Release/issue tank. • Fuel pumping station. • Filter water separator (separates water and sediments from fuel). • Defuelling tank. • Product recovery tank. • Fire water tank.	• Blending is permitted off-site only. • Commercial airports – storage should cover a minimum of three days [13]. • Commercial airports with scheduled flights (minimum of three storage tanks): – Large-scale airport storage ~11-50 million Litres total. – Medium-scale airport storage ~5-10 million Litres total. • General and Business Aviation (typically one storage tank per fuel type): – Small Airfield ~10,000-100,000 Litres (typically JetA1, AVGAS).

Subsystem	Description	Components	System data, thresholds, and constraints
Fuel loading station 	Refuellers are loaded for the subsequent refuelling of aircraft that cannot be fuelled from the hydrant system. The loader of the refueller does quality control checks prior to releasing it for refuelling an aircraft as per loading procedure.	• Loading hose. • Deadman (deadman system is a safety device with intrinsically safe wiring that confirms a critical operation is constantly supervised). • Metering system. • Grounding cable. • Quality control checks.	• Insufficient loading bays for loading of the refuellers. • Increased time for fuel delivery to aircraft compared with a fuel hydrant system.
Fuel hydrant system 	Jet fuel hydrant systems consist of a network of underground piping transporting fuel from storage tanks to aircraft while managing fuel intake.	• Underground pipeline. • Low point drain. • High point vent. • Hydrant risers. • Emergency shut-off mechanism.	• Require regular inspections of pipeline condition to avoid deterioration of fuel quality with appropriate maintenance to manage debris and water accumulation. • Access must be available to valve chambers, drains and vents for flushing and maintenance activities. • Appropriate controls must be in place to ensure compliance with environmental regulations.

Subsystem	Description	Components	System data, thresholds, and constraints
Fuelling bowser vehicles 	Refueller vehicles (bowsers) are designed for efficient and safe aircraft refuelling at any location; transferring fuel into an aircraft from its vehicle-mounted storage tank via a pump, filter, and metering system.	• Tank. • Pump. • Filter monitor (separate water and from the fuel). • Underwing fuelling hoses/coupler. • Deadman (deadman system is a safety device with intrinsically safe wiring that confirms a critical operation is constantly supervised). • Interlock system (fuelling components interlocked to the vehicle immobilisation system). • Emergency shut-off mechanisms. • Sample recovery tank. • Visi jar (closed sampling jars for the visual examination and quality control of aviation fuel). • Bonding cable (bonding cable to protect operators from electrical and static shock during the aviation ground fuelling process).	• Currently, fuel is provided to aircraft at a rate of: – ~2,000 L/min for a wide-body aircraft. – ~1,000-1,500 L/min for a narrow-body aircraft.

Subsystem	Description	Components	System data, thresholds, and constraints
Hydrant dispenser vehicles 	The hydrant dispenser can efficiently dispense aviation fuel from an underground hydrant system into a jet aircraft by aviation refuelling personnel via the underwing nozzles.	• Intake coupler. • Pump. • Filter monitor (separate water from the fuel). • Underwing fuelling hoses/coupler. • Deadman (deadman system is a safety device with intrinsically safe wiring that confirms a critical operation is constantly supervised). • Interlock system (fuelling components interlocked to the vehicle immobilisation system). • Emergency shut-off mechanisms. • Sample recovery tank. • Visi jar (closed sampling jars for visual examination and aviation fuel quality control). • Bonding cable (bonding cable to protect operators from electrical and static shock during the aviation ground fuelling process).	• Currently, fuel is provided to aircraft at a rate of: – ~1,000-1,500 L/min for a narrow-body aircraft. – Up to 4,000 L/min is possible with dual fuel points.

Supporting systems

The existing system (as represented in Figure 4) is supported by many other systems required for safe and efficient operation including during degraded and emergency operational scenarios. The key supporting systems are listed in Table 2.

Table 2: Existing fuel and SAF supporting systems

Routine Operations	Integrated Control System (ICS)	Medium and major airports tend to contain an Integrated Control System (ICS), giving an overview of fuelling and other airside operations. This automated system consists of three independent control systems, the Plant Control Systems (PCS), the Safety Integrated System for Emergency Shut Down (ESD) and the Fire Alarm System (FAS). The control systems are distributed across all the fuel infrastructure areas and are integrated via a network of Ethernet switches and fibre optic cables.
	Storage management	The safe storage and management of fuel stock is critical to supporting the fuelling of aircraft. Radar tank gauging systems measure storage tank level, temperature, and pressure. These systems are used for inventory control, fuel movement, and overfill prevention to ensure efficient storage and management operations. Each system is interfaced with the ICS to manage the receipt and discharge of certified fuel.
	Aviation refuelling management	Each user in the refuelling operation can access relevant information, allowing accurate and efficient completion of each transaction. From the office to fuel delivery, every user is updated with the progress of each transaction in real-time for billing purposes.
Commercial		Refuelling operations are usually either run in-house by the airport or airfield, or they can be contracted out to another entity to manage. A process or system for logging and billing is required. The availability of different SAF blends will involve more complex commercial management.
Maintenance		Maintenance and inspection procedures are well established for existing fuel infrastructure.
Quality		Quality control is a well-established part of existing refuelling services with mature standards in use. The introduction of SAF at different blends necessitates new standards being agreed upon and published. Following this, appropriate systems and processes must be implemented on-site.

Safety and backup	Emergency Shutdown (ESD) system	Emergency shutdown procedures and automated ESD systems are designed to prevent emergencies or hazardous situations escalating, which would endanger personnel, the fuel infrastructure, and the operational environment. An automated ESD system interfaces with the FAS and provides information to ICS. The scale of the shutdown should be proportionate to the risk and is often based on a Shutdown Level Hierarchy.
	Rescue and Fire Fighting Service (RFFS) / Fire Alarm System (FAS)	Airports and airfields in the UK must have an appropriate Rescue and Fire Fighting Service (RFFS). The service would include the personnel, procedures, equipment, and supplies. The Fire Alarm System (FAS) is responsible for the detection of fire, processing of fire signals, and notification of the fire signal to the RFFS. All fire alarm systems are linked with the central (and satellite) fire station(s) through an airport-wide data network that passes alarms, supervisory and trouble information. The system alerts the RFFS within 0.5 seconds who respond to the situation with fire trucks, foam systems and firefighters as required. Aqueous Film Forming Foam (AFFF) and water are used to fight conventional fuel and SAF fires.
	Leak Detection System (LDS)	A Leak Detection System (LDS) is often used to sense leaks from fuel pipelines. Cables are installed with the pipeline and ensure the continued protection of the whole hydrant pipeline network. The LDS should identify when and where the leak is for corrective action to be taken.
	Generator and Uninterruptible Power Supply (UPS)	UPS and generators provide backup power to the critical systems for signalling systems, air traffic control, ICS, on-site data centres and emergency lighting systems for continuity of operations in the event of a power outage.

Operations and people

Qualified personnel manage the existing fuel operations, along the entire supply chain from the refinery to fuelling the aircraft. Personnel carry out tasks including fuel transfers, supply and storage management, safety management, and quality procedures. All personnel should be thoroughly familiar with the relevant operating procedures, safety and fire protection regulations applicable to the operation of aviation fuel handling facilities at the fuel farm. All personnel require appropriate airside security clearance including visitors.

Refuelling operations should be carried out by competent personnel who are thoroughly trained in Joint Inspection Group (JIG) aircraft fuelling procedures [14]. Personnel must be fully trained in the operation of fuelling equipment and the actions to be taken in the event of an emergency as defined in the airport or airfield's aerodrome manual.

Constraints and risks

Airport and airfield operations are dependent on external stakeholders for the supply of aviation fuel. If there is any interruption to the fuel supply, there will be a shortage of fuel on-site, ultimately leading to operational disruption and closures.

The last few years have demonstrated the fragility of this complex system and the threat posed to air-service continuity. For example, pipeline explosions [15] caused stoppages that threatened to shut down airports that were dangerously close to running out of fuel. Pipelines operate as a closed system where issues can be difficult to resolve.

Refinery disruption is a significant upstream risk managed by fuel handlers. Scarcity of storage within the supply chain can lead to the cancellation of fuel shipments, placing larger airports in a precarious fuel shortage situation. Likewise, disruption to the transport network can significantly affect road delivery.

Safety

The aviation industry is highly regulated and standardised by different organisations with proven safety procedures and quality, resulting in a historically low risk of system failures.

The Civil Aviation Authority (CAA) provides oversight to ensure compliance of the aviation fuel supply chain. They carry out regulatory audits on the fuel suppliers and Fixed Base Operators (FBOs) who operate the end-to-end fuelling processes.

Airport and airfield facilities are designed, constructed, maintained, and operated as per the approved international standard bodies for jet fuel. These standards, combined with regulatory oversight, ensure the highest level of flight safety.

The fuel handling organisations ensure that the fixed and mobile facilities used for the storage and handling of fuels are adequate and properly maintained as per the applicable standards. Safety regulations and quality assurance requirements must not be infringed during maintenance work or alterations.

Conventional fuel can be dangerous if not handled carefully. First and foremost, it is easy to ignite, and burns rapidly. Secondly, exposure to jet fuel vapours can lead to various health issues, and therefore should be limited. Personnel handling jet fuel must be familiar with the Material Safety Data Sheet (MSDS) from the supplier.

Quality

Fuel quality is an integral part in ensuring flight safety and quality checks occur at multiple points in the supply chain. The fuel product specifications are a mechanism by which producers and users of a product identify and control the properties necessary for satisfactory and reliable performance.

Trained personnel carry out quality checks [16] at the storage tanks. Sampling is undertaken by competent, trained personnel using correct procedures and apparatus. This is to ensure that the sample obtained is truly representative of the material from which it has been drawn to recertify the fuel prior to releasing it to the loading station or apron. Additional quality checks occur prior to fuel loading on to the aircraft.

FUTURE SYSTEMS SCHEMATIC

04

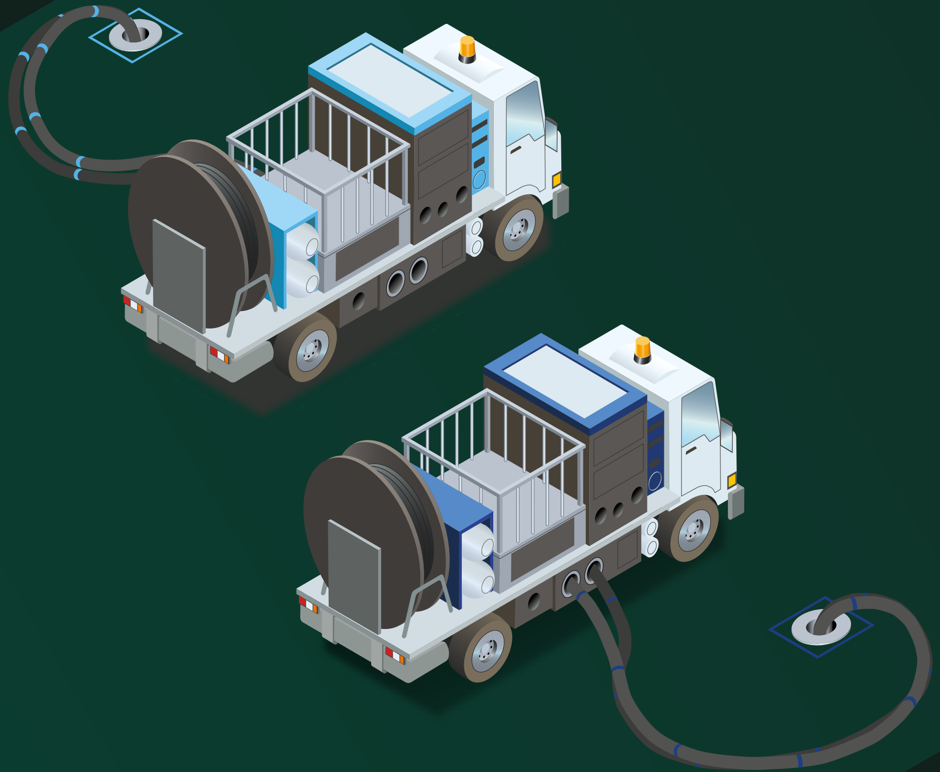


Figure 5: Future systems schematic

Future energy and fuel systems will operate in parallel within the airport or airfield environment, providing a selection of technologies suited for different aircraft and routes

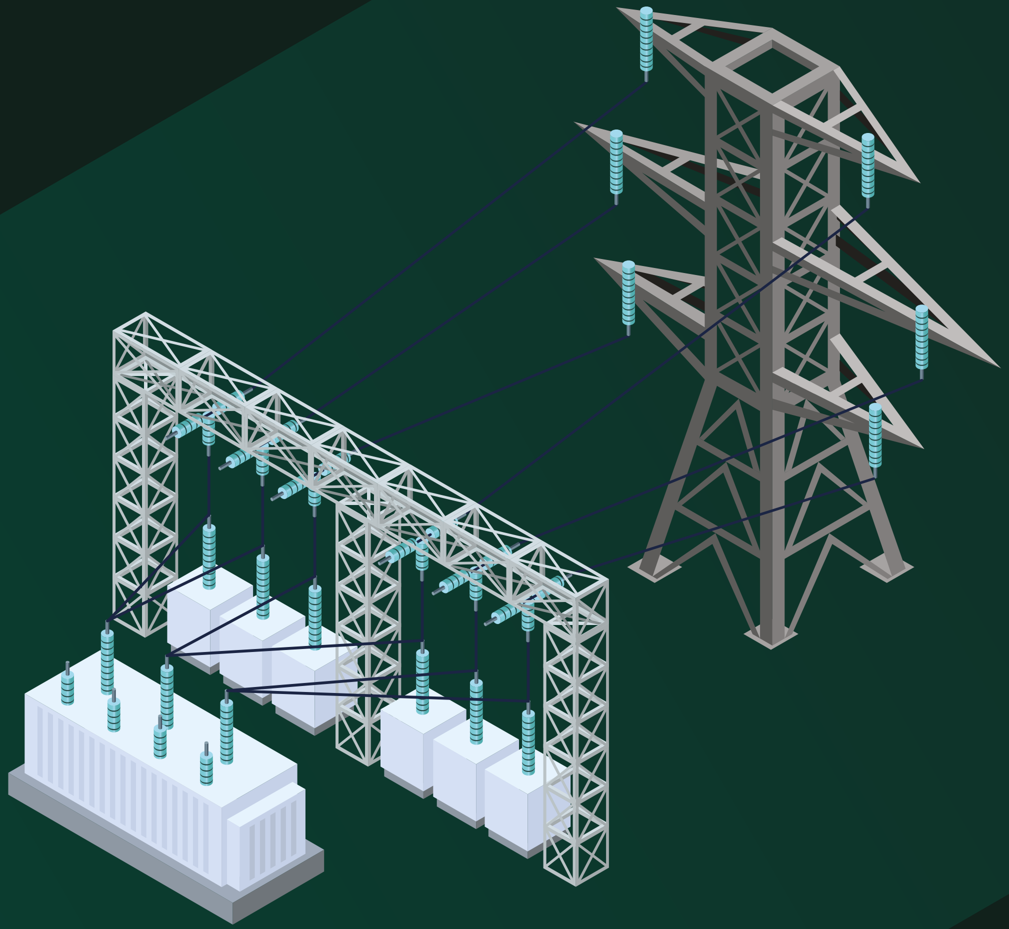
Key

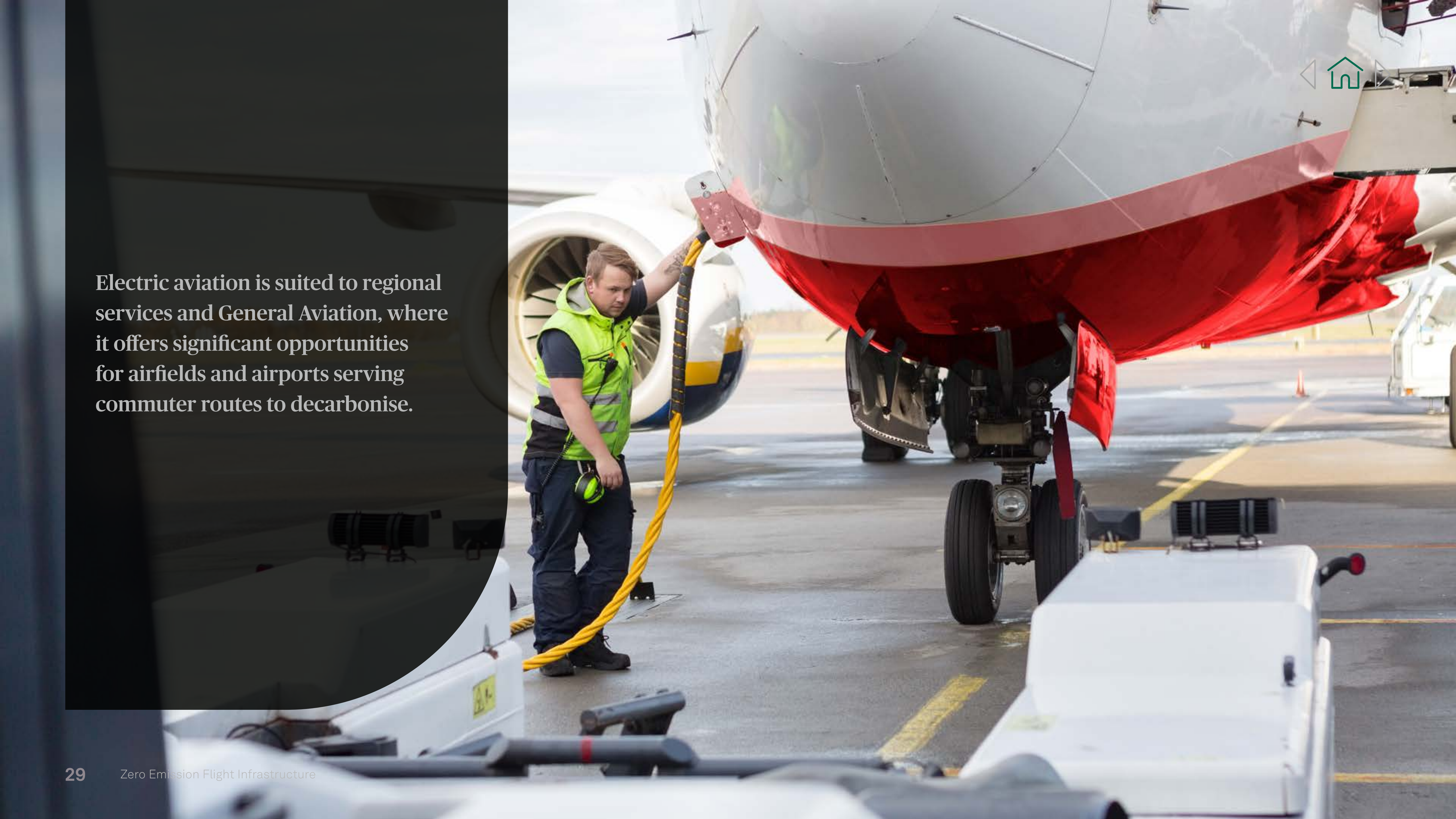
- Electric
- Hydrogen

1. Incoming feed and transformer
2. On-site renewable electricity generation
3. Energy management
4. Energy storage
5. Battery charge and storage
6. Power distribution network
7. Charging station for mobile charger
8. Mobile charger
9. Battery swap transportation
10. Fixed charger
11. Hydrogen delivery
12. Receiving and unloading station
13. Electrolyser
14. Liquefaction
15. Compression
16. Gas (H_2) storage
17. Chemical storage and conversion
18. Liquid hydrogen (LH2) storage
19. Loading station
20. Hydrant systems
21. Fuel cell and tank swapping
22. Hydrogen swap transportation
23. Refuelling vehicles
24. Dispenser vehicles

ELECTRIC AVIATION INFRASTRUCTURE

05





Electric aviation is suited to regional services and General Aviation, where it offers significant opportunities for airfields and airports serving commuter routes to decarbonise.

Introduction to electric aviation

Electric aircraft are expected to offer an economical solution for short regional and General Aviation services. Batteries may be charged within the aircraft or charged externally and swapped to deliver faster turnaround times. Due to the comparatively low energy density compared to hydrogen or SAF, battery electric technologies are not currently suitable for long-haul routes where the mass and volume of the batteries would be a limiting factor.

The technology for battery electric aircraft is rapidly evolving. The Pipistrel Velis Electro recently became the first Type Certified all-electric aeroplane to be made available for pilot training. This aircraft utilises in-aircraft battery charging with an external fixed charger powered from either single or three-phase electrical supply.

Although utilised for other transport modes, battery swapping is at a much lower level of technology maturity in aviation. Models for battery management and ownership need to be developed alongside the complex safety cases for swapping a critical aircraft component.

The limited battery lifespan will introduce new challenges and opportunities for the reuse, recycling and disposal of used batteries. Due to the high demands on battery performance from aviation, there will likely be replacement of batteries before the end of their usable life. They may be reused in other energy storage applications in the airport and beyond.

Vehicle-to-grid opportunities for electric cars exist, using the vehicle battery as additional storage for the grid. Aviation applications have more stringent requirements on battery performance and safety. During its finite aviation life, the batteries are unlikely to provide grid storage as this would reduce the number of charging cycles where it could be used for flight. Aircraft manufacturers have also highlighted safety concerns regarding dual-use applications.

For electric aircraft of all sizes, additional airport infrastructure and supporting systems [17] will be required. Airports and airfields have existing electrical infrastructure for operations and providing ground power to aircraft, however, this is likely to be insufficiently sized for electric aviation needs. Some operators are currently investigating and implementing the electrification of ground vehicles, however the scale of electrical demand for vehicular use is not at a comparable level to that for flight.

Some UK airports and airfields are currently considering on-site generation opportunities and many are looking at feeding into the grid and on-site energy storage as renewables will provide more than the current on-site demands. Electric aviation will shift airports and airfields to being net consumers of electricity as opposed to monetising on-site production.

Electric aviation may offer advantages in noise-sensitive locations where emitted noise from the aircraft is lower than combustion powered aircraft.

Electric infrastructure

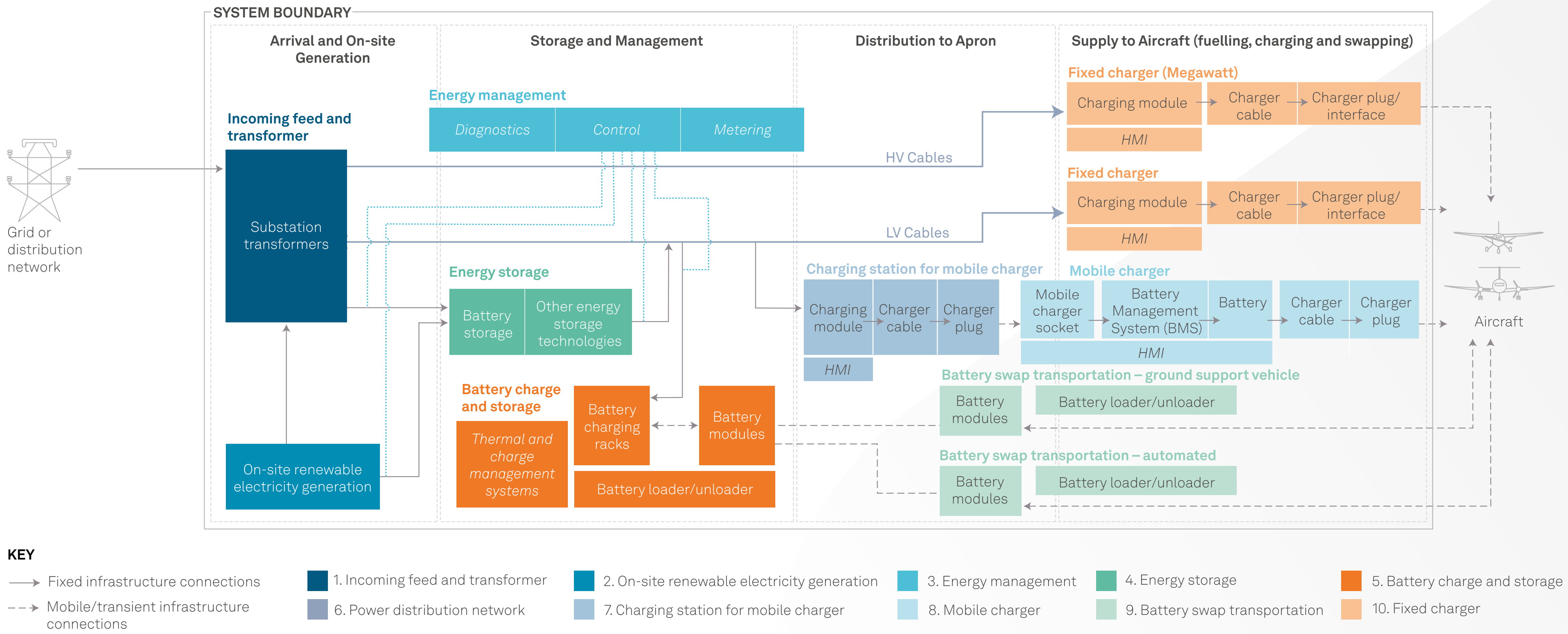
Electrical energy arrives on-site either from the distribution network, National Grid or via on-site renewable energy generation. After being suitably stepped down in voltage, energy is either stored in aircraft specific batteries for swapping, an energy storage facility, or fed directly to charging infrastructure at the apron.

To charge the aircraft, either fixed charging infrastructure, mobile charging vehicles or battery swapping can be used. In the case of battery swapping, the batteries are charged externally from the aircraft and then reinstalled. Battery swapping is likely to allow faster turnaround times for commercial operations, whereas aircraft charging may be more applicable to General Aviation, where the plane may be charged overnight.

Airports and airfields will require more comprehensive power management capabilities including energy control systems. Unlike fuels, there is less opportunity to easily store a large amount of energy for multiple days of operation. On-site storage is likely to be used to manage peak demand and the weather dependence of common renewable generation technologies. In the future, other options for higher density energy storage may be available.

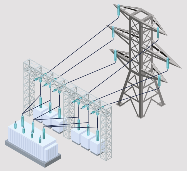
Details of the subsystems, components, technology readiness and examples of relevant organisations developing the technology are found in the subsystem breakdown table on the following pages.

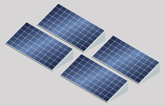
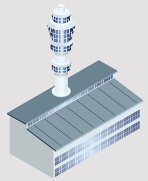
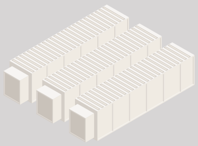
Figure 6: Electric system architecture

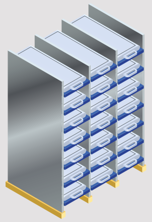
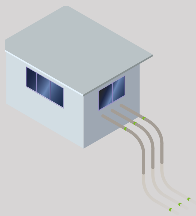


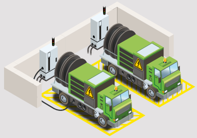
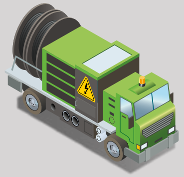
Subsystem breakdown

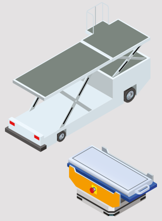
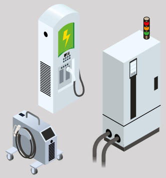
Table 3: Future electric subsystems and components

Main subsystem	Description	Components	Technology Readiness Level (TRL) and system data	Example service/equipment suppliers
1. Incoming feed and transformer 	The incoming power supply from the distribution network operator (DNO) is stepped down (depending on voltage rating required) using transformers and fed to the subsystems of the charging infrastructure. Energy use supplied from the DNO is monitored to calculate energy usage. Upgrading of the incoming feed and transformer infrastructure may be required based on the energy needs of the charging infrastructure.	● Transformer – Incoming 11 kV or higher voltage stepped down as appropriate for subsystems.	TRL: 8-9	**Distribution Network Operators include:** UK Power Networks, Scottish and Southern Electricity Networks, SP Energy Networks, Northern Ireland Electricity Networks, Electricity North West, Northern Powergrid, Western Power Distribution. **Smart meter Suppliers and Operators [18]:** EDMI Europe Ltd, EM-lite, Energy Assets, Ericsson, Iskraemeco, Samsung, Siemens, ST-Microelectronics, Toshiba, Fujitsu, E.ON, EDF, IMServ Europe Ltd, Independent Meters Ltd, Lowri Beck Metering and Data Services Ltd, Morrison Data Services, National Grid Metering, Npower Meter Operator Services.

Main subsystem	Description	Components	Technology Readiness Level (TRL) and system data	Example service/equipment suppliers
2. On-site renewable electricity generation 	Power can be generated on-site at the airport or airfield using technology such as solar panels to reduce the load on the incoming power supply.	• Solar panel. • Wind farm. • Waste to energy production.	TRL: 8-9	British Solar Renewables, Immersa, Centrica Business Solutions, SunPower, Sunrun, Tesla, LG Panasonic.
3. Energy management 	An energy management system for the charging infrastructure and other airport or airfield systems allows an operator to make the most of the energy available, prioritise competing demands, control energy storage and manage on-site generation options.	• Control system. • Diagnostics. • Metering.	TRL: 8-9	Argand Solutions Ltd, Aimteq Solutions, BEST (British Energy Saving Technology), Ameresco, Fujitsu, Open Energi London Origami Energy, Pearlstone Energy Ltd, London Smartest Energy, Toshiba.
4. Energy storage 	The energy storage system is optional to store the energy for the charging infrastructure when surplus energy is available from the on-site generation or when electricity costs are lower. It can work as a buffer for supply and demand changes. Options include energy storage in batteries, mechanical energy storage, and storage as hydrogen produced by electrolysis.	• Battery storage. • Other energy storage technology, e.g., hydrogen electrolysis.	TRL: 7-9 Energy storage systems can use batteries (i.e., Li-ion battery) or other energy storage technology (i.e., hydrogen electrolysis). Some of these new storage technologies are currently in the development/testing phase. Further standards need to be developed for energy storage systems for airport and airfield applications.	Anesco, Swanbarton, Tesla, Belectric, KiWi Power, Centrica, EnerNOC, Green Hedge Group, Wärtsilä, Pivot Power, OXTO Energy, Aura Power, InterGen, Vistra.

Main subsystem	Description	Components	Technology Readiness Level (TRL) and system data	Example service/equipment suppliers
5. Battery charge and storage 	Battery charging facilities can either be one combined facility with energy storage or a separate facility for charging batteries required for battery swapping. The loading and unloading of batteries must be done with care to avoid damaging them – automation of some or all of the processes may be required.	• Battery modules. • Battery charging racks (flexible to accommodate battery modules of different shapes and sizes). • Thermal and charge management systems (for battery modules and charger). • Battery loader/unloader.	TRL: 4-6 The battery charge and storage includes charging battery modules, thermal management and loading/unloading of battery modules manually or by automated systems at the airport or airfield. Battery charging and storage systems currently exist and are used in different applications. However, airport-specific use requires additional standards and procedures to be developed and validated as the system poses safety, manual handling, and fire hazards.	Anesco, Swanbarton, Tesla, Belectric, KiWi Power, Centrica, EnerNOC, Green Hedge Group, Wärtsilä, Pivot Power, OXTO Energy, Aura Power, InterGen, Vistra.
6. Power distribution network 	The distribution of power to and from the various subsystems involves high and low voltage systems. It will likely require significant installation work, particularly where cabling is routed underground.	• High Voltage cables. • Low Voltage cables.	TRL: 8-9 The network should be appropriately sized for the expected demands of subsystems and other airport or airfield needs.	Enertechnos, UK Power Network Services, Scottish and Southern Electricity Networks, Electricity North, Northern Powergrid, Western Power Distribution.

Main subsystem	Description	Components	Technology Readiness Level (TRL) and system data	Example service/equipment suppliers
7. Charging station for mobile charger 	Charging station connected to the airport or airfield power system provides a range of charging options for the mobile charger.	• HMI (Human Machine Interface). • Charger cable. • Charging module. • Plug/interface.	TRL: 7-8 Conventional electric passenger and goods vehicle chargers are available however these will need to be scaled or adapted to accommodate fast charging of larger capacity batteries used for mobile chargers.	
8. Mobile charger 	Mobile charging can be used to charge aircraft where fixed charging infrastructure is unavailable or not viable. Mobile charging consists of a vehicle with onboard battery electric storage. Alternative onboard energy storage options could be considered, such as hydrogen fuel cells.	• Vehicle. • Battery module. • Control panel HMI. • Charger cable. • Plug/interface. • Charging inlet/socket.	TRL: 5-7 Currently, mobile battery-powered Ground Power unit (GPU) solutions are available that supply electricity to the aircraft while it is refuelling; similar systems could be developed as mobile chargers. The battery's capacity depends on the aircraft operating at the airport or airfield and their schedule, frequency etc.	

Main subsystem	Description	Components	Technology Readiness Level (TRL) and system data	Example service/equipment suppliers
9. Battery swap transportation 	Battery swapping replaces the discharged battery modules of an aircraft with charged battery modules from the Battery Charge and Storage facility. Due to the expected size and weight of the battery modules preventing manual installation, a vehicle with loading and unloading capability will be needed. The loading and unloading of battery modules needs care to avoid damaging them; automation of some or all of the processes may be required. Automation of the transport vehicle may also aid installation and removal.	• Vehicle. • Battery module. • Battery loader/unloader.	TRL: 3-5 The battery swapping process includes removing and replacing the aircraft parts that contain the battery. This process can pose a fire risk if the battery gets damaged during swapping. There is a lack of standards for aircraft battery swapping, and the TRL is currently low.	
10. Fixed charger 	Fixed chargers vary in power, from existing chargers providing tens of kilowatts to megawatt chargers in development. Small portable chargers can be plugged into fixed power infrastructure to offer flexible access for charging small aircraft. Higher power chargers will need planning to ensure reliable access for aircraft, minimal disruption of other ground operations and suitable heat dissipation.	• Control panel (HMI). • Charger cable (connects the charging module to plug/interface). • Charging module. • Plug/interface (connects to the aircraft to charge the battery).	TRL: 7-8 Input voltage – 3 phase 300 V to 1000 V AC, 50 to 60 Hz, Input current – 3 x 32 A (22 kW). Output voltage – 530 VDC to 1000 VDC Output current – 50 A to 200 A. In around an hour, these charging systems can charge small electric aircraft such as the Pipistrel Velis Electro, mainly used for pilot training.	SkyCharge – Pipistrel, Green Motion's FLIGHT XT, RAPID 30 – Electro.Aero, ChargePoint, CharIN, ABB and Daimler

Supporting systems

Electric infrastructure will likely co-exist with current infrastructure and supporting systems, these supporting systems will be extended and adapted to support the new infrastructure. The following table highlights areas of change for existing and new supporting systems.

Table 4: Electric Supporting Systems

Routine Operations	Integrated Control System (ICS)	The existing Integrated Control System would need to be extended to detect and show the status of critical components of the electric charging infrastructure.
	Storage management	Airports and airfields are currently unlikely to have significant energy storage on-site for electric applications. The adoption of smart energy planning and on-site generation may require on-site energy storage. Energy monitoring and management is increasingly important at airports and airfields and will be even more so with electric aircraft charging, renewable electricity generation and optional on-site energy storage.
	Aviation refuelling management	Energy monitoring is increasingly used at airports and airfields to better understand and reduce energy consumption. Airlines and aircraft owners will be billed for the electricity used for charging in the future. The energy monitoring will need to be reliable, and a pricing structure agreed. A charging management system would support larger or distributed electrical charging installations providing operators on the ground, and aircraft operating companies, information relevant to them, such as charging time and billing information. The charging management system could be part of the energy management system or closely interfaced with it.
Commercial		The batteries integrated into electric aircraft and swappable batteries have a finite lifetime before they will need replacing. The re-use of retired batteries for less safety-critical applications such as renewable energy storage is well established and should be a consideration for airports and airfields. Battery swap technologies further complicate billing arrangements as ownership of the batteries may be by the airline or a handling company. Asset management systems will be required to monitor charge cycles, maintenance, and the serviceable life of batteries. Tracking and managing charging supports operators to maximise battery life. To maximise battery life, and optimise whole-life cost, the battery charge level may be route dependent and below 100%.

Maintenance		Maintenance procedures and routines would need to be implemented for the electric infrastructure to ensure reliable and efficient operation. Notably, the maintenance of high voltage infrastructure would require careful consideration and planning. Due to the finite life of the batteries, recycling and disposal facilities will be required to handle their safe replacement.
Quality		Quality concerning electric infrastructure will differ significantly from that of existing refuelling. Consideration should be given to the power quality across the infrastructure to prevent accidental damage to components, aircraft, or interference with other systems.
Safety and backup	Emergency Shutdown (ESD) system	A shutdown procedure or ESD system would need to be deployed for electrical charging infrastructure. Existing procedures and systems may need to be updated to account for the hazardous interaction between new and existing infrastructure.
	Rescue and Fire Fighting Service (RFFS) / Fire Alarm System (FAS)	The Rescue and Fire Fighting Service would need to be reviewed to account for new electrical infrastructure and associated hazards. Additional equipment, supplies, and training will be required as, for example, lithium-ion battery fires require significant quantities of water over a sustained period. The charging infrastructure would require a different fire-fighting approach for battery fires.
	Generator and Uninterruptible Power Supply (UPS)	UPS and generators provide backup power to critical systems at the airport or airfield. The addition of electric charging infrastructure and aircraft will require the backup power configuration to be reviewed.

Operations and people

Personnel changes

Training will be required for personnel operating the electric charging infrastructure. Airports and airfields are likely to operate a hybrid model with conventional fuelling available alongside electric charging. Depending on the size of the site and the scale of the infrastructure, personnel may be trained to operate both sets of infrastructure or be specialised for just one.

Arrival and on-site generation

Personnel skills and training will remain the same for arrival and on-site generation operations.

Storage and management

Additional new skills will be required for the storage and management operations for electric charging infrastructure. Personnel skilled and trained with handling, charging and moving battery electric modules will be needed to operate the energy storage and battery electric charging facilities. Currently, most airports and airfields do not have purpose-built battery electric charging and storage facilities, or the required skills to operate them. Energy management systems may need to be installed or updated in locations that aren't currently equipped to incorporate more demanding charging infrastructure. Generally, the skills and training required to operate the systems will remain similar. However, some airports and airfields may find the introduction of these systems is new to their operations requiring upskilling to operate safely and efficiently.

Distribution to apron

Personnel trained to work on high voltage power transmission lines within existing teams can transfer their skills to manage and maintain the wire network and supporting charging infrastructure. Minimal additional training will be needed as they are already aware of procedures and standards for working with high voltages safely.

Similarly, personnel trained to operate automated/semi-automated systems and vehicles for moving heavy loads around will be able to work on automated/semi-automated battery electric swapping.

Supply to aircraft

Personnel working on the high voltage equipment within the current airport or airfield infrastructure will be able to transfer their skills to operate and maintain aircraft chargers with some additional training.

The future electric aviation infrastructure may be required to operate with reduced availability in degraded modes and manage any emergency or failure situations. These different operation modes are described below:

Normal operations

In normal operation, power from the grid is supplied to the airport or airfield alongside any power generated on-site. During normal operation, the charging and battery electric infrastructure will deliver charging and battery swapping facilities according to the airline's requirements, taking into consideration turnaround time and battery electric specifications. For normal operations, the charging operation will run smoothly following the agreed procedures and timeframes.

Degraded operation and failure modes

Degraded operations include elements of the installed infrastructure not working or under maintenance where the system is still able to provide some levels of service. Degraded operation may result in delays to flights or the need to prioritise certain aircraft or flights.

The main failure modes for the aircraft charging infrastructure that may lead to degraded operation are:

- Failure of the incoming power supply.
- IT system for energy management failure.
- Management system failure.
- Failure of on-site power generation infrastructure.
- Failure in fixed power supply to the charging infrastructure.

- Failure of the mobile charging unit.
- Failure of the vehicles used for battery swapping.
- Battery storage facility not able to charge the batteries.
- Not enough batteries charged for the battery swapping demand.
- The systems used for moving the batteries failing.
- Battery not charging as expected, or near the end of their life.
- Battery thermal management issues pausing battery charging.
- Re-routing of aircraft causing charging delays.

Constraints and risks

Installation and operation of electric aircraft charging infrastructure is likely to be affected by the following constraints:

Charging technology availability: Currently, there are few commercially available battery plug-in charging solutions on the market for small aircraft. There are no existing charging solutions available for medium and large aircraft (>1 MWh battery electric capacity). Commercial electric vehicle companies, and other industries, are currently working on 1–3 MW chargers. Availability of rapid chargers which can safely charge the high capacity aircraft batteries and deliver commercially acceptable turnaround time for electric and hybrid aircraft will be the key in the wider implementation and installation of electric aircraft charging infrastructure.

Procedural and safety constraints for battery swapping: Battery swapping is a viable option for quick turnaround of high capacity battery electric (>1 MWh battery electric capacity) aircraft. Use and acceptance of the battery electric swapping option will depend on the availability of standards, and associated procedural and safety constraints imposed. Ground crew licensing should be considered as battery swapping may be deemed an aircraft maintenance activity.

Infrastructure upgrading – availability of standards and investment: Upgrading of the infrastructure for supplying power to the airport or airfield and design of the charging systems will rely on correct projections of energy use by electric aircraft and on-site utilities. There will be a requirement for significant investment to upgrade the infrastructure for electric aircraft, and standardisation will give confidence in the longevity of the infrastructure. The lead time to make changes to the upstream electrical supply to the site may be considerable and must be planned early.

Space constraint: Lack of physical space available for the electric charging infrastructure and its coexistence with legacy equipment can hamper the installation of new electric charging infrastructure.

Safety

All personnel shall be thoroughly familiar with the relevant operating procedures, safety, and fire protection regulations applicable to the battery handling and storage, high voltage and aircraft charging equipment.

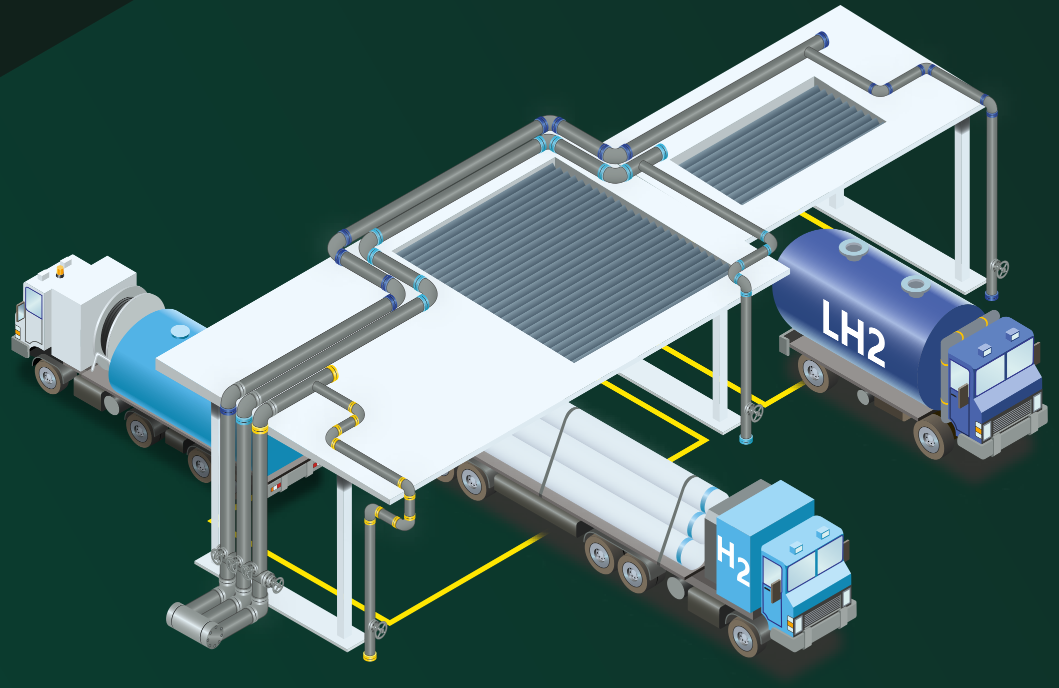
Airport and airfield authorities need to ensure that the fixed and mobile charging equipment and facilities used for storing and charging batteries are suitable and properly maintained. Safety standards for airport and airfield use of these technologies will need to be in place and respected during operation and maintenance.

Standards need further development for charging equipment, socket and plugs, battery/charger communication protocols, and battery electric storage facilities on-site. Airport and airfield authorities need to work together with standards committees and other stakeholders such as the CAA and technology developers to standardise the equipment, processes and training to ensure the safety of the personnel involved in operating the charging infrastructure at the airport or airfield.

Batteries and expanded electrical infrastructure pose additional risks including induced currents, electromagnetic compatibility effects, thermal runaway, chemical risks, and changes to fire suppression.

HYDROGEN AVIATION INFRASTRUCTURE

06



Hydrogen propulsion is expected to help sustainably decarbonise the aviation sector as we move towards the net zero world.

Introduction to hydrogen aviation

Hydrogen-powered aircraft may use either gaseous (H_2) or liquid (LH2) forms. Propulsion is delivered either by direct combustion or from electric motors powered by hydrogen fuel cell technologies. Most of the UK produced hydrogen currently comes from fossil fuels. A shift towards 'green' hydrogen produced through electrolysis using renewable energy and 'blue' hydrogen from natural gas steam reforming with carbon capture is underway [19]. Unlike conventional aviation fuel, hydrogen can be produced through on-site electrolysis using renewable energy.

Considered to be the greener technology, hydrogen fuel cells do not produce the nitrogen compounds created from hydrogen combustion. The recombination of hydrogen and atmospheric oxygen in a fuel cell releases only water and electrical energy.

The first hydrogen-powered service is expected to be operational in the UK as early as 2024. Hydrogen will be used across a wide range of routes and services in the longer term. Where the mass of batteries versus energy available limits them to shorter routes, the higher energy density per kilogram of hydrogen enables its use across long and short-haul flights.

It should be noted that whilst hydrogen has a higher energy density than aviation fuel by mass, it has a much lower energy density by volume (even in liquid form). This results in lighter aircraft but may require new designs to accommodate the large hydrogen tanks.

At room temperature, hydrogen is in gaseous form and is stored and transported under high pressure. Liquid hydrogen is cryogenically cooled to below -253 °C to keep it in liquid form. Both high pressure and low temperature requirements make handling significantly more challenging than conventional aviation fuels.

Standards for hydrogen quality in aviation are still in development. Higher grades of hydrogen are needed with fuel cells that have stricter quality requirements than combustion.

A significant investment in infrastructure will be required to support early services, and phased approaches to introduction are expected. In particular, hydrogen will require considerable changes to airport storage, distribution and emergency procedures.

Existing hydrants and natural gas pipelines are not suitable for hydrogen use without modification.

As we strive for net zero, hydrogen will form a large part of the wider local energy economy with industrial and other transport uses. There are significant opportunities for airports and airfields to get involved in the big-picture transformation of our energy supply.

Hydrogen infrastructure

Hydrogen fuel, in either gaseous or liquid form arrives on-site via road or pipeline. Some airports or airfields will choose to produce their own hydrogen using on-site electrolysis.

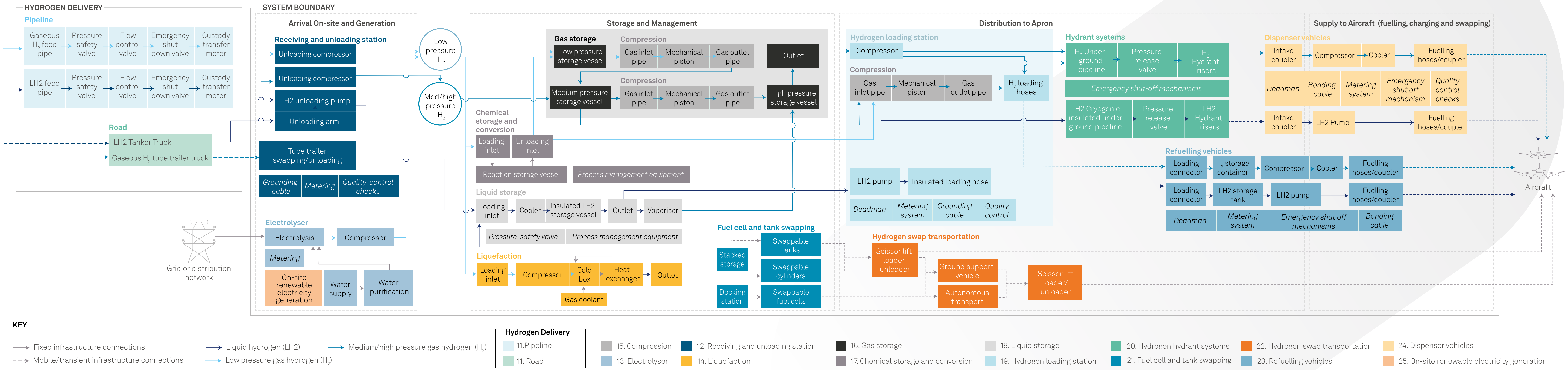
Typically, airports servicing longer distance aircraft, and with a significant aircraft throughput, would be served by dedicated pipelines supplying hydrogen to the storage systems through a series of valves and meters. Airports and airfields with lower throughput do not require a pipeline capability and will have hydrogen fuel delivery by truck. In this case, hydrogen will be offloaded through compressors, pumps or unloading arms. Quality checks will be carried out at the receiving and unloading station. Hydrogen fuel after unloading is then transferred to the storage tanks at the airport or airfield. The liquefaction of gaseous hydrogen may be carried out on-site.

From the storage system, the hydrogen will be distributed to the apron via either a hydrant system or a bowser vehicle. Swappable prefilled hydrogen fuel tanks or fuel cell units may be used in future aircraft designs, which could be stored in on-site warehouses. Ground support vehicles could collect the full units from storage and deliver them to the aircraft, swapping out the empty unit.

For initial trials, early capabilities and smaller operations it is possible that bowsers will be loaded external to the site at a producer or local hydrogen hub. The filled bowser would be used to directly supply the aircraft. In this case the airport or airfield does not need storage.

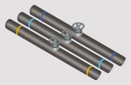
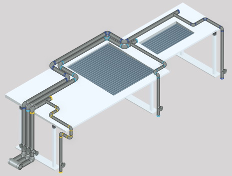
Details of the subsystems, components, technology readiness and examples of relevant organisations developing the technology are found in the subsystem breakdown table on the following pages.

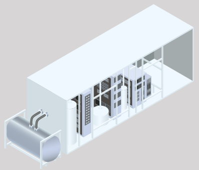
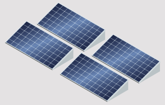
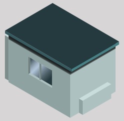
Figure 7: Hydrogen system architecture

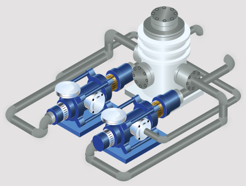
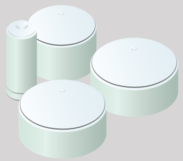
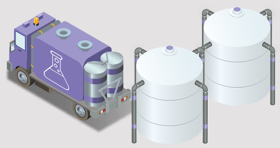


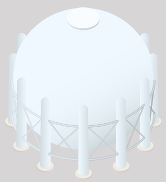
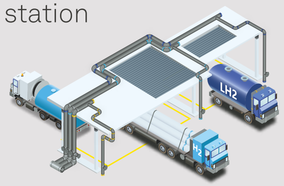
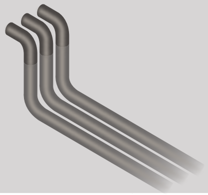
Subsystem breakdown

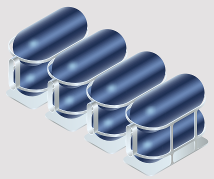
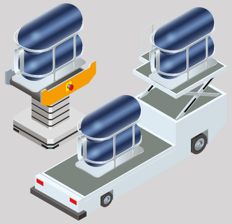
Table 5: Hydrogen subsystems and components

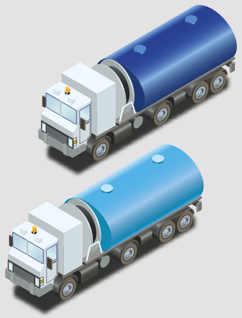
Subsystem		Description	Components	Technology Readiness Level (TRL) and system data	Example service/ equipment suppliers
11. Hydrogen delivery	Pipeline 	Fuel arrives via pipeline and is then passed onto the storage tanks.	• Feed pipe. • Pressure safety valves. • Flow Control Valves. • Emergency shut down valves. • Custody Transfer Meter.	Gaseous hydrogen – TRL: 9 [20] Gaseous H_2 hydrogen at 20 bar pressure. Liquid Hydrogen – TRL: unknown LH2 pipeline infrastructure does not exist. Short pipes are used at the liquefaction plant as a component for LH2 transfer. LH2 at -253 ˚C.	Air Products [21], Linde [22], Cadent [23]
	Road 	Fuel arrives at the fuel farm via truck. Gaseous H_2 is delivered by tube trailers (ISO containers).	• LH2 trailer. • Gas H_2 tube trailer.	TRL: 9 Currently gaseous H_2 is being delivered to hydrogen refuelling stations using tube trailers. LH2 is also delivered using cryogenic tankers [24]. Gas pressure 200-350 bar (current technology), capacity approx. 900 kg, LH2 in a cryogenic tank at -253 ˚C, capacity ~3,600 kg [25].	Linde [26]
12. Receiving and unloading station 		Fuel arrives via tanker trucks, is unloaded at the unloading station, and then passes into the storage tanks.	• Unloading pump for LH2. • Unloading compressor for gaseous H_2. • Tube trailer swapping /unloading. • Unloading arm. • Quality control checks. • Grounding cable. • Metering equipment.	TRL: 9 Current tube trailer swap technology exists at the HRS stations. Full tube trailers are unloaded, and empty trailers loaded. Time to offload gaseous H_2 tube trailer though swapping: 45 minutes. LH2 4,000 kg truck offloading: 1 hour [27].	Linde [28], AirProducts [29], ITM Power [30]

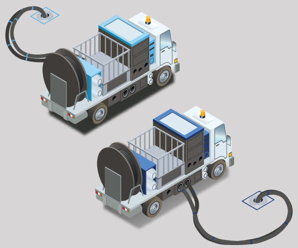
Subsystem	Description	Components	Technology Readiness Level (TRL) and system data	Example service/ equipment suppliers
13. Electrolyser 	Hydrogen generated on-site using electrolysis process, using water and electricity as an input for generation. Electric power input can be fed from the grid or renewable power generation from solar panels installed at the airport or airfield.	• Water supply. • Electricity supply. • Electrolyte inside the electrolyser. • Compressor. • Metering. • Water Purification.	TRL: 9 Current technology is 4 MW electrolyser units, with the capability of stacking the electrolyser units to scale the production. Popular types include alkaline and polymer electrolyte membrane (PEM) electrolysers. where the difference is the electrolytes and electrodes used in the design. The largest electrolyser in Europe has a capacity of 10 MW with 1,300 tonnes H_2 per year production (built by ITM power) [31].	ITM Power [32], Next Hydrogen [33], McPhy [34]]
2. On-site renewable electricity generation 	Electricity is produced on-site by using various technologies such as solar panels.	• Solar panels. • Wind turbines. • Waste to energy production.	TRL: 8-9	British Solar Renewables, Immersa, Centrica Business Solutions, SunPower, Sunrun, Tesla, LG Panasonic,
14. Liquefaction 	Gaseous H_2 from the electrolysis production is liquefied. LH2 (70.8 kg/m^3) is approximately 790 times its gas density at atmospheric pressure.	• Loading inlet. • Compressor. • Gas coolant (usually liquid N2 feed). • Liquefier cold box (cools the gas to the desired temperature). • Heat exchanger. • Outlet [35].	TRL: 9 Liquefiers are being used in other industries. Gaseous hydrogen is liquefied by cooling it to below −253 °C (using other gases, most commonly liquid nitrogen) [36]. Current hydrogen liquefaction technology uses 12 kWh to liquefy 1 kg of hydrogen. This is equivalent to 36% of the usable energy available in the hydrogen [37]. Large capacity liquefiers are capable of >60 t production of LH2 per day [38] [39].	AirLiquide [40], Linde [41]

Subsystem	Description	Components	Technology Readiness Level (TRL) and system data	Example service/ equipment suppliers
15. Compression 	Hydrogen is produced at low pressures. Due to high volumetric density, it must be compressed for transportation and storage.	• Gas inlet. • Piston compressor. • Gas outlet [42].	TRL: 9 Compressors available on the market can compress the hydrogen gas to the required 700bar pressure and above. As an example, the PDC compressor is capable of pressures up to 1100 bar [43]. Piston compressors are the most widely used compressors.	PDC machines [44], Hydro-Pac [45], Haskel [46], Linde [47] Neuman-Esser [48], Howden [49]
16. Gas storage 	After compression of hydrogen (to occupy less space), it is stored in the gaseous hydrogen vessel. Different pressure storage options are possible, e.g., low, medium and high.	• Low-pressure storage vessel. • Gas compression. • Medium pressure storage vessel. • High-pressure storage vessel.	TRL: 8-9 High pressure gas storage vessels are used in the oil and gas industry. A combination of low (20 bar) and medium/high pressure (300-500 bar and above) storage can be used on-site.	Linde [50], AirLiquide [51], CPE Pressure Vessels [52], Man Energy Solutions [53]
17. Chemical storage and conversion 	During the chemical storage process, hydrogen is bound in either solid or liquid form and stored in that form until it is required by the system.	• Hydrogen loading inlet. • Storage and reaction (hydrogenation) vessel. • Hydrogen unloading outlet. • Process management equipment [54].	TRL: 5 GKN conducted the pilot project in Tirol [55] for Hy2green chemical storage technology. H_2GO Power to test a 90 kg storage unit. Hydrogenious developed 5 t storage solution [56]. When required, hydrogen is released in gaseous form at low pressures (up to 40 bar [57]).	GKN Hydrogen [58], H_2GO Power [59], Hydrogenious [60]

Subsystem	Description	Components	Technology Readiness Level (TRL) and system data	Example service/ equipment suppliers
18. Liquid storage 	Liquefied hydrogen is stored in the insulated tank. Pressure and temperature are monitored, and the pressure is released through a pressure release valve.	• Loading inlet. • Cooler. • Insulated LH2 storage vessel. • Outlet for LH2 unloading. • Process management equipment. • Pressure safety valve [61]. • Vaporiser.	TRL: 8-9 Current LH2 storage capacity ranges from 70 t [62] to ~150 t (demonstrator test in Kobe, Japan) [63].	Wessington cryogenics [64], Linde [65], Kawasaki Heavy Industries [66]
19. Hydrogen loading station 	Fuel filling station in bowsers/ refueller truck. Quality control is undertaken at the loading station, e.g., checking the purity of the fuel, required pressure, and temperature.	• Compressor for Gaseous H_2 loading. • Hydrogen pump for LH2 pumping [67]. • Gaseous H_2 loading hoses. • LH2 insulated loading hoses. • Metering system. • Quality control. • Deadman. • Grounding cable.	TRL: 5 At present only small-scale mobile filling vehicles and fixed loading stations exist [68]. Since a full-scale refuelling bowser is not yet available there has been no testing of large loading stations in airport or airfield environments.	Barber Nichols [69], Linde [70], ITM Power, AirLiquide [71], Haskel [72] Fuel Cell Systems [73]
20. Hydrogen hydrant systems 	Fuel is transferred from the fuel storage (fuel farm) via the underground pipeline network to fuel dispensing hydrants on the apron.	• Gaseous H_2 underground pipeline. • LH2 underground pipeline. • Gaseous H_2 hydrant risers. • LH2 hydrant risers. • Emergency shut-off mechanism. • Pressure release valves.	TRL: unknown Hydrogen piping systems exist in other industries (e.g., refineries) for the transportation of hydrogen. Hydrant utilises 20-40 bar operating pressure. Airport hydrogen hydrant systems can be as much as five times more expensive than conventional fuel systems [74].	AirProducts [75], Linde, Pipelife [76], Siemens Energy [77]

Subsystem	Description	Components	Technology Readiness Level (TRL) and system data	Example service/ equipment suppliers
21. Fuel cell and tank swapping 	Liquid or gaseous hydrogen tank or cylinder would be swapped after landing. Empty container removed and full container loaded onto the plane. Fuel tanks would be stored in the warehouse stacked storage. Fuel cells would be stored at the docking station.	• Swappable fuel tank (LH2). • Swappable Gaseous H_2 cylinder. • Swappable fuel cell [78]. • Docking Station. • Stacked Storage.	TRL: 1-2 Very early stages of the technology.	HES Energy systems [79], Universal Hydrogen [80]
22. Hydrogen swap transportation 	Hydrogen tanks and cylinders, would be transported by a truck designed to load and unload the heavy tanks by automated hydraulic operation, with a scissor lift operation.	• Autonomous transport. • Ground support vehicle. • Scissor lift loader/unloader.	TRL: 2 Early stages of the technology due to no aircraft featuring this technology and low maturity for automation of the process. Existing handling technologies such as scissor lifts could be used to load the fuel tank onto the vehicle and transfer it into the aircraft.	Universal Hydrogen [81]

Subsystem	Description	Components	Technology Readiness Level (TRL) and system data	Example service/ equipment suppliers
23. Refuelling vehicles 	Hydrogen would be transported from the fuel loading station to the aircraft by the refuelling vehicle.	• Loading connector. • Hydrogen storage cylinder (Gaseous H_2). • Compressor (Gaseous H_2). • Cooler (Gaseous H_2). • Fuelling hoses and coupler (separate for Gaseous H_2 and for LH2). • LH2 storage tank. • Pump (LH2). • Metering equipment. • Emergency shut-off. • Bonding cable. • Deadman.	TRL: 5 Small scale (60 kg H_2 gas) refuelling trucks in operation in the UK, providing 350 bar and 700 bar refuelling. This was used in HyFlyer I project [82]. Mobile hydrogen refuelling stations are being developed to dispense hydrogen at the point of use [83]. Air Liquide plans to trial an LH2 refuelling truck in the airport environment [84]. Gaseous H_2 pressure would be boosted before refuelling to maintain the required pressure and cooled to -40 °C (due to gas heating up during refuelling). LH2 would be delivered through a cryogenic pump.	Fuel Cell Systems [85], NanoSun [86], ITMPower [87]

Subsystem	Description	Components	Technology Readiness Level (TRL) and system data	Example service/ equipment suppliers
24. Dispenser vehicles 	The hydrant dispenser can efficiently dispense hydrogen from an underground hydrant system into an aircraft by aviation refuelling personnel via underwing connections.	• Intake coupler. • Compressor (Gaseous H_2). • Cooler (Gaseous H_2). • Fuelling hoses and coupler (separate for Gaseous H_2 and LH2). • LH2 pump. • Emergency shut-off mechanism. • Bonding cable. • Deadman. • Quality control checks. • Metering system.	TRL: unknown	Technology does not exist.

Supporting systems

As hydrogen infrastructure is likely to co-exist with current infrastructure and supporting systems, these supporting systems will be extended and adapted to support the new infrastructure. The following table highlights areas of change for existing and new supporting systems.

Table 6: Hydrogen supporting systems

Routine Operations	Integrated Control System (ICS)	The existing Integrated Control System (ICS) will need to be extended to detect and show the status of critical components of the hydrogen infrastructure. H2GO Power has developed the AI system for the acquisition and storage of hydrogen that integrates into existing SCADA systems [88].
	Storage management	Gauging systems will be different for hydrogen storage vessels than for conventional fuels. A gaseous H_2 tank will require pressure and temperature measurement to manage the quantity of hydrogen stored. An LH2 storage tank will have a temperature sensor and an accurate level gauge.
	Aviation refuelling management	Hydrogen fuelling management will be like conventional fuel, where the quantities of fuel are measured in real-time and recorded for billing purposes. However, it will need to be made clear who would be accountable for the liquid hydrogen boil-off, capture and volume reporting and accounts.
Commercial		The array of options for hydrogen infrastructure is further complicated by the different commercial arrangements that could be put in place to support the physical infrastructure and operations.
Maintenance		Preventative maintenance of hydrogen infrastructure is recommended to reduce the risk of having to undertake maintenance in response to a potentially dangerous situation. Processes and suitably trained personnel will need to be in place for maintenance.
Quality		Quality control is an established part of existing refuelling services. Equivalent assurance processes will need to be developed, agreed, and implemented for hydrogen refuelling.

Safety and backup	Emergency Shutdown (ESD) system	A shutdown procedure or ESD system will need to be deployed for hydrogen infrastructure. Shutdown situations, systems and responses will need to be assessed for each installation and existing procedures will updated accordingly.
	Rescue and Fire Fighting Service (RFFS) / Fire Alarm System (FAS)	The Rescue and Fire Fighting Service will need to be reviewed to account for new hydrogen infrastructure and associated hazards. As hydrogen fires are colourless, appropriate detection equipment is required. Hydrogen also has a possibility of detonation. The following processes exist in the conventional fuel fire alarm system and will also be required for hydrogen operations: • Detection of fire. • Processing of fire signal. • Notification of the fire signal. The National Fire Protection Association in the US provide guidance on hazards related to compressed gases and cryogenic fluids [89].
	Leak Detection System (LDS)	A leak detection system for hydrogen should follow existing system reporting procedures, i.e., linked to the existing ICS. H2Tools [90] propose the following basic hydrogen monitoring measures: • Suitable detectors installed where hydrogen is likely to accumulate in the event of a leak. • Monitoring abnormal variation in piping pressures or flow rates. • Double containment: installing the hydrogen piping within an outer pipe and monitoring the annulus for leaks.
	Generator and Uninterruptible Power Supply (UPS)	The hydrogen safety systems will require backup power in the event of a primary power failure to ensure the safety of hydrogen storage and distribution systems. Other systems such as pumps and compressors may be shut down or operate in a degraded mode in the event of primary power loss.

Operations and people

Personnel Changes

Broadly, operations will stay the same as with conventional fuels however, skills require updating to account for the different properties of working with and handling hydrogen.

Arrival on-site and receipt of the fuel

Staff will undertake quality control checks, sampling and decision making (offload fuel or send back to refinery). Additional training will be required for staff in hydrogen hazards, properties and operating of hydrogen equipment.

Storage and apron release

Quality control checks, sampling and recertification are required to be carried out by staff. Samples would be sent to an off-site laboratory for hydrogen purity checks to ascertain that the properties of the hydrogen have not changed in the tank and are within the acceptable limits of aviation standards. Consequently, additional skills will be needed for airport and airfield staff to read and understand the recertification results. This will help in decision making for the releasing of on-spec fuel into the storage tanks. Simultaneously, additional training in hydrogen hazards, properties and operating of hydrogen equipment will be needed for staff undertaking sampling and quality checks on-site.

Distribution to apron

Quality checks and sampling take place after loading of a refuelling vehicle and while managing hydrant operations. As with storage and apron release, additional training in hydrogen hazards and properties and the operation of hydrogen equipment will need to be provided for staff.

Supply to aircraft refuelling

Staff will operate refuellers and/or hydrant dispensers, carrying out sampling and quality checks. Staff will have to be trained in hydrogen hazards, its properties and the operation of hydrogen refuelling equipment including making connections to the aircraft. Additional safety training will be required, including for other services operating around the refuelling safety area. The introduction of automation of fuelling with hydrogen will be a significant change to operations, procedures and skills required, but the changes will be similar in scale for both conventional fuel and hydrogen systems.

Degraded operation and failure modes

The hydrogen fuel system would still be able to provide refuelling under degraded operations however, there may be limited supply or delayed supply of fuel. Failure could result in the closure of refuelling operations at the airport or airfield and resulting impact to flights.

The following degraded operations are possible:

Delivery/receipt of fuel

- Reduced fuel supply from off-site production.
- Reduced power and water supply for on-site fuel production.
- Reduced pipeline delivery pressure.
- Reduced number of delivery trucks.
- Reduced throughput of pumping equipment.
- Fuel quality below required standard.

Storage/Compression

- Loss of pressure in the storage vessel.
- Higher than recommended hydrogen evaporation in the LH2 storage vessel, leading to loss of fuel.
- Lower compression ratio achieved than required from non-optimal operation of one or multiple compression components.

Into plane refuelling

- Refuelling vehicle breakdown.
- Reduced number of trucks required for delivery.
- Loss of pressure in the piping system.

The following failure modes are possible:

Delivery/Receipt of fuel

- Hydrogen quality incident – e.g., hydrogen out of specification.
- Hydrogen pump failure.
- Piping system failure.

Storage

- Tank gauging system issue – e.g., tank volume readings incorrect.
- Pressure release valve failure in the LH2 storage tank.
- Leak in the storage vessel.

Constraints and risks

Hydrogen implementation in the airport and airfield environment will have the following constraints:

Limited apron space available for the required safety zones. Hydrogen refuelling will require larger safety zones and ignition free zones than conventional fuel due to the high flammability range. Typically, apron space is optimised for conventional fuelling and turnaround operations with minimal opportunity to expand aircraft parking space. Airports designed around hydrant systems with tight spacing are particularly at risk. Additionally, LH2 aircraft are expected to be 10-15 m longer [91] than existing equivalent aircraft, increasing the space requirements at the apron.

Limited space for the hydrogen infrastructure. Depending on the refuelling operations chosen by the airport or airfield, some of the hydrogen refuelling systems may have more components than the existing system, such as an electrolyser (on-site production), liquefier and compression equipment. Additional infrastructure will require more space than conventional fuel farms and refuelling infrastructure.

Stakeholders involved in the refuelling process. Due to multiple stakeholders involved in the fuel supply, storage, and refuelling process, it will be difficult to develop and implement a hydrogen refuelling infrastructure at an airport or airfield without the agreement and cooperation of all the stakeholders.

Green hydrogen supply. Currently, there is limited production and available supply of green hydrogen. There are concerns that carbon capture technology for blue hydrogen will not be ready to meet the demands of aviation and industry.

Cost of the energy compared to the kerosene. Projected hydrogen cost per kWh required to propel a 165-passenger aircraft on a 2000 km flight in 2040 would be 42% higher than kerosene (assuming kerosene aircraft would be operational in 2040) [92].

Safety

Hydrogen behaves very differently from aviation fuels with the gas being lighter than air and highly flammable. Unlike fuel vapour, that dissipates at ground level, the hydrogen gas and LH2 boil-off will rise and could collect in confined spaces and roof areas. This may require different designs of infrastructure to mitigate the risks.

Hydrogen fires burn faster than fuel fires as the heat causes the hydrogen to dissipate. This requires different firefighting and emergency operations. Hydrogen burns with a largely colourless flame, which is unlikely to be seen in daylight with the naked eye, requiring thermal imaging technology for detection.

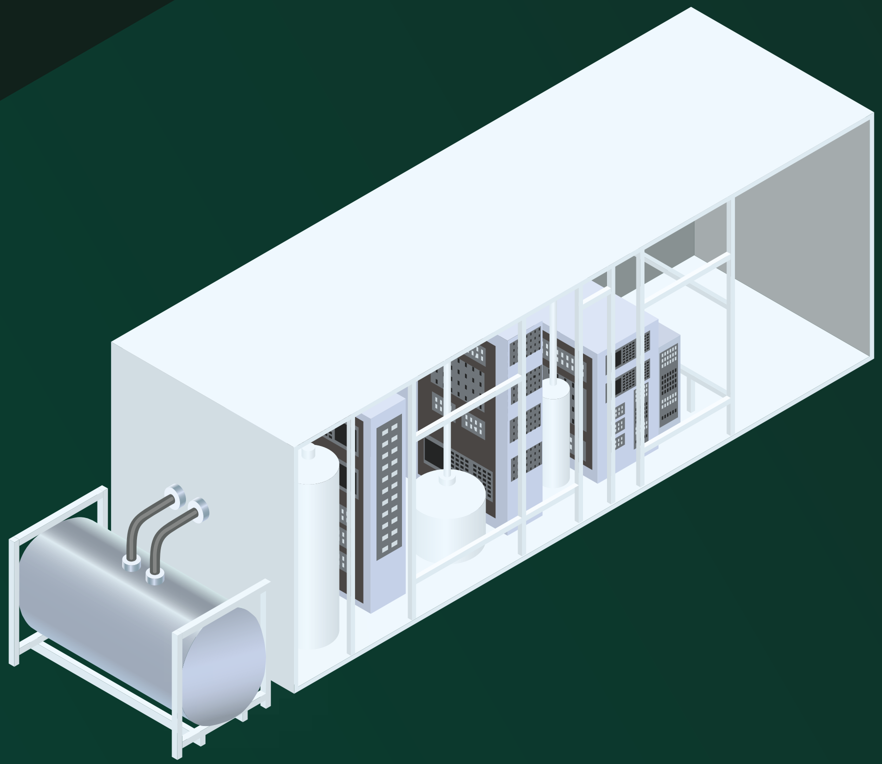
Due to the cryogenic cooling of LH2, special handling procedures and equipment are required. Furthermore, leaks of LH2 introduce new safety considerations as contact with surfaces can cause explosions.

Quality

Purity checks are expected to replace the quality checks of kerosene fuel and need to account for fuel cell and combustion requirements (combustion can utilise less pure hydrogen). The quality analysis of hydrogen is more complex than for aviation fuel and may require the use of off-site laboratories in addition to specialist equipment for sampling and testing.

CHALLENGES AND INTERVENTIONS

07



There is much to do. For the UK to stay competitive and lead the way, we must continue to accelerate forwards, implementing new innovations and concepts that address the industry's challenges.

Introduction to challenges and interventions

The introduction of airport or airfield infrastructure to support net zero flights is a significant challenge for the industry. Airports and airfields must plan for and build the required infrastructure and support multiple new technologies to meet the government targets on emissions. However, before this can happen, the technologies must first develop a level of maturity that will provide confidence in implementation.

Connected Places Catapult has engaged with stakeholders including airports and airfields of all sizes, aircraft manufacturers, fuel handling organisations and technology developers during the preparation of this report. We have summarised the key themes and messages as Stakeholder Voices and potential actions here. We have considered technology-specific challenges and proposed interventions, including projects funded in the TRIG programme. We also offer a high-level pathway consisting of a series of capability levels that allow for a staged introduction to new technologies, which we will further develop in future roadmap deliverables.

Early planning and analysis

Many airports and airfields do not currently feature hydrogen and electric technologies within their masterplans, roadmaps, or infrastructure planning for the next 5-10 years, although most are starting to analyse these areas. It is imperative that planning for these technologies starts now and takes a holistic view, of the parallel operations needed and how the airport or airfield integrates within the local environment.

Within the airport and airfield environment, the planning process should consider:

- Allocation of physical space to new technologies.
- Timescales and quiet periods for the implementation of disruptive works.
- Engagement with airlines and destination airports to agree on planning assumptions and synchronise activities.
- Implications of introducing fuelling and charging vehicles, such as the space around aircraft at stands and increased traffic movements.
- Security implications, particularly vehicle movements across the site boundaries.
- The capacity of electricity supplies.
- Changes to supporting systems and operations such as an increase in ground handling staff and changes to the fire service responses.
- Consideration of combined technologies such as electric generation from hydrogen or hydrogen-powered Combined Heat and Power Systems to replace existing boilers.

Airports and airfields should also consider the external environment, including:

- Local hydrogen hubs and pipeline projects where the airport or airfield may consider their role as a consumer and potentially a producer of hydrogen.
- Electricity supply planning to account for increased supply needs and the competing demands of road transport and household electrification as part of the local area network planning.
- City and town planning and land use discussions.

A significant planning exercise is required between the aviation industry and government to develop data supporting the transition to zero emissions and the development of new infrastructure. This should include data on demand and staged transition plans for airline fleets.

Physical space and land usage

The additional physical space requirements to support multiple new technologies are a limiting factor in handling existing aircraft volumes and simultaneously developing airport or airfield capability across parallel new technologies. Feedback from operators indicates a desire to develop neighbouring land as dedicated net zero areas, although they are often constrained by planning limitations.

New development on non-operational land would solve many space constraints and allow for new systems to be developed unconstrained by existing infrastructure limitations (e.g., physical space available at stands). It would also allow for year-round construction, shortening the time for implementation without disruption to existing operations. Engagement between the government, councils, and airport and airfield operators would be helpful to analyse the options for individual sites.

Finance and incentives

Airports and airfields face substantial costs for infrastructure implementation, and while technology is in the early stages of development and standardisation, those investments come with significant risks. New technologies will likely open additional avenues of revenue for the operators, but the payback periods may be more extended than investors desire. There is a view that airport and airfield operators will need to foot the bill of early trials, demonstrations, and interventions without certainty of the technology or outcomes. Financial incentives and support are likely to be required to mitigate risk during the early stages of development and catalyse the transition to a self-supporting market.

There may also be a need to incentivise airlines to transition fleets when there has been significant investment in conventional fuel and SAF technologies. There is likely to be a pull from passengers when net zero flights are available, similar to the desire for green domestic energy; however, this requires the infrastructure and aircraft to be in place first. Emissions trading schemes also provide an additional incentive mechanism for the airlines to transition.

Outside the airport or airfield, it may also be helpful to include emissions generated from fuel transportation in schemes to minimise the impact of transporting hydrogen and SAF long distances by road to supply airports and airfields.

Stakeholders' voices

Key themes and comments identified from stakeholder engagement activities.

COMMERCIAL

"The ROI for infrastructure is long term and requires strong confidence in the solutions we are asked to implement. There is no scope to fail- fast and experiment."

"Due to CAA regulation on airport charges, we are unlikely to be able to recover new infrastructure costs by increasing our charges. We need financial support and alternative business models."

"There is lots of funding for research and innovation but little for implementation. We were caught before with improvements to airport security technology and this has made us cautious."

"We would like to better understand the business cases for on-site production and how that may provide new revenue opportunities for the airport."

"Funding for early-stage capability will allow us to experiment with new low TRL technologies at low risk to ourselves, especially as we recover from the COVID-19 pandemic."

"More collaboration will be needed between the fuel providers, airlines and aircraft manufacturers."

MARKET HESITANCY

"Airlines will determine the technology, and they haven't yet requested the infrastructure to support alternative fuels/energy."

"The government should fund the airport demonstrators. They can't ask the airports to start building infrastructure for Zero Emission Flights now when there are no aircraft and we don't know the requirement for the aircraft."

"Is there a market for small low carbon fixed-wing aircraft, or will we move to eVTOL? Will the technologies needed at the airport be the same?"

"Will one technology win, or will we need them all? Is this the new VHS vs Betamax?"

"We would like to start making changes, but we are bound by contracts that we signed in the 1990s."

"Are there demand assessments to help us define our business cases?"

"Investor-owned airports are at a disadvantage due to payback period."

PHYSICAL/SITE CONSTRAINTS

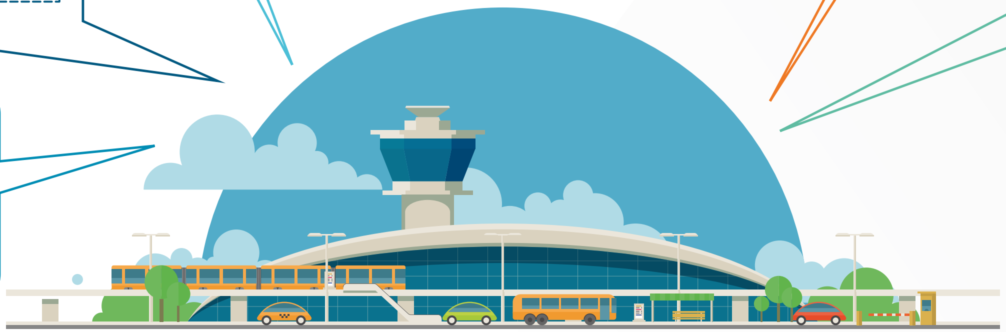
"As a large airport, we will need to support many different technologies in parallel. Finding space within the airport for infrastructure and additional ground traffic will be a significant challenge."

"Electricity supply is a significant problem. It'll cost a few million and take over three years to upgrade the supply. We are competing with housing and commercial developments near the site along with increased demands for electric vehicles and heating, which may limit availability."

PERSONNEL AND SKILLS

"As a small airport, we are finding it hard to find skilled staff. If we need specialists, is there a way they could be shared with larger airports?"

"Training, processes and techniques must be simple enough for low-skilled labour to understand and adopt."



REGULATION AND POLICY

"Regulation, policy and standards are not yet ready and will take a long time to roll out."

"We need the change to fuelling to be considered beyond the airport boundary and be included in city masterplans. This will enable hydrogen hub opportunities and advances with renewable electricity."

"How do we encourage consumer behaviour change towards low emission flights. Are consumers willing to pay more for cleaner flights, or should we incentivise through lower costs?"

"Will the government use a carrot or a stick to drive change? For instance, will we see reductions in Air Passenger Duty for cleaner flights?"

"Why are we transporting SAF long distance? This has an environmental impact using diesel trucks for transport. How can we prioritise for use by airports nearer the source?"

Capability levels

We propose a series of capability levels to enable airports and airfields to plan for the transition towards hydrogen and electric aviation. The four levels are:

- Level 1 – Basic handling and safety capability

  The airport or airfield can safely handle an aircraft but does not usually have fuel availability on-site (e.g., diversion, emergency operation, early demonstrator or there and back short routes). Safety equipment and procedures are in place to handle electric and hydrogen aircraft. A standby fuel or charging equipment supplier should be identified to cover such operations.

- Level 2 – Light-touch capability

  Basic aircraft handling where hydrogen is supplied from an off-site store and electric charging is within the aircraft only. There may be limitations on the volume of aircraft and slots that can be handled.

- Level 3 – Comprehensive capability

  Introduction of on-site storage for hydrogen and fixed electric charging infrastructure.

- Level 4 – Advanced capability

  Introduction of on-site hydrant distribution for hydrogen and electric battery swap technologies.

A small airport or airfield may only reach a lower capability level as needed for their operations, whereas a larger airport is likely to progress through the levels as they scale up. Financial support, incentivisation and prioritisation for innovation can be aligned with these capability levels.

An airport or airfield is likely to maintain different capabilities across technologies. For instance, an airport may have capability Level 1 for hydrogen fuel cell operations and capability Level 3 for LH2 and electric operations.

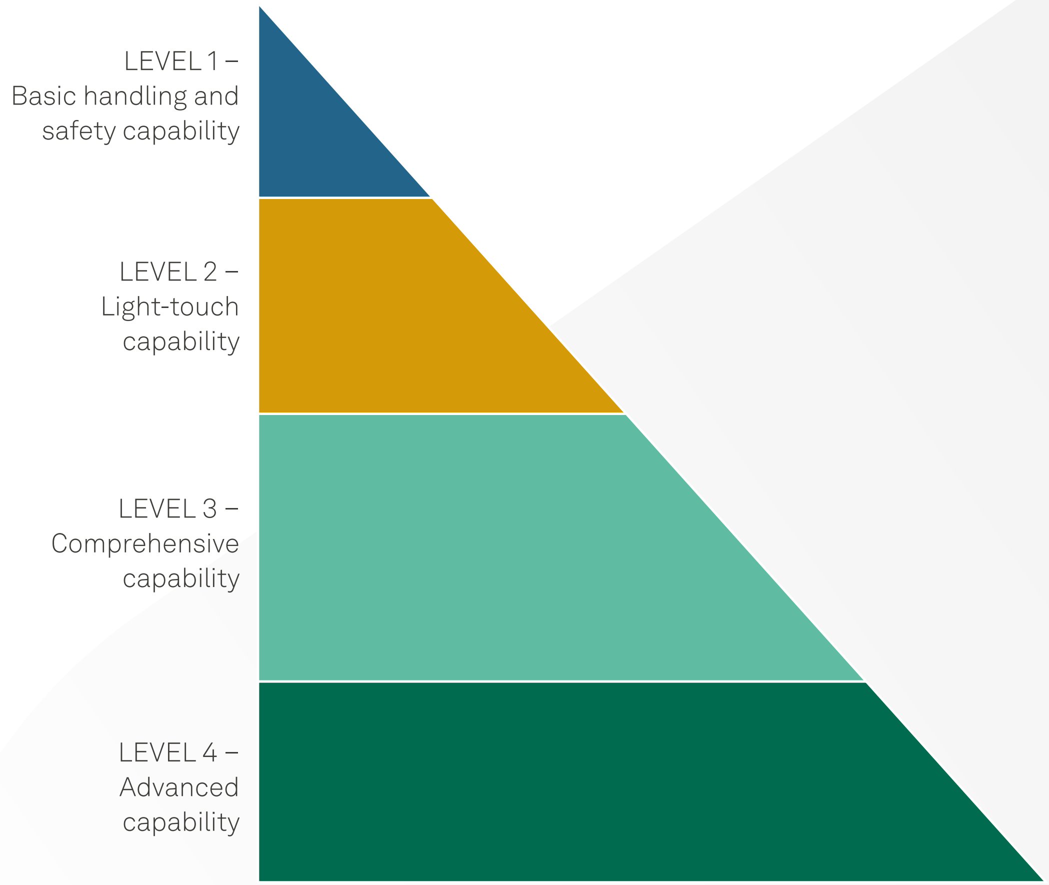


Table 7: Electric capabilities

Level	Level 1 – Basic handling and safety capability	Level 2 – Light-touch capability (basic fuelling/charging)	Level 3 – Comprehensive capability (fuelling/charging efficiency improvements)	Level 4 – Advanced capability (advanced fuelling/charging with cost reductions and supply security)
Capability	Airport or airfield can safely accommodate aircraft but does not offer charging capability*.	Charging of batteries within aircraft using mobile chargers or mobile charging vehicles with onboard power storage.	Fixed charging infrastructure available at aircraft stand locations. Fast charge capability.	On-site renewables and storage technology Charging of batteries outside the aircraft allowing for battery swap.
System elements	Fire and emergency response. Training for staff to deal with battery fire emergencies.	Operations and supporting systems (e.g., billing, quality, metering). Upgraded infrastructure (i.e., high voltage cable network supply and voltage adaptors) for charging points. Or mobile charging vehicle with sufficient battery capacity to charge aircraft. Mobile chargers suitable for aircraft serviced. Charging points for mobile charging vehicles.	Fixed charge infrastructure, including voltage adaptors.	Renewable technology. On-site/close by storage of energy.

* Aircraft may carry a suitable charger on-board to use existing airport or airfield supplies

Level	Level 1 – Basic handling and safety capability	Level 2 – Light-touch capability (basic fuelling/charging)	Level 3 – Comprehensive capability (fuelling/charging efficiency improvements)	Level 4 – Advanced capability (advanced fuelling/charging with cost reductions and supply security)
Technology challenges	Incomplete coverage of charging technology at airports and airfields affecting flight planning and routing of aircraft.	Improving charging speed and turnaround. Standardisation of charging technology (e.g., universal charger). Improvements to battery capacity, life, and cost. Procedures to be developed for safe operations. Larger exclusion zones during charging.	Availability of higher specification chargers for quick turnaround time. Charging infrastructure equipment standardisation such as plugs and sockets. Standards for high voltage wire networks to be installed at the airport or airfield. Communication protocols to communicate with the battery. Faster charging of battery and thermal issues related to faster charging. Standards and procedures to be developed for safe operations.	Risks from battery handling. Standards and procedures for battery swapping and battery swap technology at low TRL. Standardisation such as plugs, sockets and containers for battery swapping. Communication protocols to communicate with battery. CAA approval of battery swapping processes. Fire risks and other hazards related to battery/energy storage.
Airport and airfield challenges	New safety equipment. Training for staff to deal with a battery fire emergency. Obtaining emergency charging equipment if required (e.g., diversion).	Training fuelling staff in electric safety. Managing parallel operations. Limited space at stands for charging vehicles. Limited capacity of energy supply. Power capacity of existing electric cabling for fast charge. Increase in turnaround time of electric planes as mobile charger will charge slowly. Potential requirement for dedicated stands for space and safety distances.	Getting the future prediction for energy usage correct. Increased space on the airport or airfield for charging. Investment in the infrastructure. Installing infrastructure that is future proof.	Space required for energy storage facilities. Significant infrastructure work. Large financial investment. Managing battery/energy storage facilities and training staff. Increased space on the airport or airfield for charging. Training of staff to move batteries along with removing and installation of batteries on the aircraft. Business model: who owns the batteries? Shortage of the aircraft stands during the construction of infrastructure.

Level	Level 1 – Basic handling and safety capability	Level 2 – Light-touch capability (basic fuelling/charging)	Level 3 – Comprehensive capability (fuelling/charging efficiency improvements)	Level 4 – Advanced capability (advanced fuelling/charging with cost reductions and supply security)
Benefits	Airport or airfield suitable for emergency use. Can service short return flights to larger airports (e.g., small islands or nearby airport/airfield). Testing procedures before the infrastructure roll-out. Easier planning for infrastructure and future demand.	Learning can be used to upscale the operation later on. Space constraints at the airport or airfield can be managed using mobile chargers. Relatively low investment.	Faster turn-around times using fixed wire rapid chargers. Can service short there and back regional routes to larger airports.	Protects against supply disruption. Profit from on-site generation. Significantly faster turn-around times.
Opportunities	Airport or airfield could influence regulation and standards.	New local routes for airlines can be explored. Optimisation of the route/flight planning based on turnaround time and demand. Direct source of income.	Consider introduction of renewables to supplement external supply.	Sale of excess energy back to the grid. Business opportunity for the airport or airfield to invest in batteries and rent them to airlines and aircraft operators. Using on-site generation and storing the surplus on-site generated energy will help airports and airfields to reach 100% renewable energy supply target.

Table 8: Hydrogen capabilities

Level	Level 1 – Basic handling and safety capability	Level 2 – Light-touch capability (basic fuelling/charging)	Level 3 – Comprehensive capability (fuelling/charging efficiency improvements)	Level 4 – Advanced capability (advanced fuelling/charging with cost reductions and supply security)
Capability	Airport or airfield can safely accommodate aircraft but does not offer fuelling capability.	Basic refuelling of aircraft is offered with off-site hydrogen storage and truck-based delivery to the airport or airfield. Fuel cells filled off-site.	Refuelling of aircraft with on-site storage of Hydrogen. Transport of Hydrogen within the airfield is by vehicle. Fuel cells may be filled and handled on-site.	Refuelling of aircraft with on-site storage and hydrant system.
System elements	Fire and emergency response. Training for staff to deal with a hydrogen fire emergency. Thermal imaging and training for hydrogen fire risks.	Operations and supporting systems (e.g., billing, quality, metering). Hydrogen transport. Hydrogen swap transport/loading vehicles. Refuelling vehicle (LH2 or gaseous H_2).	Fuel unloading station. Fuel loading station. Storage tanks (LH2 or gaseous H_2). Safety monitoring systems. Compression if needed on-site at this stage. Liquefaction if needed on-site at this stage.	Pipework. Hydrants. Dispenser vehicle.

Level	Level 1 – Basic handling and safety capability	Level 2 – Light-touch capability (basic fuelling/charging)	Level 3 – Comprehensive capability (fuelling/charging efficiency improvements)	Level 4 – Advanced capability (advanced fuelling/charging with cost reductions and supply security)
Technology challenges	Optimising refuelling stops for airlines.	Consideration of all in one bowser vs storage truck and pump unit. Agreement of safe exclusion zones during fuelling Refuelling vehicle technology (compressor, cooling within the vehicle) for gas. No LH2 refuelling vehicle has been developed yet. If LH2 delivery vehicle must wait airside, there is increased boil-off. Fuel cell refilling or tank refilling technology is very immature at the moment. Standards to be developed for safe into-plane operations. Boil-off technology needs to be installed on each trailer.	Boil off technologies for boil off capture and reuse. Introduction of new processes such as compression and liquefaction into airport or airfield environment. High pressure storage vessels to reduce space requirements.	LH2 hydrant system. Expensive and not yet developed (low TRL). LH2 boil-off capture at all stages of LH2 handling at the airport or airfield.

Level	Level 1 – Basic handling and safety capability	Level 2 – Light-touch capability (basic fuelling/charging)	Level 3 – Comprehensive capability (fuelling/charging efficiency improvements)	Level 4 – Advanced capability (advanced fuelling/charging with cost reductions and supply security)
Airport and airfield challenges	New safety equipment. Training emergency responders in Hydrogen safety. Obtaining emergency fuel if refuelling was required (e.g., diversion).	Increase in road traffic. Busy roads may prevent just in time delivery requiring trucks to wait. Increase in airside traffic if kerosene and hydrogen vehicles operating. Training fuelling staff in hydrogen safety. Managing parallel operations. Limited quantity of gaseous fuel on the tube trailer. Multiple trailers are needed for higher fuel demand aircraft. Potential requirement for dedicated stands for space and safety distances. Increase in turnaround time of fuelling. Uncertainty between gaseous H_2 and LH2 at the start of the rollout period.	Increased space on the airport or airfield for storage, liquefaction, and compression (if gaseous H_2 and LH2 are used in parallel). Guaranteed supply of H_2 when demand increases (along with increased demand in other industries). Additional requirements for liquefiers when gas hydrogen is handled on-site and liquefaction to LH2 is required. Decision to use gas or LH2 as a primary fuel at the airport or airfield. Demand forecast and planning of fuel system (LH2, gaseous H_2 or both).	Infrastructure ownership and maintenance contracts. If owned by the airport, who carries out any maintenance? Shortage of the aircraft stands during the construction of infrastructure. Large financial investment. Significant infrastructure work. Low refuelling rates (~500 L/min). Conversion of the existing aviation fuel hydrant pipeline into H_2 /LH2. Hydrant system is 5x more expensive than for kerosene.

Level	Level 1 – Basic handling and safety capability	Level 2 – Light-touch capability (basic fuelling/charging)	Level 3 – Comprehensive capability (fuelling/charging efficiency improvements)	Level 4 – Advanced capability (advanced fuelling/charging with cost reductions and supply security)
Benefits	Airport or airfield suitable for emergency use. Can service short return flights to larger airports (e.g., small islands). Testing procedures before the infrastructure roll-out. Easier planning for infrastructure and future demand.	Low investment. Lower risk profile (e.g., fire, terrorist attack etc.) Can service all aircraft sizes with minimal investment Space saving at the airport or airfield.	Protects against supply disruption (if enough is stored on-site).	
Opportunities	Airport or airfield could influence regulation and standards.	Integration with local hydrogen hubs to reduce fuel transport distance. Shared cost of the infrastructure. If off-site infrastructure is airport or airfield owned can be rented to other industries. Infrastructure can be tested in the regulatory sandbox outside the airport and airfield environment.	Consider on-site production from green energy. Opportunity to bring the fuel handling under airport or airfield management.	Consider on-site production from green energy. Additional income to the airport, airfield, or CAA.

Challenges and interventions

The main challenge areas for airport and airfield infrastructure related to hydrogen, electric and SAF technologies are listed in the tables below. To overcome these challenges, we discuss interventions both those planned or in progress (such as TRIG projects), and those proposed or supported by the ZEFI programme. An intervention that cuts across multiple challenges for each technology is the development of Living Labs at airports and airfields. Living Labs allow early adopters to de-risk investment, learn lessons, and provide an opportunity for technology developers to demonstrate and refine their infrastructure offerings. Interventions to encourage the use of net zero flights, and give long-term confidence to industry and investors, also need to be considered in addition to the technology focused interventions outlined.

As a more developed fuel technology, there are already interventions related to SAF underway. With the ZEFI programme focussed on infrastructure within airports and airfields, and most interventions required for SAF taking place prior to fuel arrival on-site, these are listed for context only.

Electric challenges and interventions

Table 9

Electric challenge area	Current state	Challenges and barriers	Interventions	
			Planned	Proposed
Availability of appropriate equipment	Limited number of battery electric aircraft charging solutions on the market and only for small aircraft (fewer than five passengers). Existing airside infrastructure (three phase 415 V AC) can be utilised for the aircraft chargers on the market.	Existing airside electrical infrastructure will need extended to support significant numbers of battery electric aircraft. Technology challenge and supply upgrade required for megawatt charging of electric aircraft.		Cross-sector collaboration initiative on megawatt chargers to ensure aviation needs are met.
	Battery swapping proposed for battery electric aircraft but not demonstrated.	Swapping of batteries increases the risk of damage and subsequent failure. Constrains design of aircraft if common batteries used in swapping. Technology to be developed and assured.	TRIG: SafeBatt project by CDO2 Ltd "will consider and evaluate options for safe DC charging of electric aircraft using both onboard charging and removable battery electric packs" [93].	

Electric challenge area	Current state	Challenges and barriers	Interventions	
			Planned	Proposed
Turnaround time	Schedules and operating models often rely on tight turnaround time, including refuelling. Currently available chargers are for general aviation electric aircraft that are less time constrained. No charging solutions are available for larger aircraft (>1 MWh battery capacity), which would allow similar turnaround times to equivalent conventional aircraft.	Development of megawatt charging driven by road vehicle sector. Adoption of standards from other sectors will reduce development time and cost, but the needs of the aviation sector would not be explicitly considered.	TRIG: Cranfield University will "assess the feasibility of wireless battery electric charging technologies... [not as a] replacement for conventional battery electric charging methods, but rather as a complementary technology" [94].	Cross-sector collaboration initiative on megawatt chargers with a focus on universal connection and thermal management and cooling of batteries.
Planning future capacity	Few operating battery electric aircraft exist at present. There is uncertainty over future battery electric aircraft fleet size, growth rate and technology mix.	Airports and airfields cannot plan infrastructure without some confidence in battery electric (or hydrogen-powered) aircraft fleet size and technology mix.	TRIG: Multiple projects taking different approaches to model the future energy demands of hydrogen-powered and battery electric aircraft fleets [95]. Jet Zero Consultation states the government will "look at the feasibility of using zero emission aircraft on UK [Public Service Obligation] PSO routes" [96].	

Electric challenge area	Current state	Challenges and barriers	Interventions	
			Planned	Proposed
Standardisation	No existing standards for charging battery electric aircraft. Work is in progress on some standards, e.g., SAE AS6968.	Early standardisation may stifle innovation. Delayed standardisation will limit market confidence and investment.	ZEFI standards gap analysis with British Standards Institute.	
Reliability and availability of energy	Airport and airfield electrical supply sized for existing demand, i.e., not including battery electric aircraft. Airports and airfields are already looking to increase electrical capacity to decarbonise across all areas. Local distribution networks have limited capacity.	Uncertainty on future electricity demand from aircraft is compounded by the increasing demands for green electricity within airports and airfields, and their local area (e.g., electric car use).		Cross-sector deconfliction to ensure effective use of resources. Coordinated knowledge sharing between airports and airfields, and stakeholders in the electricity ecosystem. Novel energy storage technologies to be explored.
Staff	Staff experience of existing airside electrical infrastructure at some airports and airfields.	Installation, commissioning, and maintenance of charging infrastructure requires skilled personnel in demand across other sectors.		Coordination within aviation to ensure sharing of knowledge and best use of limited personnel.

Hydrogen challenges and interventions

Table 10

Hydrogen Challenge area	Current state	Challenges and barriers	Interventions	
			Planned	Proposed
Availability of appropriate equipment	No operational hydrogen aircraft or fuelling infrastructure at airports or airfields.	Significant research and development are required on aviation-suitable hydrogen fuelling infrastructure. Hydrogen expertise and capability spread thin across several growing sectors.	TRIG: Multiple projects covering liquid hydrogen refuelling vehicles, fuelling hoses for liquid hydrogen, hydrogen storage vessels and next generation piping for hydrogen distribution [97]. Hamburg airport hydrogen demonstrator project [98].	Cross-sector coordination on green hydrogen R&D. Hydrogen knowledge hubs.
Turnaround time	Refuelling times with current technology is expected to be higher than conventional fuel.	Hose and connection design, and automation of coupling to enable higher flow rates [99].	TRIG: Protium Green Solutions developing a Digital Twin for fast refuelling [100].	Cross-sector coordination on green hydrogen R&D. Hydrogen knowledge hubs.
Cost	Costs related to aircraft and operations estimated but uncertainty over infrastructure costs.	Technology maturity makes estimating costs difficult.	Tees Valley Multi-Modal Hydrogen Transport Hub Masterplan includes domestic aviation [101].	Cross-sector coordination on green hydrogen R&D. Aviation engagement in Net Zero Hydrogen Fund. Hydrogen infrastructure hubs to support multiple sectors in the local area.
Standardisation and certification	Standards and certification processes exist for hydrogen distribution and use in other sectors.	Early standardisation may stifle innovation. Delayed standardisation will limit market confidence and investment.	ZEFI Standards Gap Analysis with British Standards Institute.	

Hydrogen Challenge area	Current state	Challenges and barriers	Interventions	
			Planned	Proposed
Planning future capacity	No operational hydrogen aircraft or fuelling infrastructure at airports or airfields. Uncertainty over future hydrogen aircraft fleet size and growth rate.	Airports and airfields cannot plan hydrogen infrastructure without some confidence in hydrogen fleet size.	Jet Zero Consultation states HM Government will "look at the feasibility of using zero emission aircraft on UK [Public Service Obligation] PSO routes" [102].	Intervention is needed to de-risk investment decisions. Knowledge sharing forum for the aviation sector to remain up to date on net zero technology and build confidence in market direction – online resource.
Planning physical space	Significant space requirements for infrastructure.	Often limited space for development, particularly at larger airports.	TRIG: Stratospheric Platforms and the University of Warwick are investigating the safety zone requirements around hydrogen aircraft and infrastructure [103].	A framework for considering the positive decarbonisation impact of airport and airfield planning applications.
Supply reliability and availability of energy	No hydrogen demand for aircraft. Limited green hydrogen supply.	Green hydrogen is costly to produce currently. Aviation will be competing with other consumers of green hydrogen as production scales up.	Hydrogen hubs such as Tees Valley Multi-Modal Hydrogen Transport Hub [104].	Cross-sector coordination on green hydrogen production and distribution. Aviation representation on Hydrogen Council.
Staff	No hydrogen infrastructure at the airport or airfield, hence no trained staff.	New infrastructure, processes and safety considerations will need staff retraining or recruitment.	TRIG: Cranfield University developing an interactive training programme for airport personnel on hydrogen safety in aviation [105]. HM Government Hydrogen Strategy states, "we will set up an Early Career Professionals Forum under the Hydrogen Advisory Council" [106].	Cross-sector knowledge-sharing forum for training providers and employers. Aviation sector skills and workforce plan.

SAF challenges and interventions

Table 11

SAF Challenge area	Current state	Challenges and barriers	Interventions	
			Planned	Proposed
Cost	SAF is significantly more expensive than conventional jet fuel.	Technologies to increase and diversify supply need development and scaling up to reduce cost.	HM Government Green Fuels, Green Skies competition to demonstrate new SAF production technologies, develop production capabilities and commercial strategies [107].	Incentives to offset the additional cost of production and disincentives for fossil jet fuel.
Standardisation and certification	Standardisation and certification processes in place up to 50% blend [108].	Limited certification facilities for batches of SAF.	Jet Zero Consultation states HM Government will "establish a SAF clearing house" [109].	
Planning future capacity	0.1% of the jet fuel used by commercial airlines was SAF in 2019 [110]. Commitments by some airlines for some use of SAF.	Without firm commitments on when, where, and how much SAF will be used, airports and airfields cannot plan with confidence.	HM Government consulting on SAF blending mandate to encourage the use of SAF and give confidence to invest [111]. UK Ministry of Defence fuel specifications updated to allow for increased SAF blends will influence SAF use in commercial aviation [112].	Knowledge sharing forum for aviation sector to remain up to date on net zero technology and build confidence in market direction – online resource.

SAF Challenge area	Current state	Challenges and barriers	Interventions	
			Planned	Proposed
Reliability and availability of green energy	SAF is used in low concentrations at limited number of airports.	Limited supply of SAF. Competition with the production of biofuels for other sectors.	HM Government Green Fuels, Green Skies competition [113]. US Government multi-agency SAF Grand Challenge "to accelerate the research, development, demonstration, and deployment needed for ... the production of SAF to 35 billion gallons per year by 2050" [114].	Cross-sector deconfliction to ensure biofuel resources are used in applications that maximise decarbonisation.

CONCLUSIONS

While the path to net zero aviation is not straight forward, these findings highlight the need for action on infrastructure to start now.

The aviation industry is facing great change over the coming decades in order to achieve net zero. This Blueprint has presented the infrastructure options for airports and airfields to support net zero along with challenges and interventions to be considered. The key findings, grouped by four themes, are presented over the following pages. Core stakeholder groups are identified who need to take actions to ensure that infrastructure is developed, planned for, funded, approved and used.

The necessary transition to zero emission flight infrastructure will be at a pace, scale and novelty that is unprecedented for airports and airfields. It will require concerted efforts to innovate and successfully implement new airside infrastructure, aircraft fleets and operations.

Findings: themes

- Commercial
- Engagement and coordination
- Planning and Operations
- Technology

Action owners

- Airports and Airfields
- Airlines & FBOs
- Regulators
- Research and technology accelerators
- Government
- Energy Sector
- Public
- Academia
- Aircraft Developers
- Technology Providers

Conclusions

COMMERCIAL

Use a combination of incentivisation and disincentives, accessible to all corners of the sector, to shift approach and behaviour. An effective transition to zero emission flight is only facilitated by a gradual but targeted implementation of both a 'carrot and stick' approach.

Align funding and industry support measures with a ZEFI Capability Framework so that early adopters receive the necessary support to catalyse and stimulate new markets that will quickly become self-sufficient.

Airports and airfields, airlines and the wider industry are excited to begin transitioning to zero emission aviation. However, there are still significant barriers to investment as airports, airfields and their funders are reluctant to commit to technologies with low technology readiness and high levels of uncertainty. This concern has also delayed early actions and investigations which require only minimal investment.

There are many new opportunities for airports and airfields to realise the new sources of income available from Zero Emission technologies. However, they fall outside the distinctive competence and markets traditionally addressed (e.g., the airport as an energy producer or hydrogen hub). Many organisations are looking to make strategic partnerships in this area, although current incentives and funding primarily support road transport initiatives.

Review contracts with service providers (e.g., with Fixed Base Operators) to identify constraints to implement significant ZEFI changes or changes to operations.

Conclusions

ENGAGEMENT AND COORDINATION

Increase community engagement with people local to airports and airfields and with the general public to stimulate investment and demand for zero emission services. Capitalising on increased consumer and public awareness will help gain an understanding of the market conditions and the required policy levers needed to stimulate consumer behaviour changes. This could include, for instance, the use of aviation dashboards that report the current proportion of aviation services that are using SAF or that are zero emission.

Cross-industry bodies such as the Catapults and industry associations should continue to facilitate connections between companies within and at the periphery of the sector.

Establish coordination activities between airport and airfield operators and airlines to understand when the fleet will convert to hydrogen-powered or battery electric and associated demand from passengers.

Rationalise energy supply to the site and collaborate with others in the energy supply chain. Consider partnerships and consortia with organisations and schemes facilitating broader green transport modes (e.g., utilising hydrogen pipelines, local green electricity generation or Hydrogen Hubs).

The aviation industry is currently focused on SAF, and this must not detract from the longer-term transition to hydrogen and electric technologies. There has been little direct engagement between airport and airfield operators and airlines on hydrogen and electric needs. Operators are calling for more detailed industry coordination and planning to understand aircraft availability and likely demand timescales. Such coordination must also extend internationally to ensure destination airports bring capabilities online in parallel.

There is much to be learned from broader industry collaboration, particularly the automotive industry, where hydrogen and electric technologies are more mature. The sector must carefully manage the technology transfer into aviation to ensure standardisation and qualification for the airside environment.

Take an international viewpoint for future planning airline needs and routes to be serviced. Engagement with European and international airports is essential to achieving the longer-term goals for medium and long-haul length zero emission flights.

Be open to changes and engage with aircraft developers alongside airlines to understand future planned and commercial commitments. Don't assume the transition to zero emission flight will maintain the status quo or that the industry will be comprised of the same organisations offering comparable services.

Seek out collaboration with complementary industries as the objectives for zero emission flight can only be achieved with aviation integration as part of the holistic zero emission ecosystem.

Encourage knowledge sharing. Consider making it a requirement of all government-funded technical engagements and technology that the recipient of funding must actively release non-commercial findings and facilitate knowledge transfer throughout the industry.

Conclusions

PLANNING AND OPERATIONS

Begin planning for future infrastructure work, including electric and hydrogen changes. Consider operational availability and identify time slots for completing work with reduced commercial impact (e.g., lower passenger demand). Identify potential opportunities to synchronise new ZEFI airport developments with existing planned work.

Plan for Level 1 and Level 2 capability implementation. While operational and procedural planning may be challenging, physical space planning can be started now with existing information from other industries. Understanding constraints and requirements for these early capabilities will allow airports to tailor plans and become low-risk early adopters.

While many airports and airfields have started to think about zero emission technology implications, they are not currently featured in long term infrastructure plans. The lack of planning is a significant concern given the long lead times for major infrastructure changes and the constraints scheduling them at quieter times. There are also implications for broader local planning, including understanding the load and peak demands of electricity networks and the hydrogen volumes required. More information and modelling is necessary to inform the planning process and influence technical decisions.

Airports and airfields have also been significantly impacted by the COVID-19 pandemic, reducing passenger volumes and staff availability following Brexit. The transition to zero emissions requires operators to innovate and rethink operations on a previously unseen scale, which requires specialist technical expertise. Funding and acquiring the key people to define the strategy, design the changes, and later operate the infrastructure and upskill teams is critical for success.

Engage with local city and regional planners to ensure your needs are considered in planning decisions and regional plans. Consider land usage and whether areas of the airport or airfield could be dedicated to zero emission technologies.

Build upon the success of the Catapult's TRIG technology innovation accelerator with similar competitions targeting growth in skills and funding for short term specialist expertise for airports to build capability and enable cross-industry knowledge transfer.

Import skills and standardisation wherever possible from other industries. Where this is not possible, immediate action is needed to develop new standards and training suitable for aviation environments.

Conclusions
TECHNOLOGY

Prioritise hydrogen and electric developments equally with SAF in the short term. However, do not lose sight of the true zero emission technologies that require more planning effort and lead-time. SAF is a transitionary solution that cannot solely facilitate the end goal of net zero aviation.

Implement early capabilities using existing technologies from other industries. This focuses on the specific operational nuances and safety case for the aviation environment at minimal cost without fixed infrastructure.

While this Blueprint has focussed on the airport and airfield infrastructure, the transition to zero emissions must take a whole systems approach. Wider engagement must consider the entire energy supply chain, aircraft technology and regional energy infrastructure planning.

Interim options may be considered to kick-start technology development, such as the use of non-zero emission hydrogen and electricity when plans are in place to transition other aspects of the supply chain. Transition planning must be carefully addressed to avoid any impression of greenwashing. Longer-term, other emission sources, such as road transport of sustainable fuels, should also be considered.

Early technology standardisation is required to ensure investment focuses on the right technology mix and gives confidence to operators in the implementation. These efforts must focus on infrastructure technologies and consider aspects such as fuel quality needs.

Please see the Challenges and Interventions section for greater detail on individual electric and hydrogen technology interventions.

Local town and city planning for new electrification infrastructure in close proximity to airports and airfields (e.g., new sub-stations or connections to the national grid) should be sized to accommodate future airport charging demand for electric vehicle and aircraft charging.

Establish standards committees to collaborate on early standardisation, identify gaps and qualify technology for the aviation industry.

FURTHER AND RELATED WORK

Sign up for updates on our programme website.

We need your ideas and expertise to help shape the future of zero emission flight infrastructure.

Please get in touch with the ZEFI team.

This Blueprint Report has explored the developing technologies, the challenges faced by UK airports and airfields, and the capabilities required to transition to zero emission flight. However, further work is needed to gain a clearer understanding of the implementation support needed by the industry, including:

- **Standards analysis** — detailing standards that are missing or require expansion and where new formal regulations are needed.*
- **Road mapping** — showing the timescales associated with the transition and helping the industry understand which capabilities are needed first.*
  Providing regular horizon-scanning and technology readiness assessments.
- **Case studies** — giving a voice to airports and airfields by presenting the ZEFI benefits and challenges.*
- **Dissemination** — ensuring the aviation industry and other affected sectors understand the task at hand and that the opportunities available are shared with the industry and the public.*
- **Economic analysis** — to understand commercial challenges and interventions, including where best to focus funding support and policy levers for the greatest impact.
- **Demand analysis** — determining when capabilities will be required at airports and airfields to support target volumes of net zero air traffic.
- **Technology support** — helping airports and airfields determine the optimum technology mix to meet their needs.
- **Operations and human factors assessment of infrastructure** — to achieve a user-centric view of the changes to skills, procedures, and safety.
- **Living labs** — to enable stakeholders to demonstrate and test new technology in real-world environments and drive further investment.

** An additional output from another Work Package of the ZEFI programme.*

FURTHER AND RELATED WORK CONTINUED

Jet Zero

The ZEFI programme, as part of the Government's commitment in the Ten Point Plan for a Green Industrial Revolution, is improving the understanding of the infrastructure changes required at airports and airfields to prepare for hydrogen-powered and battery electric aircraft. However, other important research is being carried out during 2021-2022 as part of the Department for Transport's policy commitments this financial year. The FlyZero project and the Green Fuel, Green Skies (GFGS) competitions are also analysing and developing solutions that facilitate the transition to zero emission flight. These projects focus on the upstream and downstream boundaries of the ZEFI programme and consider the new aircraft and aviation fuel or hydrogen supplies. FlyZero is investigating the use of hydrogen during the refuelling process, including storage, delivery, and safety regulations with the aim to establish a safe, efficient, and fast aircraft turnaround process for a regional and single aisle sized aircraft. GFGS is supporting the development of the UK SAF sector towards the deployment of innovative SAF production technologies at commercial scale. A short synopsis of each project and links to project websites are shown on the below.

About FlyZero

Led by the Aerospace Technology Institute and backed by the UK Government FlyZero is a one-of-a-kind research project aiming to realise zero-carbon emission commercial aviation by the end of the decade. FlyZero are conducting a detailed and holistic study of the design challenges, manufacturing demands, operational requirements, and market opportunity of potential zero-carbon emission aircraft concepts.

FlyZero has concluded that green liquid hydrogen is the most viable zero-carbon emission fuel with the potential to scale to larger aircraft utilising fuel cell, gas turbine and hybrid systems. This has guided the focus, conclusions, and recommendations of their project.

The outputs of FlyZero, due to be published in March 2022, will help shape the future of global aviation with the intention of gearing up the UK to stand at the forefront of sustainable flight in design, manufacture, technology, and skills for years to come.

About Green Fuels, Green Skies (GFGS) Competition

The Green Fuels, Green Skies competition is providing up to 15 million in grant funding to UK SAF projects during the 2021/22 financial year. Specifically, it will look to support the early-stage development of UK SAF plants, referred to as "Front End Engineering Design (FEED)", "Pre-FEED" and "Feasibility Study" stages of a project's development life cycle. A key focus is on supporting activities related to the development of First-Of-A-Kind (FOAK) commercial SAF plants in the UK and demonstration scale SAF projects.

The Green Fuels, Green Skies competition is administered and managed on behalf of the DfT by the competition delivery partners Ricardo Energy & Environment and E4tech.

CONTRIBUTORS

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Flying Club Conington

FlyZero

UKRI: Future Flight Challenge

Gatwick Airport

GKN Aerospace

H_2GO Power

Heathrow Airport

ITM Power

Leeds Bradford Airport

Loganair

London Luton Airport

London Oxford Airport

MAG Airports

NEBOair

NEXT Hydrogen

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