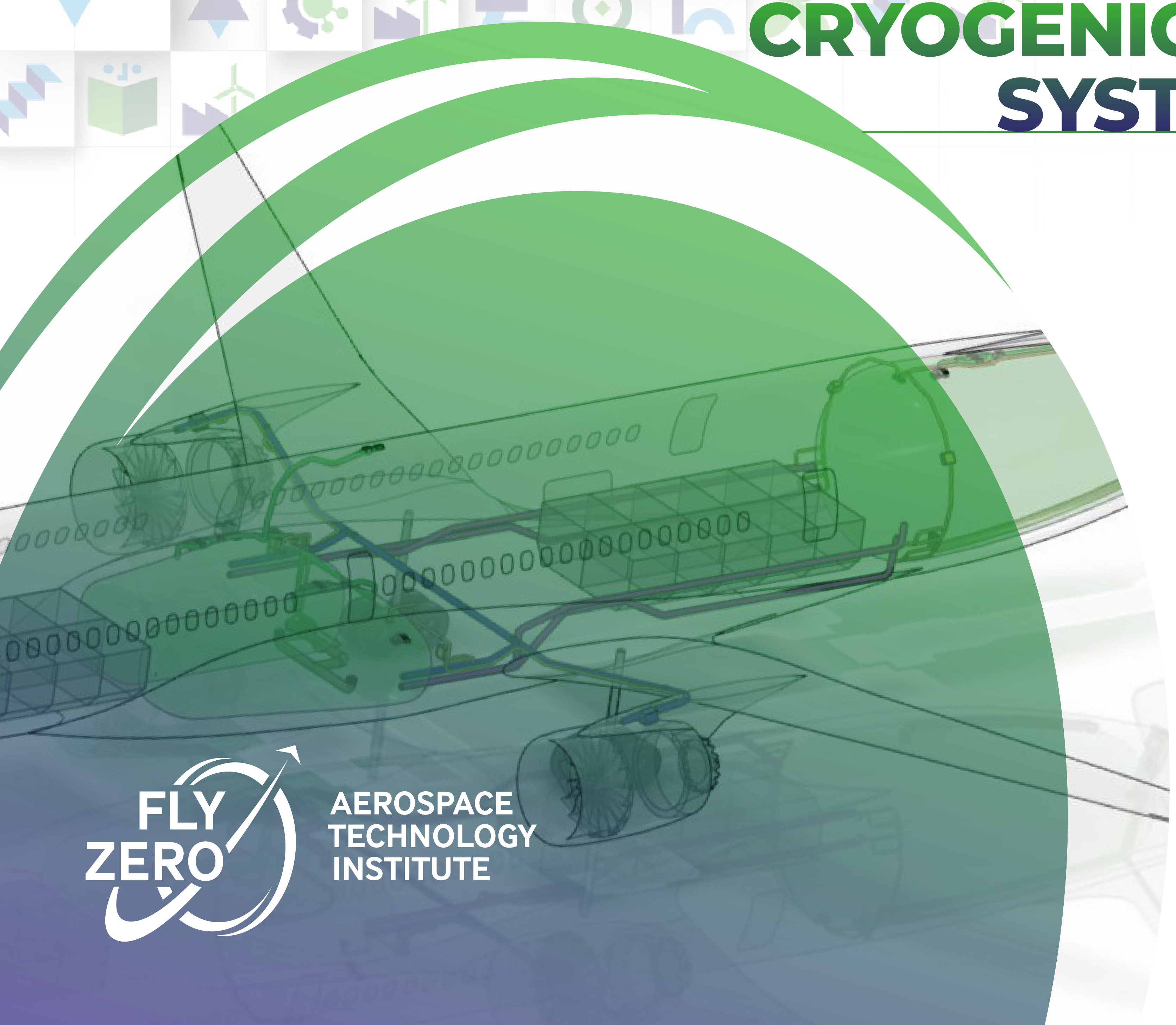
CRYOGENIC HYDROGEN FUEL SYSTEM AND STORAGE

Roadmap Report



FLY ZERO

AEROSPACE TECHNOLOGY INSTITUTE

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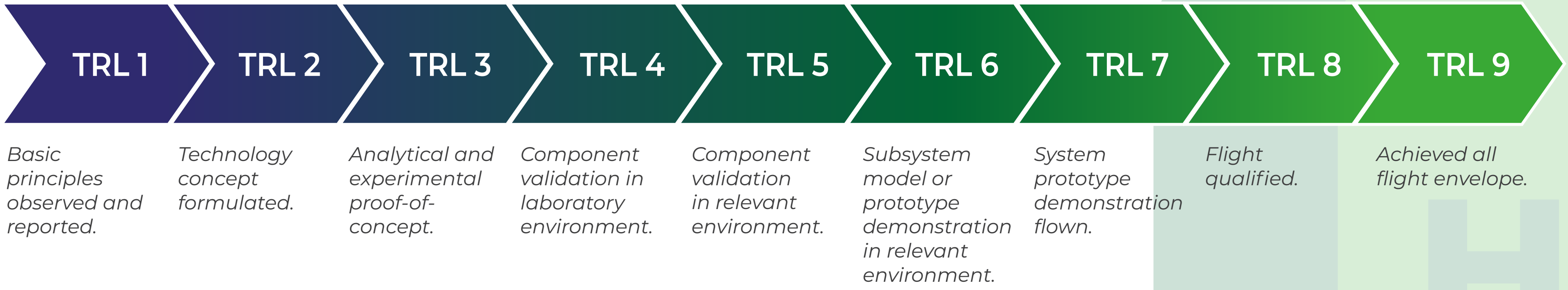
KEY

Essential Development	*Development required to bring roadmap technology to market.*
Competitive Development	*Development which delivers performance improvement.*
Technology Mature	*Transition to further integration and production readiness.*
Essential Enabler	*Supporting activity or infrastructure to enable technology development*
Competitive Enabler	*Supporting activity or infrastructure to enable technology development*
Technology Mature	*Transition to further integration and production readiness.*



TRL 1	TRL 2	TRL 3	TRL 4	TRL 5	TRL 6	TRL 7	TRL 8	TRL 9
Basic principles observed and reported.	*Technology concept formulated.*	*Analytical and experimental proof-of-concept.*	*Component validation in laboratory environment.*	*Component validation in relevant environment.*	*Subsystem model or prototype demonstration in relevant environment.*	*System prototype demonstration flown.*	*Flight qualified.*	*Achieved all flight envelope.*

Figure 1 – Technology has been assessed against the NASA Technology Readiness Level (TRL) scale

OVERVIEW: CRYOGENIC HYDROGEN FUEL SYSTEM AND STORAGE

This cryogenic hydrogen fuel system and storage roadmap report discusses the technologies required to support liquid hydrogen as the fuel of the future for commercial aircraft and their route to a 2026 Technology Readiness Level 6 (subsystem model or prototype demonstration on ground).

The roadmap includes the following essential enablers for these technologies:

- Certification, Standards, Testing, Modelling Capability, Inspection & Maintenance, Material Qualification together with the supporting manufacturing and processing technologies that might be required with the introduction of new or improved materials.

Fuel System technologies included are:

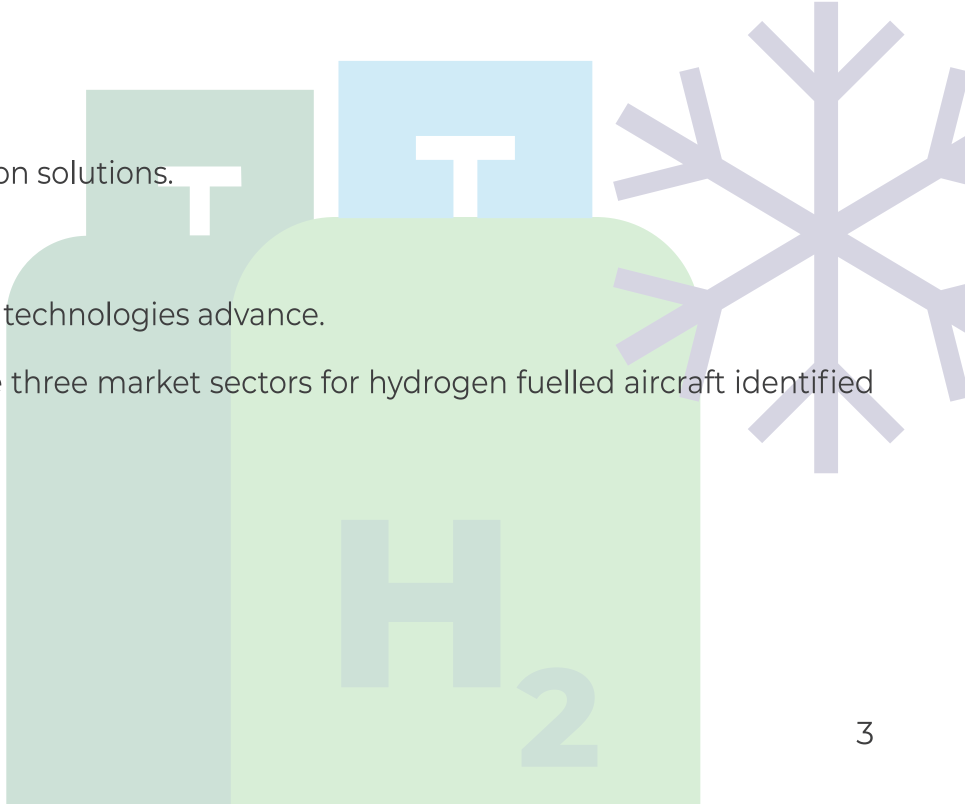
- Engine Feed System Pumps & Valves, Pressurisation, Temperature & Venting Technologies, Refuelling / Defuelling, Control & Indication, Leak Detection & Management and Pipe & Sealing Technologies.

Storage Tank technologies included are:

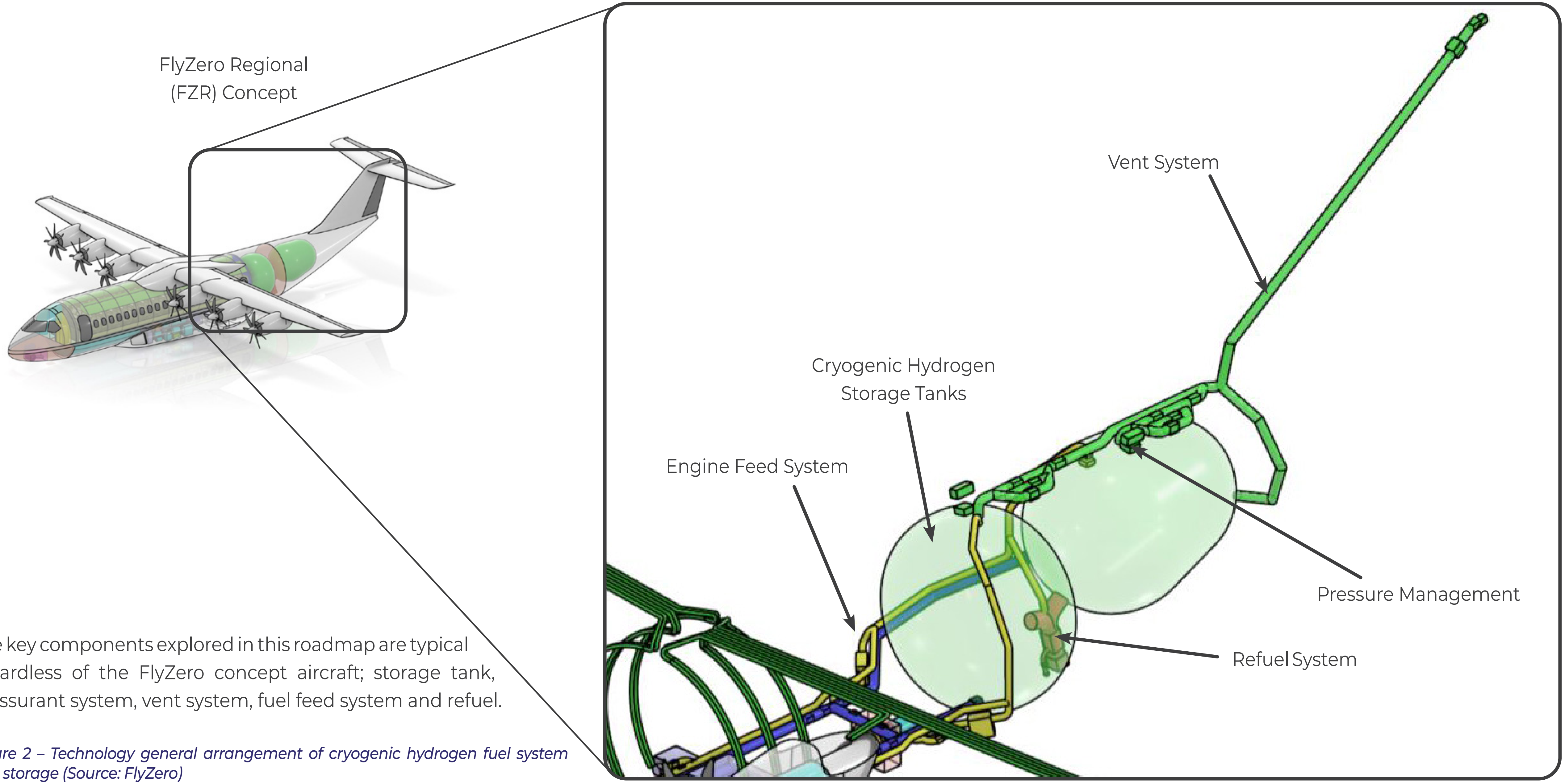
- Metallic & Composite Pressure Vessels, Insulation Architectures and Materials, Thin Walled Liners and Airframe Integration solutions.

Technology indicators are ambitious targets that industry could expect to achieve in a competitive market environment as technologies advance.

This roadmap has indicators for both the Fuel System and the Fuel Storage technologies. The indicators are aligned to the three market sectors for hydrogen fuelled aircraft identified for FlyZero of regional, narrowbody and midsize aircraft.



TECHNOLOGY GENERAL ARRANGEMENT



The key components explored in this roadmap are typical regardless of the FlyZero concept aircraft; storage tank, pressurant system, vent system, fuel feed system and refuel.

Figure 2 – Technology general arrangement of cryogenic hydrogen fuel system and storage (Source: FlyZero)

TECHNOLOGY INDICATORS

Regional

		TRL6	2026	2030	2050
Total Gravimetric Efficiency (%)			47%	61%	64%
Gravimetric Efficiency of Tank (%)		**Aft Tank 1 (Vacuum)**	57%	75%	75%
		Aft Tank 2 (Vacuum)	54%	72%	72%
Maintenance Intervals		Flight Cycles	17,000	43,500	70,000
		Flight Hours	17,000	43,500	70,000

Narrowbody

		TRL6	2026	2030	2050
Total Gravimetric Efficiency (%)			58%	66%	69%
Gravimetric Efficiency of Tank (%)		**Aft Tank 1 (Foam)**	67%	76%	77%
		Aft Tank 2 (Foam)	63%	72%	73%
Maintenance Intervals		Flight Cycles	20,000	40,000	60,000
		Flight Hours	10,000	80,500	120,000

Midsize

		TRL6	2026	2030	2050
Total Gravimetric Efficiency (%)			58%	72%	75%
Gravimetric Efficiency of Tank (%)		**Delta Tank 1 (Foam)**	45%	65%	66%
		Aft Tank 2 (Foam)	82%	89%	90%
Maintenance Intervals		Flight Cycles	15,000	27,500	40,000
		Flight Hours	45,000	87,500	130,000

TECHNOLOGY INDICATORS

Total Gravimetric Efficiency (%)

The efficiency of the cryogenic hydrogen fuel system and storage is calculated as:

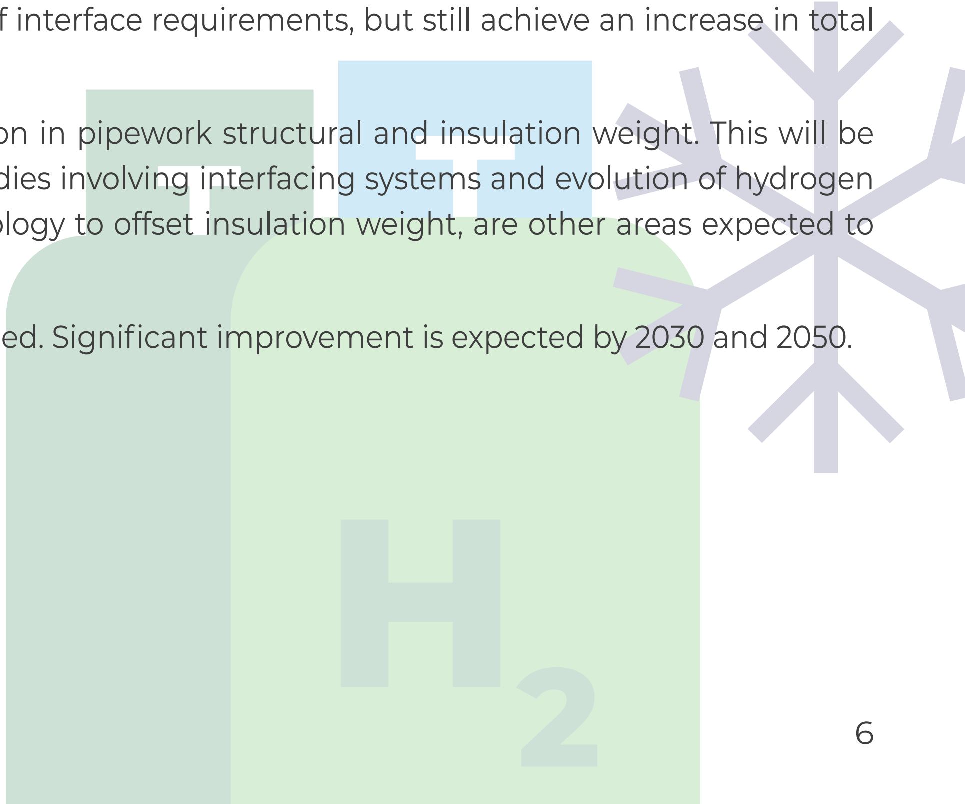
$$\text{Total Gravimetric Efficiency} = \text{Mass of Usable Fuel} \div (\text{Mass of Useable Fuel} + \text{Fuel System Mass} + \text{Empty Tank Mass})$$

The fuel system mass is considered to include fuel system equipment, pipework, and associated on-board hydrogen active cooling technology, if fitted.

As the technologies improves, the associated overall mass is expected to reduce resulting in increased gravimetric efficiency. However, the fuel system mass is significantly driven by the selected aircraft architecture as the pipework lengths between interfaces, the tank and propulsion system interfaces and pumping arrangements are key weight drivers for the fuel system. Consequently, fuel system weight could potentially increase in future aircraft concepts due to the evolution of interface requirements, but still achieve an increase in total gravimetric efficiency if the associated tank weight reduction is greater. Fuel tank technology is discussed further below.

For a given aircraft concept, the most significant fuel system weight saving is expected to be achieved through reduction in pipework structural and insulation weight. This will be achieved via material technology and the optimisation of associated thermal and leaked requirements through trade-studies involving interfacing systems and evolution of hydrogen aircraft operational requirements. Pumping technology, and the potential introduction of on-board active cooling technology to offset insulation weight, are other areas expected to enable significant improvement in total gravimetric efficiency.

The FlyZero team has estimated the 2026 total gravimetric efficiency to be 47% - 58% for the range of concept aircraft studied. Significant improvement is expected by 2030 and 2050.



TECHNOLOGY INDICATORS

Gravimetric Efficiency of Tank (%)

The efficiency of hydrogen storage tanks has been measured in different ways on various programs, but for FlyZero it is calculated as:

$$Gravimetric\ Efficiency = Mass\ of\ Usable\ Fuel \div (Mass\ of\ Useable\ Fuel + Empty\ Tank\ Mass)$$

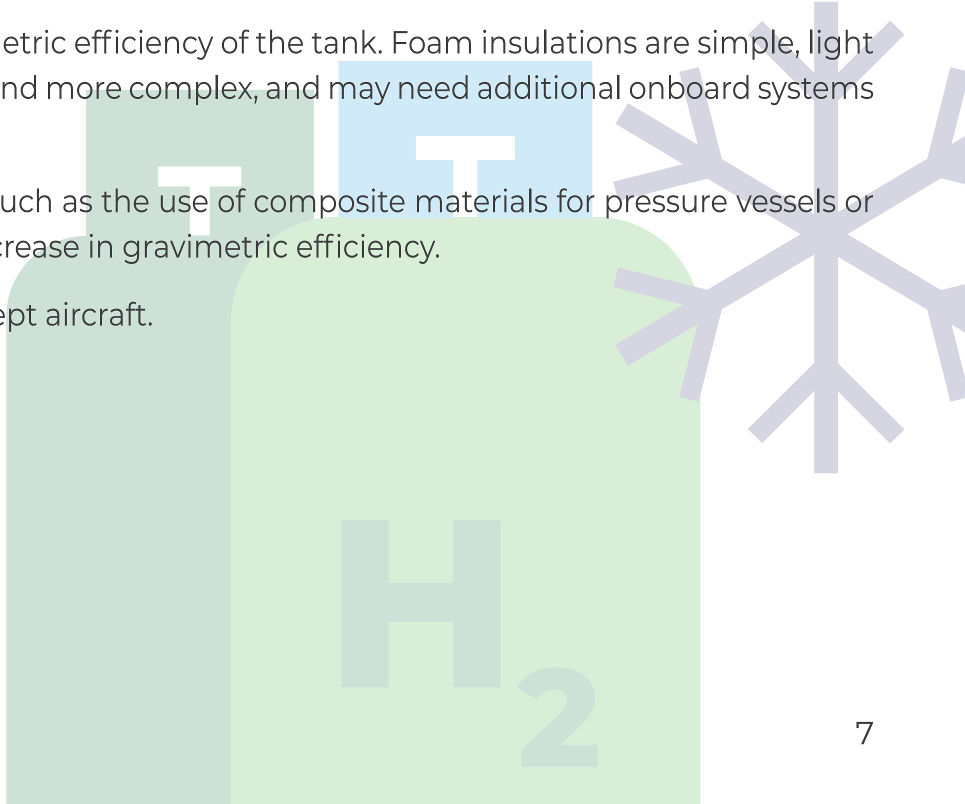
It is significant to note that this measure considers tank mass alone and does not included equipment such as pumps, sensors, mating pipework or attachments.

The size and shape of cryogenic fuel tanks are important factors in their gravimetric efficiency. For maximum gravimetric efficiency, the number of tanks in an aircraft should be minimised and their geometries should be close to spherical or low aspect ratio cylinders for thermal and structural reasons.

The thermal insulation architecture can have a significant effect on, not only the tank thermal performance, but the gravimetric efficiency of the tank. Foam insulations are simple, light solutions where as vacuum insulations (either with or without multi-layer insulation) are thermally superior but are heavier and more complex, and may need additional onboard systems to maintain the vacuum.

As technologies improve, the mass of the empty tank can reasonably be expected to reduce. New material technologies, such as the use of composite materials for pressure vessels or lower density more thermally efficient insulation materials, will provide a reduction to the tank mass with a subsequent increase in gravimetric efficiency.

The 2026 targets are estimates by the FlyZero team when evaluating the tank gravimetric efficiencies for the FlyZero concept aircraft.



TECHNOLOGY INDICATORS

Gravimetric Efficiency of Tank (%) for the FlyZero concepts

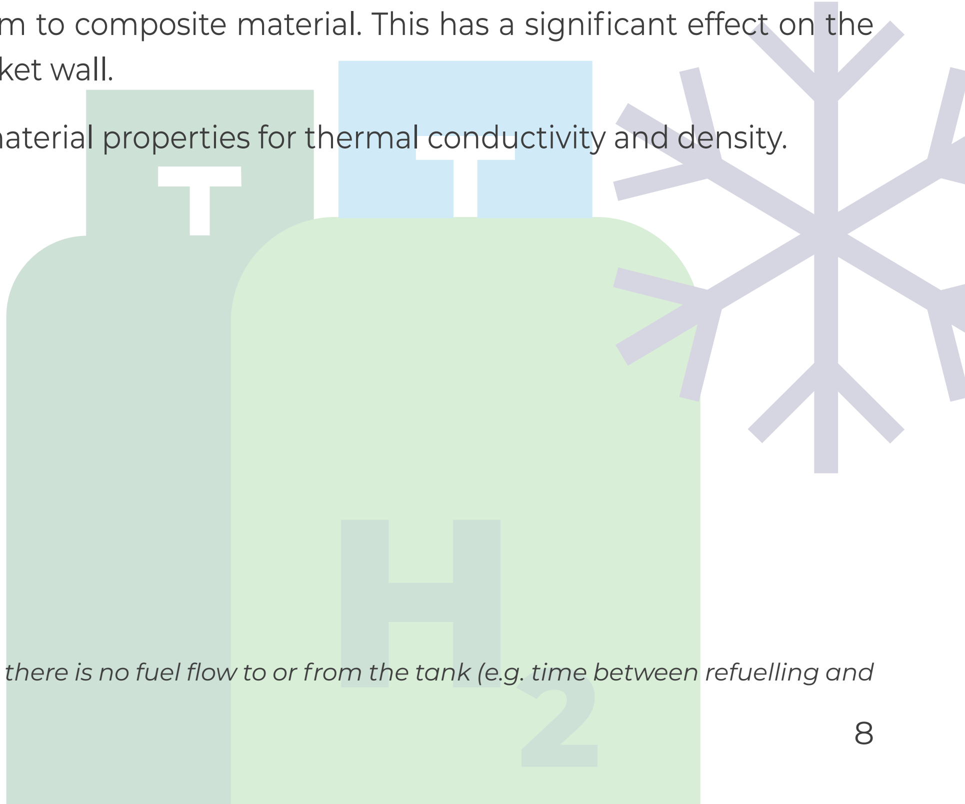
When evaluating the smaller tank sizes in the FlyZero regional concept the design requirements necessitate a vacuum insulated tank resulting in a heavy structure and consequently a low gravimetric efficiency value.

The larger tank sizes of the FlyZero narrowbody and midsize (aft tank) concepts enabled the use of foam insulation. For similarly shaped tanks that are close to cylindrical, gravimetric efficiencies of 67% for the narrowbody and 82% for the midsize concept can be realised. The higher gravimetric efficiency of the midsize tank is attributable to the larger tank volume, the superior surface to area ratio and less stringent heat leak requirements*. This allows a thinner and therefore lighter insulation layer.

The midsize concept also has two forward delta tanks. These have been shaped to fit below the cabin floor forward of the wing root. This unconventional boxed-in form requires a thicker pressure vessel wall and supporting internal structure, increasing the tank mass. Furthermore, the area to volume ratio is less efficient than a conventional shape reducing the gravimetric efficiency for these tanks to 45%.

The improvement in the gravimetric efficiency from 2026 to 2030 timescale is achieved by the change from an aluminium to composite material. This has a significant effect on the regional vacuum insulated tank with mass improvements on both the inner pressure vessel wall and the outer vacuum jacket wall.

Subsequent improvements will be achieved through to the 2050 timescale for foam insulated tanks by improvements in material properties for thermal conductivity and density.



** The heat leak from the tank is driven by dormancy time requirements. Dormancy time is the time to reach a given pressure during a period when there is no fuel flow to or from the tank (e.g. time between refuelling and next flight).*

TECHNOLOGY INDICATORS

Maintenance Intervals (Flight Cycles - FC / Flight Hours - FH)

Initially components and tanks should achieve a minimum life of an aircraft heavy maintenance interval (D-Check) to minimise maintenance burden and maximise aircraft availability.

- **Regional** - 6 years / 17,000 FC / 17,000 FH
- **Narrowbody** - 8 years / 20,000 FC / 40,000 FH
- **Midsize** - 8 years / 15,000 FC / 45,000 FH

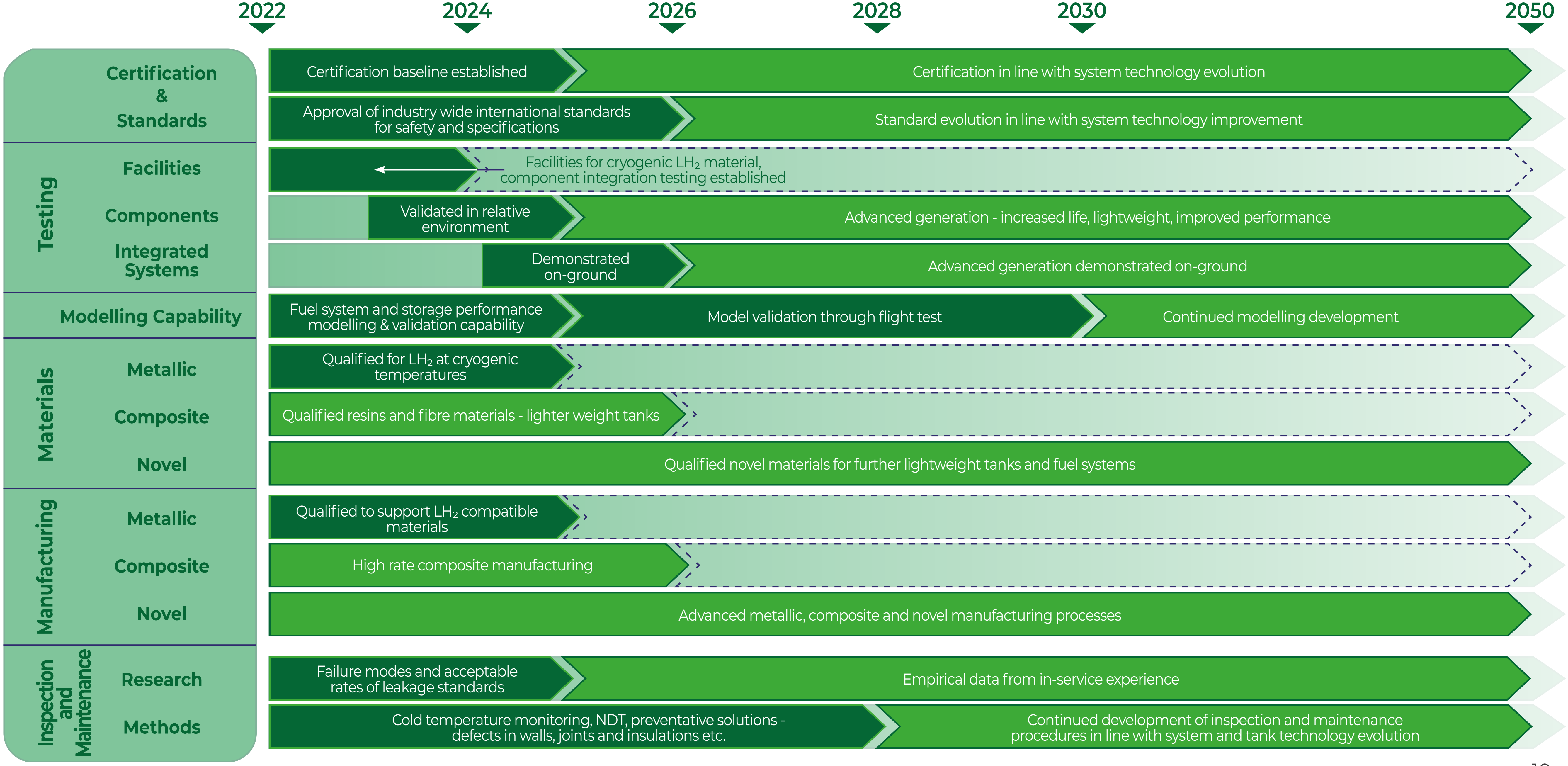
As confidence grows in predicting failure methods and rates through testing and in-service experience, maintenance procedures can be developed and scheduling periods increased with the ultimate goal of manufacturing components and tanks that achieve comparable flight cycle and flight hours targets of the aircraft over the 25 year life.

- **Regional** - 25 years / 70,000 FC / 70,000 FH
- **Narrowbody** - 25 years / 60,000 FC / 120,000 FH
- **Midsize** - 25 years / 40,000 FC / 130,000 FH

Maintenance intervals are aspirational targets. These targets may need to be revised as the knowledge of the behaviour of materials and systems exposed to hydrogen improves.

CRYOGENIC HYDROGEN FUEL SYSTEM & STORAGE ROADMAP

Key
- Essential Enabler
- Competitor Enabler
- Technology Mature



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

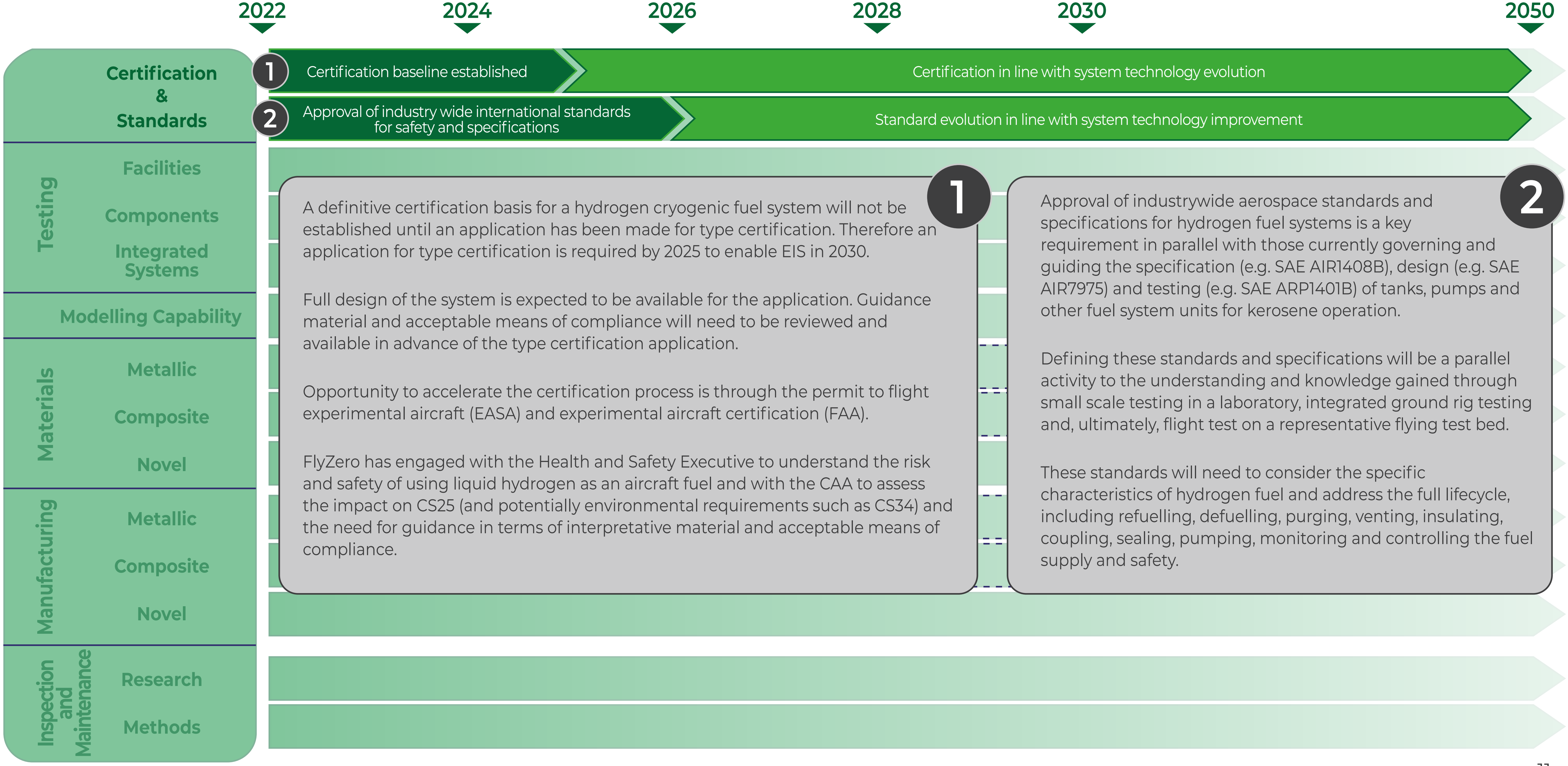
Materials
- **Metallic**: Qualified for LH_2 at cryogenic temperatures
- **Composite**: Qualified resins and fibre materials - lighter weight tanks
- **Novel**: Qualified novel materials for further lightweight tanks and fuel systems

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

CRYOGENIC HYDROGEN FUEL SYSTEM & STORAGE ROADMAP

Key
- Essential Enabler
- Competitor Enabler
- Technology Mature



1

A definitive certification basis for a hydrogen cryogenic fuel system will not be established until an application has been made for type certification. Therefore an application for type certification is required by 2025 to enable EIS in 2030.

Full design of the system is expected to be available for the application. Guidance material and acceptable means of compliance will need to be reviewed and available in advance of the type certification application.

Opportunity to accelerate the certification process is through the permit to flight experimental aircraft (EASA) and experimental aircraft certification (FAA).

FlyZero has engaged with the Health and Safety Executive to understand the risk and safety of using liquid hydrogen as an aircraft fuel and with the CAA to assess the impact on CS25 (and potentially environmental requirements such as CS34) and the need for guidance in terms of interpretative material and acceptable means of compliance.

2

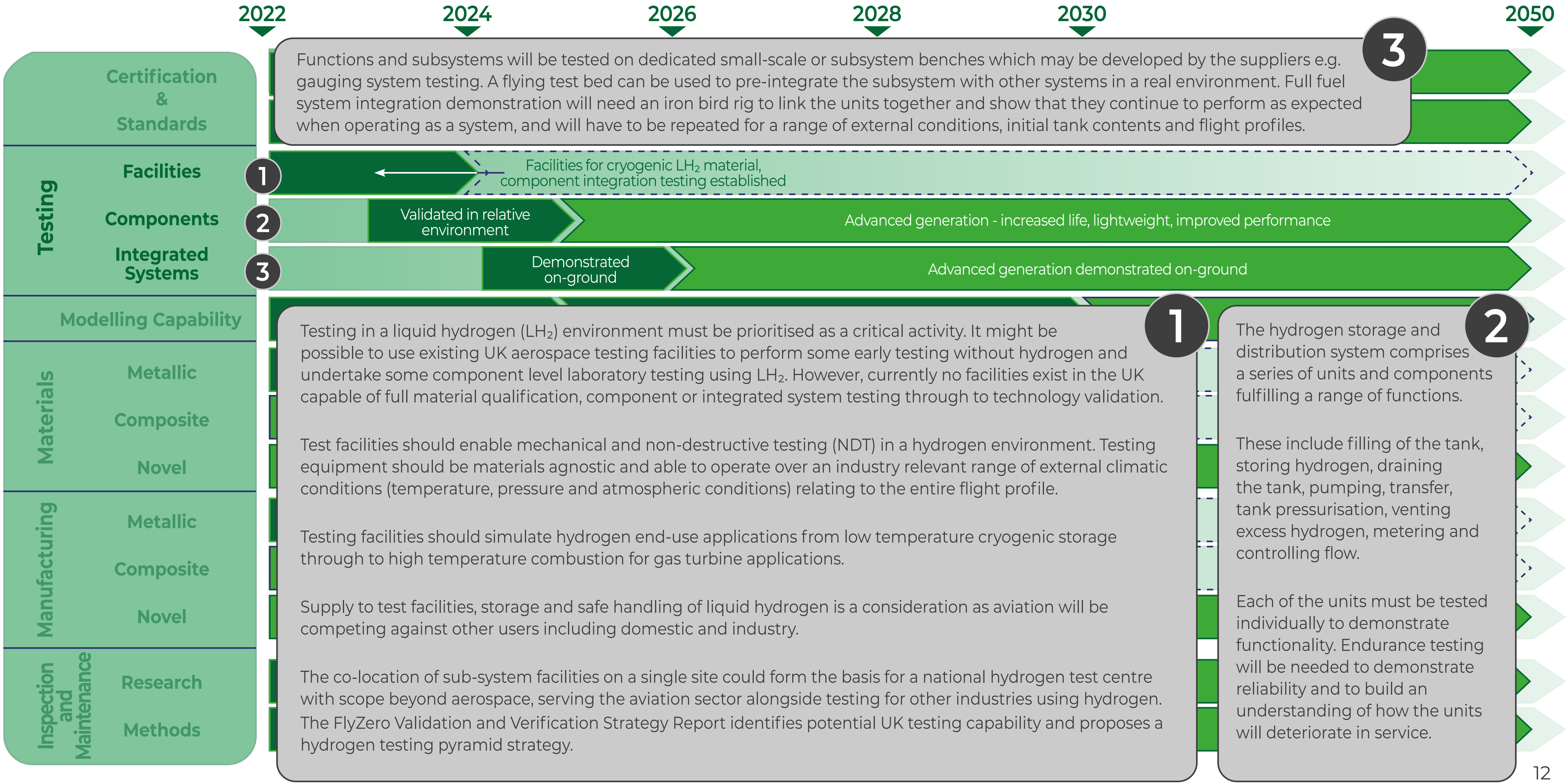
Approval of industrywide aerospace standards and specifications for hydrogen fuel systems is a key requirement in parallel with those currently governing and guiding the specification (e.g. SAE AIR1408B), design (e.g. SAE AIR7975) and testing (e.g. SAE ARP1401B) of tanks, pumps and other fuel system units for kerosene operation.

Defining these standards and specifications will be a parallel activity to the understanding and knowledge gained through small scale testing in a laboratory, integrated ground rig testing and, ultimately, flight test on a representative flying test bed.

These standards will need to consider the specific characteristics of hydrogen fuel and address the full lifecycle, including refuelling, defuelling, purging, venting, insulating, coupling, sealing, pumping, monitoring and controlling the fuel supply and safety.

CRYOGENIC HYDROGEN FUEL SYSTEM & STORAGE ROADMAP

Key Essential Enabler | Competitor Enabler | Technology Mature



2022 2024 2026 2028 2030 2050

Certification & Standards

Testing: Facilities ①, Components ②, Integrated Systems ③

Modelling Capability

Materials: Metallic, Composite, Novel

Manufacturing: Metallic, Composite, Novel

Inspection and Maintenance: Research, Methods

Facilities for cryogenic LH_2 material, component integration testing established

Validated in relative environment

Advanced generation - increased life, lightweight, improved performance

Demonstrated on-ground

Advanced generation demonstrated on-ground

③ Functions and subsystems will be tested on dedicated small-scale or subsystem benches which may be developed by the suppliers e.g. gauging system testing. A flying test bed can be used to pre-integrate the subsystem with other systems in a real environment. Full fuel system integration demonstration will need an iron bird rig to link the units together and show that they continue to perform as expected when operating as a system, and will have to be repeated for a range of external conditions, initial tank contents and flight profiles.

① Testing in a liquid hydrogen (LH_2) environment must be prioritised as a critical activity. It might be possible to use existing UK aerospace testing facilities to perform some early testing without hydrogen and undertake some component level laboratory testing using LH_2. However, currently no facilities exist in the UK capable of full material qualification, component or integrated system testing through to technology validation.

Test facilities should enable mechanical and non-destructive testing (NDT) in a hydrogen environment. Testing equipment should be materials agnostic and able to operate over an industry relevant range of external climatic conditions (temperature, pressure and atmospheric conditions) relating to the entire flight profile.

Testing facilities should simulate hydrogen end-use applications from low temperature cryogenic storage through to high temperature combustion for gas turbine applications.

Supply to test facilities, storage and safe handling of liquid hydrogen is a consideration as aviation will be competing against other users including domestic and industry.

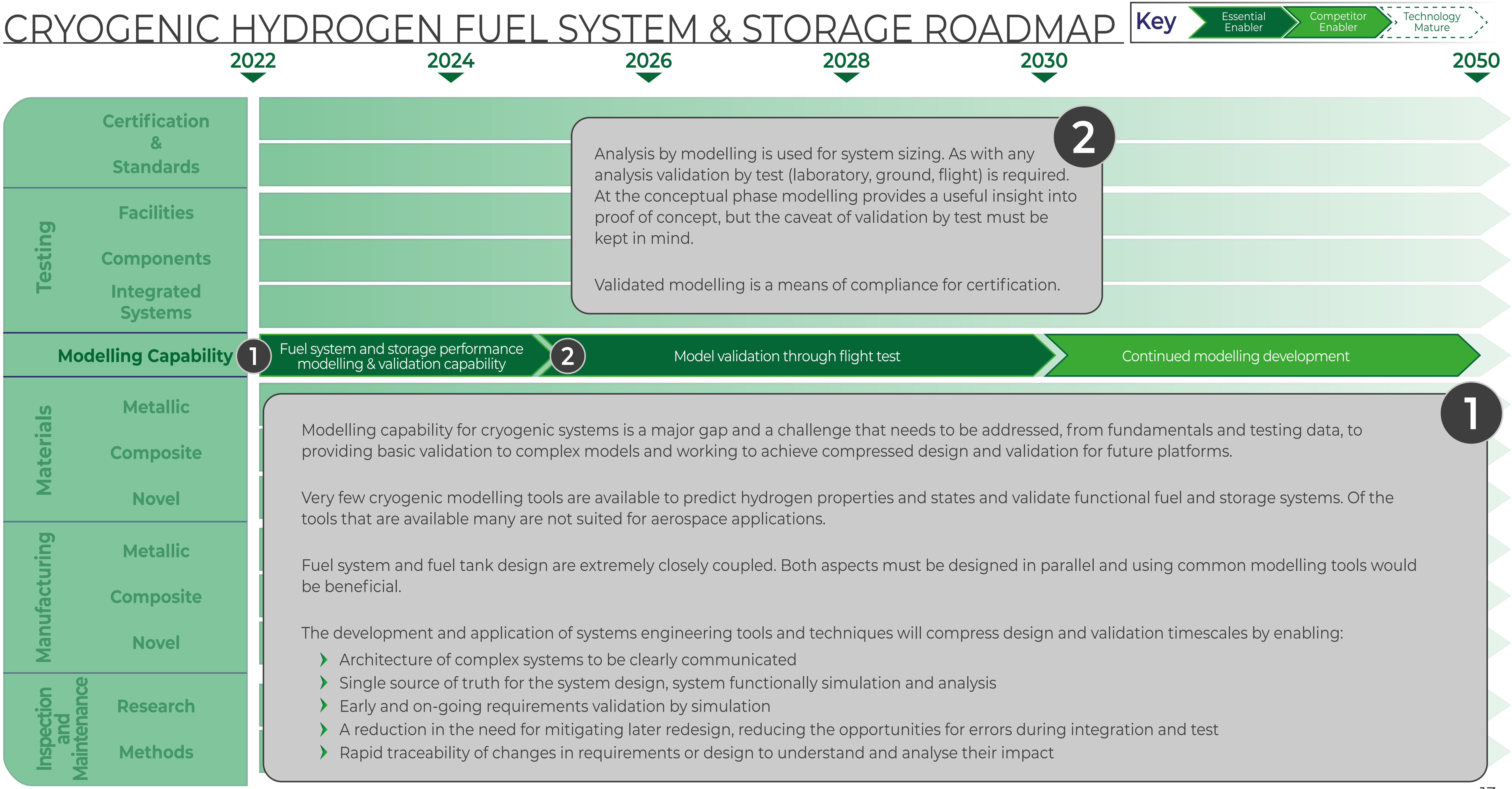
The co-location of sub-system facilities on a single site could form the basis for a national hydrogen test centre with scope beyond aerospace, serving the aviation sector alongside testing for other industries using hydrogen. The FlyZero Validation and Verification Strategy Report identifies potential UK testing capability and proposes a hydrogen testing pyramid strategy.

② The hydrogen storage and distribution system comprises a series of units and components fulfilling a range of functions.

These include filling of the tank, storing hydrogen, draining the tank, pumping, transfer, tank pressurisation, venting excess hydrogen, metering and controlling flow.

Each of the units must be tested individually to demonstrate functionality. Endurance testing will be needed to demonstrate reliability and to build an understanding of how the units will deteriorate in service.

CRYOGENIC HYDROGEN FUEL SYSTEM & STORAGE ROADMAP



2

Analysis by modelling is used for system sizing. As with any analysis validation by test (laboratory, ground, flight) is required. At the conceptual phase modelling provides a useful insight into proof of concept, but the caveat of validation by test must be kept in mind.

Validated modelling is a means of compliance for certification.

1

Modelling capability for cryogenic systems is a major gap and a challenge that needs to be addressed, from fundamentals and testing data, to providing basic validation to complex models and working to achieve compressed design and validation for future platforms.

Very few cryogenic modelling tools are available to predict hydrogen properties and states and validate functional fuel and storage systems. Of the tools that are available many are not suited for aerospace applications.

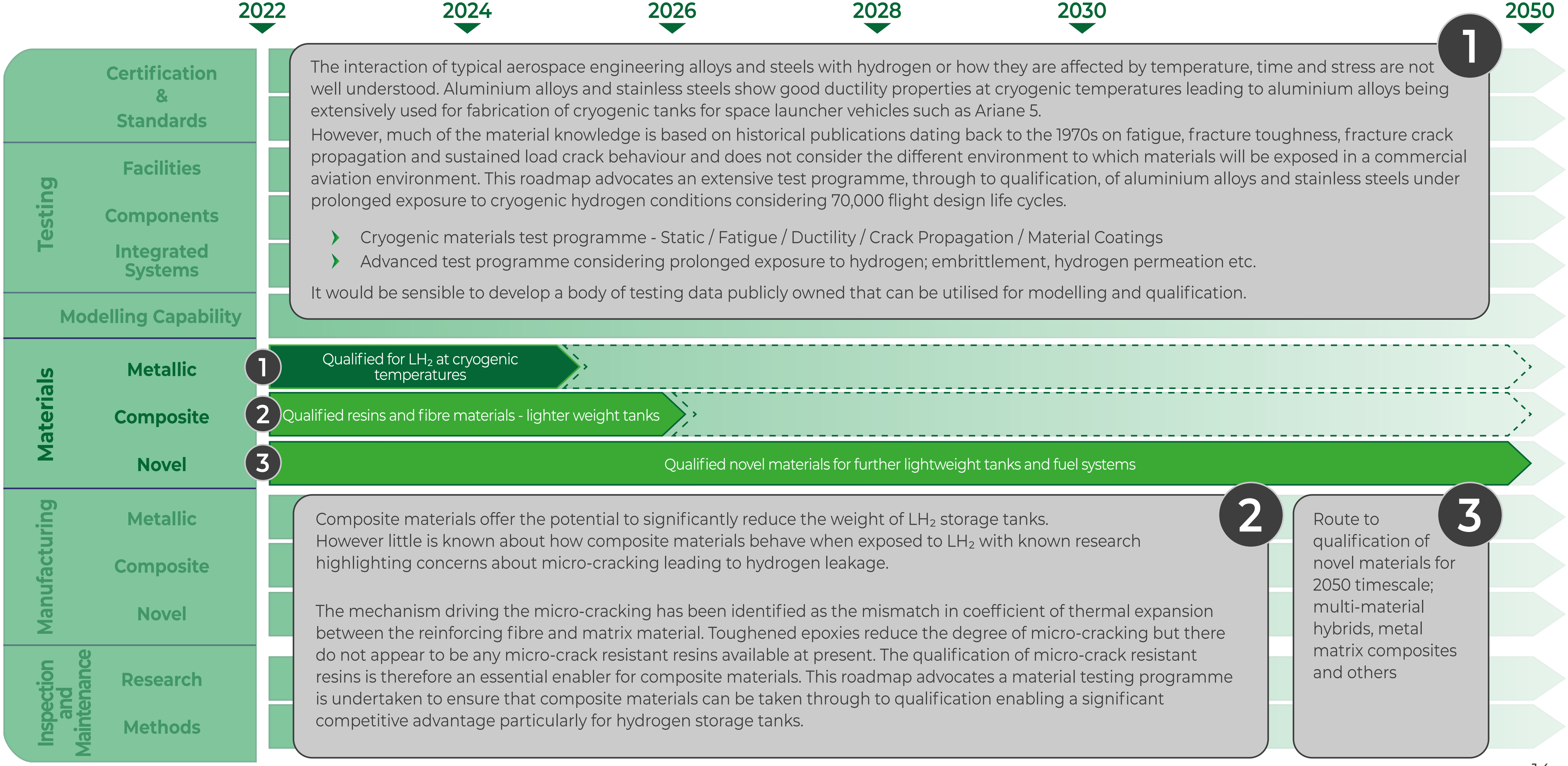
Fuel system and fuel tank design are extremely closely coupled. Both aspects must be designed in parallel and using common modelling tools would be beneficial.

The development and application of systems engineering tools and techniques will compress design and validation timescales by enabling:

- Architecture of complex systems to be clearly communicated
- Single source of truth for the system design, system functionally simulation and analysis
- Early and on-going requirements validation by simulation
- A reduction in the need for mitigating later redesign, reducing the opportunities for errors during integration and test
- Rapid traceability of changes in requirements or design to understand and analyse their impact

CRYOGENIC HYDROGEN FUEL SYSTEM & STORAGE ROADMAP

Key Essential Enabler | Competitor Enabler | Technology Mature



1 Qualified for LH_2 at cryogenic temperatures

2 Qualified resins and fibre materials - lighter weight tanks

3 Qualified novel materials for further lightweight tanks and fuel systems

1

The interaction of typical aerospace engineering alloys and steels with hydrogen or how they are affected by temperature, time and stress are not well understood. Aluminium alloys and stainless steels show good ductility properties at cryogenic temperatures leading to aluminium alloys being extensively used for fabrication of cryogenic tanks for space launcher vehicles such as Ariane 5.

However, much of the material knowledge is based on historical publications dating back to the 1970s on fatigue, fracture toughness, fracture crack propagation and sustained load crack behaviour and does not consider the different environment to which materials will be exposed in a commercial aviation environment. This roadmap advocates an extensive test programme, through to qualification, of aluminium alloys and stainless steels under prolonged exposure to cryogenic hydrogen conditions considering 70,000 flight design life cycles.

- Cryogenic materials test programme - Static / Fatigue / Ductility / Crack Propagation / Material Coatings
- Advanced test programme considering prolonged exposure to hydrogen; embrittlement, hydrogen permeation etc.

It would be sensible to develop a body of testing data publicly owned that can be utilised for modelling and qualification.

2

Composite materials offer the potential to significantly reduce the weight of LH_2 storage tanks.
However little is known about how composite materials behave when exposed to LH_2 with known research highlighting concerns about micro-cracking leading to hydrogen leakage.

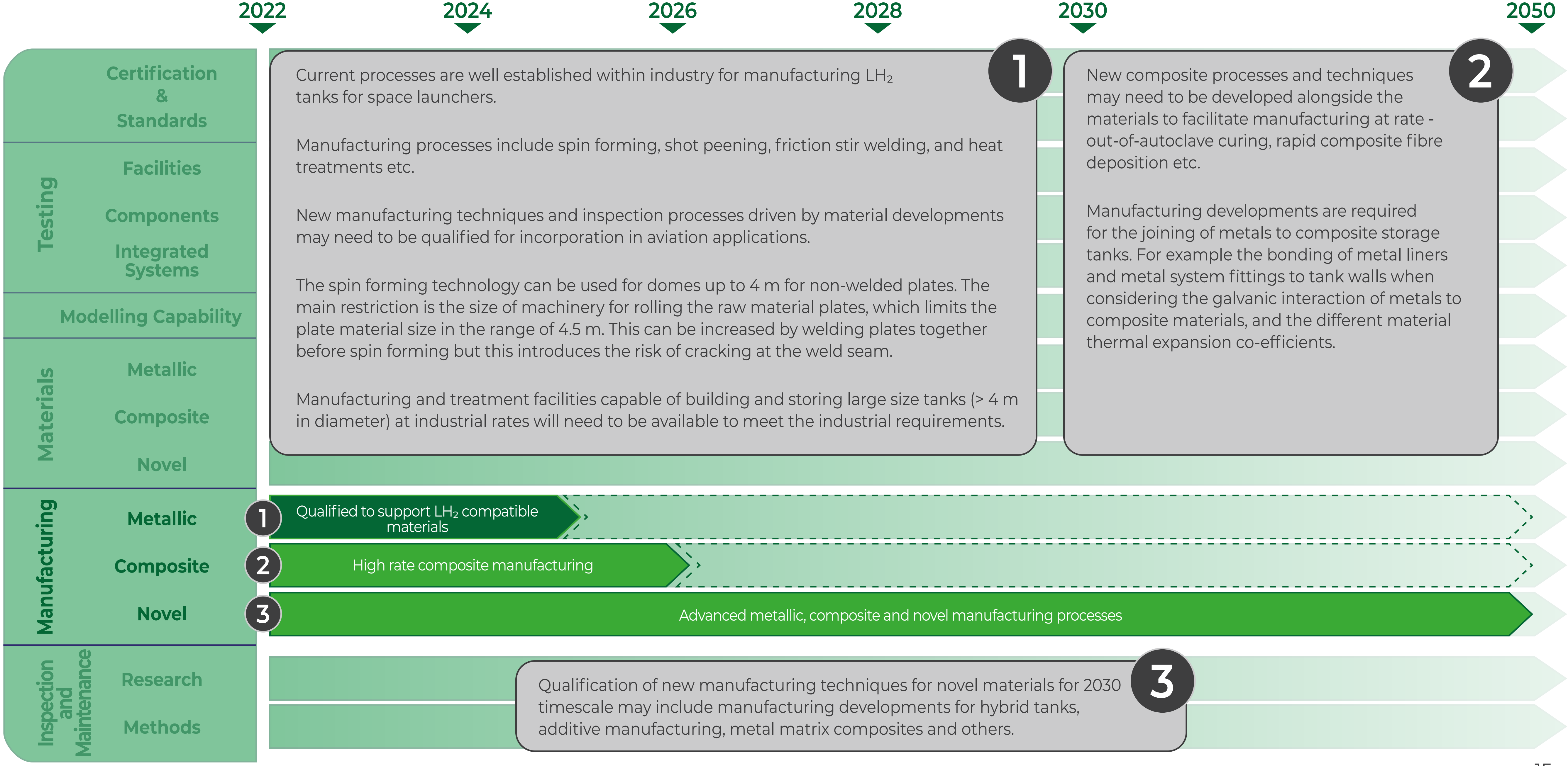
The mechanism driving the micro-cracking has been identified as the mismatch in coefficient of thermal expansion between the reinforcing fibre and matrix material. Toughened epoxies reduce the degree of micro-cracking but there do not appear to be any micro-crack resistant resins available at present. The qualification of micro-crack resistant resins is therefore an essential enabler for composite materials. This roadmap advocates a material testing programme is undertaken to ensure that composite materials can be taken through to qualification enabling a significant competitive advantage particularly for hydrogen storage tanks.

3

Route to qualification of novel materials for 2050 timescale; multi-material hybrids, metal matrix composites and others

CRYOGENIC HYDROGEN FUEL SYSTEM & STORAGE ROADMAP

Key Essential Enabler | Competitor Enabler | Technology Mature



Current processes are well established within industry for manufacturing LH_2 tanks for space launchers.

Manufacturing processes include spin forming, shot peening, friction stir welding, and heat treatments etc.

New manufacturing techniques and inspection processes driven by material developments may need to be qualified for incorporation in aviation applications.

The spin forming technology can be used for domes up to 4 m for non-welded plates. The main restriction is the size of machinery for rolling the raw material plates, which limits the plate material size in the range of 4.5 m. This can be increased by welding plates together before spin forming but this introduces the risk of cracking at the weld seam.

Manufacturing and treatment facilities capable of building and storing large size tanks (> 4 m in diameter) at industrial rates will need to be available to meet the industrial requirements.

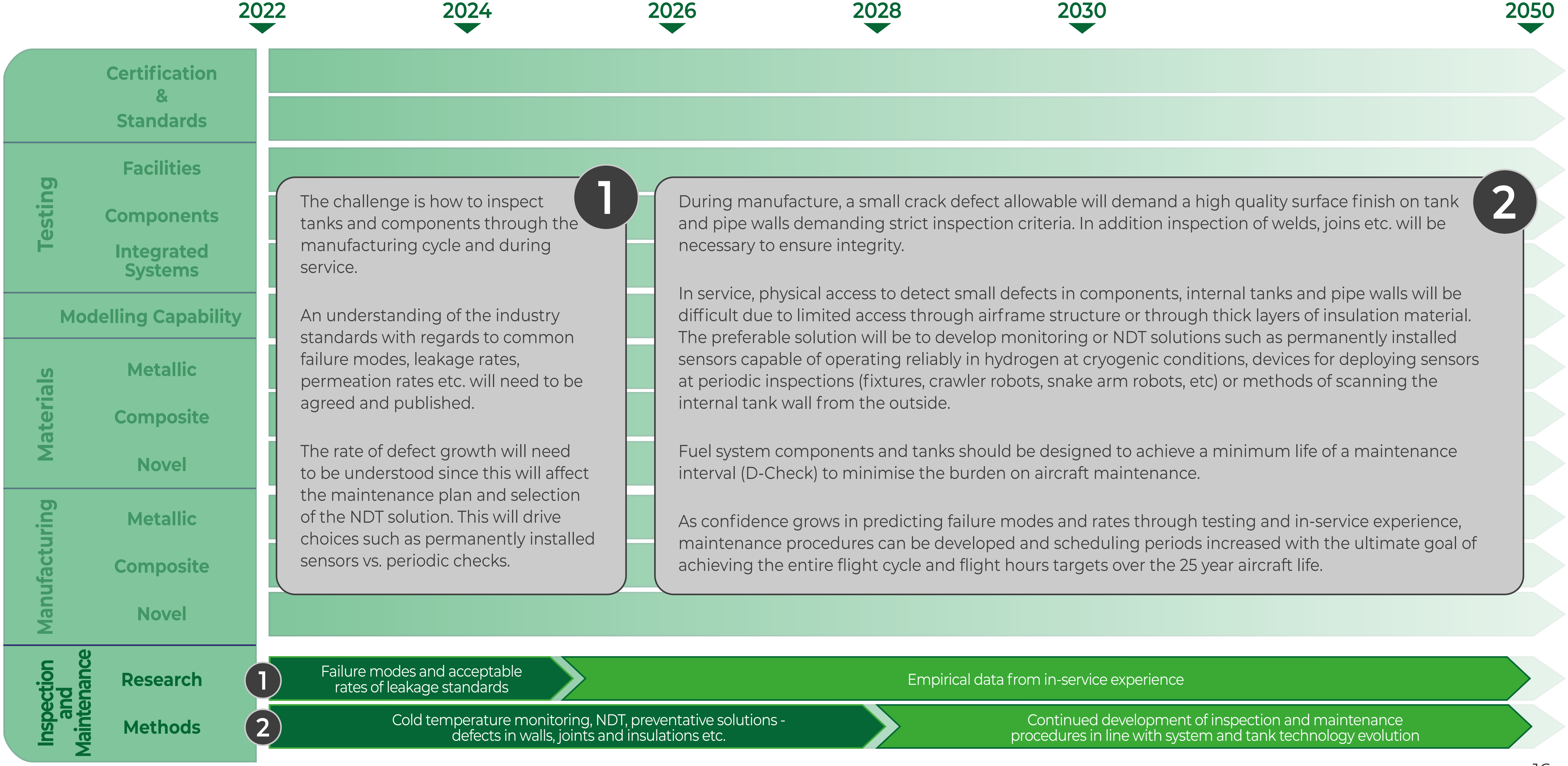
New composite processes and techniques may need to be developed alongside the materials to facilitate manufacturing at rate - out-of-autoclave curing, rapid composite fibre deposition etc.

Manufacturing developments are required for the joining of metals to composite storage tanks. For example the bonding of metal liners and metal system fittings to tank walls when considering the galvanic interaction of metals to composite materials, and the different material thermal expansion co-efficients.

Qualification of new manufacturing techniques for novel materials for 2030 timescale may include manufacturing developments for hybrid tanks, additive manufacturing, metal matrix composites and others.

CRYOGENIC HYDROGEN FUEL SYSTEM & STORAGE ROADMAP

Key Essential Enabler | Competitor Enabler | Technology Mature



1

The challenge is how to inspect tanks and components through the manufacturing cycle and during service.

An understanding of the industry standards with regards to common failure modes, leakage rates, permeation rates etc. will need to be agreed and published.

The rate of defect growth will need to be understood since this will affect the maintenance plan and selection of the NDT solution. This will drive choices such as permanently installed sensors vs. periodic checks.

2

During manufacture, a small crack defect allowable will demand a high quality surface finish on tank and pipe walls demanding strict inspection criteria. In addition inspection of welds, joins etc. will be necessary to ensure integrity.

In service, physical access to detect small defects in components, internal tanks and pipe walls will be difficult due to limited access through airframe structure or through thick layers of insulation material. The preferable solution will be to develop monitoring or NDT solutions such as permanently installed sensors capable of operating reliably in hydrogen at cryogenic conditions, devices for deploying sensors at periodic inspections (fixtures, crawler robots, snake arm robots, etc) or methods of scanning the internal tank wall from the outside.

Fuel system components and tanks should be designed to achieve a minimum life of a maintenance interval (D-Check) to minimise the burden on aircraft maintenance.

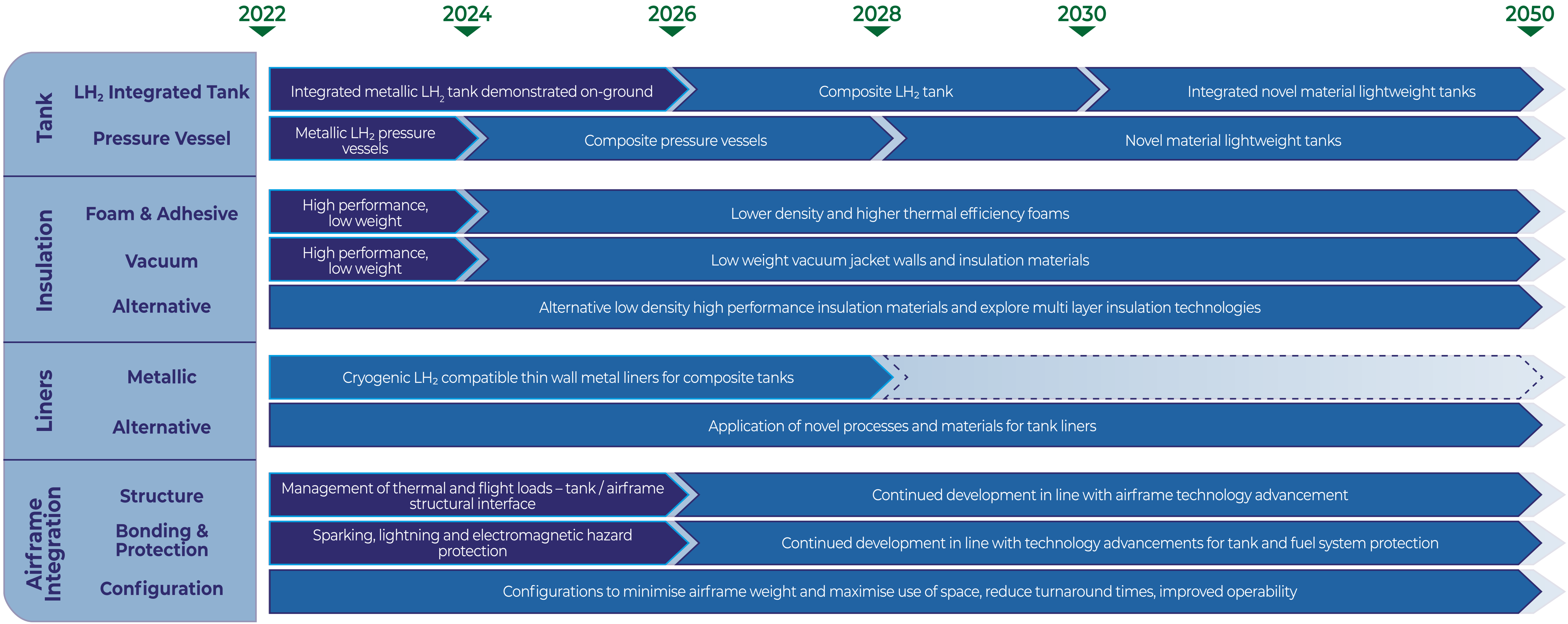
As confidence grows in predicting failure modes and rates through testing and in-service experience, maintenance procedures can be developed and scheduling periods increased with the ultimate goal of achieving the entire flight cycle and flight hours targets over the 25 year aircraft life.

Research:
1 Failure modes and acceptable rates of leakage standards
Empirical data from in-service experience

Methods:
2 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

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

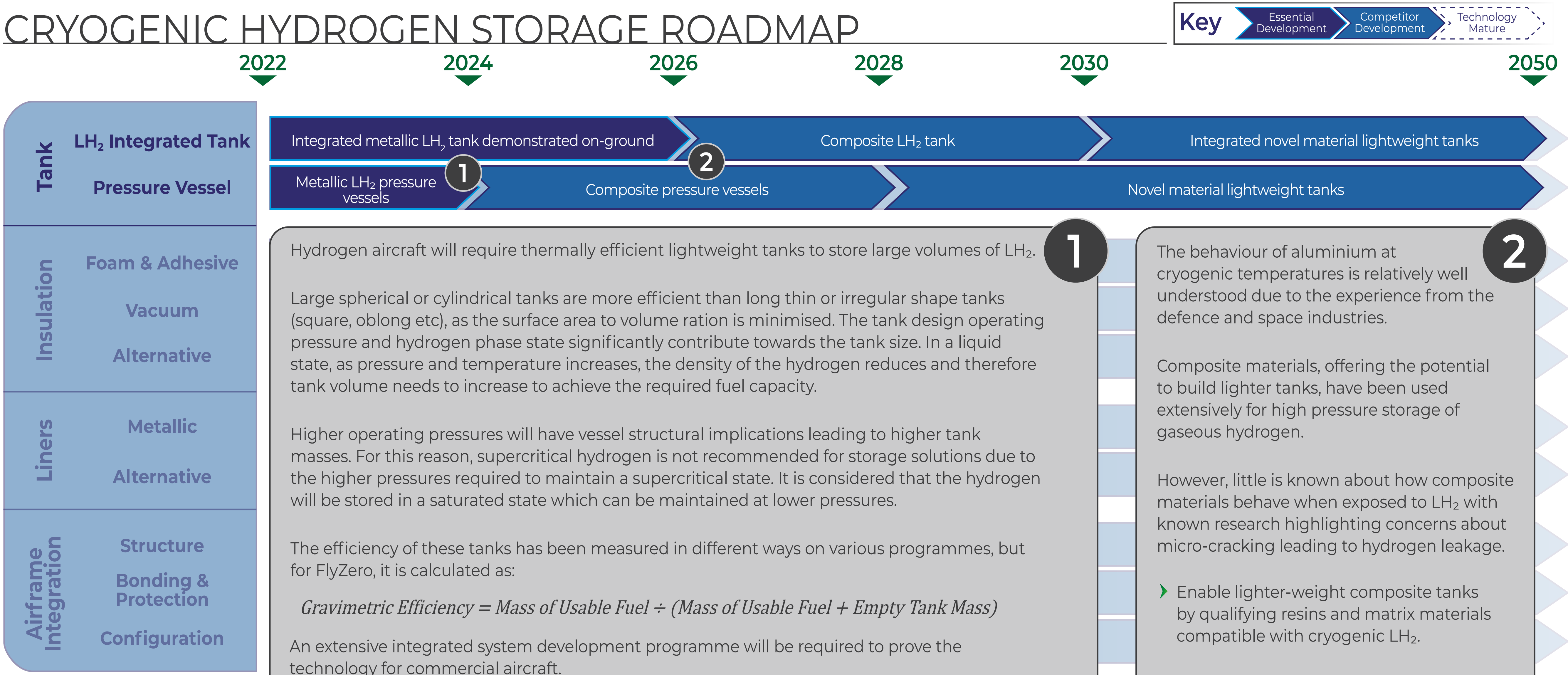
Airframe Integration

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

CRYOGENIC HYDROGEN STORAGE ROADMAP



①

Hydrogen aircraft will require thermally efficient lightweight tanks to store large volumes of LH_2.

Large spherical or cylindrical tanks are more efficient than long thin or irregular shape tanks (square, oblong etc), as the surface area to volume ration is minimised. The tank design operating pressure and hydrogen phase state significantly contribute towards the tank size. In a liquid state, as pressure and temperature increases, the density of the hydrogen reduces and therefore tank volume needs to increase to achieve the required fuel capacity.

Higher operating pressures will have vessel structural implications leading to higher tank masses. For this reason, supercritical hydrogen is not recommended for storage solutions due to the higher pressures required to maintain a supercritical state. It is considered that the hydrogen will be stored in a saturated state which can be maintained at lower pressures.

The efficiency of these tanks has been measured in different ways on various programmes, but for FlyZero, it is calculated as:

$$\mathit{Gravimetric\ Efficiency} = \mathit{Mass\ of\ Usable\ Fuel} \div (\mathit{Mass\ of\ Usable\ Fuel} + \mathit{Empty\ Tank\ Mass})$$

An extensive integrated system development programme will be required to prove the technology for commercial aircraft.

- Develop lightweight aluminium alloy tanks capable of storing cryogenic LH_2 with minimum energy loss through permeation, leakage, etc. - Current TRL 3-4 for aviation.
- Develop and qualify joining technologies for the manufacture of metallic tanks including coupon and full-scale testing in an LH_2 environment.

②

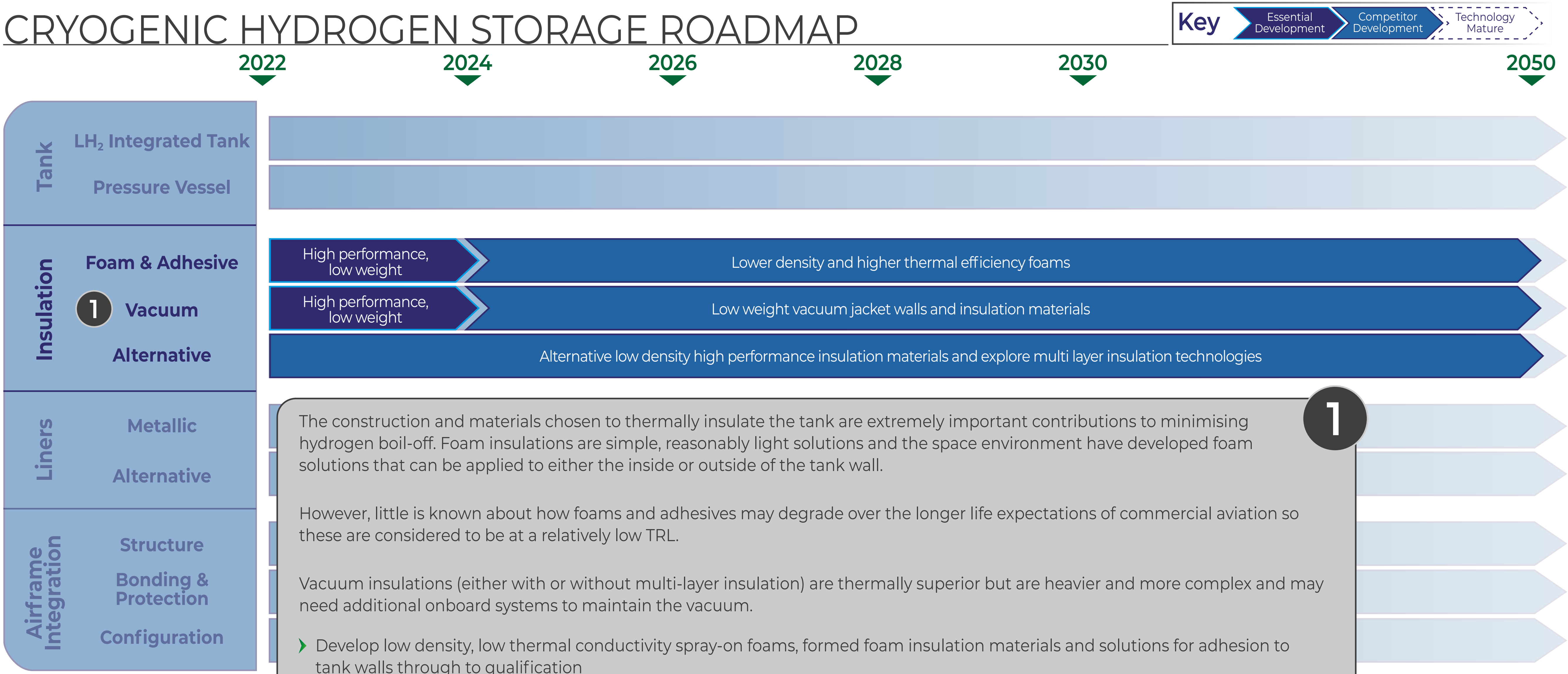
The behaviour of aluminium at cryogenic temperatures is relatively well understood due to the experience from the defence and space industries.

Composite materials, offering the potential to build lighter tanks, have been used extensively for high pressure storage of gaseous hydrogen.

However, little is known about how composite materials behave when exposed to LH_2 with known research highlighting concerns about micro-cracking leading to hydrogen leakage.

- Enable lighter-weight composite tanks by qualifying resins and matrix materials compatible with cryogenic LH_2.

CRYOGENIC HYDROGEN STORAGE ROADMAP



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

1

The construction and materials chosen to thermally insulate the tank are extremely important contributions to minimising hydrogen boil-off. Foam insulations are simple, reasonably light solutions and the space environment have developed foam solutions that can be applied to either the inside or outside of the tank wall.

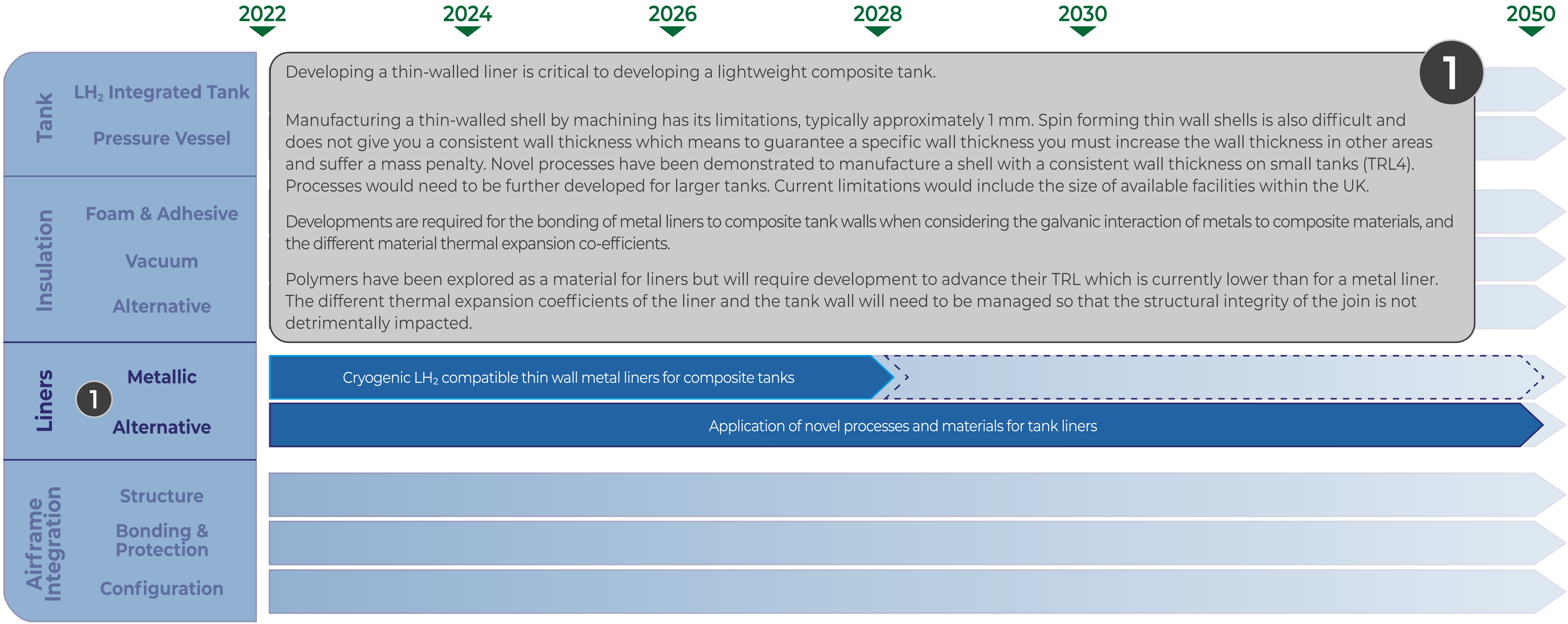
However, little is known about how foams and adhesives may degrade over the longer life expectations of commercial aviation so these are considered to be at a relatively low TRL.

Vacuum insulations (either with or without multi-layer insulation) are thermally superior but are heavier and more complex and may need additional onboard systems to maintain the vacuum.

- Develop low density, low thermal conductivity spray-on foams, formed foam insulation materials and solutions for adhesion to tank walls through to qualification
- Develop vacuum tanks with lightweight outer jackets i.e. optimised metal outer walls, composite or composite sandwich outer walls

CRYOGENIC HYDROGEN STORAGE ROADMAP

Key Essential Development | Competitor Development | Technology Mature



2022 | 2024 | 2026 | 2028 | 2030 | 2050

Tank
- LH$_2$ Integrated Tank
- Pressure Vessel

Insulation
- Foam & Adhesive
- Vacuum
- Alternative

Liners ①
- Metallic
- Alternative

Airframe Integration
- Structure
- Bonding & Protection
- Configuration

①

Developing a thin-walled liner is critical to developing a lightweight composite tank.

Manufacturing a thin-walled shell by machining has its limitations, typically approximately 1 mm. Spin forming thin wall shells is also difficult and does not give you a consistent wall thickness which means to guarantee a specific wall thickness you must increase the wall thickness in other areas and suffer a mass penalty. Novel processes have been demonstrated to manufacture a shell with a consistent wall thickness on small tanks (TRL4). Processes would need to be further developed for larger tanks. Current limitations would include the size of available facilities within the UK.

Developments are required for the bonding of metal liners to composite tank walls when considering the galvanic interaction of metals to composite materials, and the different material thermal expansion co-efficients.

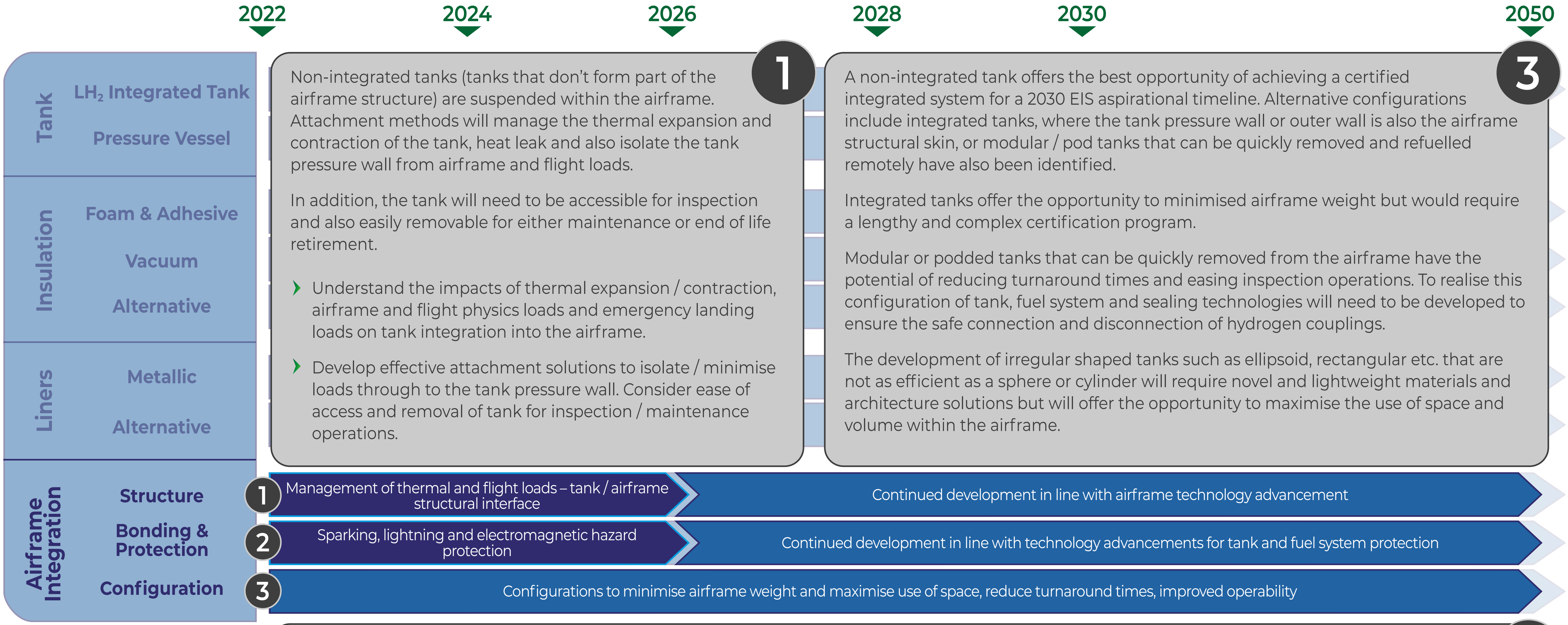
Polymers have been explored as a material for liners but will require development to advance their TRL which is currently lower than for a metal liner. The different thermal expansion coefficients of the liner and the tank wall will need to be managed so that the structural integrity of the join is not detrimentally impacted.

Cryogenic LH$_2$ compatible thin wall metal liners for composite tanks

Application of novel processes and materials for tank liners

CRYOGENIC HYDROGEN STORAGE ROADMAP

Key Essential Development | Competitor Development | Technology Mature



1

Non-integrated tanks (tanks that don't form part of the airframe structure) are suspended within the airframe. Attachment methods will manage the thermal expansion and contraction of the tank, heat leak and also isolate the tank pressure wall from airframe and flight loads.

In addition, the tank will need to be accessible for inspection and also easily removable for either maintenance or end of life retirement.

- Understand the impacts of thermal expansion / contraction, airframe and flight physics loads and emergency landing loads on tank integration into the airframe.
- Develop effective attachment solutions to isolate / minimise loads through to the tank pressure wall. Consider ease of access and removal of tank for inspection / maintenance operations.

3

A non-integrated tank offers the best opportunity of achieving a certified integrated system for a 2030 EIS aspirational timeline. Alternative configurations include integrated tanks, where the tank pressure wall or outer wall is also the airframe structural skin, or modular / pod tanks that can be quickly removed and refuelled remotely have also been identified.

Integrated tanks offer the opportunity to minimised airframe weight but would require a lengthy and complex certification program.

Modular or podded tanks that can be quickly removed from the airframe have the potential of reducing turnaround times and easing inspection operations. To realise this configuration of tank, fuel system and sealing technologies will need to be developed to ensure the safe connection and disconnection of hydrogen couplings.

The development of irregular shaped tanks such as ellipsoid, rectangular etc. that are not as efficient as a sphere or cylinder will require novel and lightweight materials and architecture solutions but will offer the opportunity to maximise the use of space and volume within the airframe.

1 Management of thermal and flight loads – tank / airframe structural interface → Continued development in line with airframe technology advancement

2 Sparking, lightning and electromagnetic hazard protection → Continued development in line with technology advancements for tank and fuel system protection

3 Configurations to minimise airframe weight and maximise use of space, reduce turnaround times, improved operability

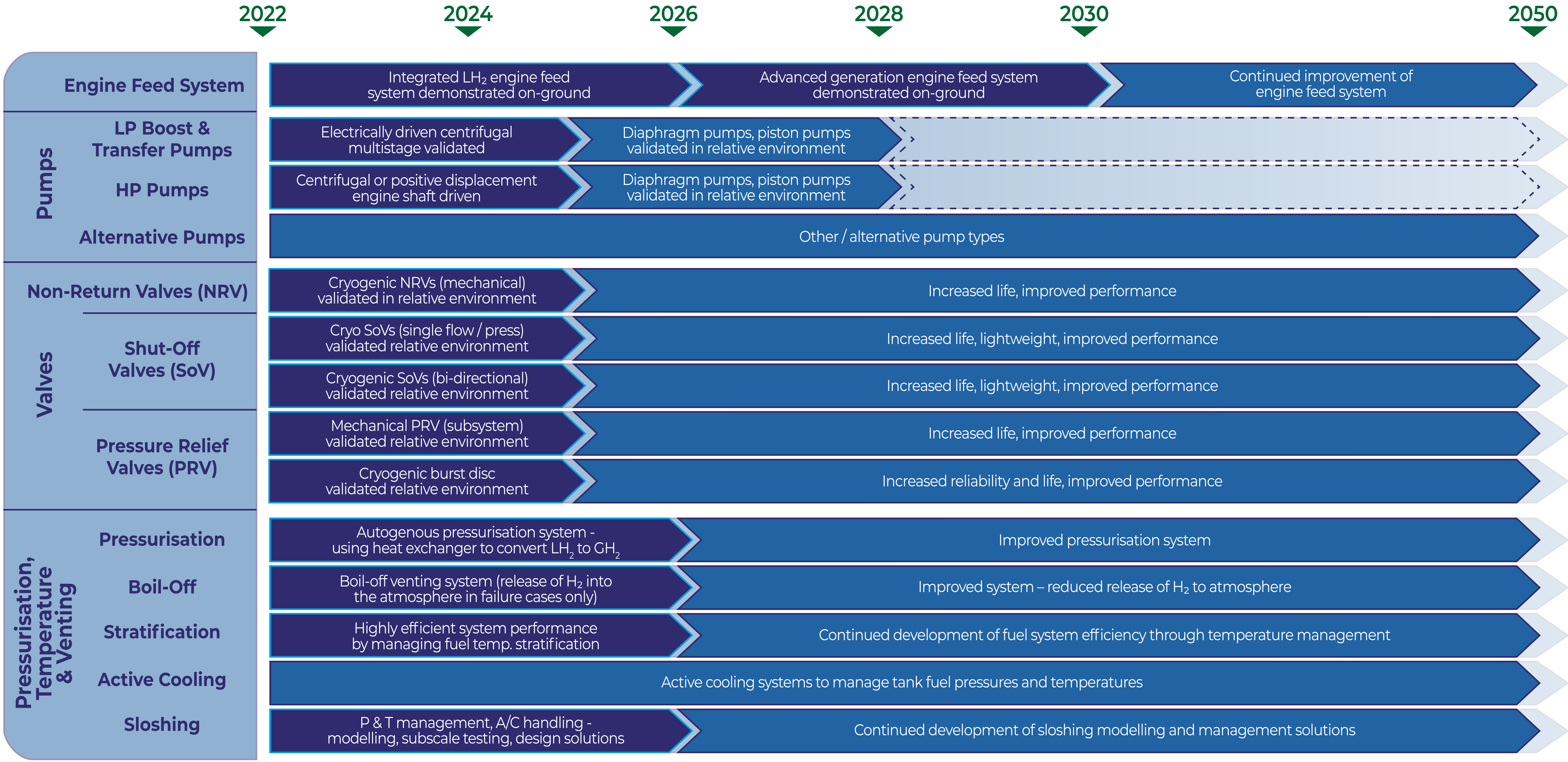
2

Liquid hydrogen will need to be protected from either the effects of indirect lightning strikes, or exposure to electromagnetic hazard (EMH). Design solutions will need to electrically bond the storage tank and the fuel system components to the airframe either via inherent bonding through the attachments or by a dedicated bonding solution.

- Design solutions to electrically bond the tank and fuel system components and protect the liquid hydrogen from either lightning strike or EMH exposure.

CRYOGENIC HYDROGEN FUEL SYSTEM ROADMAP

Key
- Essential Development
- Competitor Development
- Technology Mature



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

HP Pumps
- Centrifugal or positive displacement engine shaft driven
- Diaphragm pumps, piston pumps validated in relative environment

Alternative Pumps
- Other / alternative pump types

Valves

Non-Return Valves (NRV)
- Cryogenic NRVs (mechanical) validated in relative environment
- Increased life, improved performance

Shut-Off Valves (SoV)
- Cryo SoVs (single flow / press) validated relative environment
- Increased life, lightweight, improved performance
- Cryogenic SoVs (bi-directional) validated relative environment
- Increased life, lightweight, improved performance

Pressure Relief Valves (PRV)
- Mechanical PRV (subsystem) validated relative environment
- Increased life, improved performance
- 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

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

Stratification
- Highly efficient system performance by managing fuel temp. stratification
- Continued development of fuel system efficiency through temperature management

Active Cooling
- Active cooling systems to manage tank fuel pressures and temperatures

Sloshing
- P & T management, A/C handling - modelling, subscale testing, design solutions
- Continued development of sloshing modelling and management solutions

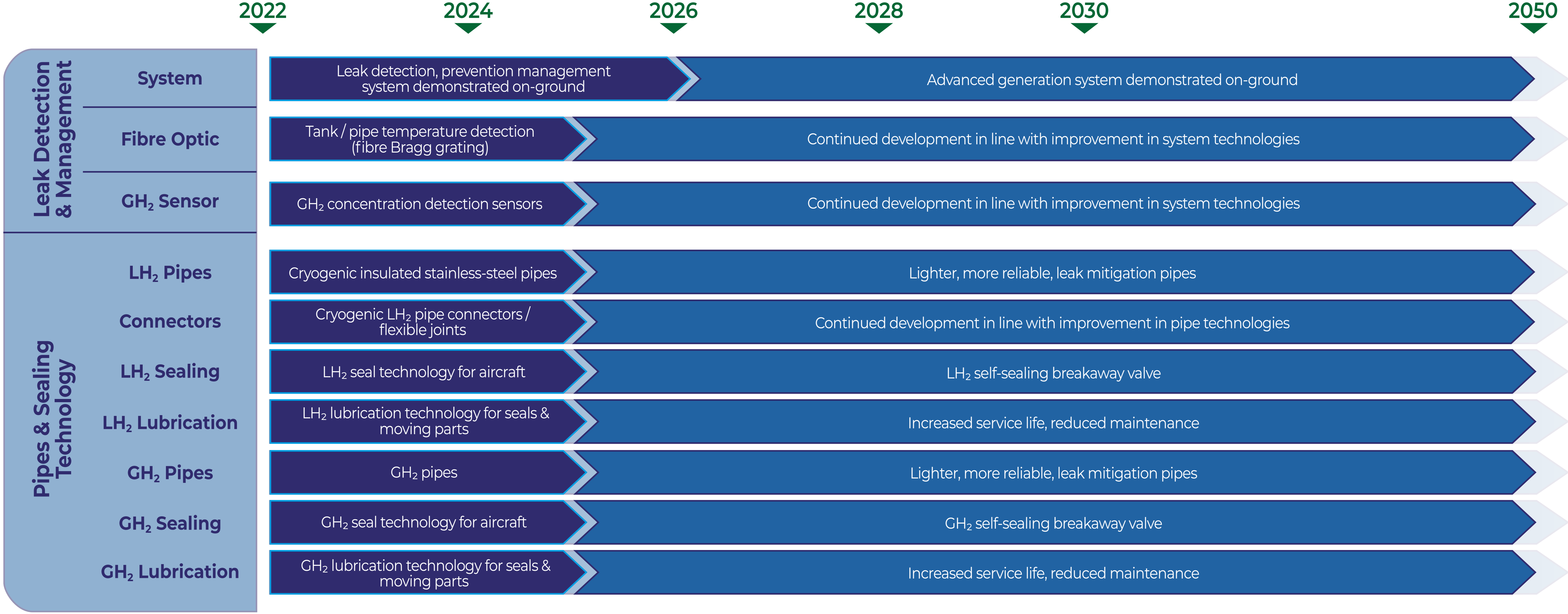
CRYOGENIC HYDROGEN FUEL SYSTEM ROADMAP

Key: Essential Development | Competitor Development | Technology Mature

Refuel /Defuel		**System**	Integrated refuel / defuel system demonstrated on-ground	Continued development of refuelling/defuelling technologies integrated with ground support equipment
		Equipment	LH_2 refuel / ground venting coupling	Continued development in line with improvement in system technologies
Control & Indication	**LH_2**	**C & I System**	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	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	Temperature sensors validated in laboratory environment	Continued development in line with improvement in system technologies

CRYOGENIC HYDROGEN FUEL SYSTEM ROADMAP

Key
- Essential Development
- Competitor Development
- Technology Mature



Leak Detection & Management	**System**	Leak detection, prevention management system demonstrated on-ground	Advanced generation system demonstrated on-ground
	Fibre Optic	Tank / pipe temperature detection (fibre Bragg grating)	Continued development in line with improvement in system technologies
	GH_2 Sensor	GH_2 concentration detection sensors	Continued development in line with improvement in system technologies
Pipes & Sealing Technology	**LH_2 Pipes**	Cryogenic insulated stainless-steel pipes	Lighter, more reliable, leak mitigation pipes
	Connectors	Cryogenic LH_2 pipe connectors / flexible joints	Continued development in line with improvement in pipe technologies
	LH_2 Sealing	LH_2 seal technology for aircraft	LH_2 self-sealing breakaway valve
	LH_2 Lubrication	LH_2 lubrication technology for seals & moving parts	Increased service life, reduced maintenance
	GH_2 Pipes	GH_2 pipes	Lighter, more reliable, leak mitigation pipes
	GH_2 Sealing	GH_2 seal technology for aircraft	GH_2 self-sealing breakaway valve
	GH_2 Lubrication	GH_2 lubrication technology for seals & moving parts	Increased service life, reduced maintenance

CRYOGENIC HYDROGEN FUEL SYSTEM ROADMAP

Key: Essential Development | Competitor Development | Technology Mature

2022 | 2024 | 2026 | 2028 | 2030 | 2050

① 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
- HP Pumps
- Alternative Pumps

Non-Return Valves (NRV)

Valves
- Shut-Off Valves (SoV)
- Pressure Relief Valves (PRV)

Pressurisation, Temperature & Venting
- Pressurisation
- Boil-Off
- Stratification
- Active Cooling
- Sloshing

①

The supply of hydrogen at a specified pressure and flow rate from a storage vessel to an interface with a gas turbine or a fuel cell is required as part of the aircraft propulsion system. While cryogenic fuel feed systems exist in space launcher and ground based industry, the required combination of long life, low weight, high safety and reliability is a key difference for a civil aircraft application. Pump technology development is required in order to address performance, life of wearing surfaces including potential cavitation, sealing and safety. This is true for all potential pump solutions, including electrically driven boost and transfer pumps, and centrifugal or positive displacement pumping technology. Mechanically driven high pressure pumps will also require (engine) drive system integration development.

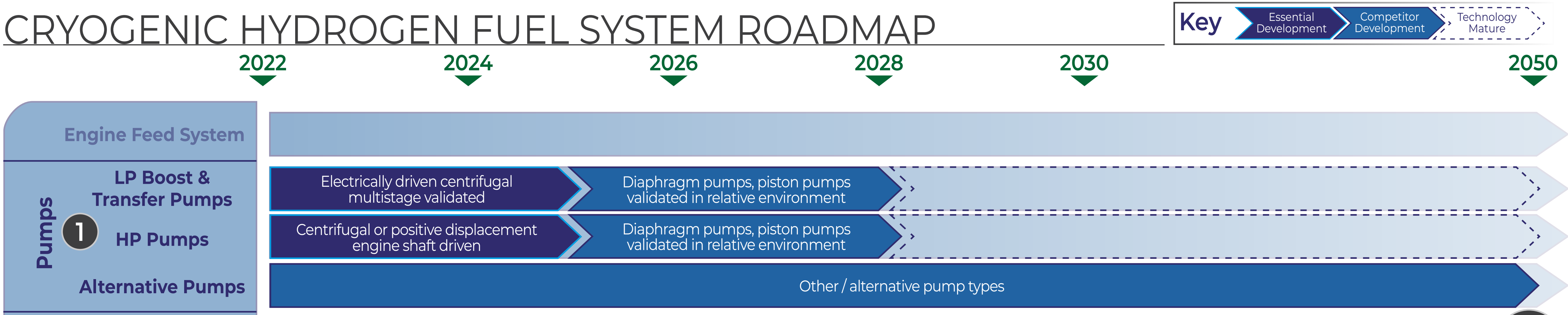
The overall heat load transferred to the hydrogen throughout the system, pipework and tank needs to be carefully considered and managed under the full range of aircraft operating and non-operating conditions. The ability for the system to handle transient temperature conditions during chill-down of the system and engine start needs to be considered, and potentially integrated with the refuelling chill-down process described on page 25. The heat loads and hydrogen temperature rise associated with fuel pumps at the full range of operating conditions need to be considered in detail, and the associated performance will vary according to the selected technology and configuration. Valve technology needs to be developed to address performance, wear, cycle life, insulation and internal leakage rates. Transient behaviour of relief valves and regulating valves need to be addressed, in addition to the propagation and potential interaction of forcing frequencies with adjacent systems.

Much higher levels of uncertainty exist in the modelling predictions for cryogenic systems than for conventional aircraft kerosene fuel systems. This major gap needs to be addressed. This can be achieved by development testing and model validation, including the associated update of system models and building block analysis capability. Refer to the “Modelling Capabilities” page 12.
Equipment transient behaviour and interaction are often more challenging to predict, and this challenge will be increased in a cryogenic environment. The potential for acoustic / vibrational interaction with interfacing systems should be considered through the compressible fluid system and so this may create an integrated test and validation and verification (V&V) risk that may be difficult to address until full system test.

Some alternative engine feed architecture solutions include additional interfaces with other systems, for example turbo-pump solutions. Such solutions will require additional interfaces to be included, and early integration with the actual interfacing system should be planned.

The services capability to support cryogenic hydrogen fuel systems needs to be developed. This includes maintenance and standard hydrogen operating procedures for commercial aerospace applications.

CRYOGENIC HYDROGEN FUEL SYSTEM ROADMAP



Key: Essential Development | Competitor Development | Technology Mature

2022 | 2024 | 2026 | 2028 | 2030 | 2050

Engine Feed System

Pumps

LP Boost & Transfer Pumps ①: Electrically driven centrifugal multistage validated → Diaphragm pumps, piston pumps validated in relative environment

HP Pumps: Centrifugal or positive displacement engine shaft driven → Diaphragm pumps, piston pumps validated in relative environment

Alternative Pumps: Other / alternative pump types

Valves

Non-Return Valves (NRV)

Shut-Off Valves (SoV)

Pressure Relief Valves (PRV)

Pressurisation, Temperature & Venting

Pressurisation

Boil-Off

Stratification

Active Cooling

Sloshing

①

Cryogenic hydrogen test capabilities are required to be able to significantly advance TRL level for any of the pump technologies considered. This is needed in addition to hydrogen system standards and the identification of proven and qualified materials.

Cryogenic liquid hydrogen boost pumps are required to deliver hydrogen to a high pressure pump at sufficient pressure. The boost pumps will need to be optimised to function with a minimum inlet pressure and consider pump life and performance capability including the presence of vapour at the pump inlet. Initial boost pump technology is expected to be multi-stage centrifugal and electrically driven. Centrifugal pumps in particular will require high speed, long-life bearing solutions compatible with the cryogenic hydrogen environment.

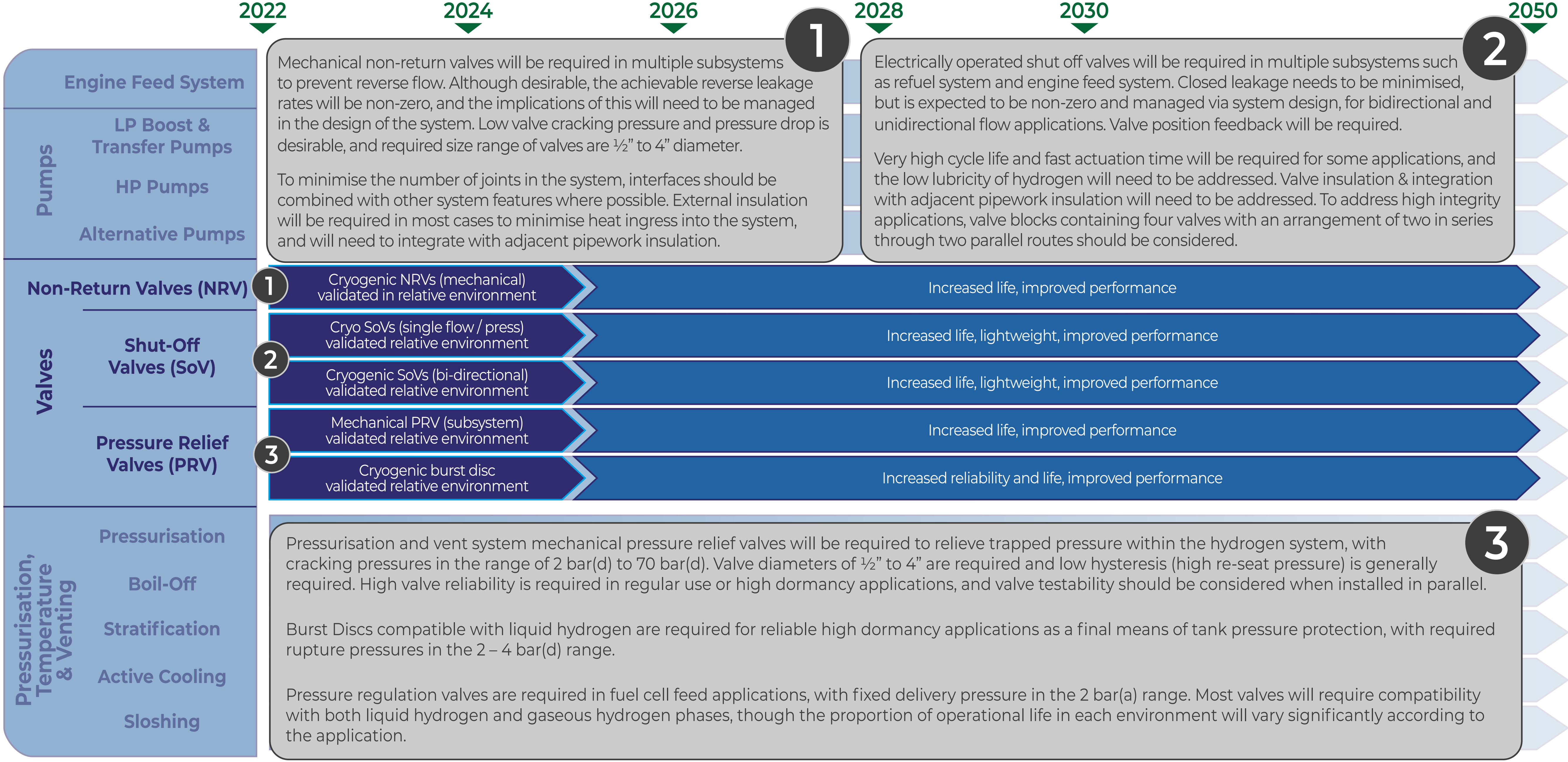
Cryogenic rotating seal technology and overall pump design will need to address the equipment life requirements and the tolerable leakage or permeation of hydrogen from the equipment. Alternate pump technologies include actuated diaphragm and piston pumps. Although currently less mature for this application, these types of technologies present advantages in terms of sealing simplicity and potentially vapour handling.

Transfer pumps are required to move liquid hydrogen between tanks, or between tank compartments. Electrically driven centrifugal and jet pump technologies are considered for these functions. High Pressure pumps are required to raise the hydrogen pressure from an intermediate pressure (architecture dependent) to the pressure required to support combustion in the gas turbine. Initial technology is anticipated to be engine shaft-driven and of centrifugal or positive displacement type. The high pressure pumps will need to achieve similar failure rates to kerosene engine mounted high pressure pumps. They must also be compatible with higher fuel temperatures (vapour handling) during engine start as well as the lower lubricity fuel, with acceptable life.

A future pump technology that may allow a lower weight and simpler system are turbo-pumps. These are similar to those used in spacecraft launcher applications, but must achieve the much longer operating life of the aircraft application. This technology must also address engine start requirements, and will require early integration with the engine. Pump ignition hazards will need to be managed and the mitigations will need to be aligned to be compatible with the system hydrogen leak management and detection approach.

CRYOGENIC HYDROGEN FUEL SYSTEM ROADMAP

Key: Essential Development | Competitor Development | Technology Mature



①

Mechanical non-return valves will be required in multiple subsystems to prevent reverse flow. Although desirable, the achievable reverse leakage rates will be non-zero, and the implications of this will need to be managed in the design of the system. Low valve cracking pressure and pressure drop is desirable, and required size range of valves are ½” to 4” diameter.

To minimise the number of joints in the system, interfaces should be combined with other system features where possible. External insulation will be required in most cases to minimise heat ingress into the system, and will need to integrate with adjacent pipework insulation.

②

Electrically operated shut off valves will be required in multiple subsystems such as refuel system and engine feed system. Closed leakage needs to be minimised, but is expected to be non-zero and managed via system design, for bidirectional and unidirectional flow applications. Valve position feedback will be required.

Very high cycle life and fast actuation time will be required for some applications, and the low lubricity of hydrogen will need to be addressed. Valve insulation & integration with adjacent pipework insulation will need to be addressed. To address high integrity applications, valve blocks containing four valves with an arrangement of two in series through two parallel routes should be considered.

Non-Return Valves (NRV)	①	Cryogenic NRVs (mechanical) validated in relative environment	Increased life, improved performance
Shut-Off Valves (SoV)	②	Cryo SoVs (single flow / press) validated relative environment	Increased life, lightweight, improved performance
		Cryogenic SoVs (bi-directional) validated relative environment	Increased life, lightweight, improved performance
Pressure Relief Valves (PRV)	③	Mechanical PRV (subsystem) validated relative environment	Increased life, improved performance
		Cryogenic burst disc validated relative environment	Increased reliability and life, improved performance

③

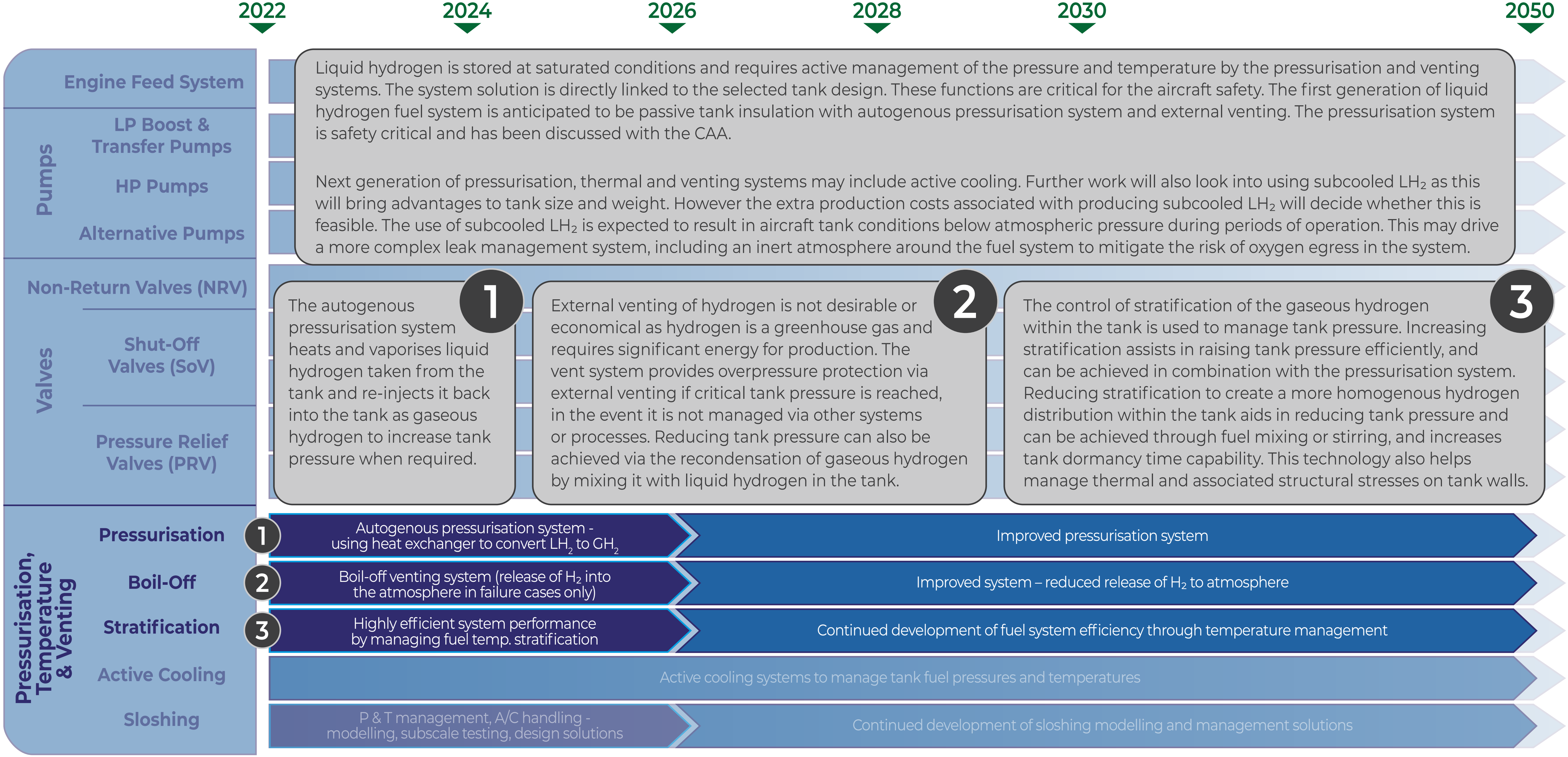
Pressurisation and vent system mechanical pressure relief valves will be required to relieve trapped pressure within the hydrogen system, with cracking pressures in the range of 2 bar(d) to 70 bar(d). Valve diameters of ½” to 4” are required and low hysteresis (high re-seat pressure) is generally required. High valve reliability is required in regular use or high dormancy applications, and valve testability should be considered when installed in parallel.

Burst Discs compatible with liquid hydrogen are required for reliable high dormancy applications as a final means of tank pressure protection, with required rupture pressures in the 2 – 4 bar(d) range.

Pressure regulation valves are required in fuel cell feed applications, with fixed delivery pressure in the 2 bar(a) range. Most valves will require compatibility with both liquid hydrogen and gaseous hydrogen phases, though the proportion of operational life in each environment will vary significantly according to the application.

CRYOGENIC HYDROGEN FUEL SYSTEM ROADMAP

Key Essential Development | Competitor Development | Technology Mature



Liquid hydrogen is stored at saturated conditions and requires active management of the pressure and temperature by the pressurisation and venting systems. The system solution is directly linked to the selected tank design. These functions are critical for the aircraft safety. The first generation of liquid hydrogen fuel system is anticipated to be passive tank insulation with autogenous pressurisation system and external venting. The pressurisation system is safety critical and has been discussed with the CAA.

Next generation of pressurisation, thermal and venting systems may include active cooling. Further work will also look into using subcooled LH_2 as this will bring advantages to tank size and weight. However the extra production costs associated with producing subcooled LH_2 will decide whether this is feasible. The use of subcooled LH_2 is expected to result in aircraft tank conditions below atmospheric pressure during periods of operation. This may drive a more complex leak management system, including an inert atmosphere around the fuel system to mitigate the risk of oxygen egress in the system.

1 The autogenous pressurisation system heats and vaporises liquid hydrogen taken from the tank and re-injects it back into the tank as gaseous hydrogen to increase tank pressure when required.

2 External venting of hydrogen is not desirable or economical as hydrogen is a greenhouse gas and requires significant energy for production. The vent system provides overpressure protection via external venting if critical tank pressure is reached, in the event it is not managed via other systems or processes. Reducing tank pressure can also be achieved via the recondensation of gaseous hydrogen by mixing it with liquid hydrogen in the tank.

3 The control of stratification of the gaseous hydrogen within the tank is used to manage tank pressure. Increasing stratification assists in raising tank pressure efficiently, and can be achieved in combination with the pressurisation system. Reducing stratification to create a more homogenous hydrogen distribution within the tank aids in reducing tank pressure and can be achieved through fuel mixing or stirring, and increases tank dormancy time capability. This technology also helps manage thermal and associated structural stresses on tank walls.

Pressurisation 1
- Autogenous pressurisation system - using heat exchanger to convert LH_2 to GH_2
- Improved pressurisation system

Boil-Off 2
- Boil-off venting system (release of H_2 into the atmosphere in failure cases only)
- Improved system – reduced release of H_2 to atmosphere

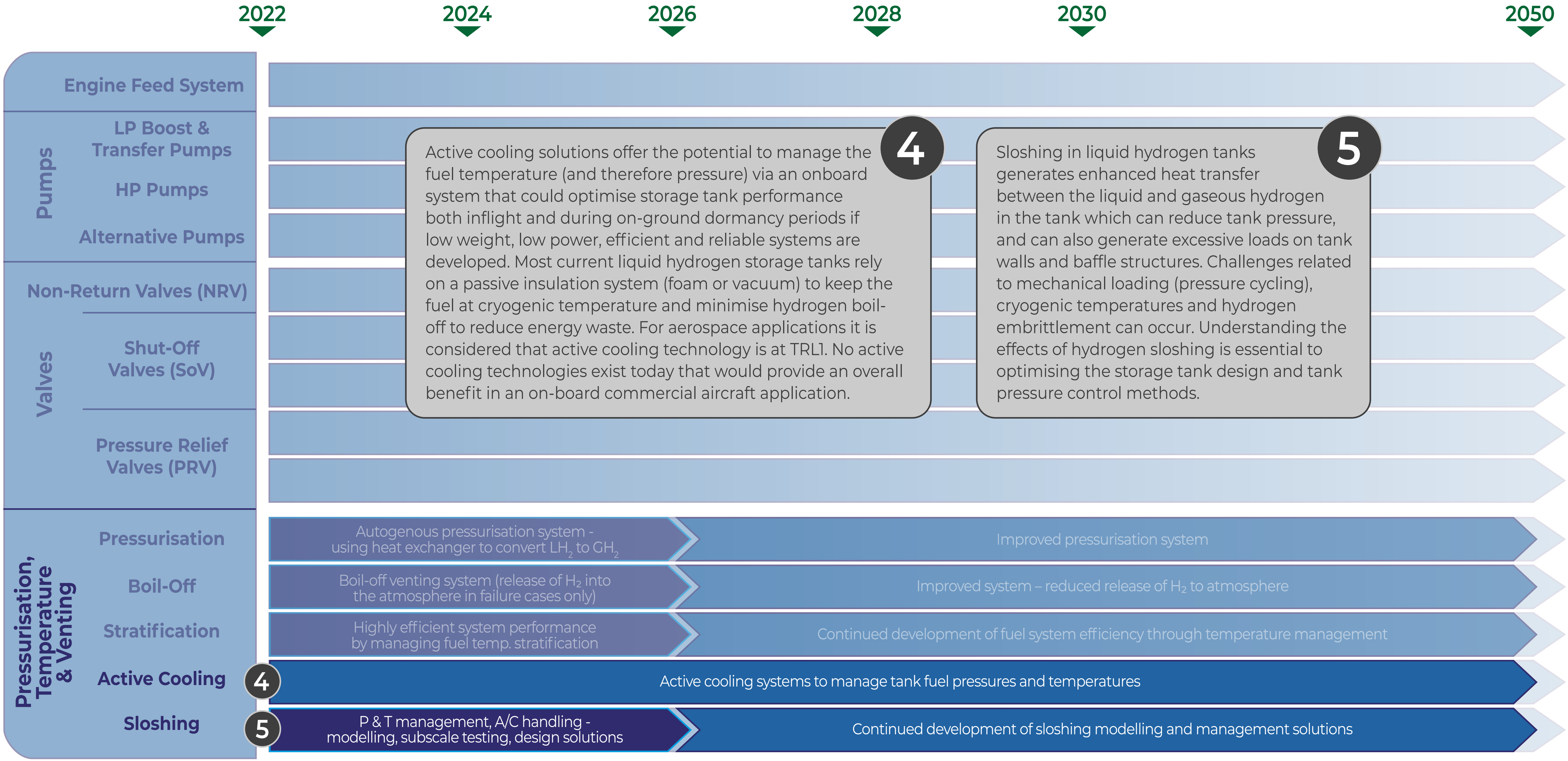
Stratification 3
- Highly efficient system performance by managing fuel temp. stratification
- Continued development of fuel system efficiency through temperature management

Active Cooling
- Active cooling systems to manage tank fuel pressures and temperatures

Sloshing
- P & T management, A/C handling - modelling, subscale testing, design solutions
- Continued development of sloshing modelling and management solutions

CRYOGENIC HYDROGEN FUEL SYSTEM ROADMAP

Key
- Essential Development
- Competitor Development
- Technology Mature



Pressurisation: Autogenous pressurisation system - using heat exchanger to convert LH_2 to GH_2 → Improved pressurisation system

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

Stratification: Highly efficient system performance by managing fuel temp. stratification → Continued development of fuel system efficiency through temperature management

Active Cooling (4): Active cooling systems to manage tank fuel pressures and temperatures

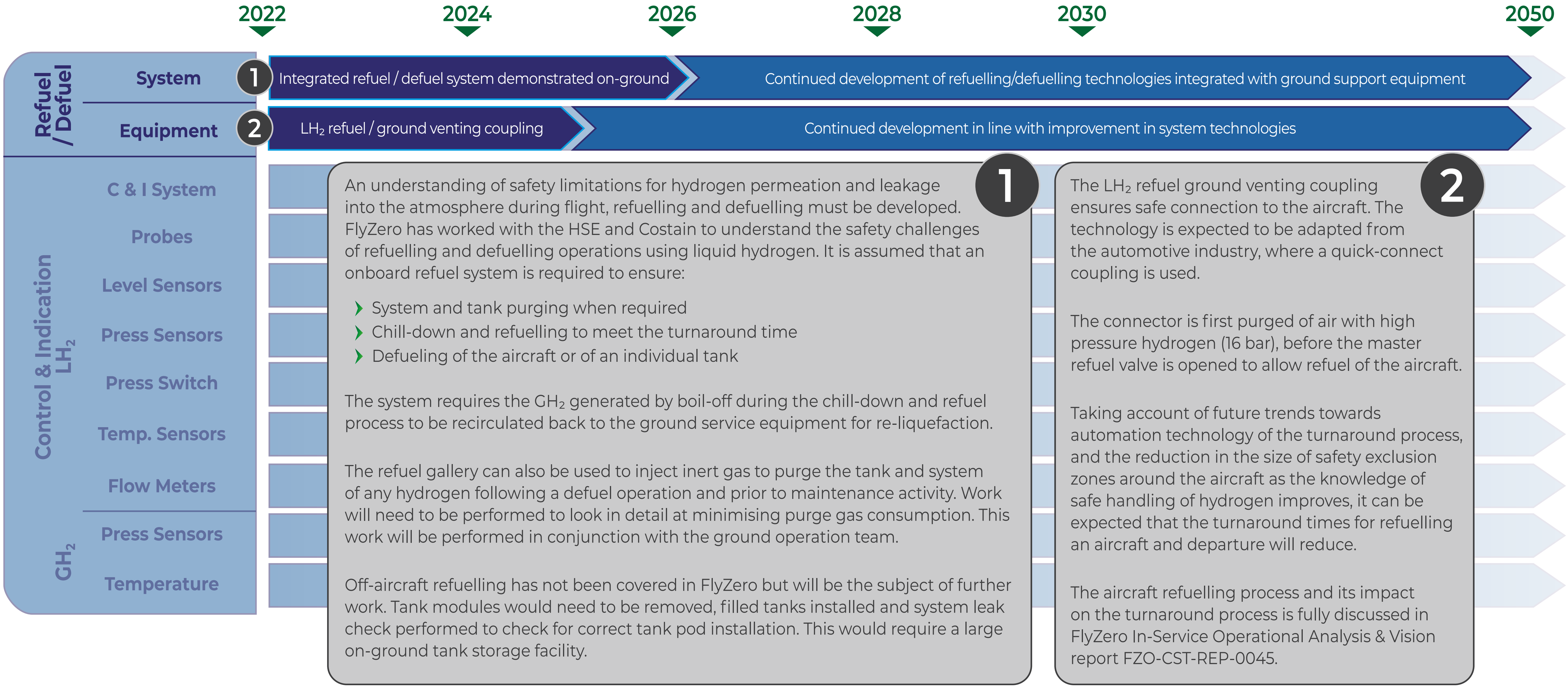
Sloshing (5): P & T management, A/C handling - modelling, subscale testing, design solutions → Continued development of sloshing modelling and management solutions

4 Active cooling solutions offer the potential to manage the fuel temperature (and therefore pressure) via an onboard system that could optimise storage tank performance both inflight and during on-ground dormancy periods if low weight, low power, efficient and reliable systems are developed. Most current liquid hydrogen storage tanks rely on a passive insulation system (foam or vacuum) to keep the fuel at cryogenic temperature and minimise hydrogen boil-off to reduce energy waste. For aerospace applications it is considered that active cooling technology is at TRL1. No active cooling technologies exist today that would provide an overall benefit in an on-board commercial aircraft application.

5 Sloshing in liquid hydrogen tanks generates enhanced heat transfer between the liquid and gaseous hydrogen in the tank which can reduce tank pressure, and can also generate excessive loads on tank walls and baffle structures. Challenges related to mechanical loading (pressure cycling), cryogenic temperatures and hydrogen embrittlement can occur. Understanding the effects of hydrogen sloshing is essential to optimising the storage tank design and tank pressure control methods.

CRYOGENIC HYDROGEN FUEL SYSTEM ROADMAP

Key Essential Development | Competitor Development | Technology Mature



2022 2024 2026 2028 2030 2050

Refuel / Defuel

System ① Integrated refuel / defuel system demonstrated on-ground → Continued development of refuelling/defuelling technologies integrated with ground support equipment

Equipment ② LH_2 refuel / ground venting coupling → Continued development in line with improvement in system technologies

Control & Indication

LH_2

C & I System

Probes

Level Sensors

Press Sensors

Press Switch

Temp. Sensors

Flow Meters

GH_2

Press Sensors

Temperature

1

An understanding of safety limitations for hydrogen permeation and leakage into the atmosphere during flight, refuelling and defuelling must be developed. FlyZero has worked with the HSE and Costain to understand the safety challenges of refuelling and defuelling operations using liquid hydrogen. It is assumed that an onboard refuel system is required to ensure:

- System and tank purging when required
- Chill-down and refuelling to meet the turnaround time
- Defueling of the aircraft or of an individual tank

The system requires the GH_2 generated by boil-off during the chill-down and refuel process to be recirculated back to the ground service equipment for re-liquefaction.

The refuel gallery can also be used to inject inert gas to purge the tank and system of any hydrogen following a defuel operation and prior to maintenance activity. Work will need to be performed to look in detail at minimising purge gas consumption. This work will be performed in conjunction with the ground operation team.

Off-aircraft refuelling has not been covered in FlyZero but will be the subject of further work. Tank modules would need to be removed, filled tanks installed and system leak check performed to check for correct tank pod installation. This would require a large on-ground tank storage facility.

2

The LH_2 refuel ground venting coupling ensures safe connection to the aircraft. The technology is expected to be adapted from the automotive industry, where a quick-connect coupling is used.

The connector is first purged of air with high pressure hydrogen (16 bar), before the master refuel valve is opened to allow refuel of the aircraft.

Taking account of future trends towards automation technology of the turnaround process, and the reduction in the size of safety exclusion zones around the aircraft as the knowledge of safe handling of hydrogen improves, it can be expected that the turnaround times for refuelling an aircraft and departure will reduce.

The aircraft refuelling process and its impact on the turnaround process is fully discussed in FlyZero In-Service Operational Analysis & Vision report FZO-CST-REP-0045.

CRYOGENIC HYDROGEN FUEL SYSTEM ROADMAP

Key: Essential Development | Competitor Development | Technology Mature

			Essential Development	Competitor Development
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	②	Float operated level sensor	More reliable, and longer life level sensors
	Press Sensors		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	③	Pressure sensors validated in laboratory environment	Continued development in line with improvement in system technologies
	Temperature		Temperature sensors validated in laboratory environment	Continued development in line with improvement in system technologies

CRYOGENIC HYDROGEN FUEL SYSTEM ROADMAP

Key: Essential Development | Competitor Development | Technology Mature

2022 | 2024 | 2026 | 2028 | 2030 | 2050

1

The control and indication system allows control of the fuel system during normal and abnormal operations including refuelling.

The system includes all sensors required to control the fuel flow within the aircraft, maintain the tank pressure to an acceptable level, detect abnormal operation, failures and activate mitigation action. The system also includes the associated data processing and control computers.

The system definition will require modelling capabilities to be available to identify the correct data required for the fuel system management, as well as the required sensitivity and response time. Testing will be required to confirm the system's operation in normal and degraded cases.

The system safety analysis will confirm the design assurance level of the system and the equipment.

Note that the system is expected to be less reliable than the current kerosene system. There will be no in-service data and therefore, one critical aspect to consider is the ability to perform trend analysis during development and in-service. Predictive maintenance is expected to be a key feature of the fuel system control and indication system to identify changes to the system. The ability to anticipate failures before they occur will support airline maintenance scheduling. In addition, self-assessment capability to ensure the system's health and reduce the risk exposure before flight (e.g. during refuel) is also to be considered.

2

The control and indication function will require gauging of the fuel quantity and associated temperature and pressure sensors. The technology identified for measuring the liquid hydrogen is listed below:

- LH_2 gauging probes using either electric or optical technology. Optical technology would be an advantage to address ignition risk.
- Level sensors to assess critically high or low fuel levels in the tanks in operation or during refuel.
- Pressure and temperature sensors to monitor the hydrogen in the tank. LP switches are used to turn off the associated pump in case of low pressure. Temperature sensors will monitor the temperature within the tank for fuel system operation and will be used for the chill-down and refuel process.
- Flow meters can be used to measure the fuel flow in the feed lines to the engine. The fuel is expected to be in supercritical phase after the HP pump.

The first generation is expected to be an adaptation of the currently existing technology while the next generation is expected improvement on weight, reliability and life.

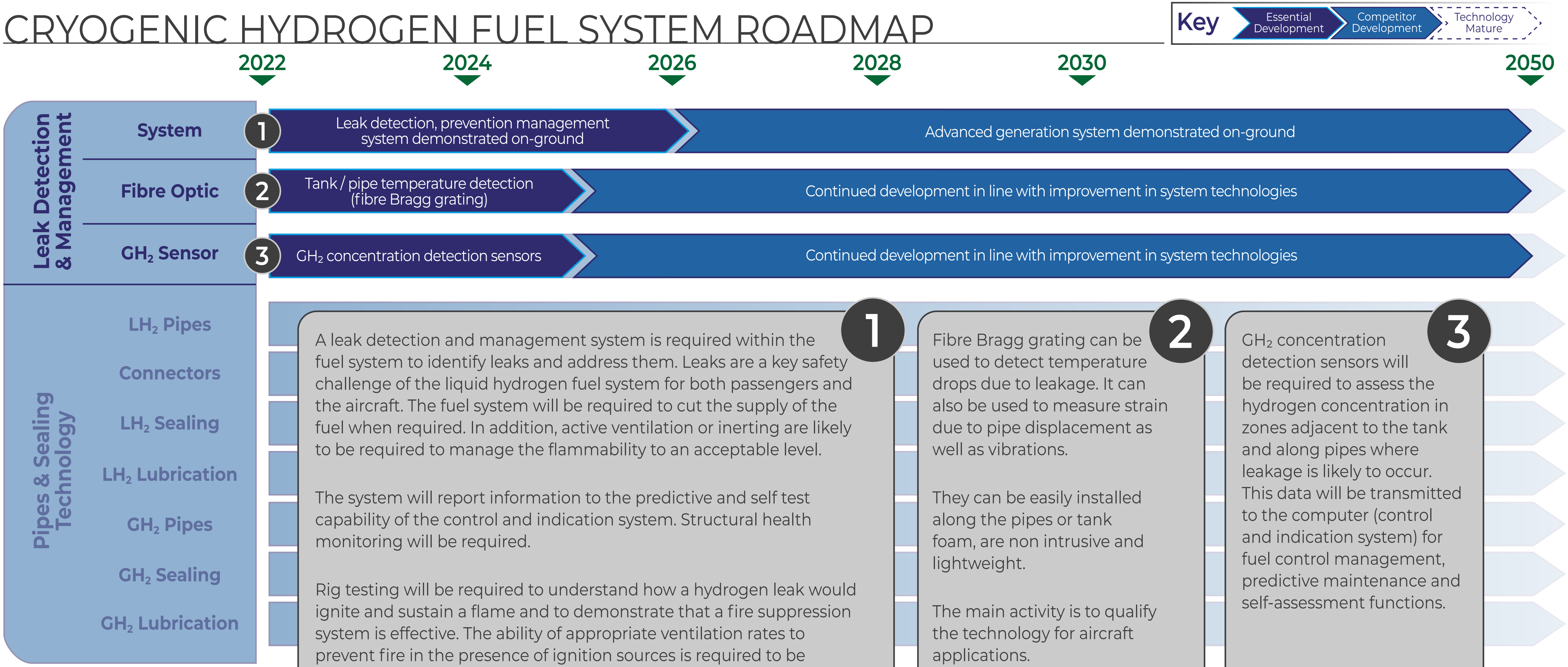
3

The control and indication function will require measurement of the tank ullage temperature and pressure and other gaseous system temperatures and pressures outside the tank. The sensor technology is identified as:

- Gaseous hydrogen temperature and pressure sensors. These are required to monitor the tank ullage temperature and pressure. The pressure sensors will monitor tank pressure to allow pressure control via the pressurisation system. Pressurisation system temperature sensors are required to identify system failures to allow mitigation of the failure or shutdown of the system.

These technologies are already existing and very mature in other industry sectors. The main effort is qualification to cryogenic and aircraft environment.

CRYOGENIC HYDROGEN FUEL SYSTEM ROADMAP



1

A leak detection and management system is required within the fuel system to identify leaks and address them. Leaks are a key safety challenge of the liquid hydrogen fuel system for both passengers and the aircraft. The fuel system will be required to cut the supply of the fuel when required. In addition, active ventilation or inerting are likely to be required to manage the flammability to an acceptable level.

The system will report information to the predictive and self test capability of the control and indication system. Structural health monitoring will be required.

Rig testing will be required to understand how a hydrogen leak would ignite and sustain a flame and to demonstrate that a fire suppression system is effective. The ability of appropriate ventilation rates to prevent fire in the presence of ignition sources is required to be assessed by test.

The software aspect is expected to be included in the control and indication system.

2

Fibre Bragg grating can be used to detect temperature drops due to leakage. It can also be used to measure strain due to pipe displacement as well as vibrations.

They can be easily installed along the pipes or tank foam, are non intrusive and lightweight.

The main activity is to qualify the technology for aircraft applications.

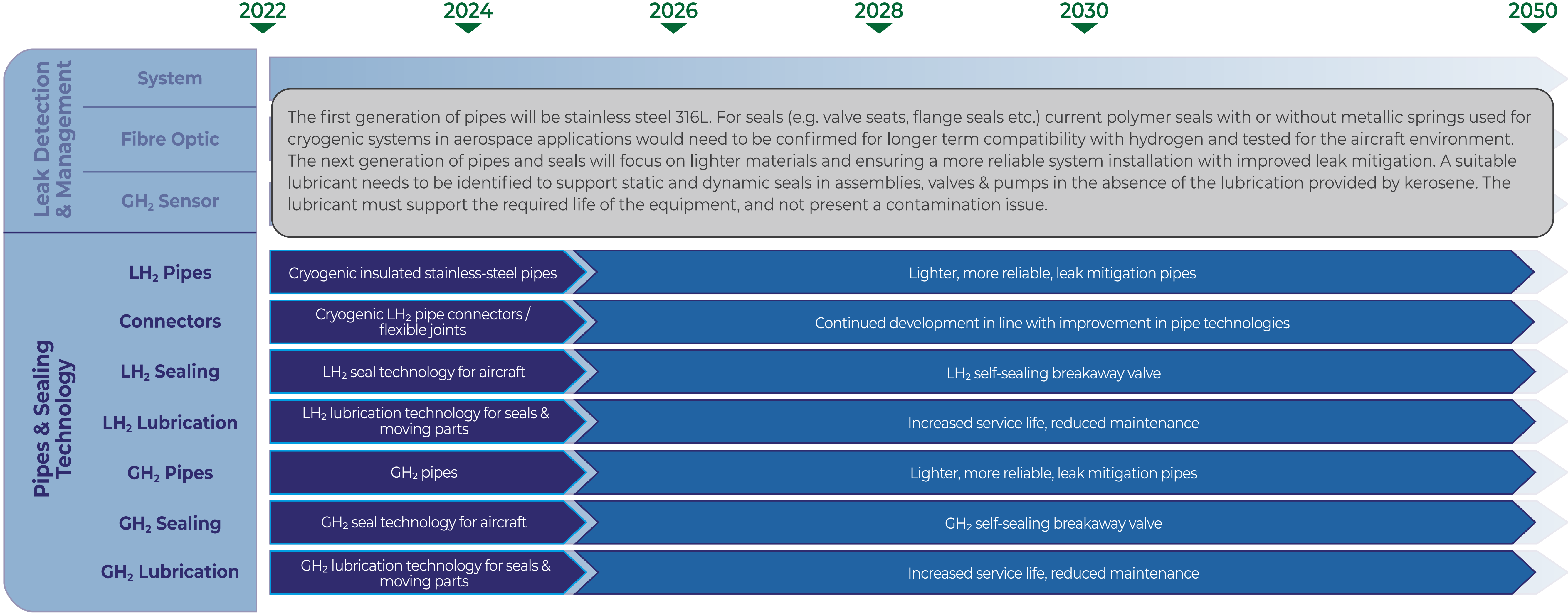
Life and repair aspects are to be assessed.

3

GH_2 concentration detection sensors will be required to assess the hydrogen concentration in zones adjacent to the tank and along pipes where leakage is likely to occur. This data will be transmitted to the computer (control and indication system) for fuel control management, predictive maintenance and self-assessment functions.

CRYOGENIC HYDROGEN FUEL SYSTEM ROADMAP

Key Essential Development | Competitor Development | Technology Mature



Leak Detection & Management

- System
- Fibre Optic
- GH_2 Sensor

The first generation of pipes will be stainless steel 316L. For seals (e.g. valve seats, flange seals etc.) current polymer seals with or without metallic springs used for cryogenic systems in aerospace applications would need to be confirmed for longer term compatibility with hydrogen and tested for the aircraft environment. The next generation of pipes and seals will focus on lighter materials and ensuring a more reliable system installation with improved leak mitigation. A suitable lubricant needs to be identified to support static and dynamic seals in assemblies, valves & pumps in the absence of the lubrication provided by kerosene. The lubricant must support the required life of the equipment, and not present a contamination issue.

Pipes & Sealing Technology

LH_2 Pipes	Cryogenic insulated stainless-steel pipes	Lighter, more reliable, leak mitigation pipes
Connectors	Cryogenic LH_2 pipe connectors / flexible joints	Continued development in line with improvement in pipe technologies
LH_2 Sealing	LH_2 seal technology for aircraft	LH_2 self-sealing breakaway valve
LH_2 Lubrication	LH_2 lubrication technology for seals & moving parts	Increased service life, reduced maintenance
GH_2 Pipes	GH_2 pipes	Lighter, more reliable, leak mitigation pipes
GH_2 Sealing	GH_2 seal technology for aircraft	GH_2 self-sealing breakaway valve
GH_2 Lubrication	GH_2 lubrication technology for seals & moving parts	Increased service life, reduced maintenance

Joining technologies will need to be developed for standard pipework joints and dissimilar transition joints such as aluminium to stainless steel and 2xxx series to 6xxx series aluminium, considering the cryogenic hydrogen environment. Lubrication technology will need to be developed in conjunction with sealing design to support gaseous and liquid hydrogen environments, encompassing a range of applications from static to dynamic seals, and specific pump shaft sealing applications.

Self-sealing break-away valves are expected to be required to mitigate large pipework leak events, particularly relating to survivable crash scenarios. These valves would be installed at pipework joints, or at critical locations. The closed failure rate for these devices is critical. The electrical bonding capability and ignition sources around these joints would need to be addressed.

RELATED FLYZERO FURTHER READING

The ATI FlyZero project developed its technology roadmaps through a combination of broad industry consultation and assessment of technologies by experts. Technology assessment was carried out both by the FlyZero team and by approximately 50 industrial and academic organisations that partnered with FlyZero to support delivery. During the project, FlyZero developed three concept aircraft and used this exercise to gain a deep understanding of requirements and challenges for systems and technologies, which have been reflected in the roadmaps. Further detail of these technologies and developments can be found in the following reports, available to download from **ati.org.uk**:

FlyZero

Zero-Carbon Emission Aircraft Concepts

Report
Ref. FZO-AIN-REP-0007

Technology Roadmaps

Report
Ref. FZO-IST-MAP-0012

Workforce to Deliver Liquid Hydrogen Powered Aircraft

Report
Ref. FZO-IST-PPL-0053

Hydrogen Aircraft

Aerodynamic Structures

Technical Report
Ref. FZO-AIR-REP-014
Roadmap
Ref. FZO-AIR-MAP-0015
Roadmap Report
Ref. FZO-AIR-COM-0016
Capability Report
Ref. FZO-AIR-CAP-0066

Thermal Management

Technical Report
Ref. FZO-PPN-REP-017
Roadmap
Ref. FZO-PPN-MAP-0018
Roadmap Report
Ref. FZO-PPN-COM-0019
Capability Report
Ref. FZO-PPN-CAP-0067

Hydrogen Gas Turbines & Thrust Generation

Gas Turbine Technical Report
Ref. FZO-PPN-REP-020
Thrust Devices Technical Report
Ref. FZO-PPN-REP-021
Roadmap
Ref. FZO-PPN-MAP-0022
Roadmap Report
Ref. FZO-PPN-COM-0023
Capability Report
Ref. FZO-PPN-CAP-0068

Electrical Propulsion System

Technical Report
Ref. FZO-PPN-REP-0028
Roadmap
Ref. FZO-PPN-MAP-0029
Roadmap Report
Ref. FZO-PPN-COM-0030
Capability Report
Ref. FZO-PPN-CAP-0070

Fuel Cells

Technical Report
Ref. FZO-PPN-REP-0031
Roadmap
Ref. FZO-PPN-MAP-0032
Roadmap Report
Ref. FZO-PPN-COM-0033
Capability Report
Ref. FZO-PPN-CAP-0071

Cryogenic Hydrogen Fuel System & Storage

Fuel System Technical Report
Ref. FZO-PPN-REP-024
Fuel Storage Technical Report
Ref. FZO-PPN-REP-025
Roadmap
Ref. FZO-PPN-MAP-0026
Roadmap Report
Ref. FZO-PPN-COM-0027
Capability Report
Ref. FZO-PPN-CAP-0069

Cross-Cutting

Aircraft Systems
Ref. FZO-AIR-POS-0013

Airports, Airlines, Airspace - Operations & Hydrogen Infrastructure
Ref. FZO-CST-POS-0035

Advanced Materials
Ref. FZO-IST-POS-0036

Lifecycle Impact
Ref. FZO-STY-POS-0034

Sustainable Cabin Design
Ref. FZO-AIR-POS-0039

Compressed Design and Validation - Culture and Digital Tools
Ref. FZO-IST-POS-0038

Advanced Manufacturing
Ref. FZO-IST-POS-0037

ABOUT FLYZERO

Led by the Aerospace Technology Institute and backed by the UK government, FlyZero began in early 2021 as an intensive research project investigating zero-carbon emission commercial flight. This independent study has brought together experts from across the UK to assess the design challenges, manufacturing demands, operational requirements and market opportunity of potential zero-carbon emission aircraft concepts.

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

This report forms part of a suite of FlyZero outputs which will help shape the future of global aviation with the intention of gearing up the UK to stand at the forefront of sustainable flight in design, manufacture, technology and skills for years to come. To discover more and download the FlyZero reports, visit **ati.org.uk**

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Lead authors

John Turner
Structural Design Lead

Stephanie Contaut
Fuel Systems Lead

Co-authors
Alessio Tarantino, Andrew Masson

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These roadmaps have been developed with a view to accelerate zero-carbon technology development and maximise the potential future value for the UK. They are unconstrained by the availability of funding.

Department for
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CRYOGENIC HYDROGEN FUEL SYSTEM AND STORAGE

Roadmap Report

FLY ZERO

AEROSPACE
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