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D5.2: Roadmap for the Introduction and Transition to Liquid Hydrogen for Civil Aviation

Authors: Andrew Rolt, Cranfield University; Anders Lundbladh, GKN; and Ian Williamson, EHA.

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Executive Summary

EnableH2 has identified thirteen research and technology strands for the development of liquid hydrogen aircraft for potential initial entry into service between 2035 and 2050:

- Ensuring safety with hydrogen-fuelled aviation
- Materials development and qualification for hydrogen aircraft systems
- Regulation and certification of hydrogen aircraft, fuel and operations
- Hydrogen aircraft environmental impact and life cycle assessment
- Decarbonisation of energy sources for aviation
- Hydrogen production, liquefaction and distribution
- Airport LH_2 infrastructure and aircraft fuelling
- Design of aircraft fuel systems and fuel storage for liquid hydrogen
- Propulsion systems design for liquid hydrogen
- Hydrogen combustor design and emissions reduction
- New transport aircraft designs for liquid hydrogen
- Liquid hydrogen aircraft operation and maintenance
- Economics of liquid hydrogen vs. alternative fuels

Contents

Introduction

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Introduction

Today larger aircraft are almost exclusively provided with energy via kerosene refined from crude oil (Jet A or Jet A-1), but the environmental and climate impact of burning fossil fuels has driven the aviation industry to consider alternative energy sources.

‘Drop-in’ replacement fuels are certified to be mixed into kerosene at up to 50%, but today less than 0.1% of aviation fuel is sustainable aviation fuel (SAF). Moreover, its feedstocks are scarce and have alternative uses.

Electrified propulsion also has large hurdles to overcome, even just to power a small proportion of short-range flights, and battery powered aviation is unlikely ever to have a significant impact on the environment and global warming.

Hydrogen has been studied as a fuel throughout the history of aviation because of its very high energy density, potential production from renewable resources, and not generating long-lived greenhouse gases upon combustion. Its use in air transportation still poses significant engineering challenges, but paths to their solution are described in this report.

The ENABLEH2 project was created because of these perceived advantages of cryogenic liquid hydrogen (LH_2) as an aircraft fuel. The project has researched critical engineering challenges, including safe use of LH_2 in jet airliners, its combustion with minimum nitrogen oxide formation and fuel systems to deliver and preheat the hydrogen to maximize engine efficiency.

Acknowledging the breadth of the challenge, the project team is supplementing the specific research actions with this roadmap. It illustrates the wide scope of technologies being developed and describes how knowledge gaps can be researched in a structured framework: progressing from basic understanding to testing and demonstration. We believe this academic approach will provide useful input for the planning and execution of upcoming European and global efforts to mature hydrogen aircraft technology.

History of Hydrogen Aviation

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Hydrogen in Aviation: 1800s to 1950s

Hydrogen was used in the 18th century to fill balloons, providing more lift than heated air. A century later, as airships were introduced, hydrogen was the most common source of lift. By the 20th century some German zeppelin engines were fueled with “Blaugas”. This mixture of hydrocarbons and a small percentage of hydrogen has a density close to air, and consequently its consumption did not affect the buoyancy of the craft.

The jet engine, developed in the beginning of the 20th century, can achieve very high specific power. To exploit this potential, a liquid fuel must evaporate and burn in the brief time it remains in a relatively small combustion chamber. The German engineer Von Ohain, realized the evaporation phase could be avoided by hydrogen fuel, which was consequently used for in tests in 1937. His engine became the first to power a flying jet aircraft in 1939.

In the mid-40s liquid hydrogen (LH_2) fuel was evaluated by the US for jet engines and rocket applications, but dismissed primarily because of its low density, production and handling difficulties. Nevertheless, the US military and Ohio State University researched LH_2 production and its use as a fuel, including hydrogen-air combustion for aircraft propulsion, up to the early 1950s. Studies of using LH_2 for other purposes continued, leading to progress on LH_2 turbo pumps and on the large-scale liquefaction and catalytic conversion of ortho- to para-hydrogen to reduce evaporation losses.

Hydrogen research shifted to the NACA, initially concentrating on rocket launchers for satellites, but towards the mid 1950s military interest in flight above 20 km altitude increased. Lightweight foam insulated tanks, made rigid by internal overpressure, were studied. The goal was a tank weight of only 10-15% of the fuel it carried. Investigations considered fuel systems for aircraft and engines as well as combustor design for jet engines.

Hydrogen in Aviation: 1950s to 2000

In 1957 the practical operation of a hydrogen jet aircraft was tested. A B-57B Canberra was equipped with a wing-tip tank containing 1.7 m^3 of LH_2 and a ram-air hydrogen heater on the wing. Hydrogen gas was injected into one of the aircraft's jet engines which retained also its conventional kerosene fuel system. A metering valve for the gaseous hydrogen was used to govern engine speed, operated by the modified control system. Flights of up to 30 minutes operation on hydrogen were made with the stainless-steel foam-insulated tank pressurized by helium. Later flights used a piston pump inside the tank to pressurize and feed fuel to the engine.

Subsequently, Pratt & Whitney designed a jet engine to run on hydrogen and tested it on the ground. Although it was never flight tested, a working engine was developed with an exhaust-heated hydrogen vaporizer and a combustor for gaseous hydrogen.

The studies of LH_2 as an aircraft fuel reignited interest in it for rocket launchers, with an engine contract awarded to Pratt & Whitney in 1958. The Atlas Centaur rocket was first flown in 1962 using liquid oxygen and a 53 m^3 tank for LH_2. The use of hydrogen in rockets has since become a common practice, especially for upper stages. The space shuttle external tank had a volume of about 1500 m^3.

Interest in hydrogen propulsion of aircraft resurfaced several times subsequently. During the oil crises in the 1970s there was a spike of interest in finding a fuel that did not rely on petroleum. Lockheed and other contractors conceptually designed an aircraft, engines and fuel systems. Supersonic and subsonic transport aircraft were considered.

In the 1980s, in the Soviet Union, Tupolev also began investigating using hydrogen as a fuel. In 1988 a Tu-155 flew with one engine fed from a 17 m^3 LH_2 tank. The tank and other equipment were housed within the cabin, reducing potential passenger capacity. Also in 1988, a piston powered single engine Grumman American AA-5 became the first manned aircraft to take off and fly solely on LH_2. Subsequently, in 1992, Deutsche Aerospace Airbus reported some initial studies on LH_2 for aviation.

Hydrogen in Aviation: 2000 to 2016

In 2000, the EU funded CRYOPLANE project, led by Airbus, studied LH_2 as a fuel for subsonic transport aircraft. Conceptual designs of aircraft ranging in size from a business jet to a large long-range airliner were created. Analysis indicated that an aircraft using LH_2 would not be less safe than one using kerosene. The climate impact from the remaining emissions of nitrogen oxide and water and the elimination of carbon dioxide was simulated. It was concluded that use of hydrogen would offer significant environmental and climate change benefits, despite the increased water vapour emissions.

In 2008 Boeing flew a Diamond DA20 converted to fuel cell propulsion for 20 minutes at 100 km/h. From 2009, researchers at NASA have presented studies on a N3-X 300 seat aircraft concept powered by two gas turbines running on hydrogen stored as LH_2. Key takeaways include 70% reduced energy use compared to a Boeing 777-200LR and NOx emissions 80% below upcoming regulation.

The EU sponsored ENFICA project team set a world record of 135 km/h over a 3 km course with a fuel cell aircraft in 2010, with 150-160 km/h cruise for up to one hour claimed to be feasible. Between 2012 and 2014 Boeing tested the Phantom Eye unmanned aircraft at up to 54,000 feet altitude and 9 hours duration. The aircraft stored LH_2 in two spherical aluminium alloy tanks having about 5 inches of sprayed-on foam insulation (SOFI).

In 2013 the US Office Naval Research Laboratory demonstrated a 48-hour fuel cell powered flight using LH_2 in a drone weighing 16 kg. At the time of writing, fuel cells for small unmanned drones are commercially available.

The impact of air traffic on the climate was analyzed by the UN in the 1990s, and more focus on mitigation has followed, especially after the Paris Agreement in 2015. While this did not set a specific target for international aviation, it is implicitly covered as a part of national obligations to avoid exceed 2°C global warming.

Hydrogen in Aviation: 2016 to 2022

The ENABLEH2 initiative began in 2016 and was funded by the EU from 2018.

European countries have started to set goals and target years for the reduction of aviation emissions and climate impact. In the process, several countries have been promoting hydrogen as a potential or preferred path for emissions reduction. The pace of announcements regarding hydrogen-powered aircraft has therefore increased markedly from 2020 onwards.

The EU funded Joint Undertakings Clean Sky 2 and Fuel Cell and Hydrogen 2, commissioned a study of hydrogen as an aviation fuel. The outcome, presented in May 2020, stated that hydrogen was a suitable fuel for short/medium range commercial aircraft with introduction targeted before 2035. The study considered both fuel cell and gas turbine propulsion. The projected cost impact was estimated as less than 20 USD/passenger for short range flights, with an associated climate impact reduction of 50-90%.

In July 2020, the UK Aerospace Technology Institute launched the FlyZero project to study concepts and market opportunities for zero carbon emission aircraft. In 2021, FlyZero presented a concept aircraft with a range of 10,000 km using LH_2 storage.

In September 2020, Airbus announced its ambition to develop a zero emission commercial aircraft by 2035. Three concept aircraft were described, using turbofans, fuel cell powered propellers, and hybrid electric turbine propulsion, respectively.

In 2020, the EU funded MAHEPA consortium, flew the 4-seat HY4 on fuel cells and ZeroAvia flew a converted Piper M350, partly on fuel cell power. A cruising flight using power solely from fuel cells followed in 2021.

In October 2022, the Hydrogen Aviation Lab, a project designed to prepare for handling and maintenance of hydrogen-powered aircraft, was announced. The project partners, including DLR and Lufthansa Technik, will use a decommissioned A320 as a test bed.

Background

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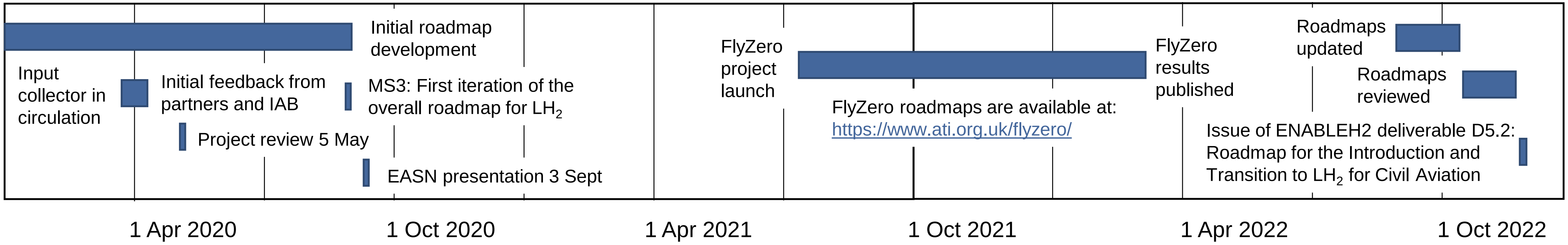
Roadmapping in ENABLEH2

- The ENABLEH2 project has included roadmapping for the introduction of liquid hydrogen (LH_2) as a commercial aviation fuel. Roadmaps help serve the EU's industrial strategy ambition.
- This slide shows how the roadmaps developed – subsequent slides focus on the particular R&D activities needed, proposing timelines for enabling technologies to be raised to TRL 6.
- Preliminary roadmaps generated for MS3 were described at the EASN conference in 2020.
- FlyZero was then launched by the UK's ATI, with ENABLEH2 industry advisory board (IAB) members and Cranfield University providing inputs. Results were published in March 2022.
- The final ENABLEH2 roadmaps reflect FlyZero results and include longer-term perspectives.

Roadmap for the ENABLEH2 roadmapping:



Initial roadmap development

Input collector in circulation

Initial feedback from partners and IAB

MS3: First iteration of the overall roadmap for LH_2

Project review 5 May

EASN presentation 3 Sept

FlyZero project launch

FlyZero roadmaps are available at: https://www.ati.org.uk/flyzero/

FlyZero results published

Roadmaps updated

Roadmaps reviewed

Issue of ENABLEH2 deliverable D5.2: Roadmap for the Introduction and Transition to LH_2 for Civil Aviation

Clean Hydrogen: the New Industrial Strategy for Europe

The EU Commission on March 10, 2020, presented its New industrial strategy for Europe

- ‘Europe needs an industry that becomes greener and more digital while remaining competitive on the global stage’

Main points:

- An energy efficiency first principle and a secure and sufficient supply of low-carbon energy
- Planning and investment in low-carbon power technologies, capacity and infrastructure
- A strategic approach to renewable energy (RE) industries, offshore energy and their supply chain
- All carriers of energy, including electricity, gas and liquid fuels will need to be used more effectively by linking different sectors: a new strategy for smart sector integration, which will also set out the Commission’s vision on clean hydrogen
- Trans-European energy networks to support the transition to ‘climate neutrality’
- Special focus on sustainable and smart mobility industries to support Europe’s industrial competitiveness and improve connectivity (twin transitions: notably automotive, aerospace, rail and ship building industries, as well as for alternative fuels and smart and connected mobility
- New industrial ecosystems: approach of industrial alliances using knowledge of SMEs, big companies, researchers and regions to remove barriers and improve policy coherence
- The EU takes Clean Hydrogen as a prime example and will shortly propose launching the new European Clean Hydrogen Alliance bringing investors together with governmental, institutional and industrial partners. The Alliance will build on existing work to identify technology needs, investment opportunities, regulatory barriers and enablers

These principles have been included within two further EU support packages: ‘Fit for 55’ and ‘RERowerEU’

- They have at their heart the scaling-up of renewable energy supply associated with hydrogen production and its application
- Hydrogen use in heavy duty and hard to abate mobility, including aviation, is a key focus area

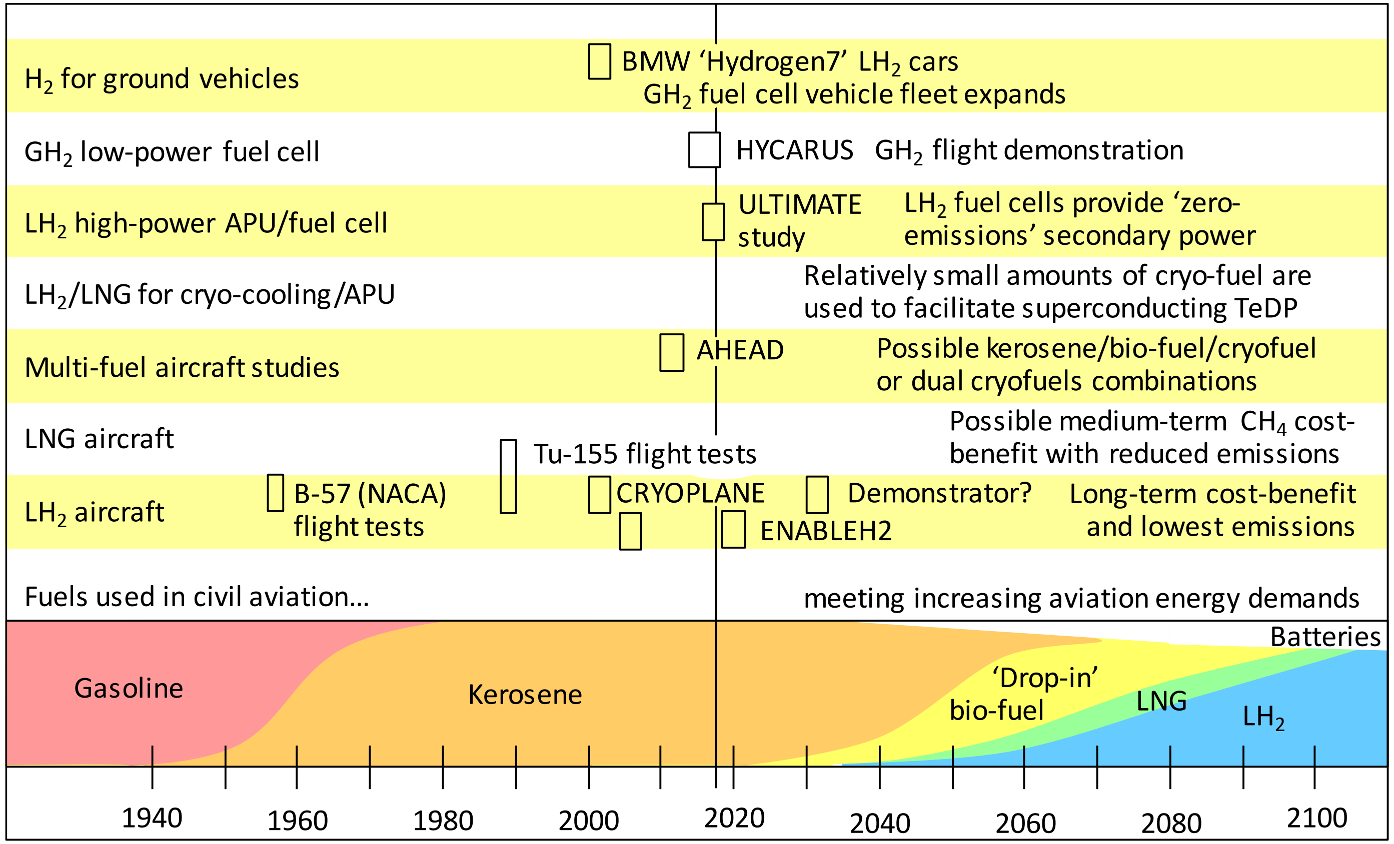
Development of a Global Hydrogen Economy and Infrastructure

- While the EU may take a lead with its New Industrial Strategy, this lead will need to be followed around the whole world if global warming is to be arrested
- Significant growth is anticipated in the use of hydrogen as a fuel for a range of applications from electricity generation and heating to automotive, maritime and rail transportation
- Development of this parallel ‘hydrogen economy’ will help create infrastructure for production, storage and distribution of hydrogen, thus reducing its cost and facilitating its use in aviation
- Use of hydrogen together with biomass or CO_2 to synthesise drop-in hydrocarbon fuels for existing aircraft designs may be seen as a stop-gap position for aviation, but it should also help to facilitate the development of the wider, larger scale, hydrogen supply system
- This supply system may then be used to provide hydrogen fuel directly, when the technology and economic environments are ready for the direct use of LH_2 in commercial aircraft
- The wider uses for hydrogen are largely beyond the scope of our ENABLEH2 roadmapping exercise, but other roadmaps have been, and are being, developed for such applications

Developments since the start of ENABLEH2

This chart was included in the ENABLEH2 proposal in 2018 to indicate the state of the art for the development of LH_2-fuelled aviation and the introduction of alternative low-carbon energy sources

- All-electric battery-powered aircraft are expected to fly very short-range routes
- H_2 fuel cell and hybrid-electric regional aircraft are now under development
- Gas turbine powered medium-range LH_2 fuelled aircraft are seen to be attractive environmentally and also economically given reducing renewable energy costs
- Long-range LH_2-fuelled aircraft are now considered feasible in the medium term
- Projected costs for green LH_2 are lower than for drop-in bio-fuels or synthetic fuels that use direct air capture of CO_2
- LNG has been shown to offer only a small net CO_2 reduction, so it may now be replaced by LH_2 in this chart



References: ENABLEH2 WP1 deliverables and FlyZero: https://www.ati.org.uk/wp-content/uploads/2022/03/FZO-ALL-REP-0004-FlyZero-Our-Vision-for-Zero-Carbon-Emission-Air-Travel.pdf

Technological basis for the introduction of liquid hydrogen as a civil aviation fuel

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- Various technologies need to be developed before liquid hydrogen (LH_2) can be considered a credible economic option as a sustainable carbon-free fuel for commercial aviation.
- LH_2 does not provide a ‘quick fix’ for reducing the global warming effects from aviation, since it is first necessary to decarbonise hydrogen production and reduce its cost, but in the longer term LH_2 can provide a major solution for sustainable growth in air transportation.
- LH_2 has higher energy density than alternative fuels, but its low physical density means the fuel generally cannot all be fitted inside the wings of conventional ‘tube and wing’ aircraft.
- ‘Tube and wing’ aircraft will need larger fuselages to accommodate LH_2 fuel tanks, but should still be feasible and scalable to most market segments. However, novel architectures, such as blended wing body (BWB) designs for long-range aircraft, may offer higher energy efficiencies.
- Larger fuel tanks mean LH_2 aircraft tend to have more drag and higher empty weight, reducing energy efficiency, but lower fuel mass can reduce maximum take-off weight if the LH_2 tanks have high gravimetric efficiency (ratio of useable fuel mass to mass of fuel plus tanks).
- LH_2 is needed because compressed hydrogen gas (GH_2) tanks are much too heavy except for very short ranges where GH_2 use can be competitive on weight with battery-powered aircraft.
- Fuel cell technology is not yet sufficiently advanced to displace gas turbines from commercial aircraft cruising at over 0.75 Mach, but may soon be developed to power slower-flying aircraft.

Overall Roadmap Results

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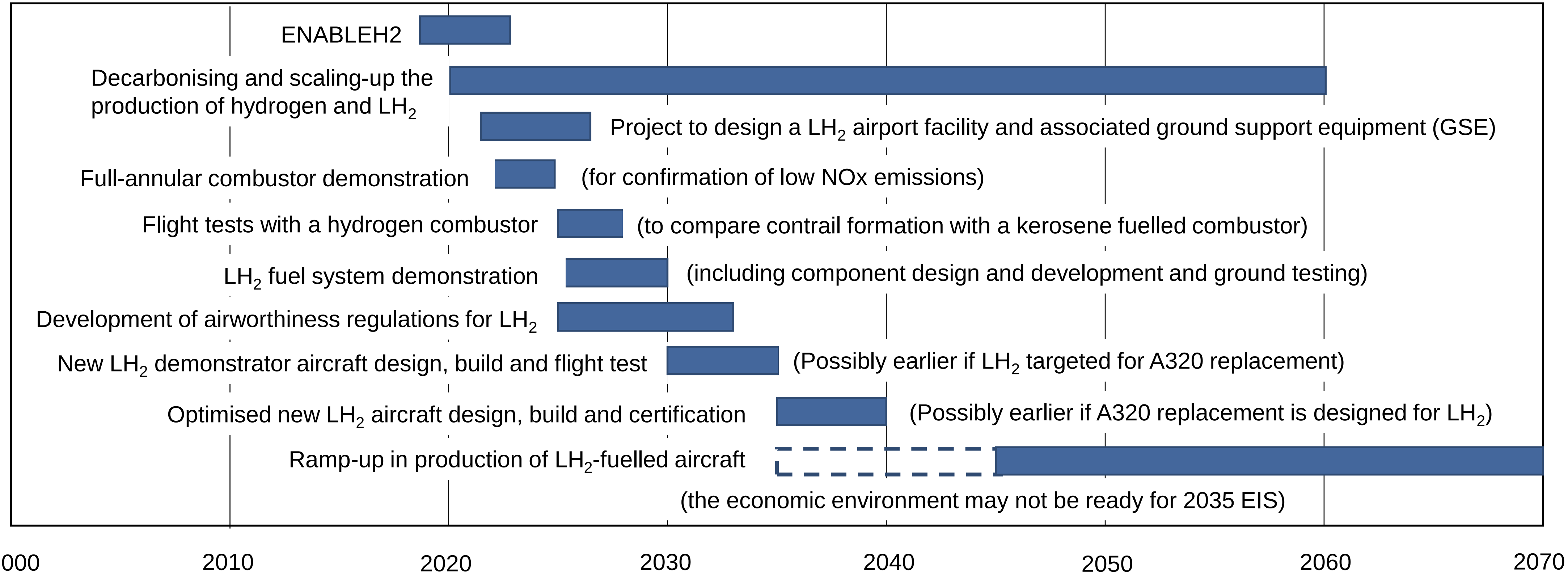
Enabling Research Strands for LH_2

Thirteen research and technology strands have been identified as necessary to enable the development of LH_2 aircraft for potential initial entry into service between 2035 and 2050:

- Ensuring safety with hydrogen-fuelled aviation
- Materials development and qualification for hydrogen aircraft systems
- Regulation and certification of hydrogen aircraft, fuel and operations
- Hydrogen aircraft environmental impact and life cycle assessment
- Decarbonisation of energy sources for aviation
- Hydrogen production, liquefaction and distribution
- Airport LH_2 infrastructure and aircraft fuelling
- Design of aircraft fuel systems and fuel storage for LH_2
- Propulsion systems design for LH_2
- Hydrogen combustor design and emissions reduction
- New transport aircraft designs for LH_2
- LH_2 aircraft operation and maintenance
- Economics of LH_2 vs. alternative fuels

Integration of timeframe and funding for the introduction of LH_2-fuelled aircraft

- Summary of major initiatives and timescales for introducing LH_2 fuelled aircraft



Description of the Research Strands

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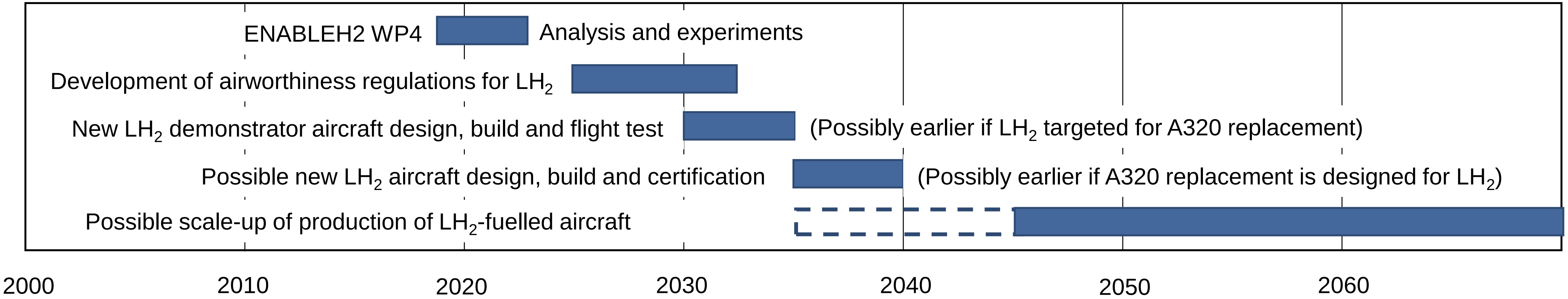
Ensuring safety with hydrogen-fuelled aviation

- Safe integration of LH_2/GH_2 systems into airframe
  - Key (but not the only) challenge: managing explosion risk from leaks into confined volumes (potentially serious consequences even from minor leaks)
  - Evaluate risk: assess leak sizes/frequency and determine potential consequences
  - Evaluate/develop appropriate strategies/systems to reduce risks to acceptable levels – early detection of leaks/cracks, ventilation, inerting, ignition likelihood, explosion withstand, etc.
- Develop design rules and operating protocols for LH_2 aircraft.
- Assess risks from large scale LH_2 releases (dispersion, pool fire/fireball, blast wave) and examine implications for aircraft/airport design and operation.
  - Crash landing / release at airport LH_2 storage facility / aircraft refuelling spillage
- Develop fire-fighting requirements and procedures for LH_2 enabled airports
  - Procedures for Jet A and LH_2 incompatible


ENABLEH2 WP4 Analysis and experiments

Development of airworthiness regulations for LH_2

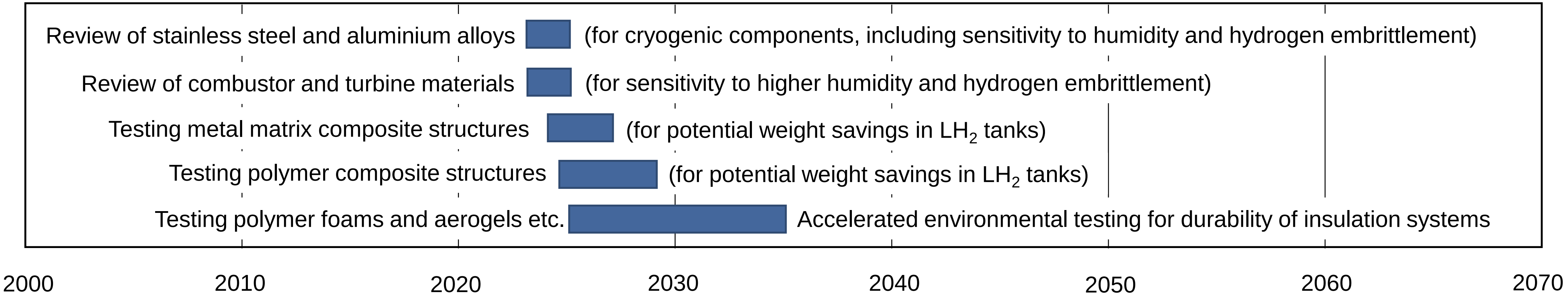
New LH_2 demonstrator aircraft design, build and flight test (Possibly earlier if LH_2 targeted for A320 replacement)

Possible new LH_2 aircraft design, build and certification (Possibly earlier if A320 replacement is designed for LH_2)

Possible scale-up of production of LH_2-fuelled aircraft

Materials development and qualification for hydrogen aircraft systems

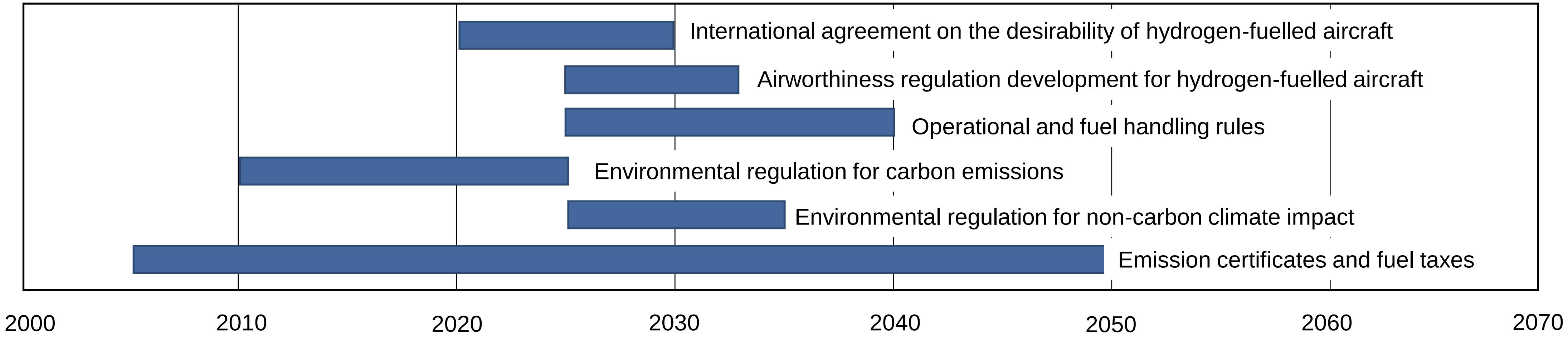
- Materials and manufacturing processes will need to be qualified for aviation applications.
- Hydrogen-compatible materials are used today for cryogenic and spacecraft systems, but most aircraft components are expected to remain in service for decades and to withstand many more stress and thermal fatigue cycles.
- Combustor and turbine materials and coatings are to be reassessed for their hot corrosion resistance in the more humid exhaust gasses produced by hydrogen combustion.
- Metal matrix and polymer composite materials to be developed for lightweight tanks.
- Accelerated environmental testing is needed to demonstrate the long-term durability of polymer foams and/or aerogels, and their adhesives for lightweight insulation systems.



Regulation and Certification – 1

- The regulation of hydrogen aviation will require international agreements, extensions to the certification rules in FAR/JAR 21, 25 and 33/CS-E regulations. New regulations will be developed based on demonstration activities and on theoretical research and analysis.
- Safety regulation must be developed to ensure a positive view of hydrogen in the industry, by travellers, and in general public opinion. This is essential for a sizeable market for hydrogen aircraft. Non-aviation applications of hydrogen may also affect public acceptance.
- Further regulation is needed to cover flight and ground operations including ATM, airport operations and emergency response, fuel production, liquefaction and transportation. Such regulation may be general to all activities using hydrogen fuel and/or specific to aviation.
- Environmental regulation will be needed to govern green hydrogen and other low carbon fuels for aviation. Regulations may provide for calculation of life-cycle carbon emissions and requirements for emissions certificates and taxes. The impact on non-CO_2 emissions in the Landing and Takeoff (LTO) cycle, cruise NOx emissions, contrails and Aviation Induced Cloudiness (AIC) may require additional regulations.
- Relative aviation fuel costs including emissions charges and taxes will be important drivers for the introduction of various low carbon fuels including hydrogen.

Regulation and Certification – 2

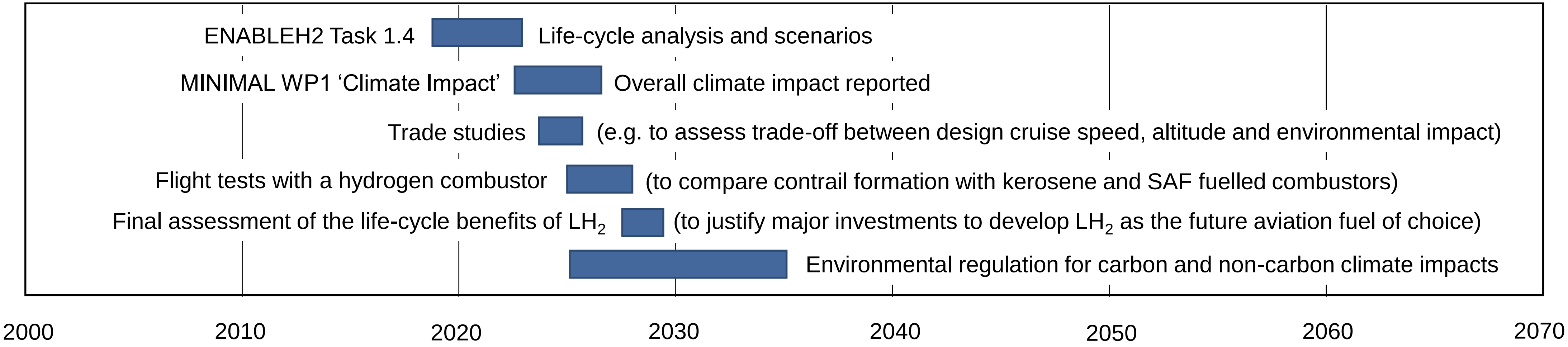


Hydrogen aircraft environmental impact and life cycle assessment – 1

- The case for hydrogen-fuelled aircraft rests on them eliminating the majority of aviation’s climate impacts and other environmental effects.
- Global warming effects of fossil-fuelled aircraft at high altitude have been extensively studied, but large uncertainty remains.
- The climate impact of high-altitude hydrogen-fuelled aircraft is even more uncertain, but flight tests with hydrogen combustors should narrow the gap in understanding.
- Relative assessment of hydrogen and other fuels, and hydrogen combustion vs. fuel cells for both long and short range flights, necessitates advanced atmospheric modelling.
- The impacts of fuel production and aircraft production on climate change and the wider environment need to be evaluated.
- A reasonable consensus on the environmental impact of hydrogen-fuelled aviation is a necessary pre-requisite for applying environmental regulation and/or taxation on competing fuels that would seem to be necessary to incentivise its introduction.

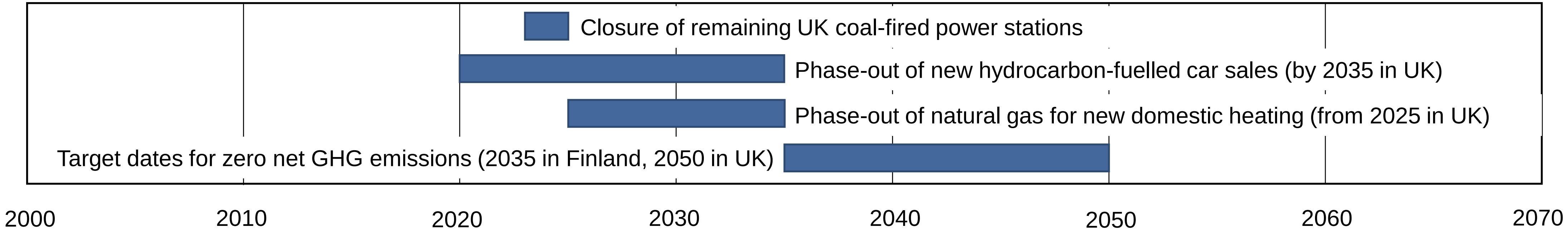
Hydrogen aircraft environmental impact and life cycle assessment – 2

- A detailed and integrated cradle-to-grave assessment is needed on the environmental impact of global aviation when using hydrogen and alternative fuels. The Horizon Europe MINIMAL project will build on ENABLEH2 to make progress in this area.
- The effects of different fuels and fuel production routes on global warming, the ozone layer and local air quality should also be quantified.
- Further scientific research into the total effects of aviation emissions on the atmosphere and the resulting impacts on climate is also needed to fully validate the modelling.



Decarbonisation of energy sources for aviation

- Cradle-to-grave decarbonisation of global electricity supplies is a prerequisite for LH_2 to be able to reduce the net radiative forcing from aviation.
- This may be achieved with biofuels, nuclear or renewable energy production, or by carbon sequestration from fossil fuels, though all of these technologies have environmental costs including CO_2 emissions associated with the construction of their production facilities.
- Stabilising and even reducing levels of CO_2 in the atmosphere will still require offsetting to compensate for the residual life-cycle CO_2 generated by 'low-carbon' technologies.
- Offsetting may include reforestation, iron fertilization and DAC (direct air capture of CO_2) [1]
- Successful decarbonisation of alternative fuels, e.g. biofuels and electrofuels, and their cost and availability, will be important for their competitiveness vs. hydrogen-fuelled aviation.



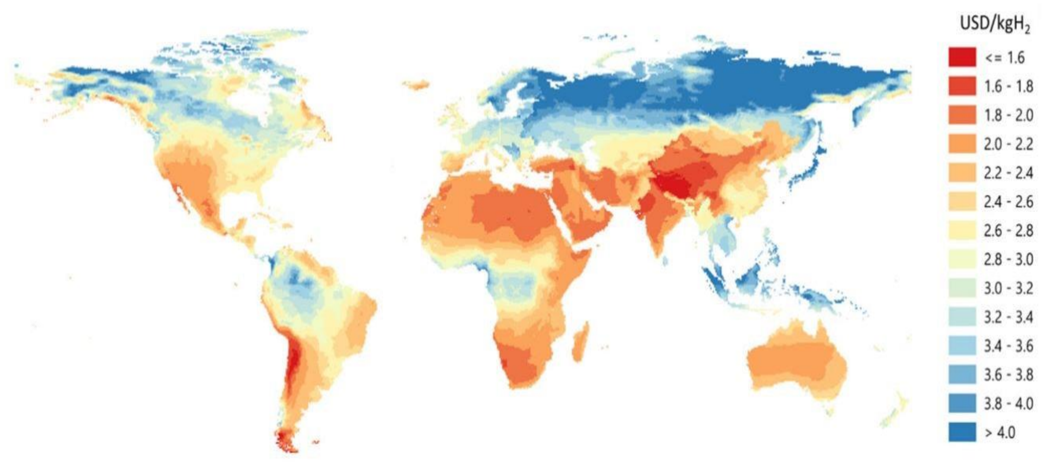
1. https://en.wikipedia.org/wiki/Iron_fertilization https://en.wikipedia.org/wiki/Direct_air_capture

Hydrogen production, liquefaction and distribution – 1

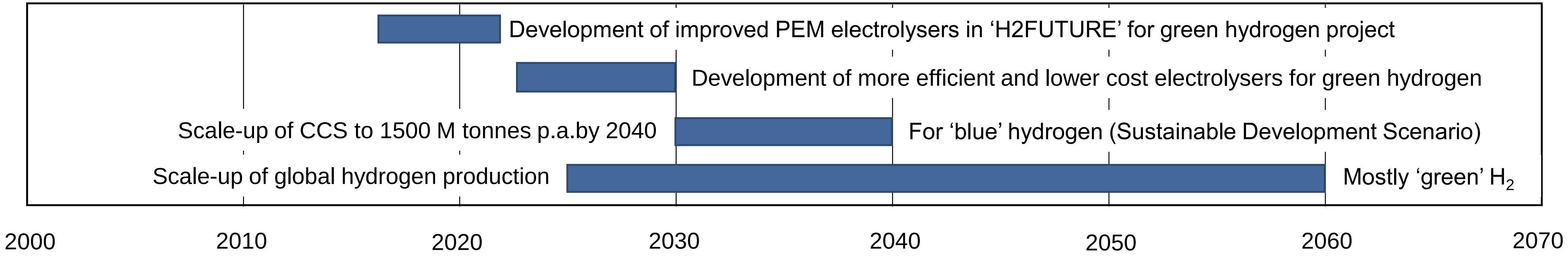
- By 2050, global H_2 production is forecast to increase tenfold to meet the demands of new applications [1].
- It will be radically transformed, and generated CO_2-free from renewables, or from natural gas with sequestration.
- GW-scale electrolysis and CCUS projects are under way.
- Future global energy transfer will use alternative vectors.
- Some LH_2 might be generated locally using SMR nuclear reactors, but disconnection of production from use seems likely as some populous regions may be 'hydrogen poor' and a global market in hydrogen is expected develop.
- The IEA predicts H_2 production will grow for other energy applications [2] (before aviation demand scales-up).

Hydrogen costs from hybrid solar PV and onshore wind systems in the long term

https://www.iea.org/reports/the-future-of-hydrogen (2019)



[1] Hydrogen Council [2] https://www.iea.org/fuels-and-technologies/hydrogen


Development of improved PEM electrolysers in 'H2FUTURE' for green hydrogen project

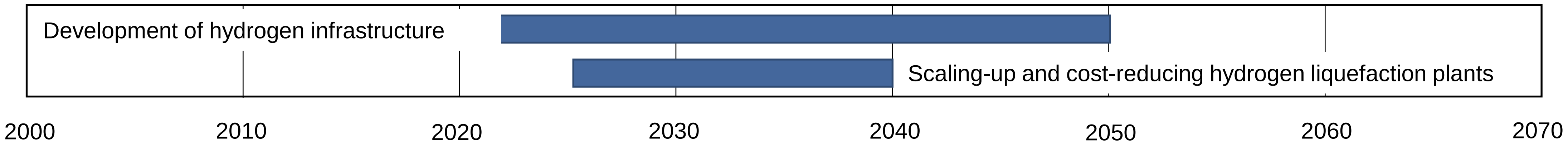
Development of more efficient and lower cost electrolysers for green hydrogen

Scale-up of CCS to 1500 M tonnes p.a.by 2040 For 'blue' hydrogen (Sustainable Development Scenario)

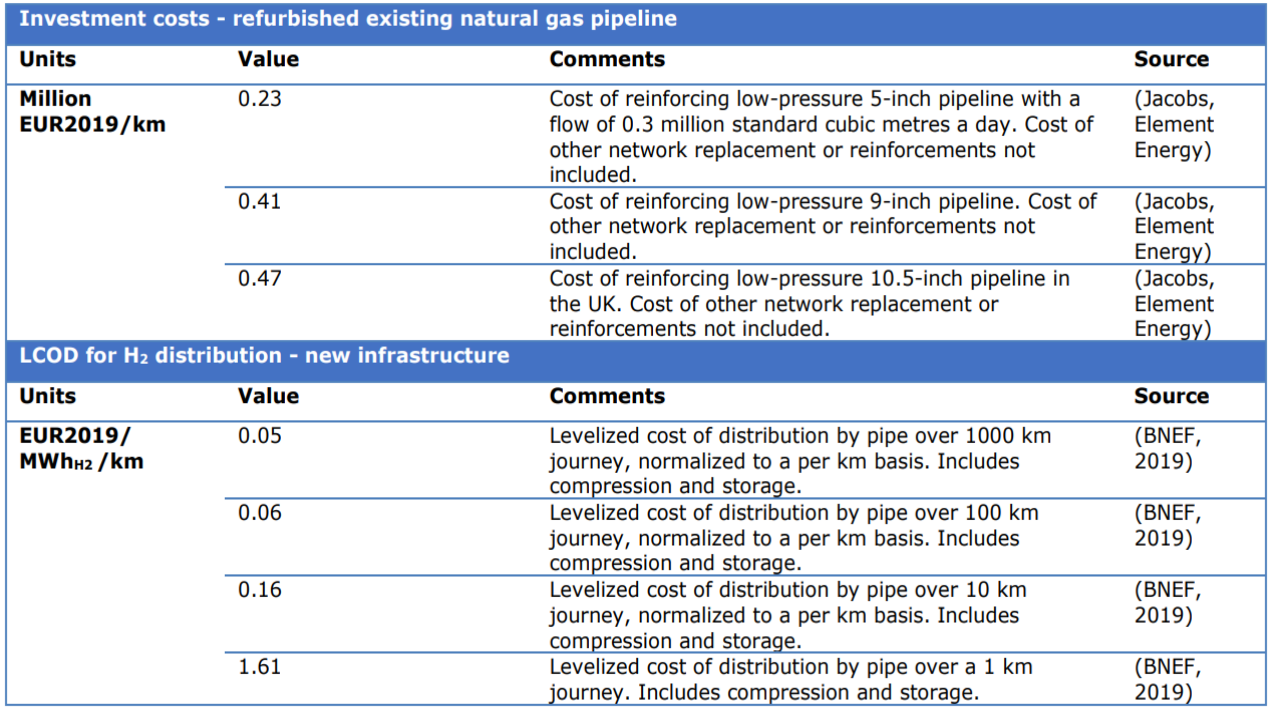
Scale-up of global hydrogen production Mostly 'green' H_2

Hydrogen production, liquefaction and distribution – 2

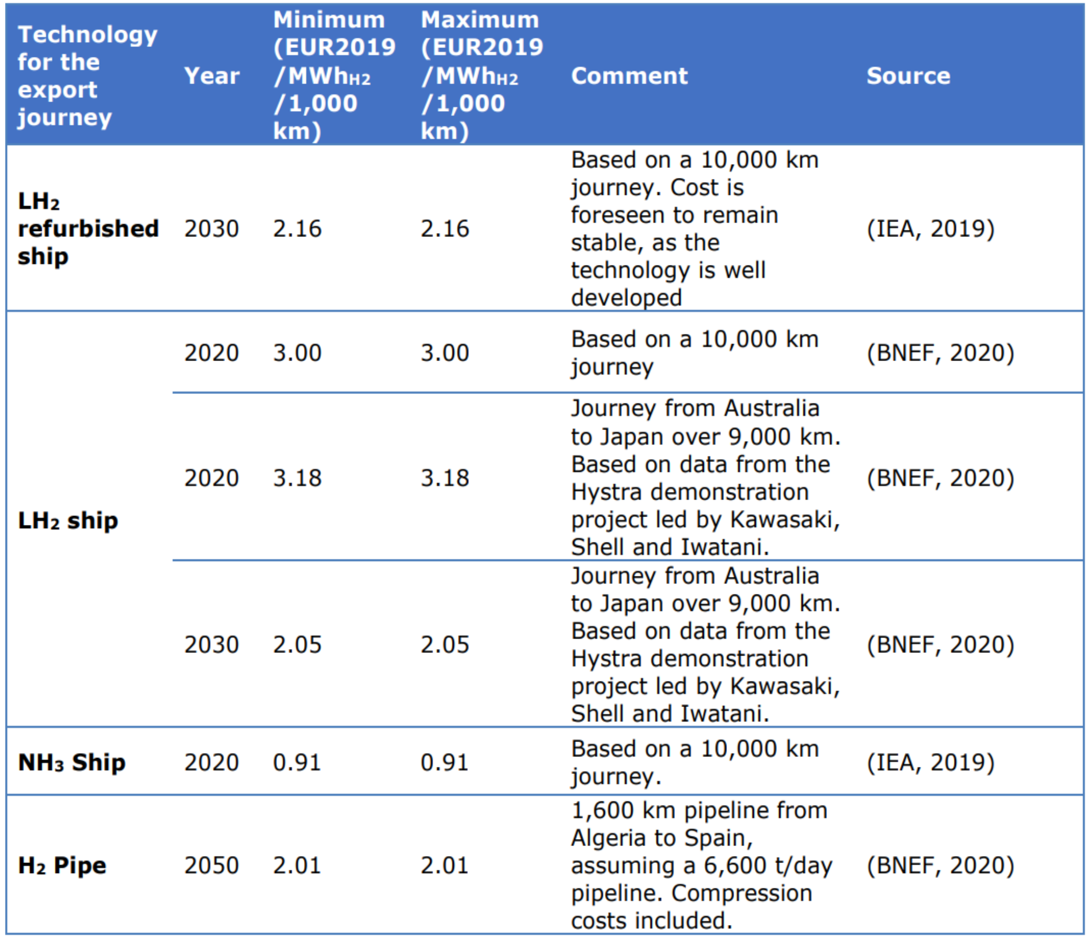
- Hydrogen is stored and transported as a compressed gas, and not liquefied, for most applications in Europe.
- Hydrogen gas (GH_2) pipeline networks will expand as new applications for hydrogen proliferate.
- Inter-regional energy-transfer pilot projects are underway supplying national import terminals and user sites using various hydrogen carriers: GH_2, LH_2, ammonia, methanol, and some liquid organic hydrogen carriers (LOHC) such as methylcyclohexane.
- LH_2 production will scale-up to meet future demand. It adds about 30% to the energy needed for electrolysis.
- To ensure continuity of fuel supply, and to minimise on-site storage, airports will want multiple sources of LH_2 or GH_2 with liquefaction, and more electric power, maybe delivered by long-distance HVDC interconnectors.
- On-site production and liquefaction of hydrogen at a large airport like Heathrow would need about 10 GW of electric power, even if LH_2 would only be used by half of the aircraft.
- Where LH_2 production is remote, rail or barge distribution will be more energy-efficient than road tanker transportation. Long-distance LH_2 pipelines are not considered commercially viable at this time.



Hydrogen liquefaction and distribution: some recent initiatives



Investment costs - refurbished existing natural gas pipeline			
Units	**Value**	**Comments**	**Source**
Million EUR2019/km	0.23	Cost of reinforcing low-pressure 5-inch pipeline with a flow of 0.3 million standard cubic metres a day. Cost of other network replacement or reinforcements not included.	(Jacobs, Element Energy)
	0.41	Cost of reinforcing low-pressure 9-inch pipeline. Cost of other network replacement or reinforcements not included.	(Jacobs, Element Energy)
	0.47	Cost of reinforcing low-pressure 10.5-inch pipeline in the UK. Cost of other network replacement or reinforcements not included.	(Jacobs, Element Energy)
LCOD for H_2 distribution - new infrastructure			
Units	**Value**	**Comments**	**Source**
EUR2019/ MWh_{H2} /km	0.05	Levelized cost of distribution by pipe over 1000 km journey, normalized to a per km basis. Includes compression and storage.	(BNEF, 2019)
	0.06	Levelized cost of distribution by pipe over 100 km journey, normalized to a per km basis. Includes compression and storage.	(BNEF, 2019)
	0.16	Levelized cost of distribution by pipe over 10 km journey, normalized to a per km basis. Includes compression and storage.	(BNEF, 2019)
	1.61	Levelized cost of distribution by pipe over a 1 km journey. Includes compression and storage.	(BNEF, 2019)

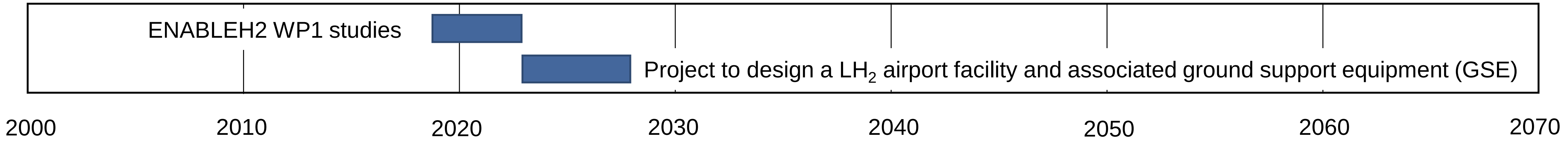


Technology for the export journey	Year	Minimum (EUR2019 / MWh_{H2} /1,000 km)	Maximum (EUR2019 / MWh_{H2} /1,000 km)	Comment	Source
LH_2 refurbished ship	2030	2.16	2.16	Based on a 10,000 km journey. Cost is foreseen to remain stable, as the technology is well developed	(IEA, 2019)
LH_2 ship	2020	3.00	3.00	Based on a 10,000 km journey	(BNEF, 2020)
	2020	3.18	3.18	Journey from Australia to Japan over 9,000 km. Based on data from the Hystra demonstration project led by Kawasaki, Shell and Iwatani.	(BNEF, 2020)
	2030	2.05	2.05	Journey from Australia to Japan over 9,000 km. Based on data from the Hystra demonstration project led by Kawasaki, Shell and Iwatani.	(BNEF, 2020)
NH_3 Ship	2020	0.91	0.91	Based on a 10,000 km journey.	(IEA, 2019)
H_2 Pipe	2050	2.01	2.01	1,600 km pipeline from Algeria to Spain, assuming a 6,600 t/day pipeline. Compression costs included.	(BNEF, 2020)

https://op.europa.eu/en/publication-detail/-/publication/7e4afa7d-d077-11ea-adf7-01aa75ed71a1/language-en

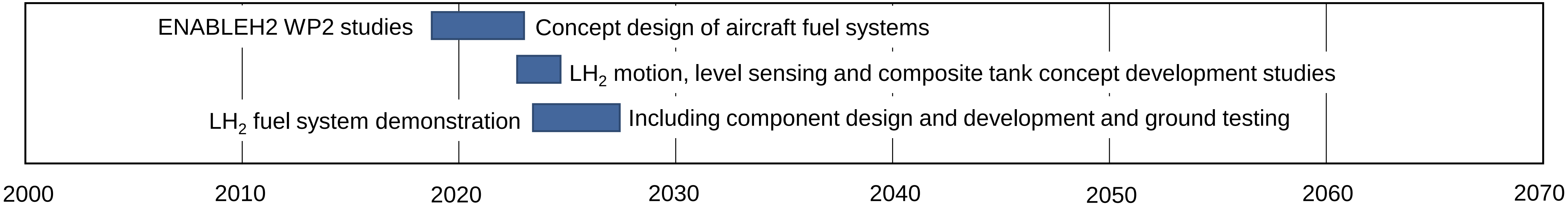
Airport LH_2 infrastructure and aircraft fuelling

- An inclusive stakeholder approach will be required to deliver infrastructure change.
- Co-ordinated, industry wide, internationally planned steps will allow infrastructure roll-out.
- Agreeing aircraft type, size, routes and airports will enable a phased introduction.
- Airside H_2 infrastructure will need to be developed, as it is unlikely to mirror other applications.
- Technical development is required for airport fuel distribution systems and aircraft refuelling infrastructure capable of meeting turnaround times whilst minimising H_2 losses.
- In parallel, legacy aircraft may switch to synthetic liquid fuels, which may continue in use for ultra-long-haul aircraft to avoid the weight and volume penalties of large LH_2 tanks.
- At some airports having multiple fuels may raise space and safety concerns to be addressed.
- In an initial roll-out phase, interim technical solutions are likely to be piloted.
- Piping LH_2 to each gate may a be long-term solution, but it would require major investment.



Design of aircraft fuel systems and fuel storage for LH_2

- Safe fuel system components with airframe life need to be developed and integrated to provide the required flow, pressure and temperature of fuel to the combustor.
- Baseline configuration has non-structural aluminium alloy LH_2 tanks with conventional closed-cell foam insulation, all enclosed within the airframe. A competing technology is vacuum insulation (Dewar flask) which reduces heat influx but may increase weight. Fuel lines are likely to use conventional insulation.
- LH_2 will be stored at its boiling point and in equilibrium with the GH_2 ullage at the top of the tanks.
- NASA studies reported by Brewer [1] proposed low-pressure backing pumps to supply LH_2 to engines, but pumps supplying supercritical cold GH_2 (i.e. in excess of 13 bar) may be preferable.
- Preheating of the fuel can be integrated with a gas turbine, with options to increase cycle efficiency.
- Optionally LH_2 might cool superconducting aircraft electrical components via closed-circuit supercritical hydrogen or helium systems, and/or cool the airframe locally to maintain laminar flow to reduce drag.



ENABLEH2 WP2 studies

Concept design of aircraft fuel systems

LH_2 motion, level sensing and composite tank concept development studies

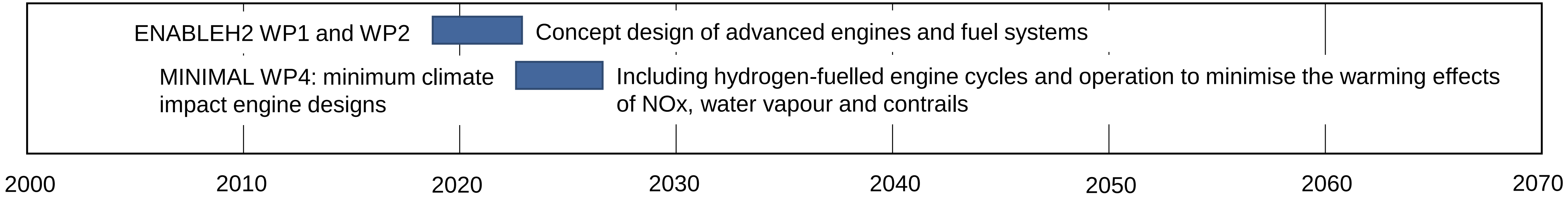
LH_2 fuel system demonstration

Including component design and development and ground testing

1. D. G. Brewer, Hydrogen Aircraft Technology, CRC Press, 1991

Propulsion systems design for LH_2

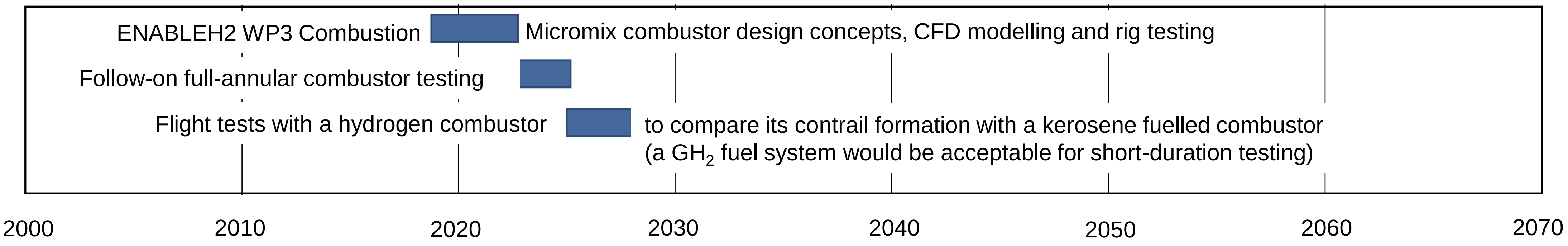
- A wide range of propulsion systems is possible, including conventional turbofans mounted under-wing, counter-rotating open rotors adjacent to the rear fuselage, and boundary layer ingesting turbo-electric distributed propulsion (TeDP) systems.
- Hydrogen fuel cells may be incorporated for secondary power and environmental control, or to provide motive power in a distributed propulsion system. Hybrid arrangements of fuel cells in combination with gas turbines should also be considered for propulsion.
- Cold hydrogen arriving at a main engine may be used to cool electrical equipment and engine oil, and also used for intercooling and/or for cooling the turbine cooling air.
- Gas turbine combustors need fuel to be delivered at high pressure, which probably requires engine-powered HP pumps to raise the pressure supplied by the aircraft fuel systems.
- The fuel might also be preheated by the turbine exhaust gas to raise its effective heating value, provided that this would not be in conflict with achieving lean low-NOx combustion


ENABLEH2 WP1 and WP2 — Concept design of advanced engines and fuel systems

MINIMAL WP4: minimum climate impact engine designs — Including hydrogen-fuelled engine cycles and operation to minimise the warming effects of NOx, water vapour and contrails

Hydrogen combustor design and emissions reduction

- ENABLEH2 has researched ‘micromix’ combustor designs to give low NOx emissions and a further reduction in emissions may be achieved by water/steam injection.
- Lean direct injection, rapid mixing, high flame speed, and wide combustion limits for hydrogen, should enable shorter combustors with reduced residence times, limiting the formation of thermal NOx without compromising the engine’s altitude relight envelope.
- The higher water vapour content of the exhaust with hydrogen, relative to a hydrocarbon fuel, will provide some greenhouse gas warming, partially offsetting the benefit from reducing CO_2
- Cleaner exhaust may reduce the optical density and warming effects of contrails [1] but this conjecture needs testing by measurements on actual contrails and induced cirrus cloudiness.



ENABLEH2 WP3 Combustion — Micromix combustor design concepts, CFD modelling and rig testing

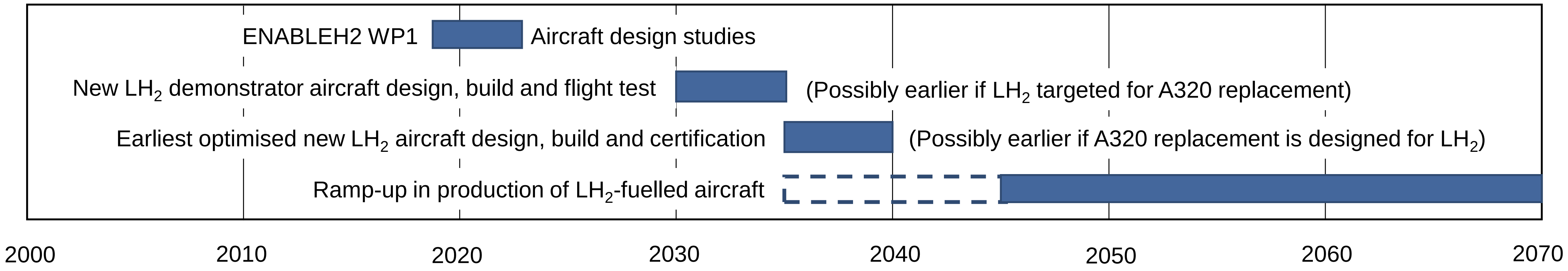
Follow-on full-annular combustor testing

Flight tests with a hydrogen combustor — to compare its contrail formation with a kerosene fuelled combustor (a GH_2 fuel system would be acceptable for short-duration testing)

[1] https://doi.org/10.1016/j.atmosenv.2006.06.036

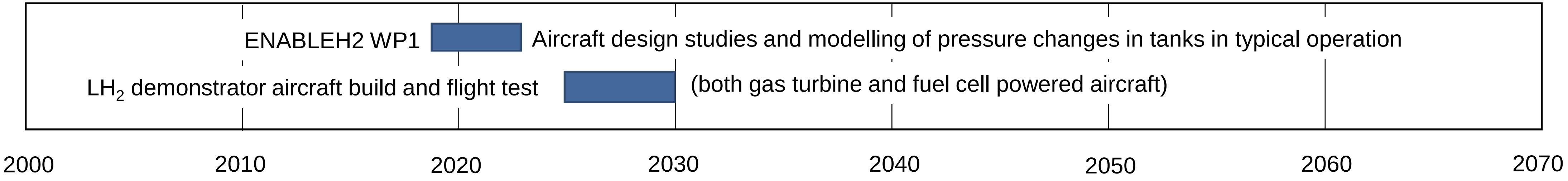
New transport aircraft designs for LH_2

- Commercial, business and other transport aircraft designed for LH_2 will need increased internal volume to accommodate the fuel tanks and will have higher empty weight than equivalent kerosene-fuelled aircraft, but their maximum take-off weight might be lower, reducing take-off thrust requirements. Mission requirements, e.g. range and speed, might want to be reduced.
- LH_2 offers potential synergies with TeDP (by providing a heat sink for superconducting electrical components) and with BWB airframes (having increased internal volume).
- Aircraft design studies in ENABLEH2 have covered a range of potential aircraft architectures.
- Market segments to be addressed by liquid hydrogen gas turbine powered aircraft will depend on competition from electrofuels, fuel-cell and battery-powered aircraft.
- Notwithstanding flight experience obtained with the Tu-155, one or more new demonstrator aircraft will be required to prove the practicality and operability of LH_2 commercial aircraft.



LH_2 aircraft operation and maintenance

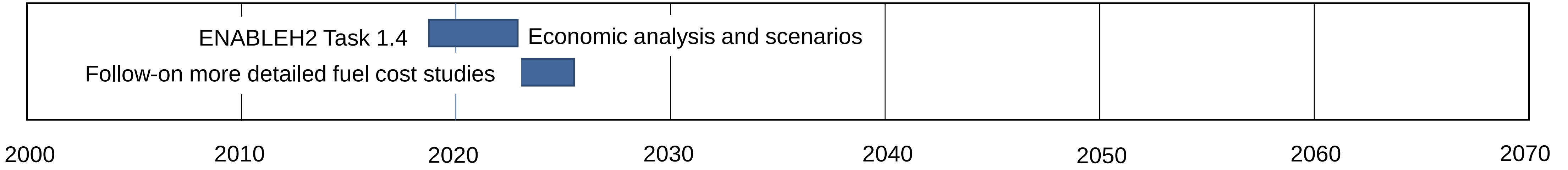
- As heat seeps into tanks the pressure will rise, but as LH_2 is extracted the pressure falls, so with adequate pressure margins, it should be unnecessary to vent gas during a typical flight, or to meet overnight ‘dormancy’ requirement for a normal duration ground stopover.
- For more extended stopovers, the boil-off gas might be collected and re-liquefied, or could be used to generate electricity for export to a grid, or otherwise the aircraft may need defueling.
- Vacuum insulated tanks can reduce the heat leakage and the need for venting or defueling, but at the cost of reduced gravimetric efficiency relative to single-wall foam-insulated tanks, so, particularly for long-range aircraft, the reserve fuel might be retained in better insulated tanks to minimise boil-off during stopovers, while the fuel normally used in flight could stored in lighter tanks having higher gravimetric efficiency.
- Robotic systems handling heavier fuel hoses can enable more rapid refuelling of large aircraft.
- More assessments of LH_2 aircraft maintenance and operating costs are needed, for example, re. the benefits of tankering fuel, and how aircraft may be refuelled following diversions.


ENABLEH2 WP1 — Aircraft design studies and modelling of pressure changes in tanks in typical operation

LH_2 demonstrator aircraft build and flight test — (both gas turbine and fuel cell powered aircraft)

Economics of LH_2 vs. alternative fuels

- Predictions of aircraft economics vs. timeframes with LH_2 and alternative fuels are needed:
    - Drop-in replacement biofuels and synthetic fuels and electrofuels from various feedstocks commonly referred to as Sustainable Aviation Fuels (SAF)
    - Liquid methane (biomethane), ethane/propane/butane (from H_2 and DAC) or alcohols
    - For the next decade or two, environment-friendly alternative jet fuels may be in limited supply and more expensive than kerosene (Jet A or Jet A-1).
- The Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA) will enable aviation targets to be met in the near term, but offsetting may be untenable in the longer term.
- A long-term international agreement on a carbon tax (or equivalent) will likely be necessary before the industry will move away from kerosene.
- Improvements in aircraft efficiency could offset increased fuel costs to maintain affordability.



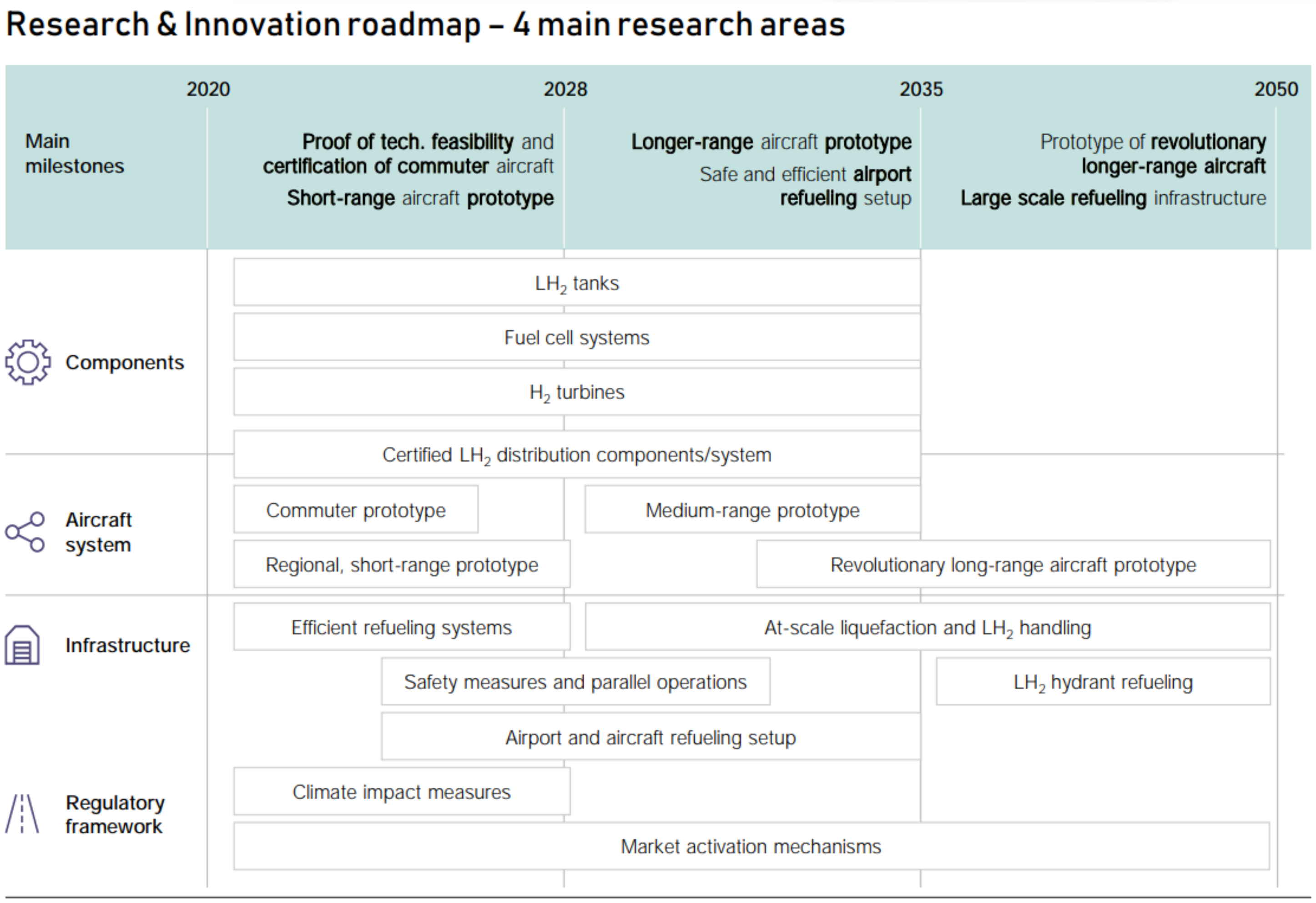
Hydrogen-powered aviation A fact-based study of hydrogen technology, economics, and climate impact by 2050

Third-Party Roadmaps

Third Party Roadmaps

- Interest in hydrogen-fuelled aviation has grown rapidly since ENABLEH2 was launched in 2018, and roadmaps for its development have been proposed by several organisations including Clean Sky 2, Hydrogen Europe, and the UK ATI (from its FlyZero project).
- The most relevant roadmap charts from these projects follow.
- The main technologies to be developed include onboard hydrogen storage (LH_2 and GH_2), fuel systems, and propulsion systems (using fuel cells and/or combustion engines).
- The Clean Sky 2 and Fuel Cells and Hydrogen Joint Undertaking identified four top-level research areas: components, aircraft system, infrastructure and regulatory framework.
- Roadmaps from the ‘Hydrogen Europe Strategic Research and Innovation Agenda’ cover a broader range of stationary and transportation hydrogen-fuelled applications, including a ‘detailed deployment roadmap’ for aviation.
- FlyZero issued multiple reports in March 2022 including FZO-IST-MAP-0012 ‘Technology Roadmaps – Technology Pathways to Enable Zero-Carbon Emission Flight’. Individual roadmap charts published separately cover aerodynamic structures, thermal management, gas turbine systems, cryogenic fuel systems, electrical propulsion systems and fuel cells: https://www.ati.org.uk/wp-content/uploads/2022/03/FZO-IST-MAP-0012-FlyZero-Technology-Roadmaps.pdf

Roadmap from Clean Sky 2 and Fuel Cells and Hydrogen Joint Undertaking



Research & Innovation roadmap – 4 main research areas

2020
2028
2035
2050

Main milestones

Proof of tech. feasibility and **certification of commuter** aircraft
Short-range aircraft **prototype**

Longer-range aircraft **prototype**
Safe and efficient **airport refueling** setup

Prototype of **revolutionary longer-range aircraft**
Large scale refueling infrastructure

Components
- LH_2 tanks
- Fuel cell systems
- H_2 turbines
- Certified LH_2 distribution components/system

Aircraft system
- Commuter prototype
- Medium-range prototype
- Regional, short-range prototype
- Revolutionary long-range aircraft prototype

Infrastructure
- Efficient refueling systems
- At-scale liquefaction and LH_2 handling
- Safety measures and parallel operations
- LH_2 hydrant refueling
- Airport and aircraft refueling setup

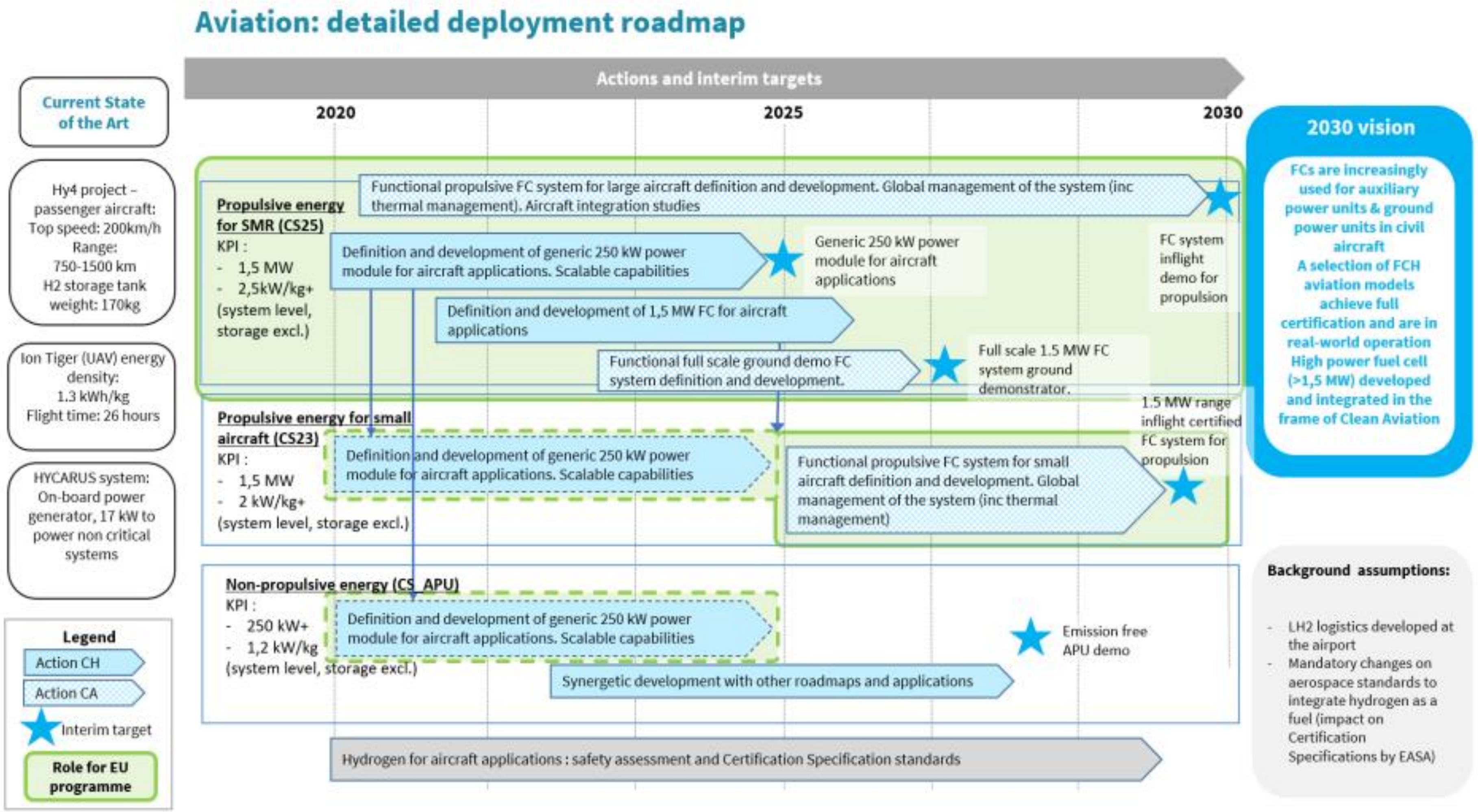
Regulatory framework
- Climate impact measures
- Market activation mechanisms

Clean Sky 2, and Fuel Cells and Hydrogen Joint Undertaking: Hydrogen-powered Aviation, 2020.

For more details refer to:

https://cleansky.paddlecms.net/sites/default/files/2021-10/20200507_Hydrogen-Powered-Aviation-report.pdf

Roadmap from Hydrogen Europe – 1



Aviation: detailed deployment roadmap

Actions and interim targets

2020 2025 2030

Current State of the Art

Hy4 project – passenger aircraft: Top speed: 200km/h Range: 750-1500 km H2 storage tank weight: 170kg

Ion Tiger (UAV) energy density: 1.3 kWh/kg Flight time: 26 hours

HYCARUS system: On-board power generator, 17 kW to power non critical systems

Propulsive energy for SMR (CS25)
KPI :
- 1,5 MW
- 2,5kW/kg+

(system level, storage excl.)

Functional propulsive FC system for large aircraft definition and development. Global management of the system (inc thermal management). Aircraft integration studies

Definition and development of generic 250 kW power module for aircraft applications. Scalable capabilities

Generic 250 kW power module for aircraft applications

FC system inflight demo for propulsion

Definition and development of 1,5 MW FC for aircraft applications

Functional full scale ground demo FC system definition and development.

Full scale 1.5 MW FC system ground demonstrator.

1.5 MW range inflight certified FC system for propulsion

Propulsive energy for small aircraft (CS23)
KPI :
- 1,5 MW
- 2 kW/kg+

(system level, storage excl.)

Definition and development of generic 250 kW power module for aircraft applications. Scalable capabilities

Functional propulsive FC system for small aircraft definition and development. Global management of the system (inc thermal management)

Non-propulsive energy (CS_APU)
KPI :
- 250 kW+
- 1,2 kW/kg

(system level, storage excl.)

Definition and development of generic 250 kW power module for aircraft applications. Scalable capabilities

Emission free APU demo

Synergetic development with other roadmaps and applications

Hydrogen for aircraft applications : safety assessment and Certification Specification standards

2030 vision

FCs are increasingly used for auxiliary power units & ground power units in civil aircraft
A selection of FCH aviation models achieve full certification and are in real-world operation
High power fuel cell (>1,5 MW) developed and integrated in the frame of Clean Aviation

Background assumptions:
- LH2 logistics developed at the airport
- Mandatory changes on aerospace standards to integrate hydrogen as a fuel (impact on Certification Specifications by EASA)

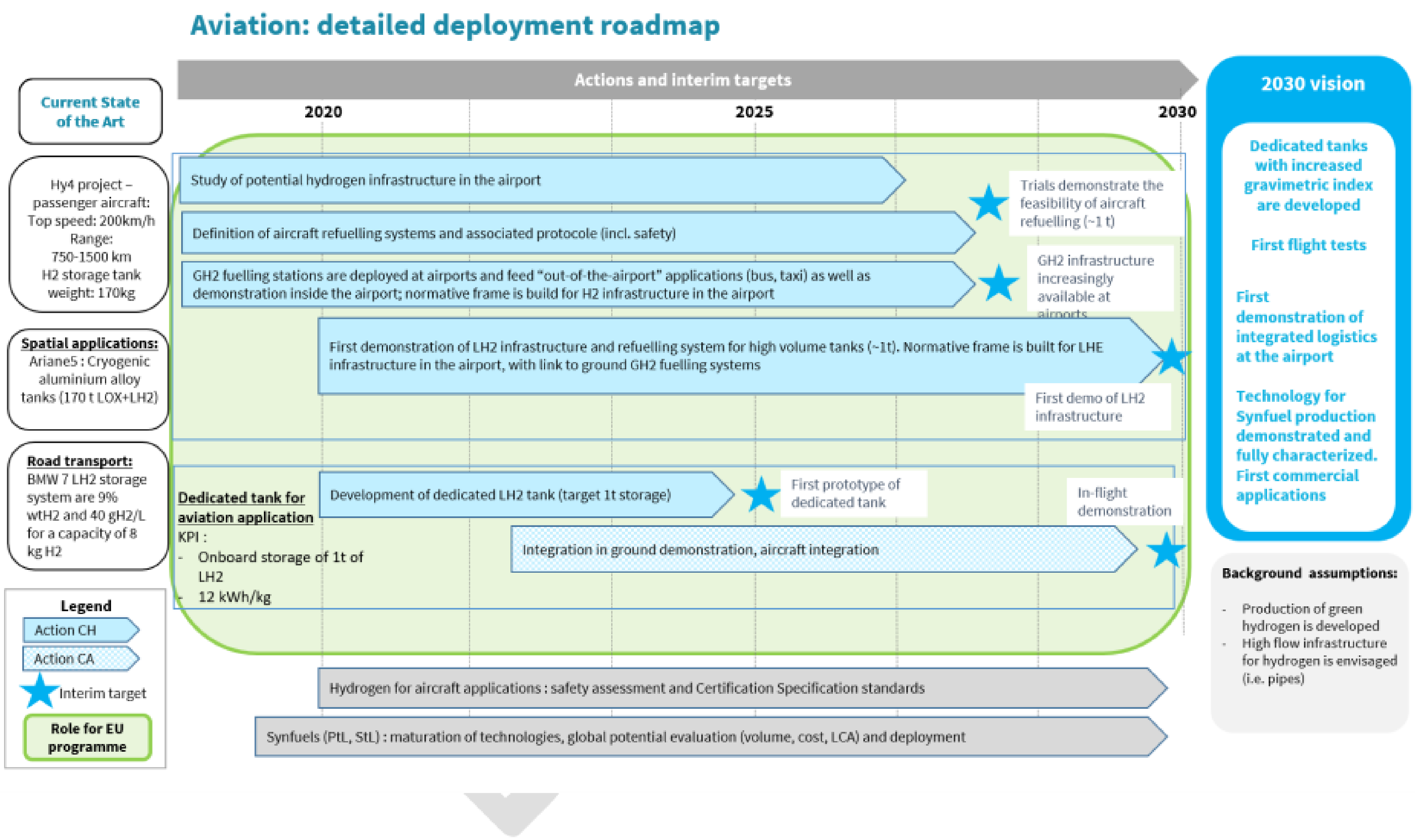
Legend
- Action CH
- Action CA
- ★ Interim target
- Role for EU programme

For more details refer to Hydrogen Europe: Strategic Research and Innovation Agenda, 2020.

The final draft report is available at:

https://hydrogeneurope.eu/reports/

Roadmap from Hydrogen Europe – 2



Aviation: detailed deployment roadmap

Current State of the Art

Hy4 project – passenger aircraft:
Top speed: 200km/h
Range:
750-1500 km
H2 storage tank weight: 170kg

Spatial applications:
Ariane5 : Cryogenic aluminium alloy tanks (170 t LOX+LH2)

Road transport:
BMW 7 LH2 storage system are 9% wtH2 and 40 gH2/L for a capacity of 8 kg H2

Actions and interim targets

2020 – 2025 – 2030

- Study of potential hydrogen infrastructure in the airport
- Definition of aircraft refuelling systems and associated protocole (incl. safety)
- ★ Trials demonstrate the feasibility of aircraft refuelling (~1 t)
- GH2 fuelling stations are deployed at airports and feed "out-of-the-airport" applications (bus, taxi) as well as demonstration inside the airport; normative frame is build for H2 infrastructure in the airport
- ★ GH2 infrastructure increasingly available at airports
- First demonstration of LH2 infrastructure and refuelling system for high volume tanks (~1t). Normative frame is built for LHE infrastructure in the airport, with link to ground GH2 fuelling systems
- ★ First demo of LH2 infrastructure

Dedicated tank for aviation application
KPI :
- Onboard storage of 1t of LH2
- 12 kWh/kg

- Development of dedicated LH2 tank (target 1t storage)
- ★ First prototype of dedicated tank
- Integration in ground demonstration, aircraft integration
- ★ In-flight demonstration
- Hydrogen for aircraft applications : safety assessment and Certification Specification standards
- Synfuels (PtL, StL) : maturation of technologies, global potential evaluation (volume, cost, LCA) and deployment

2030 vision

Dedicated tanks with increased gravimetric index are developed

First flight tests

First demonstration of integrated logistics at the airport

Technology for Synfuel production demonstrated and fully characterized. First commercial applications

Background assumptions:
- Production of green hydrogen is developed
- High flow infrastructure for hydrogen is envisaged (i.e. pipes)

Legend

Action CH

Action CA

★ Interim target

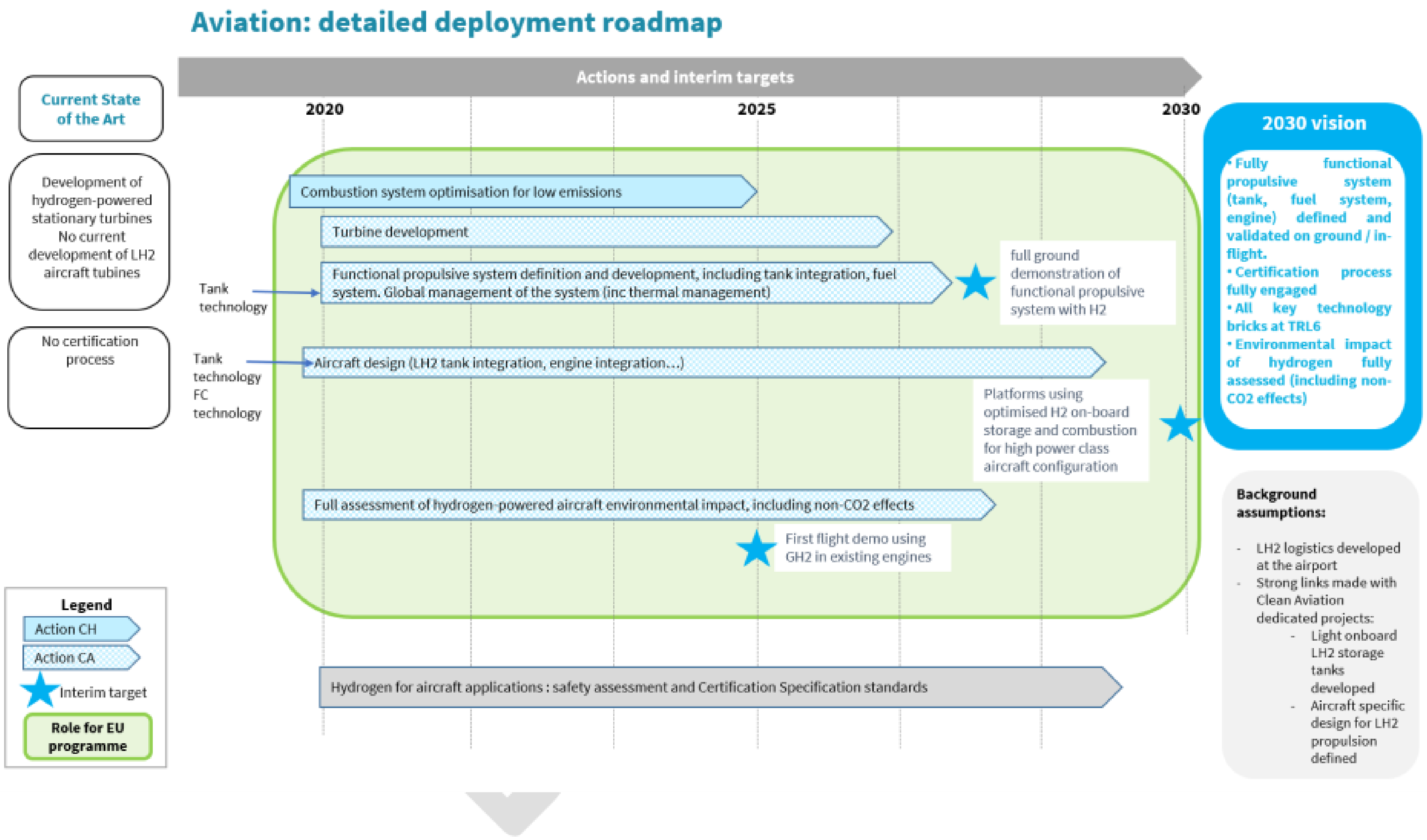
Role for EU programme

For more details refer to Hydrogen Europe: Strategic Research and Innovation Agenda, 2020.

The final draft report is available at:

https://hydrogeneurope.eu/reports/

Roadmap from Hydrogen Europe – 3



Aviation: detailed deployment roadmap

Development of hydrogen-powered stationary turbines
No current development of LH2 aircraft tubines

No certification process

Combustion system optimisation for low emissions

Turbine development

Functional propulsive system definition and development, including tank integration, fuel system. Global management of the system (inc thermal management)

full ground demonstration of functional propulsive system with H2

Aircraft design (LH2 tank integration, engine integration…)

Platforms using optimised H2 on-board storage and combustion for high power class aircraft configuration

Full assessment of hydrogen-powered aircraft environmental impact, including non-CO2 effects

First flight demo using GH2 in existing engines

Hydrogen for aircraft applications : safety assessment and Certification Specification standards

2030 vision

- Fully functional propulsive system (tank, fuel system, engine) defined and validated on ground / in-flight.
- Certification process fully engaged
- All key technology bricks at TRL6
- Environmental impact of hydrogen fully assessed (including non-CO2 effects)

Background assumptions:

- LH2 logistics developed at the airport
- Strong links made with Clean Aviation dedicated projects:
  - Light onboard LH2 storage tanks developed
  - Aircraft specific design for LH2 propulsion defined

Legend

Action CH
Action CA
★ Interim target
Role for EU programme

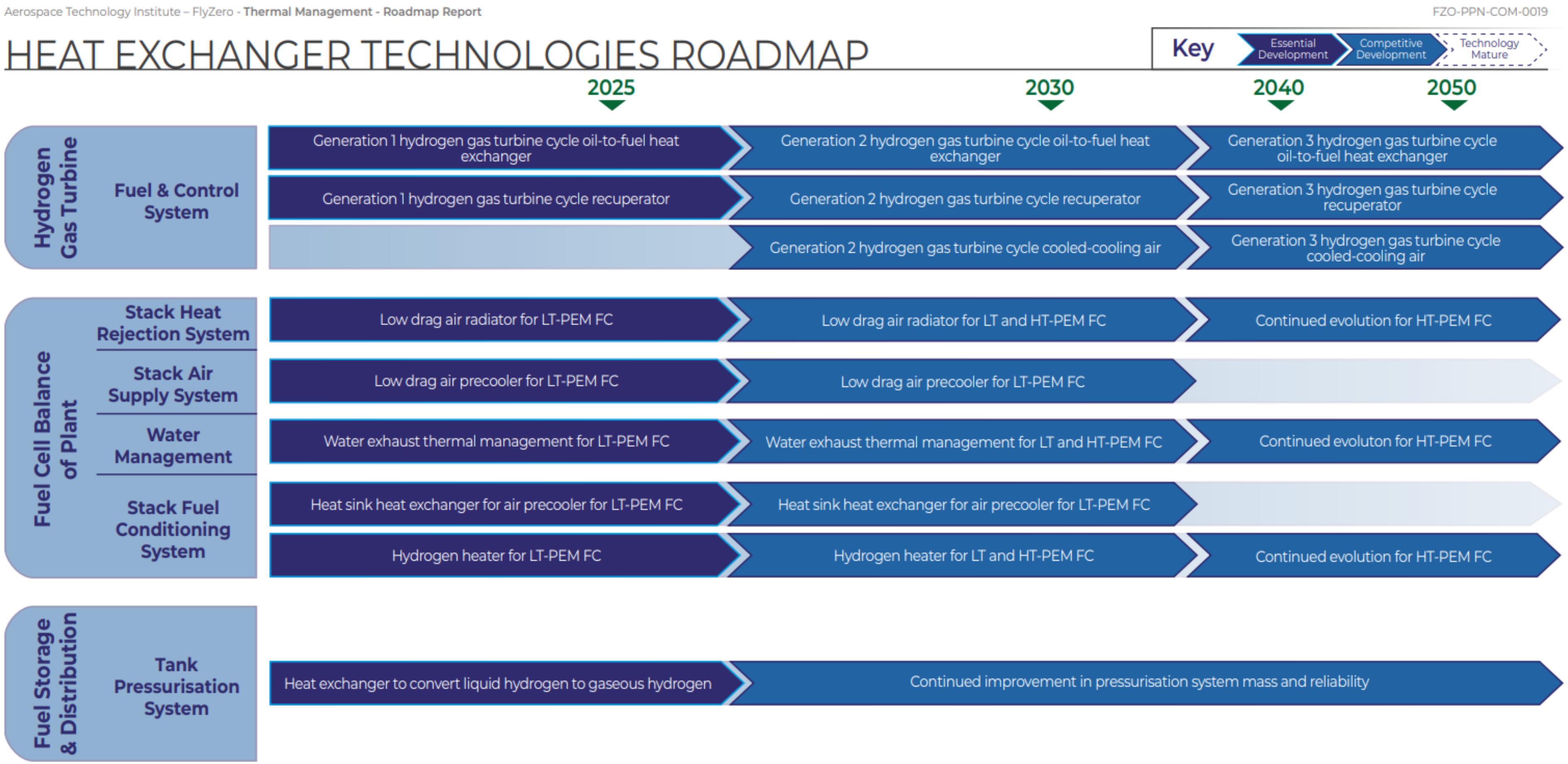
For more details refer to Hydrogen Europe: Strategic Research and Innovation Agenda, 2020.

The final draft report is available at:

https://hydrogeneurope.eu/reports/

FlyZero Thermal Management Roadmap – 1

- FZO-PPN-MAP-0018 and FZO-PPN-COM-0019 ‘Thermal Management Roadmap Report’ cover heat exchanger technologies and heat exchanger enablers. For more details see: https://www.ati.org.uk/wp-content/uploads/2022/03/FZO-PPN-COM-0019-Thermal-Management-Roadmap-



Aerospace Technology Institute – FlyZero - **Thermal Management - Roadmap Report**

FZO-PPN-COM-0019

HEAT EXCHANGER TECHNOLOGIES ROADMAP

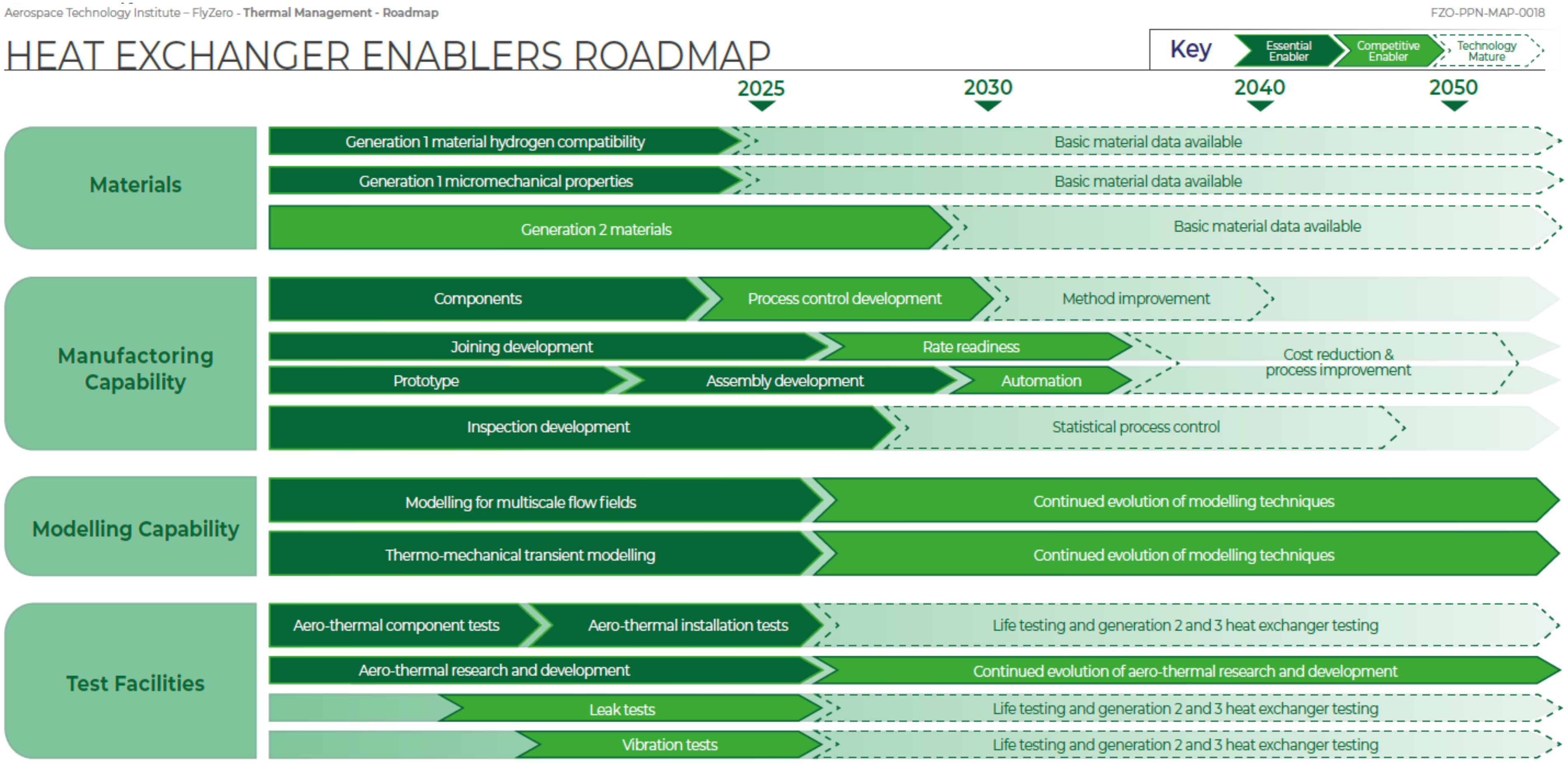
Key: Essential Development | Competitive Development | Technology Mature

2025 2030 2040 2050

		2025	2030	2040 – 2050
Hydrogen Gas Turbine	**Fuel & Control System**	Generation 1 hydrogen gas turbine cycle oil-to-fuel heat exchanger	Generation 2 hydrogen gas turbine cycle oil-to-fuel heat exchanger	Generation 3 hydrogen gas turbine cycle oil-to-fuel heat exchanger
		Generation 1 hydrogen gas turbine cycle recuperator	Generation 2 hydrogen gas turbine cycle recuperator	Generation 3 hydrogen gas turbine cycle recuperator
			Generation 2 hydrogen gas turbine cycle cooled-cooling air	Generation 3 hydrogen gas turbine cycle cooled-cooling air
Fuel Cell Balance of Plant	**Stack Heat Rejection System**	Low drag air radiator for LT-PEM FC	Low drag air radiator for LT and HT-PEM FC	Continued evolution for HT-PEM FC
	Stack Air Supply System	Low drag air precooler for LT-PEM FC	Low drag air precooler for LT-PEM FC	
	Water Management	Water exhaust thermal management for LT-PEM FC	Water exhaust thermal management for LT and HT-PEM FC	Continued evoluton for HT-PEM FC
	Stack Fuel Conditioning System	Heat sink heat exchanger for air precooler for LT-PEM FC	Heat sink heat exchanger for air precooler for LT-PEM FC	
		Hydrogen heater for LT-PEM FC	Hydrogen heater for LT and HT-PEM FC	Continued evolution for HT-PEM FC
Fuel Storage & Distribution	**Tank Pressurisation System**	Heat exchanger to convert liquid hydrogen to gaseous hydrogen	Continued improvement in pressurisation system mass and reliability	

FlyZero Thermal Management Roadmap – 2

- FZO-PPN-MAP-0018 and FZO-PPN-COM-0019 ‘Thermal Management Roadmap Report’ cover heat exchanger technologies and heat exchanger enablers. For more details see: https://www.ati.org.uk/wp-content/uploads/2022/03/FZO-PPN-COM-0019-Thermal-Management-Roadmap-



Aerospace Technology Institute – FlyZero - **Thermal Management - Roadmap**

FZO-PPN-MAP-0018

HEAT EXCHANGER ENABLERS ROADMAP

Key: Essential Enabler · Competitive Enabler · Technology Mature

2025 · 2030 · 2040 · 2050

Materials
- Generation 1 material hydrogen compatibility → Basic material data available
- Generation 1 micromechanical properties → Basic material data available
- Generation 2 materials → Basic material data available

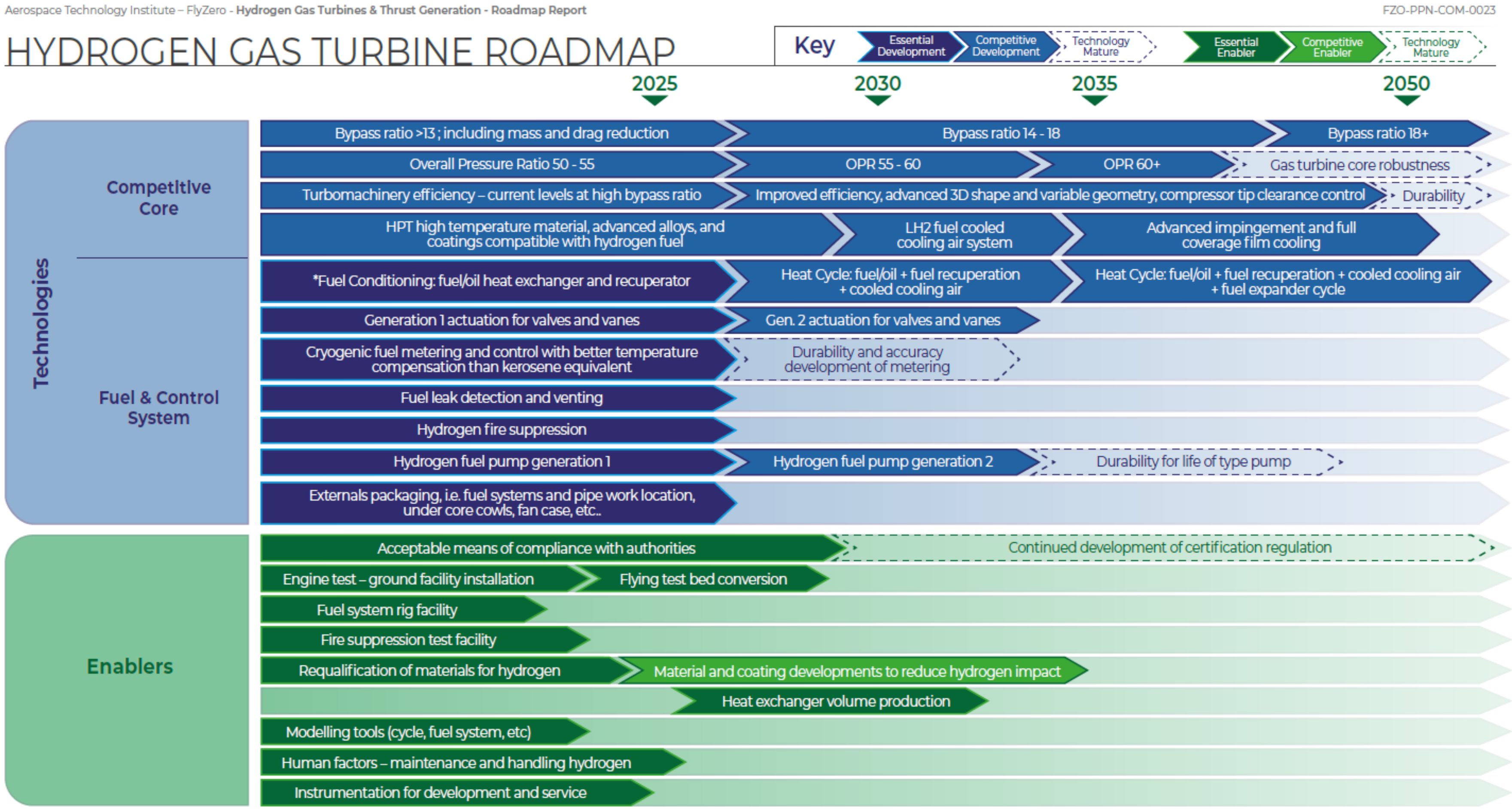
Manufacturing Capability
- Components → Process control development → Method improvement
- Joining development → Rate readiness → Cost reduction & process improvement
- Prototype → Assembly development → Automation → Cost reduction & process improvement
- Inspection development → Statistical process control

Modelling Capability
- Modelling for multiscale flow fields → Continued evolution of modelling techniques
- Thermo-mechanical transient modelling → Continued evolution of modelling techniques

Test Facilities
- Aero-thermal component tests → Aero-thermal installation tests → Life testing and generation 2 and 3 heat exchanger testing
- Aero-thermal research and development → Continued evolution of aero-thermal research and development
- Leak tests → Life testing and generation 2 and 3 heat exchanger testing
- Vibration tests → Life testing and generation 2 and 3 heat exchanger testing

FlyZero Hydrogen Gas Turbines and Thrust Generation Roadmap – 1

- FZO-PPN-MAP-0022 and FZO-PPN-COM-0023 ‘Hydrogen Gas Turbines and Thrust Generation Roadmap Report’ cover aero engines and hydrogen combustion. For more details see: https://www.ati.org.uk/wp-content/uploads/2022/03/FZO-PPN-COM-0023-Hydrogen-Gas-Turbines-and-Thrust-Generation-Roadmap-Report.pdf



Aerospace Technology Institute – FlyZero - **Hydrogen Gas Turbines & Thrust Generation - Roadmap Report**

FZO-PPN-COM-0023

HYDROGEN GAS TURBINE ROADMAP

Key: Essential Development | Competitive Development | Technology Mature | Essential Enabler | Competitive Enabler | Technology Mature

2025 | 2030 | 2035 | 2050

Technologies

Competitive Core

- Bypass ratio >13; including mass and drag reduction → Bypass ratio 14 - 18 → Bypass ratio 18+
- Overall Pressure Ratio 50 - 55 → OPR 55 - 60 → OPR 60+ → Gas turbine core robustness
- Turbomachinery efficiency – current levels at high bypass ratio → Improved efficiency, advanced 3D shape and variable geometry, compressor tip clearance control → Durability
- HPT high temperature material, advanced alloys, and coatings compatible with hydrogen fuel → LH2 fuel cooled cooling air system → Advanced impingement and full coverage film cooling

Fuel & Control System

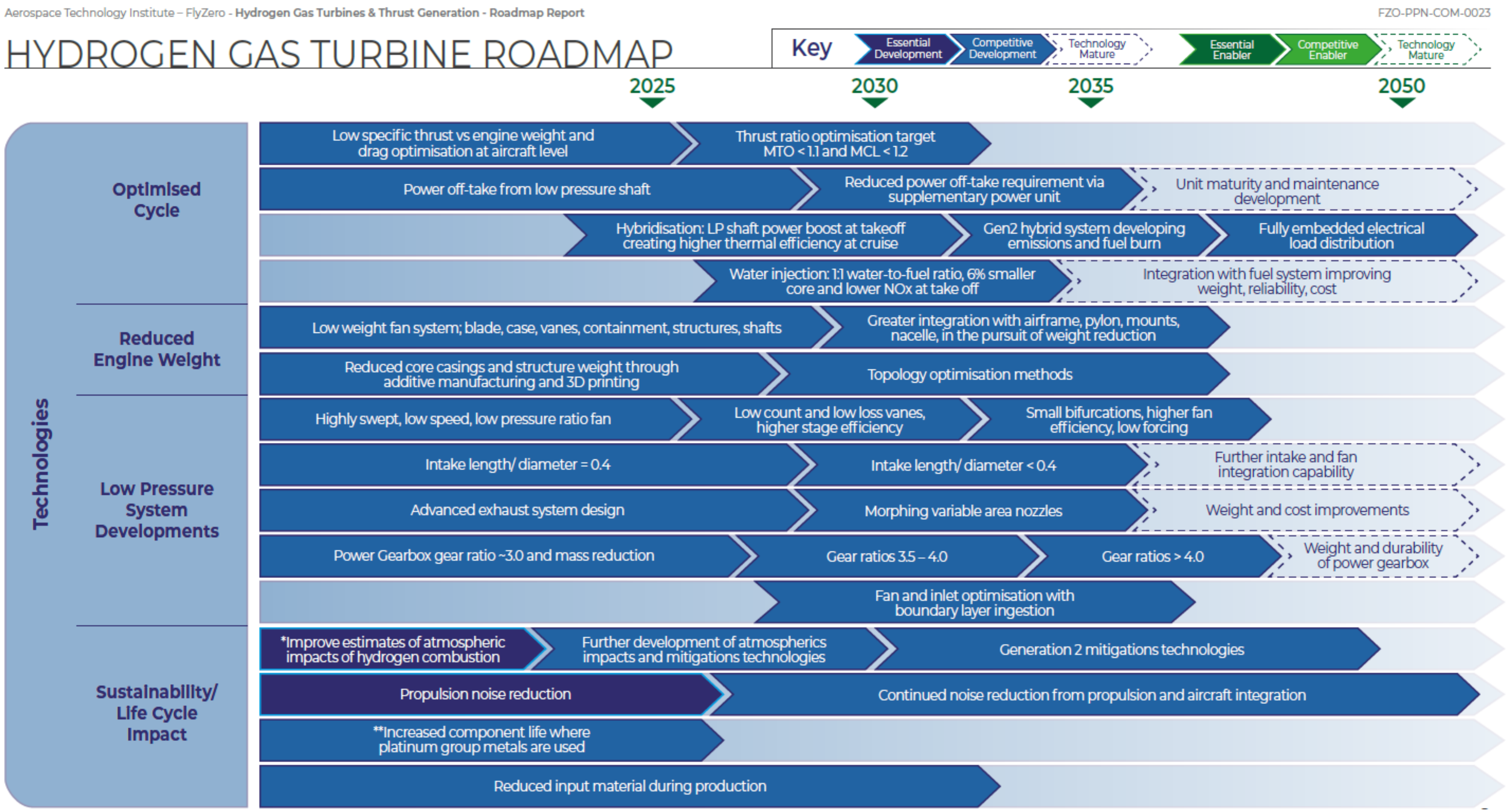
- *Fuel Conditioning: fuel/oil heat exchanger and recuperator → Heat Cycle: fuel/oil + fuel recuperation + cooled cooling air → Heat Cycle: fuel/oil + fuel recuperation + cooled cooling air + fuel expander cycle
- Generation 1 actuation for valves and vanes → Gen. 2 actuation for valves and vanes
- Cryogenic fuel metering and control with better temperature compensation than kerosene equivalent → Durability and accuracy development of metering
- Fuel leak detection and venting
- Hydrogen fire suppression
- Hydrogen fuel pump generation 1 → Hydrogen fuel pump generation 2 → Durability for life of type pump
- Externals packaging, i.e. fuel systems and pipe work location, under core cowls, fan case, etc..

Enablers

- Acceptable means of compliance with authorities → Continued development of certification regulation
- Engine test – ground facility installation → Flying test bed conversion
- Fuel system rig facility
- Fire suppression test facility
- Requalification of materials for hydrogen → Material and coating developments to reduce hydrogen impact
- Heat exchanger volume production
- Modelling tools (cycle, fuel system, etc)
- Human factors – maintenance and handling hydrogen
- Instrumentation for development and service

FlyZero Hydrogen Gas Turbines and Thrust Generation Roadmap – 2

- FZO-PPN-MAP-0022 and FZO-PPN-COM-023 ‘Hydrogen Gas Turbines and Thrust Generation Roadmap Report’ cover aero engines and hydrogen combustion. For more details see: https://www.ati.org.uk/wp-content/uploads/2022/03/FZO-PPN-COM-0023-Hydrogen-Gas-Turbines-and-Thrust-Generation-Roadmap-Report.pdf



Aerospace Technology Institute – FlyZero - **Hydrogen Gas Turbines & Thrust Generation - Roadmap Report**

FZO-PPN-COM-0023

HYDROGEN GAS TURBINE ROADMAP

Key: Essential Development; Competitive Development; Technology Mature; Essential Enabler; Competitive Enabler; Technology Mature

2025 · 2030 · 2035 · 2050

Technologies

Optimised Cycle
- Low specific thrust vs engine weight and drag optimisation at aircraft level → Thrust ratio optimisation target MTO < 1.1 and MCL < 1.2
- Power off-take from low pressure shaft → Reduced power off-take requirement via supplementary power unit → Unit maturity and maintenance development
- Hybridisation: LP shaft power boost at takeoff creating higher thermal efficiency at cruise → Gen2 hybrid system developing emissions and fuel burn → Fully embedded electrical load distribution
- Water injection: 1:1 water-to-fuel ratio, 6% smaller core and lower NOx at take off → Integration with fuel system improving weight, reliability, cost

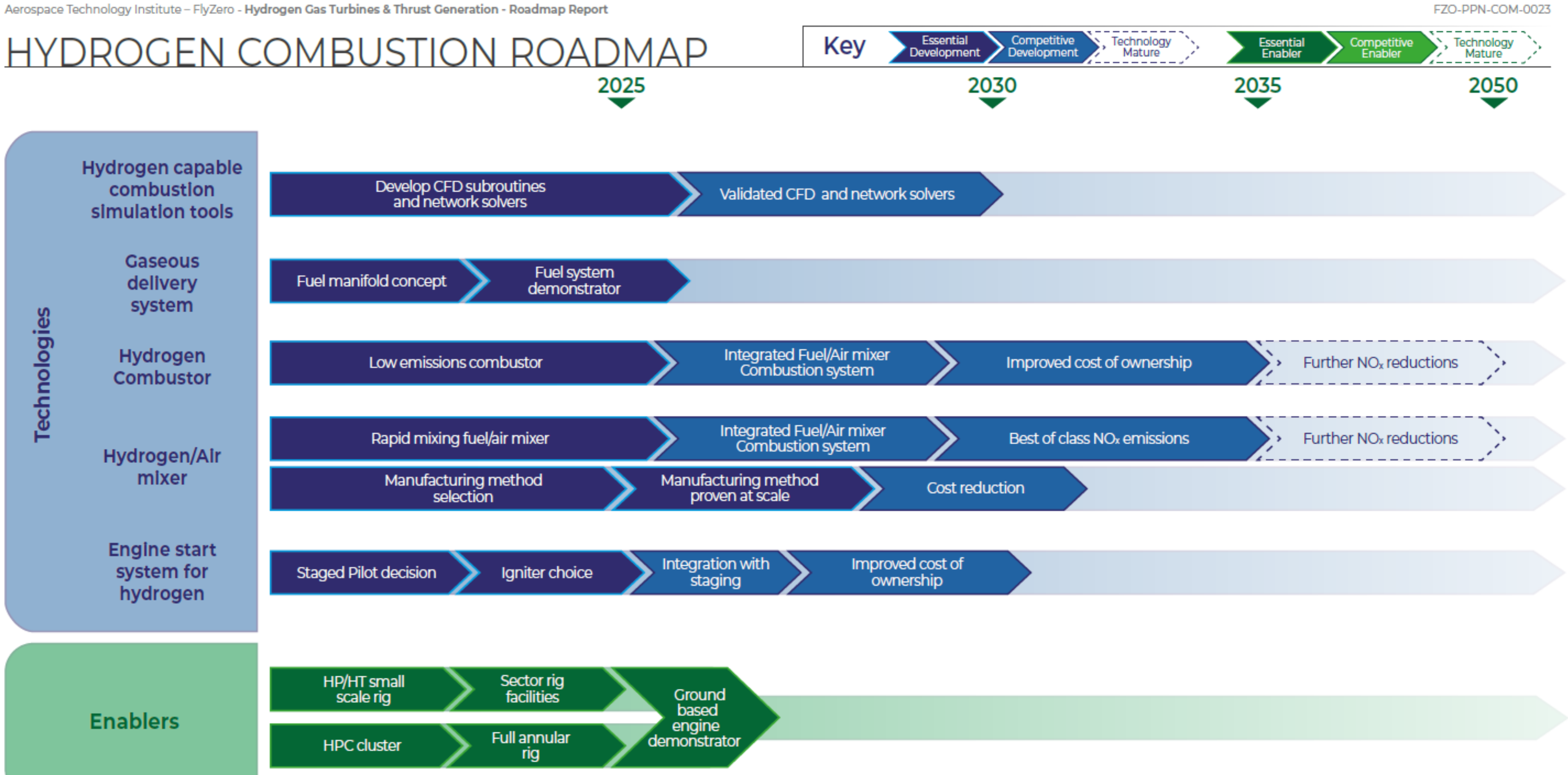
Reduced Engine Weight
- Low weight fan system; blade, case, vanes, containment, structures, shafts → Greater integration with airframe, pylon, mounts, nacelle, in the pursuit of weight reduction
- Reduced core casings and structure weight through additive manufacturing and 3D printing → Topology optimisation methods

Low Pressure System Developments
- Highly swept, low speed, low pressure ratio fan → Low count and low loss vanes, higher stage efficiency → Small bifurcations, higher fan efficiency, low forcing
- Intake length/ diameter = 0.4 → Intake length/ diameter < 0.4 → Further intake and fan integration capability
- Advanced exhaust system design → Morphing variable area nozzles → Weight and cost improvements
- Power Gearbox gear ratio ~3.0 and mass reduction → Gear ratios 3.5 – 4.0 → Gear ratios > 4.0 → Weight and durability of power gearbox
- Fan and inlet optimisation with boundary layer ingestion

Sustainability/ Life Cycle Impact
- *Improve estimates of atmospheric impacts of hydrogen combustion → Further development of atmospherics impacts and mitigations technologies → Generation 2 mitigations technologies
- Propulsion noise reduction → Continued noise reduction from propulsion and aircraft integration
- **Increased component life where platinum group metals are used
- Reduced input material during production

FlyZero Hydrogen Gas Turbines and Thrust Generation Roadmap – 3

- FZO-PPN-MAP-0022 and FZO-PPN-COM-0023 ‘Hydrogen Gas Turbines and Thrust Generation Roadmap Report’ cover aero engines and hydrogen combustion. For more details see: https://www.ati.org.uk/wp-content/uploads/2022/03/FZO-PPN-COM-0023-Hydrogen-Gas-Turbines-and-Thrust-Generation-Roadmap-Report.pdf



Aerospace Technology Institute – FlyZero - **Hydrogen Gas Turbines & Thrust Generation - Roadmap Report**

FZO-PPN-COM-0023

HYDROGEN COMBUSTION ROADMAP

Key: Essential Development | Competitive Development | Technology Mature | Essential Enabler | Competitive Enabler | Technology Mature

2025 | 2030 | 2035 | 2050

Technologies

Hydrogen capable combustion simulation tools: Develop CFD subroutines and network solvers → Validated CFD and network solvers

Gaseous delivery system: Fuel manifold concept → Fuel system demonstrator

Hydrogen Combustor: Low emissions combustor → Integrated Fuel/Air mixer Combustion system → Improved cost of ownership → Further NO_x reductions

Hydrogen/Air mixer: Rapid mixing fuel/air mixer → Integrated Fuel/Air mixer Combustion system → Best of class NO_x emissions → Further NO_x reductions

Manufacturing method selection → Manufacturing method proven at scale → Cost reduction

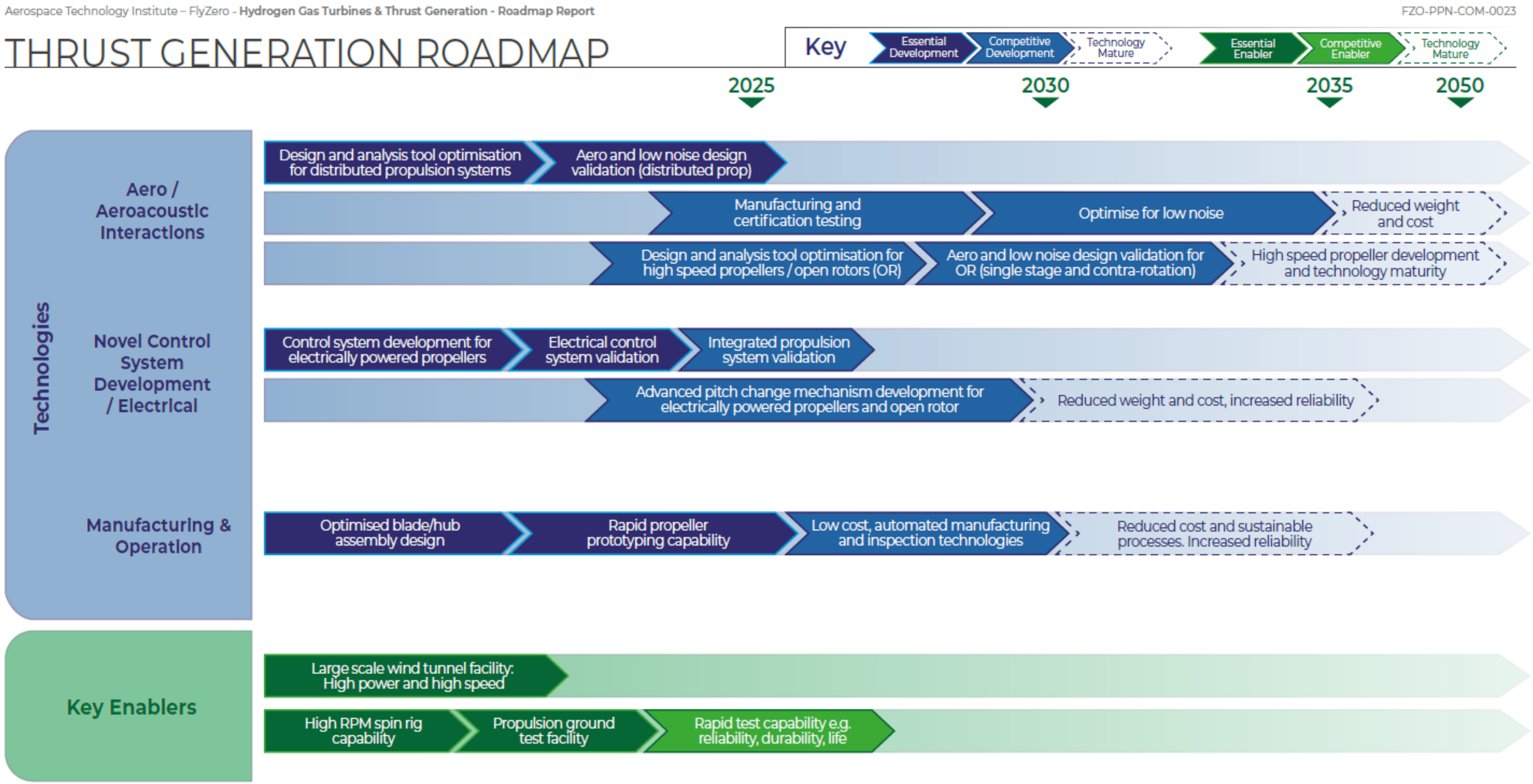
Engine start system for hydrogen: Staged Pilot decision → Igniter choice → Integration with staging → Improved cost of ownership

Enablers: HP/HT small scale rig → Sector rig facilities → Ground based engine demonstrator

HPC cluster → Full annular rig → Ground based engine demonstrator

FlyZero Hydrogen Gas Turbines and Thrust Generation Roadmap – 4

- FZO-IST-MAP-0022 and FZO-PPN-COM-0023 ‘Hydrogen Gas Turbines and Thrust Generation Roadmap Report’ cover aero engines and hydrogen combustion. For more details see: https://www.ati.org.uk/wp-content/uploads/2022/03/FZO-PPN-COM-0023-Hydrogen-Gas-Turbines-and-Thrust-Generation-Roadmap-Report.pdf



Aerospace Technology Institute – FlyZero - **Hydrogen Gas Turbines & Thrust Generation - Roadmap Report**

FZO-PPN-COM-0023

THRUST GENERATION ROADMAP

Key: Essential Development; Competitive Development; Technology Mature; Essential Enabler; Competitive Enabler; Technology Mature

2025 2030 2035 2050

Technologies

Aero / Aeroacoustic Interactions

Design and analysis tool optimisation for distributed propulsion systems → Aero and low noise design validation (distributed prop)

Manufacturing and certification testing → Optimise for low noise → Reduced weight and cost

Design and analysis tool optimisation for high speed propellers / open rotors (OR) → Aero and low noise design validation for OR (single stage and contra-rotation) → High speed propeller development and technology maturity

Novel Control System Development / Electrical

Control system development for electrically powered propellers → Electrical control system validation → Integrated propulsion system validation

Advanced pitch change mechanism development for electrically powered propellers and open rotor → Reduced weight and cost, increased reliability

Manufacturing & Operation

Optimised blade/hub assembly design → Rapid propeller prototyping capability → Low cost, automated manufacturing and inspection technologies → Reduced cost and sustainable processes. Increased reliability

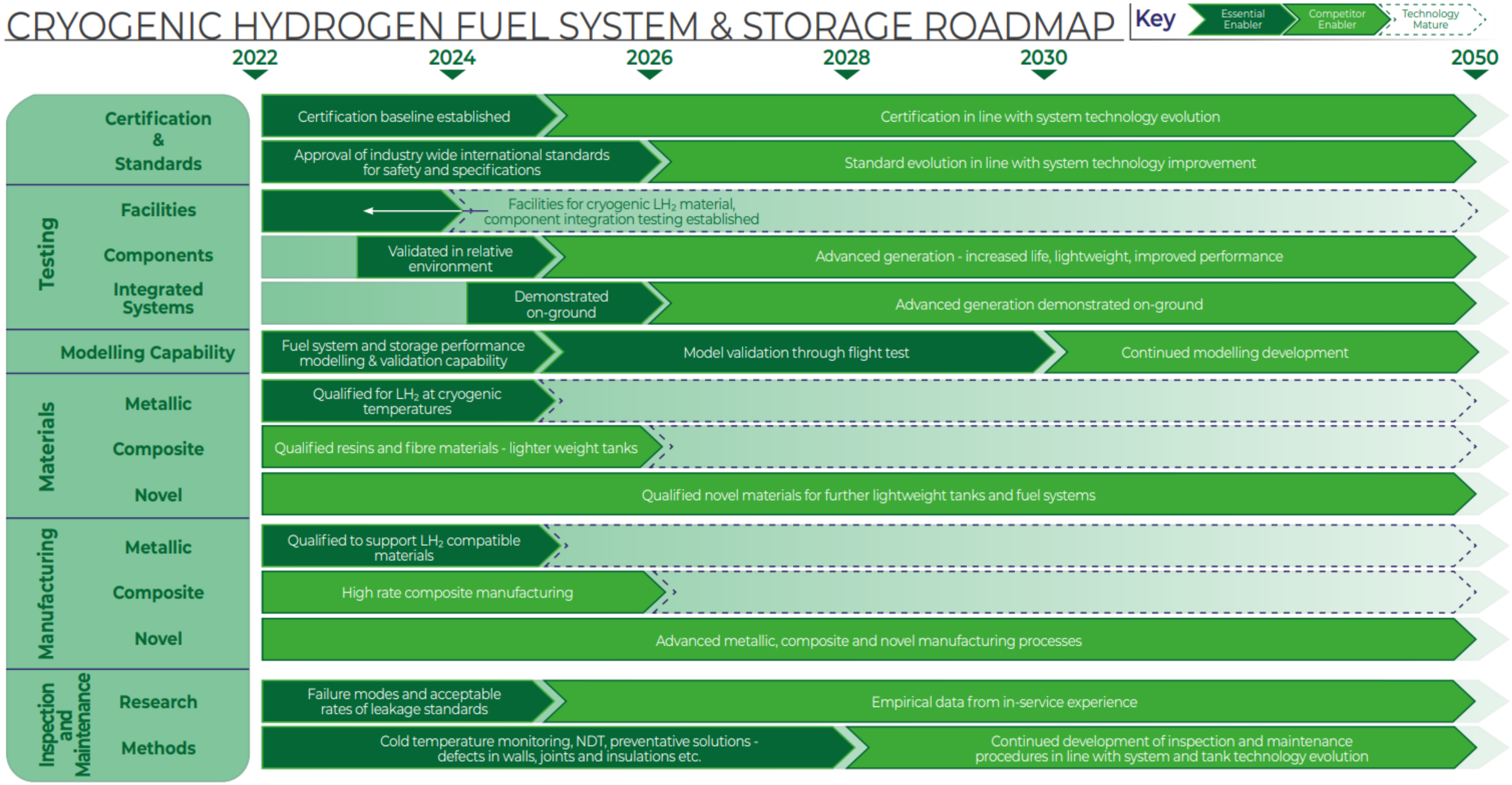
Key Enablers

Large scale wind tunnel facility: High power and high speed

High RPM spin rig capability → Propulsion ground test facility → Rapid test capability e.g. reliability, durability, life

FlyZero Cryogenic Hydrogen Fuel System and Storage Roadmap – 1

- FZO-PPN-MAP-0026 and FZO-PPN-COM-0027 ‘Cryogenic Hydrogen Fuel System and Storage Roadmap Report’ cover aircraft fuel systems and tanks. For more details see: https://www.ati.org.uk/wp-content/uploads/2022/03/FZO-PPN-COM-0027-Cryogenic-Hydrogen-Fuel-System-and-Storage-Roadmap-Report.pdf



CRYOGENIC HYDROGEN FUEL SYSTEM & STORAGE ROADMAP

Key: Essential Enabler | Competitor Enabler | Technology Mature

2022 | 2024 | 2026 | 2028 | 2030 | 2050

Certification & Standards
- Certification baseline established → Certification in line with system technology evolution
- Approval of industry wide international standards for safety and specifications → Standard evolution in line with system technology improvement

Testing
- **Facilities**: Facilities for cryogenic LH_2 material, component integration testing established
- **Components**: Validated in relative environment → Advanced generation - increased life, lightweight, improved performance
- **Integrated Systems**: Demonstrated on-ground → Advanced generation demonstrated on-ground

Modelling Capability
- Fuel system and storage performance modelling & validation capability → Model validation through flight test → Continued modelling development

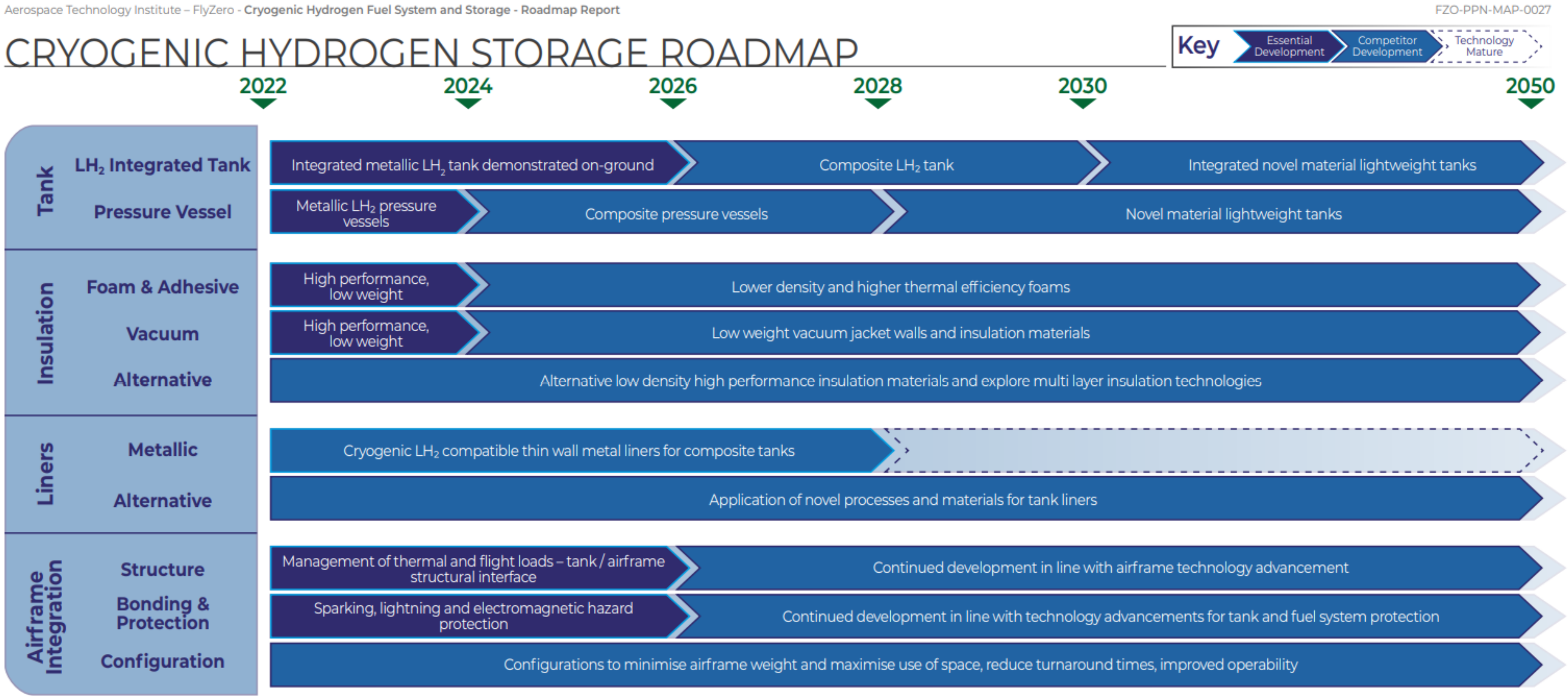
Materials
- **Metallic**: Qualified for LH_2 at cryogenic temperatures
- **Composite**: Qualified resins and fibre materials - lighter weight tanks
- **Novel**: Qualified novel materials for further lightweight tanks and fuel systems

Manufacturing
- **Metallic**: Qualified to support LH_2 compatible materials
- **Composite**: High rate composite manufacturing
- **Novel**: Advanced metallic, composite and novel manufacturing processes

Inspection and Maintenance
- **Research**: Failure modes and acceptable rates of leakage standards → Empirical data from in-service experience
- **Methods**: Cold temperature monitoring, NDT, preventative solutions - defects in walls, joints and insulations etc. → Continued development of inspection and maintenance procedures in line with system and tank technology evolution

FlyZero Cryogenic Hydrogen Fuel System and Storage Roadmap – 2

- FZO-PPN-MAP-0026 and FZO-PPN-COM-0027 ‘Cryogenic Hydrogen Fuel System and Storage Roadmap Report’ cover aircraft fuel systems and tanks. For more details see: https://www.ati.org.uk/wp-content/uploads/2022/03/FZO-PPN-COM-0027-Cryogenic-Hydrogen-Fuel-System-and-Storage-Roadmap-Report.pdf



Aerospace Technology Institute – FlyZero - **Cryogenic Hydrogen Fuel System and Storage - Roadmap Report** FZO-PPN-MAP-0027

CRYOGENIC HYDROGEN STORAGE ROADMAP

Key: Essential Development | Competitor Development | Technology Mature

2022 | 2024 | 2026 | 2028 | 2030 | 2050

Tank
- **LH_2 Integrated Tank**: Integrated metallic LH_2 tank demonstrated on-ground → Composite LH_2 tank → Integrated novel material lightweight tanks
- **Pressure Vessel**: Metallic LH_2 pressure vessels → Composite pressure vessels → Novel material lightweight tanks

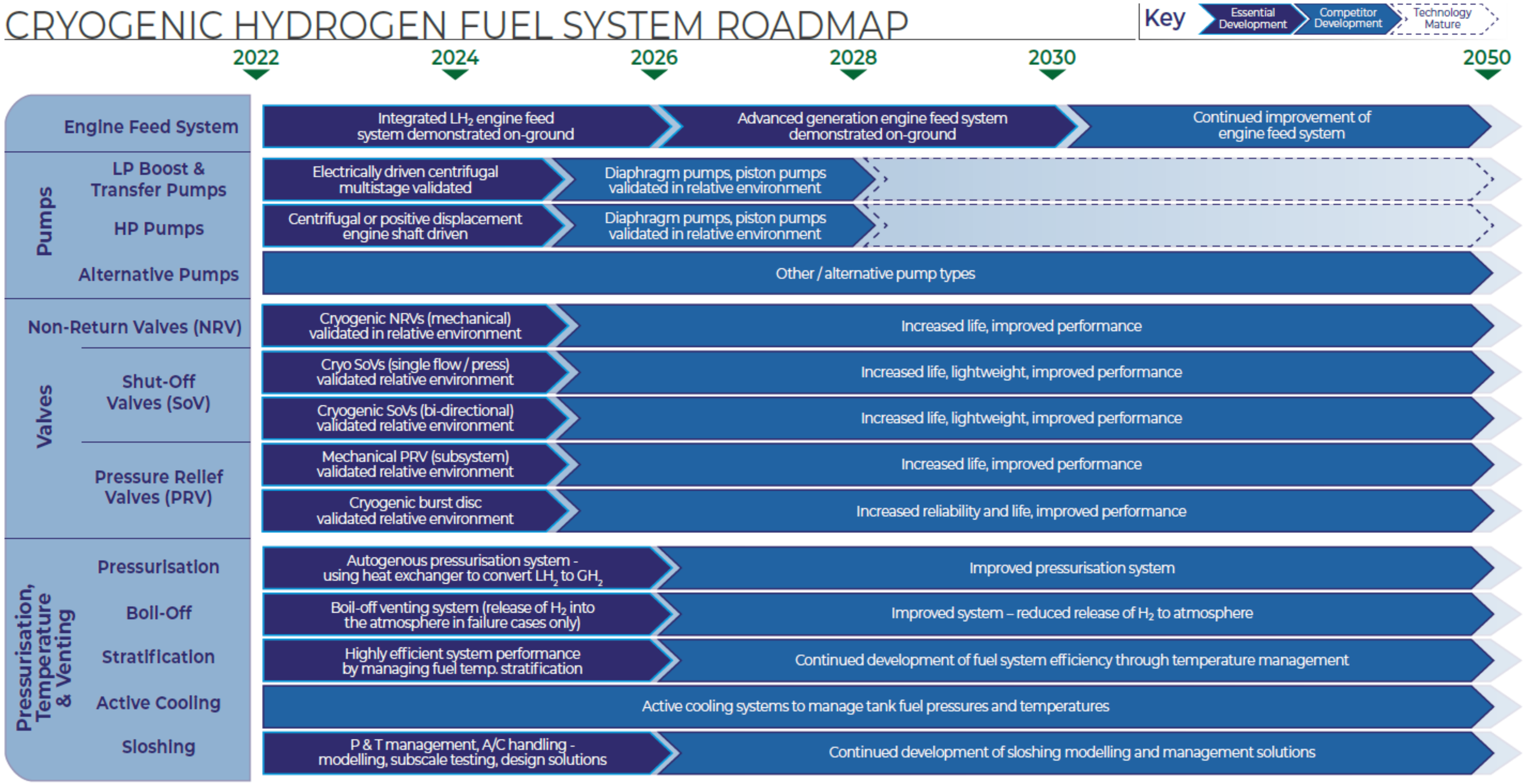
Insulation
- **Foam & Adhesive**: High performance, low weight → Lower density and higher thermal efficiency foams
- **Vacuum**: High performance, low weight → Low weight vacuum jacket walls and insulation materials
- **Alternative**: Alternative low density high performance insulation materials and explore multi layer insulation technologies

Liners
- **Metallic**: Cryogenic LH_2 compatible thin wall metal liners for composite tanks
- **Alternative**: Application of novel processes and materials for tank liners

Airframe Integration
- **Structure**: Management of thermal and flight loads – tank / airframe structural interface → Continued development in line with airframe technology advancement
- **Bonding & Protection**: Sparking, lightning and electromagnetic hazard protection → Continued development in line with technology advancements for tank and fuel system protection
- **Configuration**: Configurations to minimise airframe weight and maximise use of space, reduce turnaround times, improved operability

FlyZero Cryogenic Hydrogen Fuel System and Storage Roadmap – 3

- FZO-PPN-MAP-0026 and FZO-PPN-COM-0027 ‘Cryogenic Hydrogen Fuel System and Storage Roadmap Report’ cover aircraft fuel systems and tanks. For more details see: https://www.ati.org.uk/wp-content/uploads/2022/03/FZO-PPN-COM-0027-Cryogenic-Hydrogen-Fuel-System-and-Storage-Roadmap-Report.pdf



CRYOGENIC HYDROGEN FUEL SYSTEM ROADMAP

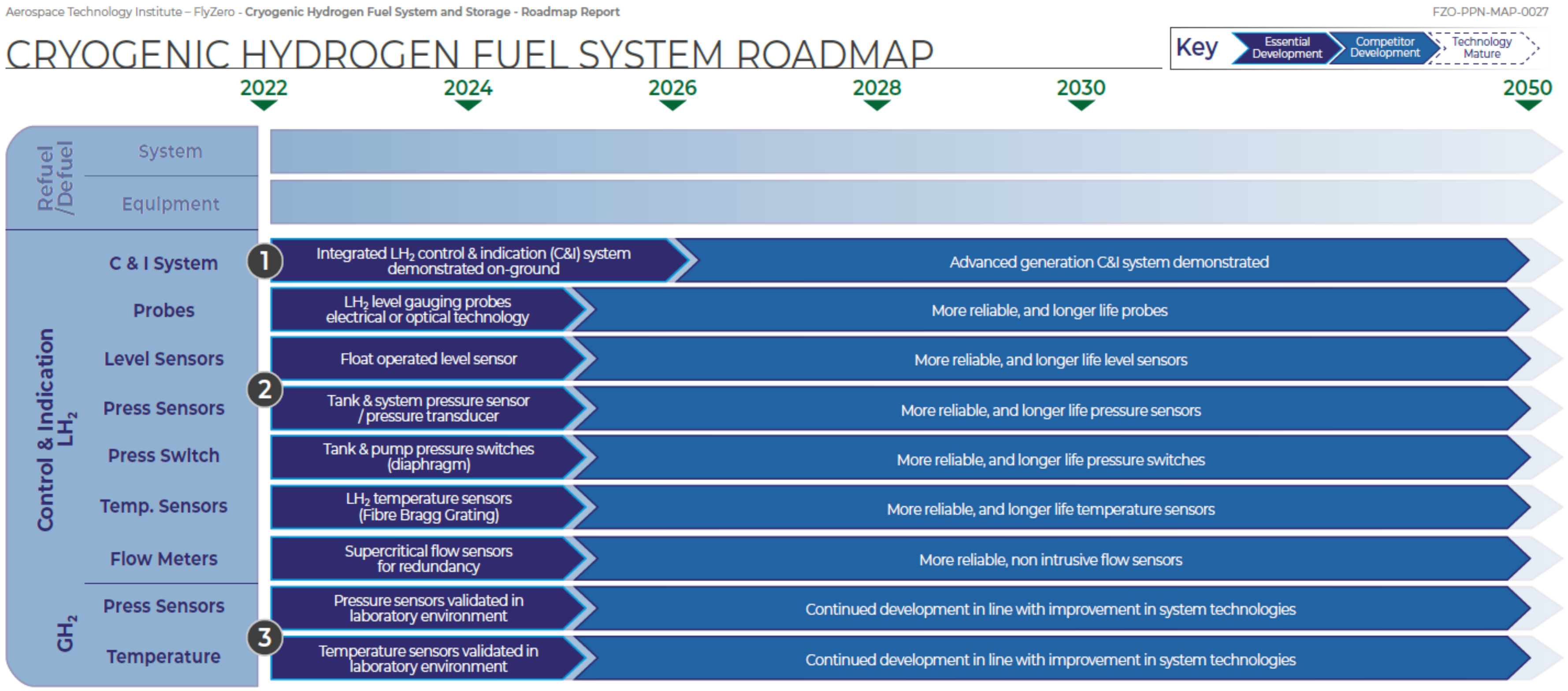
Key: Essential Development · Competitor Development · Technology Mature

2022 · 2024 · 2026 · 2028 · 2030 · 2050

	Engine Feed System	Integrated LH_2 engine feed system demonstrated on-ground	Advanced generation engine feed system demonstrated on-ground	Continued improvement of engine feed system
Pumps	LP Boost & Transfer Pumps	Electrically driven centrifugal multistage validated	Diaphragm pumps, piston pumps validated in relative environment	
Pumps	HP Pumps	Centrifugal or positive displacement engine shaft driven	Diaphragm pumps, piston pumps validated in relative environment	
Pumps	Alternative Pumps	Other / alternative pump types		
	Non-Return Valves (NRV)	Cryogenic NRVs (mechanical) validated in relative environment	Increased life, improved performance	
Valves	Shut-Off Valves (SoV)	Cryo SoVs (single flow / press) validated relative environment	Increased life, lightweight, improved performance	
Valves	Shut-Off Valves (SoV)	Cryogenic SoVs (bi-directional) validated relative environment	Increased life, lightweight, improved performance	
Valves	Pressure Relief Valves (PRV)	Mechanical PRV (subsystem) validated relative environment	Increased life, improved performance	
Valves	Pressure Relief Valves (PRV)	Cryogenic burst disc validated relative environment	Increased reliability and life, improved performance	
Pressurisation, Temperature & Venting	Pressurisation	Autogenous pressurisation system - using heat exchanger to convert LH_2 to GH_2	Improved pressurisation system	
Pressurisation, Temperature & Venting	Boil-Off	Boil-off venting system (release of H_2 into the atmosphere in failure cases only)	Improved system – reduced release of H_2 to atmosphere	
Pressurisation, Temperature & Venting	Stratification	Highly efficient system performance by managing fuel temp. stratification	Continued development of fuel system efficiency through temperature management	
Pressurisation, Temperature & Venting	Active Cooling	Active cooling systems to manage tank fuel pressures and temperatures		
Pressurisation, Temperature & Venting	Sloshing	P & T management, A/C handling - modelling, subscale testing, design solutions	Continued development of sloshing modelling and management solutions	

FlyZero Cryogenic Hydrogen Fuel System and Storage Roadmap – 4

- FZO-PPN-MAP-0026 and FZO-PPN-COM-0027 ‘Cryogenic Hydrogen Fuel System and Storage Roadmap Report’ cover aircraft fuel systems and tanks. For more details see: https://www.ati.org.uk/wp-content/uploads/2022/03/FZO-PPN-COM-0027-Cryogenic-Hydrogen-Fuel-System-and-Storage-Roadmap-Report.pdf



Aerospace Technology Institute – FlyZero - **Cryogenic Hydrogen Fuel System and Storage - Roadmap Report**

FZO-PPN-MAP-0027

CRYOGENIC HYDROGEN FUEL SYSTEM ROADMAP

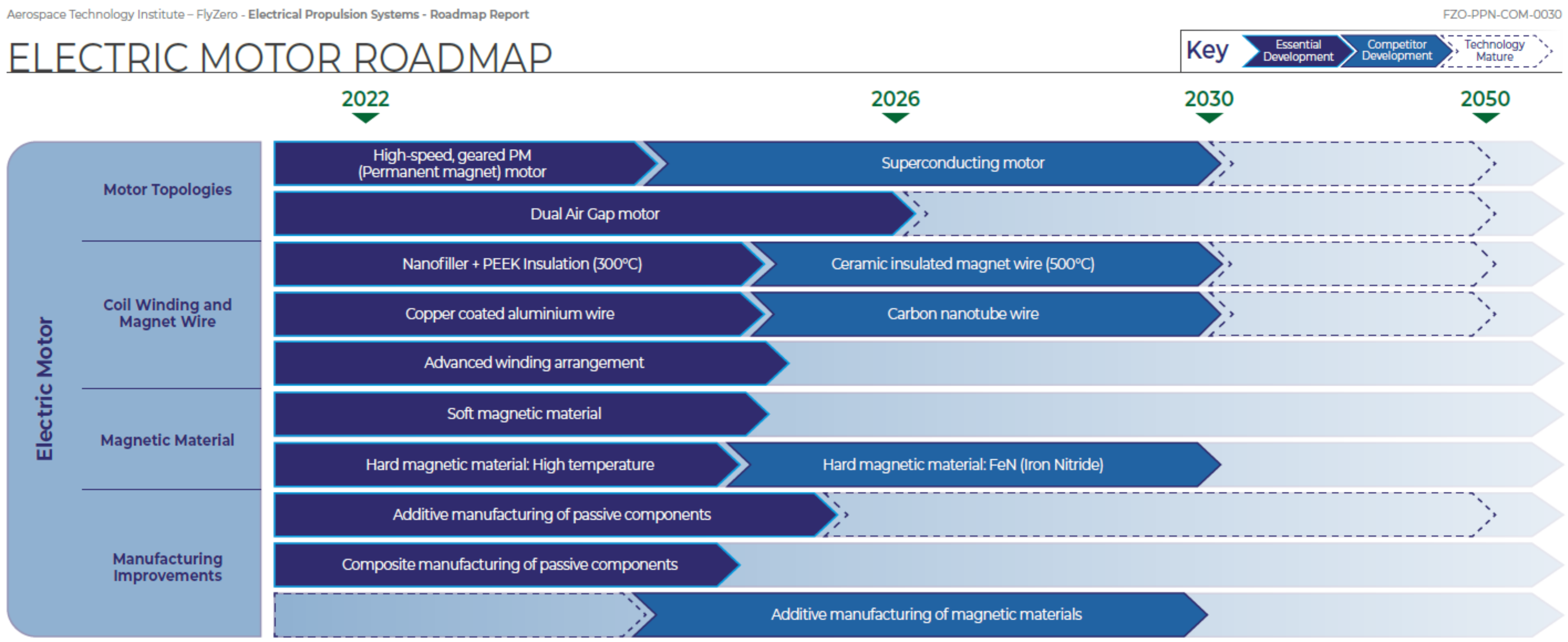
Key: Essential Development; Competitor Development; Technology Mature

2022 2024 2026 2028 2030 2050

Refuel /Defuel	System		
	Equipment		
Control & Indication LH_2	C & I System	① Integrated LH_2 control & indication (C&I) system demonstrated on-ground	Advanced generation C&I system demonstrated
	Probes	LH_2 level gauging probes electrical or optical technology	More reliable, and longer life probes
	Level Sensors	Float operated level sensor	More reliable, and longer life level sensors
	Press Sensors	② Tank & system pressure sensor / pressure transducer	More reliable, and longer life pressure sensors
	Press Switch	Tank & pump pressure switches (diaphragm)	More reliable, and longer life pressure switches
	Temp. Sensors	LH_2 temperature sensors (Fibre Bragg Grating)	More reliable, and longer life temperature sensors
	Flow Meters	Supercritical flow sensors for redundancy	More reliable, non intrusive flow sensors
GH_2	Press Sensors	Pressure sensors validated in laboratory environment	Continued development in line with improvement in system technologies
	Temperature	③ Temperature sensors validated in laboratory environment	Continued development in line with improvement in system technologies

FlyZero Electrical Propulsion Systems Roadmap – 1

- FZO-PPN-MAP-0029 and FZO-PPN-COM-0030 ‘Electrical Propulsion Systems Roadmap Report’ cover electric motors, power electronics and cooling. For more details see: https://www.ati.org.uk/wp-content/uploads/2022/03/FZO-PPN-COM-0030-Electrical-Propulsion-Systems-Roadmap-Report.pdf



Aerospace Technology Institute – FlyZero - **Electrical Propulsion Systems - Roadmap Report**

FZO-PPN-COM-0030

ELECTRIC MOTOR ROADMAP

Key: Essential Development, Competitor Development, Technology Mature

2022, 2026, 2030, 2050

Electric Motor

Motor Topologies
- High-speed, geared PM (Permanent magnet) motor → Superconducting motor
- Dual Air Gap motor

Coil Winding and Magnet Wire
- Nanofiller + PEEK Insulation (300°C) → Ceramic insulated magnet wire (500°C)
- Copper coated aluminium wire → Carbon nanotube wire
- Advanced winding arrangement

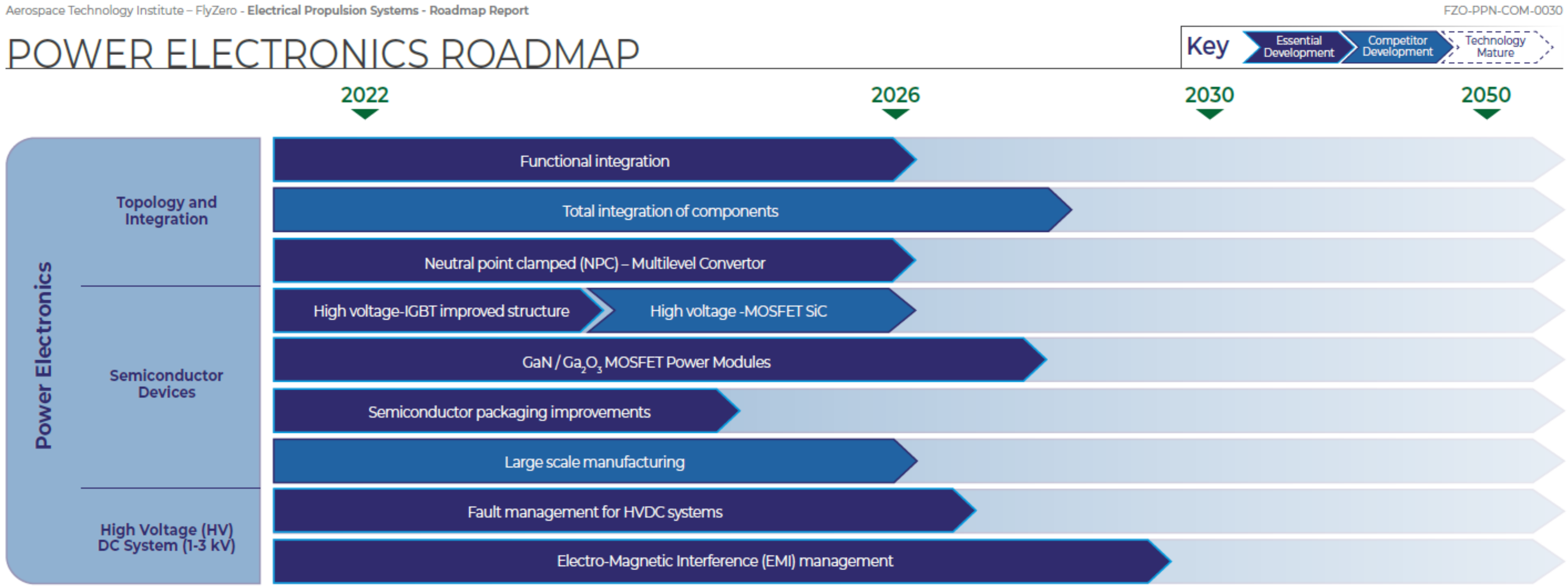
Magnetic Material
- Soft magnetic material
- Hard magnetic material: High temperature → Hard magnetic material: FeN (Iron Nitride)

Manufacturing Improvements
- Additive manufacturing of passive components
- Composite manufacturing of passive components
- Additive manufacturing of magnetic materials

- This roadmap is relevant for the electrical machines to be used together with hydrogen fuel cells and for hybrid electric propulsion systems to improve fuel economy.

FlyZero Electrical Propulsion Systems Roadmap – 2

- FZO-PPN-MAP-0029 and FZO-PPN-COM-0030 ‘Electrical Propulsion Systems Roadmap Report’ cover electric motors, power electronics and cooling. For more details see: https://www.ati.org.uk/wp-content/uploads/2022/03/FZO-PPN-COM-0030-Electrical-Propulsion-Systems-Roadmap-Report.pdf

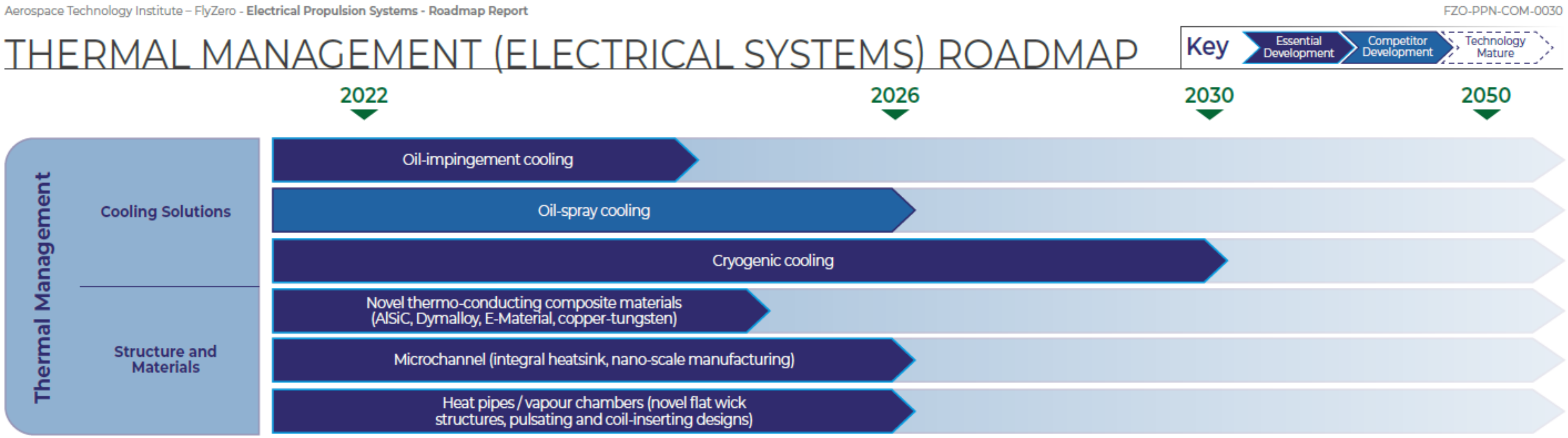

Aerospace Technology Institute – FlyZero - **Electrical Propulsion Systems - Roadmap Report** FZO-PPN-COM-0030

POWER ELECTRONICS ROADMAP

- This roadmap is relevant for the power electronic systems to be used together with hydrogen fuel cells and hybrid electric propulsion systems to improve fuel economy.

FlyZero Electrical Propulsion Systems Roadmap – 3

- FZO-PPN-MAP-0029 and FZO-PPN-COM-0030 ‘Electrical Propulsion Systems Roadmap Report’ cover electric motors, power electronics and cooling. For more details see: https://www.ati.org.uk/wp-content/uploads/2022/03/FZO-PPN-COM-0030-Electrical-Propulsion-Systems-Roadmap-Report.pdf



Aerospace Technology Institute – FlyZero - **Electrical Propulsion Systems - Roadmap Report**

FZO-PPN-COM-0030

THERMAL MANAGEMENT (ELECTRICAL SYSTEMS) ROADMAP

Key: Essential Development | Competitor Development | Technology Mature

2022 | 2026 | 2030 | 2050

Thermal Management

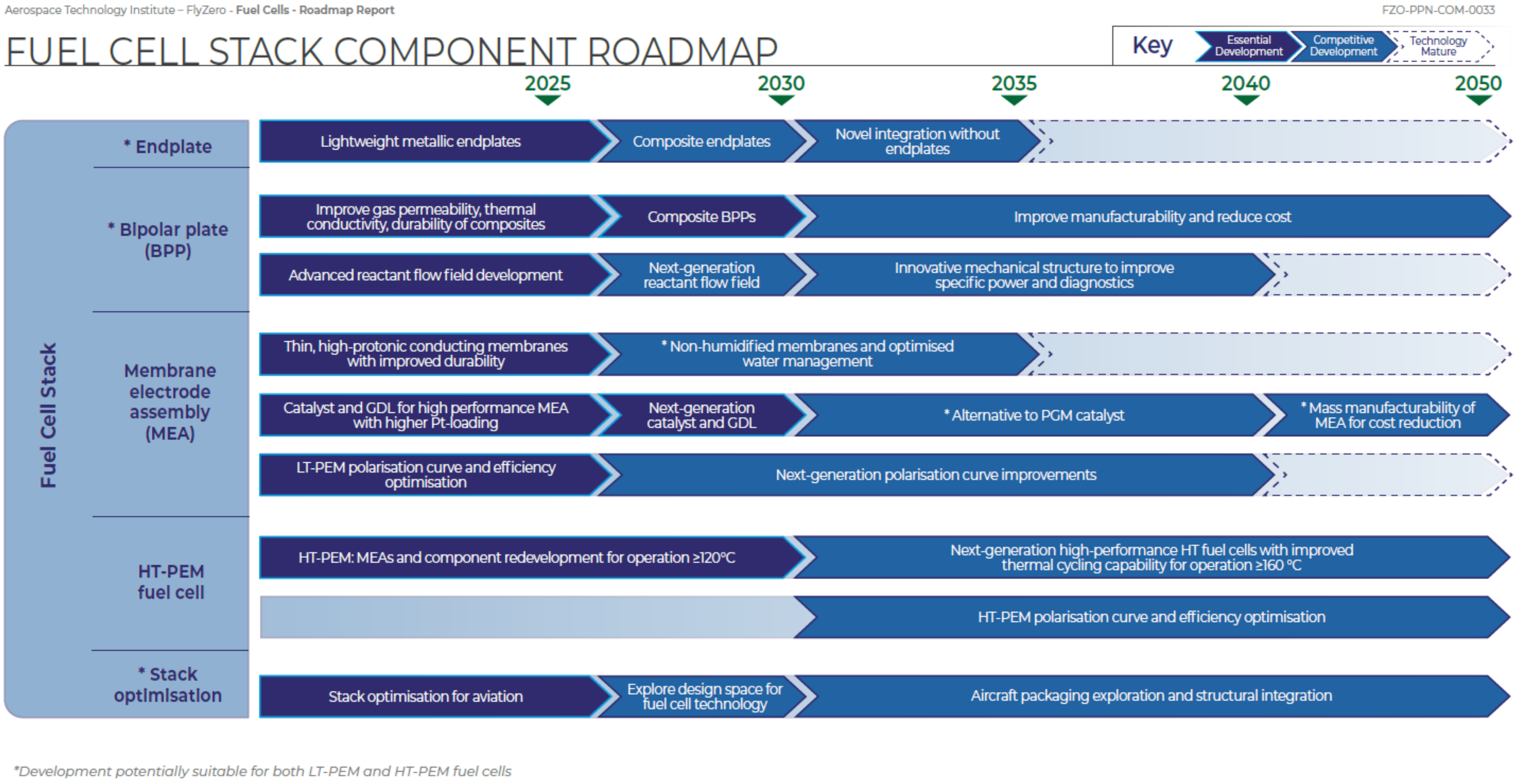
Cooling Solutions
- Oil-impingement cooling
- Oil-spray cooling
- Cryogenic cooling

Structure and Materials
- Novel thermo-conducting composite materials (AlSiC, Dymalloy, E-Material, copper-tungsten)
- Microchannel (integral heatsink, nano-scale manufacturing)
- Heat pipes / vapour chambers (novel flat wick structures, pulsating and coil-inserting designs)

- This roadmap is relevant for advanced cooling systems to be used together with electrical machines and power electronics to improve hydrogen-fuelled aircraft performance.

FlyZero Fuel Cells Roadmap – 1

- FZO-PPN-MAP-0032 and FZO-PPN-COM-0033 ‘Fuel Cells Roadmap Report’ cover fuel cell stack components and systems. For more details see: https://www.ati.org.uk/wp-content/uploads/2022/03/FZO-PPN-COM-0033-Fuel-Cells-Roadmap-Report.pdf



Aerospace Technology Institute – FlyZero - **Fuel Cells - Roadmap Report**

FZO-PPN-COM-0033

FUEL CELL STACK COMPONENT ROADMAP

Key: Essential Development | Competitive Development | Technology Mature

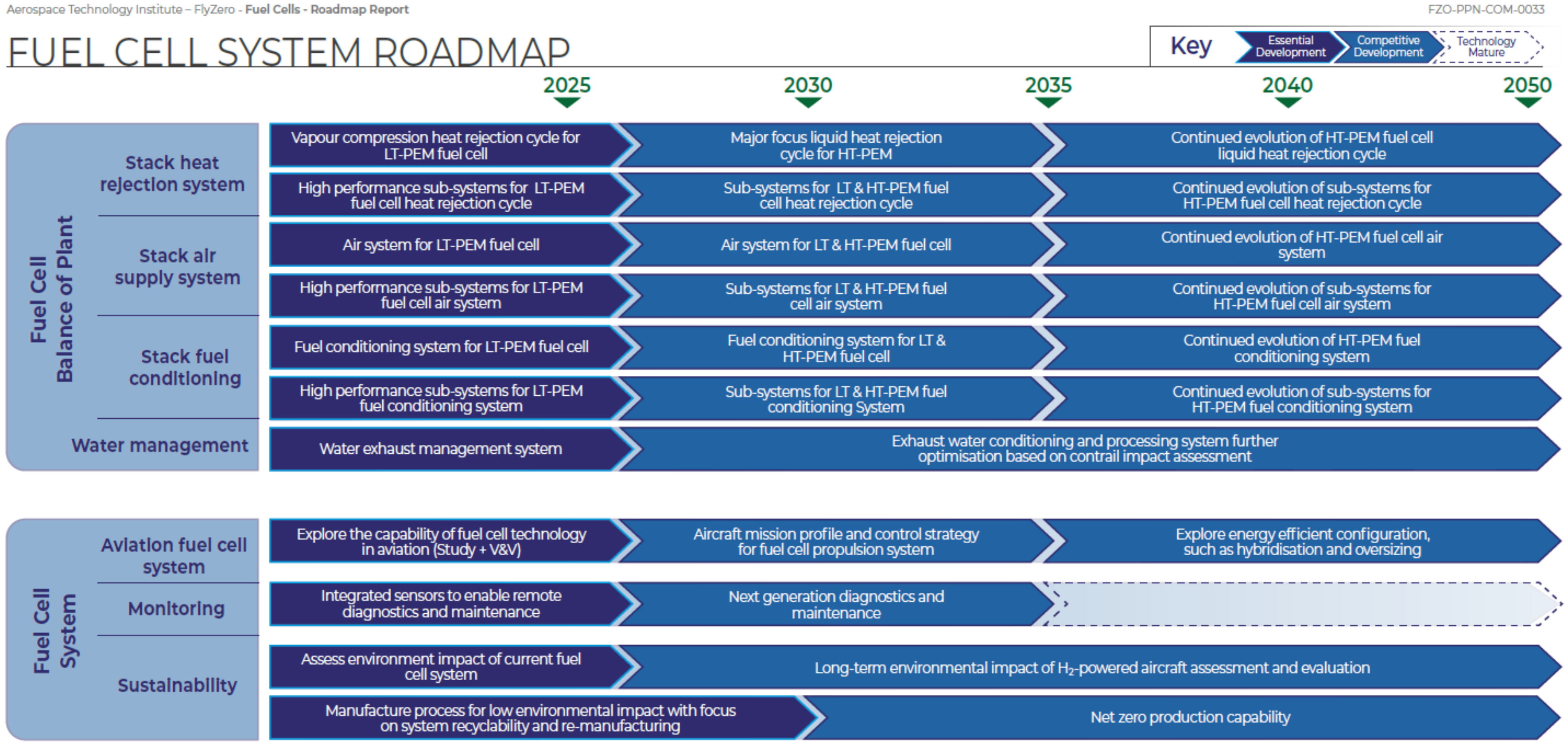
2025 | 2030 | 2035 | 2040 | 2050

Fuel Cell Stack				
* Endplate	Lightweight metallic endplates	Composite endplates	Novel integration without endplates	
* Bipolar plate (BPP)	Improve gas permeability, thermal conductivity, durability of composites	Composite BPPs	Improve manufacturability and reduce cost	
	Advanced reactant flow field development	Next-generation reactant flow field	Innovative mechanical structure to improve specific power and diagnostics	
Membrane electrode assembly (MEA)	Thin, high-protonic conducting membranes with improved durability	* Non-humidified membranes and optimised water management		
	Catalyst and GDL for high performance MEA with higher Pt-loading	Next-generation catalyst and GDL	* Alternative to PGM catalyst	* Mass manufacturability of MEA for cost reduction
	LT-PEM polarisation curve and efficiency optimisation	Next-generation polarisation curve improvements		
HT-PEM fuel cell	HT-PEM: MEAs and component redevelopment for operation ≥120°C	Next-generation high-performance HT fuel cells with improved thermal cycling capability for operation ≥160 °C		
		HT-PEM polarisation curve and efficiency optimisation		
* Stack optimisation	Stack optimisation for aviation	Explore design space for fuel cell technology	Aircraft packaging exploration and structural integration	

*Development potentially suitable for both LT-PEM and HT-PEM fuel cells

FlyZero Fuel Cells Roadmap – 2

- FZO-PPN-MAP-0032 and FZO-PPN-COM-0033 ‘Fuel Cells Roadmap Report’ cover fuel cell stack components and systems. For more details see: https://www.ati.org.uk/wp-content/uploads/2022/03/FZO-PPN-COM-0033-Fuel-Cells-Roadmap-Report.pdf



Aerospace Technology Institute – FlyZero - **Fuel Cells - Roadmap Report** FZO-PPN-COM-0033

FUEL CELL SYSTEM ROADMAP

Key: Essential Development | Competitive Development | Technology Mature

2025 2030 2035 2040 2050

Fuel Cell Balance of Plant	**Stack heat rejection system**	Vapour compression heat rejection cycle for LT-PEM fuel cell	Major focus liquid heat rejection cycle for HT-PEM	Continued evolution of HT-PEM fuel cell liquid heat rejection cycle
		High performance sub-systems for LT-PEM fuel cell heat rejection cycle	Sub-systems for LT & HT-PEM fuel cell heat rejection cycle	Continued evolution of sub-systems for HT-PEM fuel cell heat rejection cycle
	Stack air supply system	Air system for LT-PEM fuel cell	Air system for LT & HT-PEM fuel cell	Continued evolution of HT-PEM fuel cell air system
		High performance sub-systems for LT-PEM fuel cell air system	Sub-systems for LT & HT-PEM fuel cell air system	Continued evolution of sub-systems for HT-PEM fuel cell air system
	Stack fuel conditioning	Fuel conditioning system for LT-PEM fuel cell	Fuel conditioning system for LT & HT-PEM fuel cell	Continued evolution of HT-PEM fuel conditioning system
		High performance sub-systems for LT-PEM fuel conditioning system	Sub-systems for LT & HT-PEM fuel conditioning System	Continued evolution of sub-systems for HT-PEM fuel conditioning system
	Water management	Water exhaust management system	Exhaust water conditioning and processing system further optimisation based on contrail impact assessment	
Fuel Cell System	**Aviation fuel cell system**	Explore the capability of fuel cell technology in aviation (Study + V&V)	Aircraft mission profile and control strategy for fuel cell propulsion system	Explore energy efficient configuration, such as hybridisation and oversizing
	Monitoring	Integrated sensors to enable remote diagnostics and maintenance	Next generation diagnostics and maintenance	
	Sustainability	Assess environment impact of current fuel cell system	Long-term environmental impact of H_2-powered aircraft assessment and evaluation	
		Manufacture process for low environmental impact with focus on system recyclability and re-manufacturing	Net zero production capability	

Case Studies

ENABLE·H2

Heathrow

ENABLE·H2

The Airport

The seventh busiest airport in the world by total passenger traffic, Heathrow is a major hub for travel located west of central London. In 2019 there were a record number of passengers at 80.8 million, as well as around 475,000 aircraft movements. Currently there are 2 runways, while plans for a third runway have been postponed.

London as a whole has been commercialising hydrogen mobility for some time now. Fuel cell cars are in use in a number of public and private sectors. Fuel cell taxis have been operational in London since the 2012 Olympics with more from private companies planning to hit the road soon. Fuel cell buses have had their own routes in London with at least 20 more buses operational back in 2020. With steady improvements in hydrogen combustion engines, aviation is next on the list.

Heathrow airport already has a hydrogen refuelling station for ground vehicles that was put in place in 2012 by Air Products. It carries out 350 bar and 700 bar refuelling thanks to an infrastructure update as of 2014. There are plans to expand this station and potential to extend this offering to airside locations.

The Hydrogen Vision

Due to the size of Heathrow compared to most airports, transition to hydrogen will have to be more gradual. With its size also comes the variance in the distance of flights it offers, many of which are long-haul/international. Whilst both technologies need more development for longer flights, hydrogen holds more prospects than battery electric with regards to longer flight times. International aviation has been a focus of both the UK sustainable aviation roadmap and the Climate Change Committee's 6th carbon budget.

In general, more infrastructure will be required, as well as more hydrogen for logistical and aircraft applications. The use of other sustainable aviation fuels which use traditional combustion engines will be key to ease the transition and help decarbonise in the short term. Decarbonising will require significant hydrogen storage sites, of both gaseous for fuel cell applications and liquidus for future hydrogen combustion engines.

Future Hydrogen Use

Whilst Heathrow will have a more challenging time decarbonising due to its size and passenger flow, its general path will be similar to smaller regional airports.

Airport logistics will be a strong place to start. Heathrow has a vast ecosystem of ground vehicles and specialist non-road mobile machinery that could be adapted to enable use of hydrogen FC versions. Such as buses, catering trucks, De-icing trucks, luggage transporters, refuellers etc.

Supply of hydrogen will need to be adapted as applications transfer to hydrogen usage. Initial small volumes for ground FC vehicles might suffice with trailers. However, as scale up and aircraft roll out occurs, pipeline supply is a necessity for the amount of hydrogen combustion engines would require.

Gaseous hydrogen could be used to power on-board electrical systems through fuel cells which would be lighter than a RES sourced battery equivalent. On-board hydrogen power systems have another distinct advantage. Aircraft could be connected to the terminal and any left over hydrogen not used in flight can be transferred to airport application before refuelling is needed. On-board hydrogen applications will serve to decarbonise aircraft as they transition from conventional fuels, to SAF alternatives.

As hydrogen combustion engine TRLs reach deployment levels, select short distance airliners could be replaced to be fully powered by liquid hydrogen. This would require the addition of a liquefaction plant on site at Heathrow to convert the pipped gaseous hydrogen into liquid ready to be used in a combustion engine. LHY requires cryogenic storage which comes with its own set of challenges and increased costs at the benefit of a completely carbon free output, when using green hydrogen. Although space is limited at Heathrow, on site storage would be required. Currently the only way to efficiently transport LHY is through trailers with specialised cooling. Pipelines are not an option for bulk LHY transport and therefore coupling its production and application location would be most beneficial.

Select commuter and short distance airliners will be used first to destinations that have also invested in the hydrogen infrastructure required to refuel the airliners. Whilst there will be many small and medium scale airports that are easily able to adapt to hydrogen usage, Heathrow has the potential to be the first large scale airport that can enable carbon free flight through hydrogen. Serving as a major hub for hydrogen aviation which can connect the smaller regions of Europe. As other major airports transition to become hydrogen hubs, Heathrow will undoubtedly already have connections available to utilise the new infrastructure. As well as entice other participants to take up hydrogen by displaying its use and offering hydrogen flightpaths.

As a major hydrogen hub, Heathrow would invite strong collaboration throughout the hydrogen, RES, aviation and logistics sectors to achieve a truly sustainable airport

Groningen Airport Eelde

ENABLE·H2

The Airport

Groningen Airport Eelde (GRQ)is a small, one-runway airport located south of the City of Groningen. In 2018, 242,000 passengers passed through the airport. Most frequent flights from the airport go to Mediterranean destinations and London Southend. All of which have around 15 flights per week as of 2019/2020.

GRQ is the first international airport to have installed a large solar park, with around 63,000 solar panels between the runway and taxiways. The panels provide power for up to 6,400 households, the airport and offer electric aircraft charging. There are plans to build more panels on the roof of the airport's carpark to deliver to the grid and also charge cars of passengers that park there.

The local provinces of Groningen and Drenthe are no strangers to implementing hydrogen into their transport infrastructure. There are significant plans to implement regional hydrogen fuel cell buses for public use and is currently the city with the most electrified buses in use in the world. The Netherlands as a whole aiming for all public buses to be emission free by 2030.

The Hydrogen Vision

The size of GRQ enables it to be one of the first movers and a key hydrogen hub for the future success of hydrogen aviation. As a small airport, it will be much easier to transition both the day-to-day operations and aircraft.

The airport alongside the New Energy Coalition are already looking to establish hydrogen usage on site. Hydrogen production produced from the solar park will be used in various applications such as in a multi-fuel station that serves both land and air vehicles. In addition, existing equipment will be converted to innovative hydrogen-powered ground equipment not yet on the market.

Unique Opportunities

However, GRQ is more than just a passenger airport. The KLM flight academy, a pilot training and flight school, is based there. Given its instruction remit, it is expected to become an early-stage initiator of electric and hydrogen electric aviation. The concept is for the operation of the academy to be run on renewable hydrogen locally produced at the airport.

In addition, GRQ began commercial drone operations in 2017 from the DroneHub GAE. The DroneHub began looking at hydrogen as a potential fuel for drones back in 2018 and has since increased its interest in this novel hydrogen application. GRQ has all the necessary permits to fly drones and allows drone research to be conducted at the airport focused on hydrogen fuelling and scaling up cargo drones. Hydrogen powered aircraft are also being researched at GRQ, and through the hydrogen plans of the region may prove successful.

Future Hydrogen Use

Groningen Airport Eelde has the intention to become a frontrunner in hydrogen use within the aviation sector. The airport has developed some initial combined hydrogen and electric concepts which it is beginning to position.

To maximise efficiency of the still expanding solar farm, reducing any wastage of intermittent renewable energy produced, the installation is planned to be coupled with an electrolyser – and hydrogen storage. From here, the green hydrogen can either be fed back into a fuel cell to produce electricity for the airport/EV charging stations when renewable energy production is low, or be used in other hydrogen based applications. These applications will include a hydrogen refuelling station for logistic applications around the airport (land and airside), and for passenger refuelling as demand grows. FCE busses, trucks and airport service vehicles are planned to be introduced. GRQ expects demand from landside heavy-duty vehicles to drive a potential need for additional hydrogen beyond the capacity of the phase one electrolyser. With hydrogen production infrastructure in place, removing the traditional investment/lead time barriers, it will enable the economic viability of both the flying school and the DroneHub to deliver a hydrogen future.

Initially, onboard power could be supplied via gaseous hydrogen. This could be supplied from on airport hydrogen production or local deliveries from other regional production hubs to store on site till use.

The northern Netherlands as a region has many active hydrogen projects and is seeing an increase in numbers of electrolyser each year. After the initial small-scale applications are up and running, technology for hydrogen aviation will most likely be at a TRL ready for deployment. A steady supply of hydrogen, likely via a pipeline network from one or multiple of these new sources, will need to connect to GRQ to enable this expansion of hydrogen aviation.

As the type and range of hydrogen aircraft increases, alongside the hydrogen storage infrastructure at the airport, hydrogen liquefaction and cryogenic storage of LHY will be required to replace kerosene on. Initial hydrogen aviation roll out will be most effective with interconnectivity of smaller airports. Regional airports that have the necessary hydrogen refuelling infrastructure will enable flights between these destinations. GRQ is in a great position to be a front runner for a small airport hydrogen hub. Airlines that wish to utilise early hydrogen aviation will be looking for flights to/from locations with green hydrogen refuelling infrastructure. GRQ expect this to provide a 'green hydrogen boost' and increase their passenger numbers.

Tallinn

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The Airport

Tallinn Airport (TLL) is the largest airport, in Estonia, located south of the capital city. The airport has gained popularity as the world's cosiest airport by repeatedly being chosen as an airport with the best service in Europe. In 2019, Tallinn Airport provided services to more than 3.26 million passengers and had a EUR 9.7 million operating profit.

Recently, AS Tallinn Airport (ASTA), who operate the airport, began implementing decarbonisation programmes across their airports portfolio which include Kuressaare, Kärdla, Pärnu, and Tartu airports and airfields in Kihnu and Ruhnu.

Furthermore, ASTA has become a member of the European Clean Hydrogen Alliance, indicating its positive approach towards hydrogen and willingness to be a first mover.

Solar

In 2020, ASTA began the construction of solar farms at all its owned airports with the long term goal of delivering all its electrical energy use. 0.3GWh/yr is generated today and this will increase to 1.3GWh/yr in 2021 and, by the end of 2024, production will reach 5GWh/yr, equating to a third of ASTA's annual electrical energy consumption.

These solar parks will enable a smoother transition to hydrogen-based aviation. Outsourced renewable energy will not be required for the initial production of green hydrogen at the small-scale.

Future Hydrogen Use

First investments in hydrogen infrastructure are planned to include an electrolyser with coupled storage to bolster the existing RES's reliability. Storing excess energy from the solar park as hydrogen can be an effective way of initially utilising hydrogen on a small scale. The hydrogen can be used either at a later date, feeding energy back to the airport's terminal via a fuel cell to help power the combined heat and power system. Once hydrogen becomes readily available, ASTA plans to begin refuelling fuel cell variants of airport ground vehicles, and be ready to refuel hydrogen aircraft upon their development.

With the small-scale hydrogen infrastructure set up. Scale up of hydrogen processes and applications would be the next step. Increasing the fleet of fuel cell ground vehicles, particularly heavy duty vehicles that are difficult to decarbonise through batteries. In addition, increasing usage of energy using stored hydrogen in times of low solar power output.

These changes most likely require the importing of hydrogen from an alternative production site, in addition to increased gaseous hydrogen storage on site. As the scaling-up occurs there will be a transfer from trucked to piped hydrogen systems.

As can be seen from the ENABLEH2 report, hydrogen powered turbines/engines are in the latter stages of development for use in commercial aircraft. Until their deployment, ASTA is also considering alternatives for decarbonising aviation. ASTA see batteries as offering some smaller, short range aircraft a potential solution. These may eventually be replaced by hydrogen as infrastructure develops and costs decrease.

The development of carbon neutral synfuels which can use existing propulsion engines may also allow for decarbonisation of flights before the hydrogen aircraft are ready. In future, a mix of solutions is likely to be deployed depending on aircraft range. Indeed, synfuels may offer the only future sustainable solution for longer range, inter-continental aircraft.

With the introduction of renewable energy production at its airports, ASTA is making the first step. Its planned hydrogen investments allow it to position for future hydrogen and fully electric flying. Synfuels will also be part of the mix via longer, off-airport supply chains.

Over time, ASTA expect the supply of gaseous hydrogen will increase from off-airport facilities. This will be transferred via a pipeline, and will likely be integrated with a liquefaction plant on site. Hydrogen is needed in its liquid form to increase on aircraft storage capacities. Obviously, this comes with its own set of costs and challenges. However, ASTA agree with the ENABLEH2 partners in liquid hydrogen playing a significant part in the future of sustainable aviation.

TLL as a Future Hydrogen Hub

To achieve these challenges, collaboration will be essential. Locally, just less than 3km away, the Port of Tallinn is making large scale plans to become the key hydrogen port of the Baltic Sea, by investing €500 million. Much of the planned hydrogen infrastructure can be utilised by both the port and the airport and enabling both to benefit in the longer term.

The port looks to import and store hydrogen until the production of hydrogen in Estonia exceeds its needs, when the process could be reversed and exporting could begin.

ASTA anticipate that these global scale hydrogen investments will result in many hydrogen applications making the region a low-cost hydrogen centre/hub, which will, in turn, enable the development of further downstream sectors, including aviation. Its planned hydrogen investments allow it to position for future hydrogen and fully electric flying. Synfuels will also be part of the mix via longer, off-airport supply chains.

Preparing for Hydrogen Aviation

Having strong ground infrastructure and hydrogen availability means that Xfly, one of the most innovative airline operators in the region, is able to proceed with their ambitious plans for converting a ATR72-600 to hydrogen by 2030 serving as a blueprint and benchmark for airplane retrofitting. In 2021, the first preparations have also been taken to establish cooperation with early aviation hydrogen movers such as ZeroAvia.

With the already strong leadership ASTA has shown with its solar installations, and planned quick scale-up of investment, Tallinn is shaping up to be a committed first-mover for aviation decarbonisation. ASTA expect to maintain the momentum to deliver and adapt its goals and solutions as more hydrogen technology becomes more readily available.

Additional Information

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Glossary

AIC	Aviation Induced Cloudiness
BWB	Blended Wing Body
CO_2	Carbon Dioxide
CORSIA	Carbon Offsetting and Reduction Scheme
CCUS	Carbon Capture Utilisation and Storage
DAC	Direct Air Capture
EU	European Union
GH_2	Gaseous Hydrogen
GHG	Greenhouse Gas
GW	Gigawatt
H_2	Hydrogen
HVDC	High-Voltage Direct Current
IAB	Industry Advisory Board
km	Kilometre
kg	Kilogram
LH_2	Liquid Hydrogen

LNG	Liquid Natural Gas
LOHC	Liquid Organic Hydrogen Carriers
LTO	Landing and Take-Off
MW	Megawatt
NH_3	Ammonia
NOx	Nitrogen Oxides
RE	Renewable Energy
RES	Renewable Energy System
R&D	Research and Development
SAF	Sustainable Aviation Fuel
SME	Small/Medium Enterprise
TeDO	Turbo-electric Distribution Propulsion
TRL	Technology Readiness Level
UK	United Kingdom
US	United States
USD	United States Dollar

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