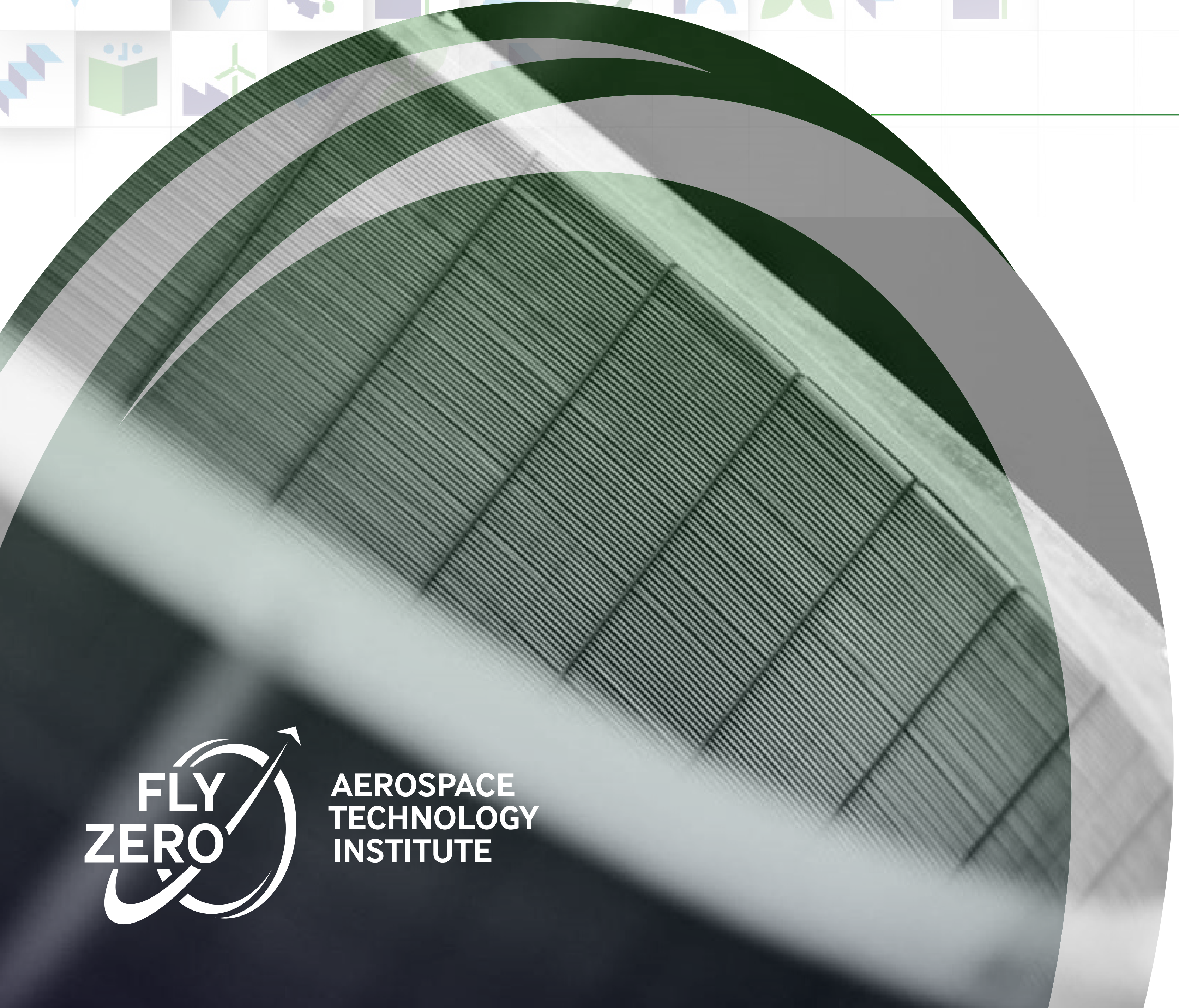
THERMAL MANAGEMENT

Roadmap Report



FLY ZERO

AEROSPACE
TECHNOLOGY
INSTITUTE

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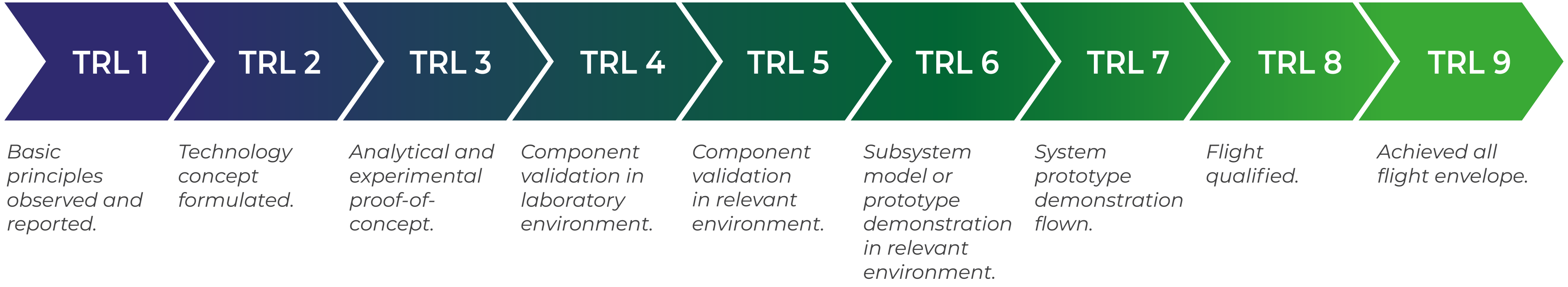
CONTENTS

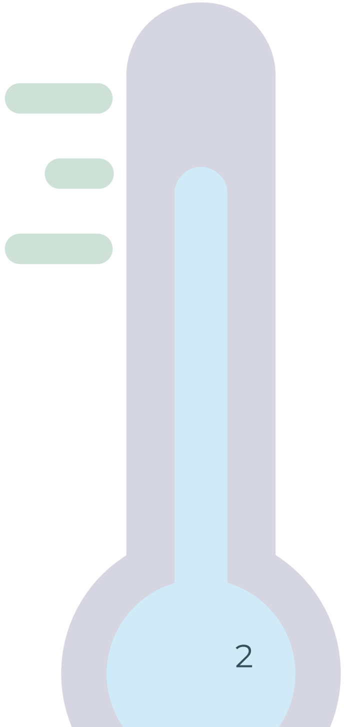
KEY

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: THERMAL MANAGEMENT

The Thermal Management Roadmap Report summarises the heat exchanger technologies considered essential for enabling zero-carbon liquid hydrogen fuelled aircraft. Competitive heat exchanger technologies are also outlined for later Entry Into Service (EIS) aircraft. Enabling technologies (materials, manufacturing, design and testing capability), underpinning both the essential and competitive heat exchanger technologies, are subsequently provided. The essential and competitive heat exchanger technologies and enabling technologies are outlined to Technology Readiness Level (TRL) 6 (prototype demonstration on the ground).

The heat exchanger technologies focus on those required to manage the thermal challenges of hydrogen fuelled gas turbines and fuel cells (where the hydrogen fuel is stored on board the aircraft as a liquid at cryogenic temperatures in the tanks).

For hydrogen gas turbines, technology development of heat exchangers to heat the hydrogen fuel is essential prior to entry to the combustion chamber. Further heating can also provide substantial reductions in fuel burn. Some hydrogen heating can be achieved with oil cooling, with additional heating required via alternative means. A low pressure drop heat exchanger in the exhaust gas path (a recuperator) provides effective heating and desirable gas turbine performance gains.

For hydrogen fuel cells, a low pressure drop, high power density air radiator is essential to dissipate the heat from a fuel cell. Current technology using vapour-condensation cycles and low temperature fuel cells drive added system complexity and mass. Developing high temperature fuel cells is a key enabler to reducing the size of air radiators and allowing for much greater simplification of the fuel cell balance of plant.

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.

FUEL CELL THERMAL MANAGEMENT TECHNOLOGY INDICATORS

		2026	2035	2050
LT-PEM FC operating temperature	°C	80	100	
HT-PEM FC operating temperature	°C	–	160	> 160
Heat rejection temperature	°C	100	100 (LT-PEM), 160 (HT-PEM)	> 160 (HT-PEM)
Heat rejection cycle	–	Vapour Compression	Liquid	
FC thermal management system specific heat rejection	kW/kg	5	10 (LT-PEM), 20 (HT-PEM)	> 20 (HT-PEM)

Notes and Commentary

- The main thermal management challenge presented by hydrogen fuel cells is the heat rejection system for the fuel cell stacks (a result of stack operating efficiency, aircraft power demand and having to reject heat with small temperature differences between the fuel cell and ambient air).
- For near term low temperature proton-exchange membrane (LT-PEM) fuel cell (FC) solutions, the heat rejection temperature difference can be increased marginally (~20°C) with the use of a vapour compression cycle. This offers some reduction in the size of heat rejection heat exchangers, at the expense of increased cycle complexity, and a resulting system specific heat rejection (heat rejection rate / thermal management total system mass) of ~ 5 kW/ kg.
- If high temperature (HT) PEM fuel cells can be developed, substantial gains in specific heat rejection performance are possible due to the significant reduction in heat exchanger size and the transition to simpler liquid coolant cycles.
- The transition from LT-PEM to HT-PEM FC systems is driven by both the fuel cell stack performance and the balance of plant performance (for which the heat rejection system is the biggest contributor). If 2035 HT-PEM performance targets can be met, the overall specific power of LT-PEM and HT-PEM FC systems becomes comparable. Further increases in fuel cell operating temperature beyond this would enable a complete transition to HT-PEM FC systems.
- For more detail see the ATI FlyZero 'Thermal Management Technical Report' and the ATI FlyZero 'Fuel Cells Technical Report'.

FUEL CELL THERMAL MANAGEMENT TECHNOLOGY INDICATORS

			2026	2035	2050
Reference Fuel Cell and Operating Temperature			LT (80 °C)	HT (160 °C)	HT (>160 °C)
Air radiator	Specific heat rejection	kW/kg	10	20	30
(Heat rejection system)	Power loss	kW/kW (%)	20	15	10
Air precooler	Specific heat rejection	kW/kg	5	n/a	
(Air delivery system)	Power loss	kW/kW (%)	5		
Precooler heat sink (Air and fuel delivery systems)	Specific heat rejection	kW/kg	10		
Fuel heater (Fuel delivery system)	Specific heat rejection	kW/kg	25	35	> 35
Time to first shop visit / overhaul (hrs)			30,000	35,000	45,000
Cost $/kW			120	100	80

Notes and Commentary

- Technology indicators are provided for the key fuel cell balance of plant heat exchangers in terms of specific heat rejection (heat rejection rate / heat exchanger mass) and power loss (the drag and pumping power of both the heatant and coolant streams per kilowatt of heat rejected).
- The air radiators that dissipate the heat generated from the fuel cell stack present the biggest challenge, with heat transfer rates in the order of megawatts. Near term low specific heat rejection and high power loss values are driven by low fuel cell stack operating temperatures.
- Precooling of the air source for LT-PEM FCs is required. Although the heat transfer demand is much less than required of the air radiators, low specific heat rejection values (driven by surface temperature control) and modest drag factors present a not insignificant impact to aircraft performance.
- Power loss is minimal for high density fluid heat exchangers such as the air precooler heat sink and hydrogen fuel heater, with improving values of specific heat rejection as surface and fluid temperature constraints ease.
- Time on wing in hours will need to be maintained and improved as it is a major part of the operating costs for an airline. Components operating in the hydrogen environment face the additional challenges of hydrogen embrittlement and wide operating temperatures.
- Unit cost divided by heat transfer demand: continued cost reductions through advances in manufacturing, design simplification and batch processing etc.

GAS TURBINE THERMAL MANAGEMENT TECHNOLOGY INDICATORS

		2026	2035	2050
Hydrogen gas turbine cycle	–	Generation 1	Generation 2	Generation 3
Hydrogen gas turbine cycle heat exchangers		Oil / Fuel Recuperator	Oil / Fuel Recuperator Cooled-cooling	Oil / Fuel* Recuperator* Cooled-cooling*
Contribution to total efficiency (relative to kerosene engine)	%	1.5	1.7	2.9

Notes and Commentary

- The thermal management challenge presented by hydrogen fuelled gas turbines is centred around the need to heat the hydrogen fuel from cryogenic storage temperatures (-253˚C) to warmer temperatures that aid combustion and improve the overall performance of the gas turbine.
- Three generations of hydrogen gas turbine cycles, of increasing complexity but increasing engine performance are proposed.
- The first-generation hydrogen gas turbine cycle proposes two stages of heat exchange; first using the heat available from oil cooling, and secondly using the heat from the engine core exhaust, known as recuperation (for optimum engine performance, and to achieve temperatures aiding combustion efficiency, further heating of the hydrogen is required beyond that available from the oil alone). Beyond this, further performance could be achieved with the addition of a cooled-cooling air heat exchanger (Generation 2), and with the use of a high-pressure hydrogen expander cycle (Generation 3).
- *Generation 3 hydrogen gas turbine cycle heat exchangers will need to withstand much higher hydrogen operating pressures.
- The net contribution to gas turbine total efficiency (made by the use of hydrogen as a fuel, enabled by the heat exchanger technology) for each of the three generations of cycles is provided.
- For more details see the ATI FlyZero 'Hydrogen Gas Turbines Technical Report'.

GAS TURBINE THERMAL MANAGEMENT TECHNOLOGY INDICATORS

			2026	2035	2050
Oil / fuel	Specific heat rejection	kW/kg	20	> 20	> 20*
Recuperator	Specific heat rejection	kW/kg	20	> 20	> 20*
	Power loss	kW/kW (%)	10	> 10	> 10*
Cooled-cooling air	Specific heat rejection	kW/kg	–	20	> 20*
	Power loss	kW/kW (%)		10	> 10*
Time to first shop visit / overhaul (hrs)			30,000	35,000	45,000
Cost $/kW			120	100	80

Notes and Commentary

- Technology indicators are provided for the hydrogen gas turbine cycle heat exchangers in terms of specific heat rejection (heat rejection rate / heat exchanger mass) and power loss (the drag and pumping power of both the heatant and coolant streams per kilowatt of heat rejected).
- Heat exchangers with low density gas paths (recuperator and cooled-cooling air) are particularly sensitive to air-side pressure drop, which will need to be minimised in order not to erode the gains in fuel burn made by warming the hydrogen. Note, a detailed heat exchanger sizing study has not been conducted on the cooled-cooling air heat exchangers, and thus the recuperator indicators are assumed in this instance given the similarity in temperature differences between heatant and coolant and the constraints on drag power.
- The specific heat rejection capability of the oil/fuel and recuperator heat exchangers solutions will be challenged by the need to manage wall temperatures to prevent congealing of the oil and surface frost in surfaces exposed to air respectively.
- *Generation 3 hydrogen gas turbine cycle heat exchangers will need to withstand much higher hydrogen operating pressures.
- The heat transfer demand for the gas turbine cycle heat exchangers is relatively low. Achieving mass and drag performance targets will be much less challenging than achieving life targets. In particular, the recuperator and cooled-cooling air heat exchangers will be subject to both hydrogen and high temperatures, requiring the development of high temperature/strength and hydrogen embrittlement resistant materials.
- Unit cost divided by heat transfer demand: continued cost reductions through advances in manufacturing, design simplification and batch processing etc.

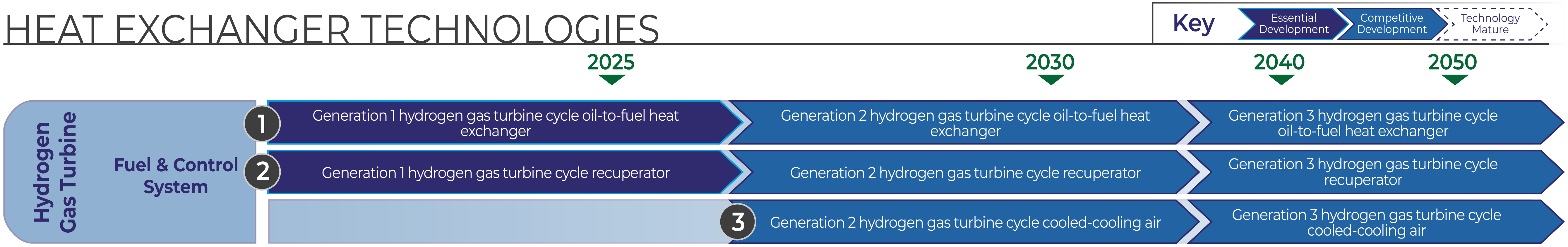
HEAT EXCHANGER TECHNOLOGIES ROADMAP

Key: Essential Development | Competitive Development | Technology Mature

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	

Note: The Thermal Management Roadmap Report summarises the essential and competitive heat exchanger technologies necessary to achieve the technology indicators outlined in ATI FlyZero 'Hydrogen Gas Turbines and Thrust Generation Roadmap Report', ATI FlyZero 'Fuel Cells Roadmap Report' and ATI FlyZero 'Cryogenic Hydrogen Fuel System and Storage Roadmap Report' respectively.

HEAT EXCHANGER TECHNOLOGIES



1 Oil-to-fuel heat exchanger

A fundamental part of the cryogenic fuel system design is heating the fuel to an acceptable level before combustion. As the oil in the gas turbine needs cooling and the fuel needs heating a fuel/oil heat exchanger is a logical device to deliver this functionality. The oil/fuel heat exchanger will need to be designed to accept hydrogen at cryogenic temperatures (~20 - 40K) whilst ensuring sufficiently high wall temperatures so as not to overly cool the oil. Should this pose significant risk, a warmer / intermediate fluid could be used. Generation 2 oil/fuel heat exchanger indicates an improvement on mass and pressure drop. Generation 3 oil/fuel heat exchanger may need to be designed for much higher operating pressures for compatibility with the generation 3 hydrogen gas turbine expander cycle.

2 Recuperator

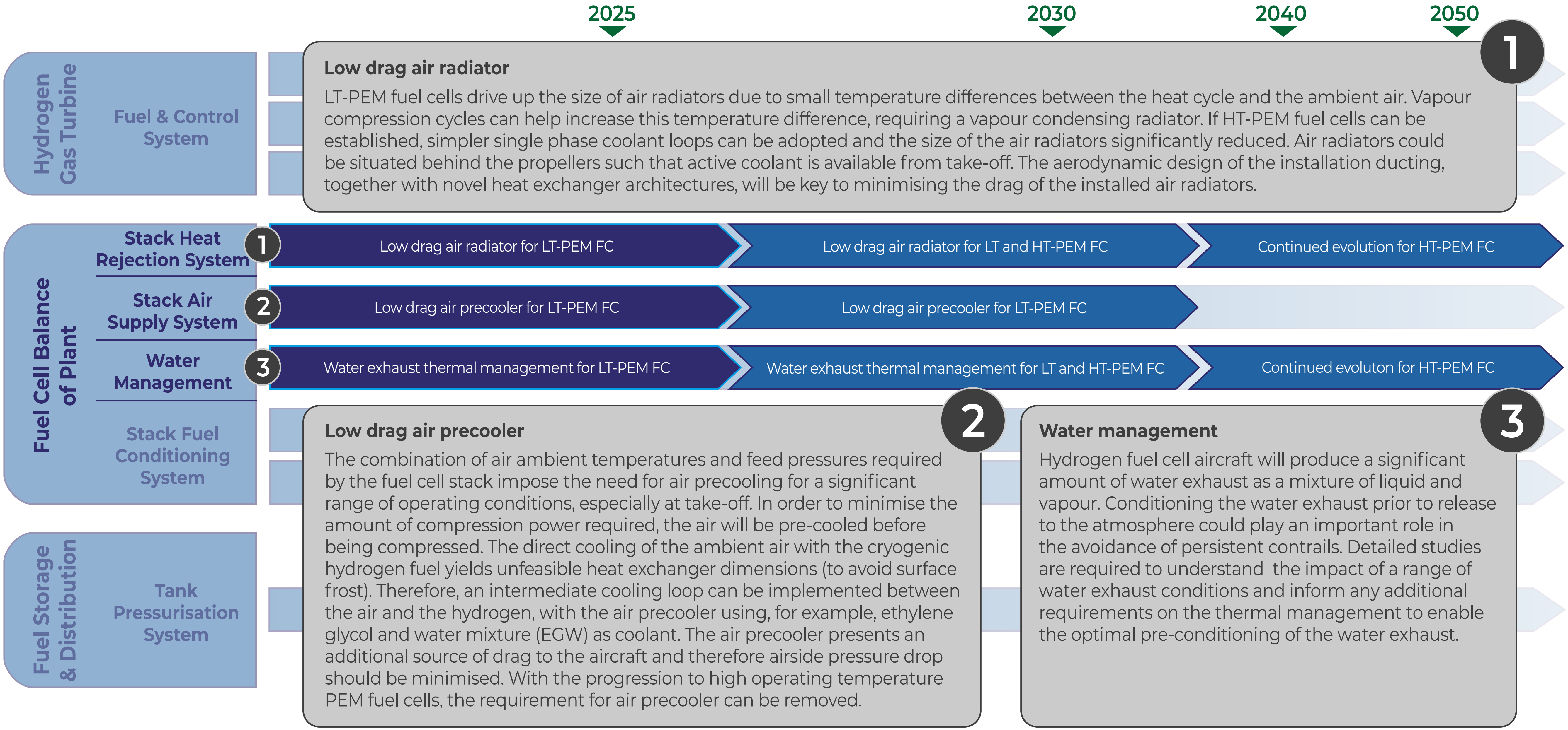
The heat capacity from the oil of the gas turbine may not be sufficient to heat the hydrogen to the desired combustor conditions. In addition, heating the fuel further can decrease the engine specific fuel consumption, provided this benefit is not eroded by the heat exchanger pressure losses. The recuperator uses the hot turbine gas exhaust to heat the hydrogen fuel. To minimise system mass, the hydrogen can be passed directly through the recuperator and will need to be sized accordingly to maintain wall surface temperatures above zero on the exhaust side to prevent frost formation. Minimising the recuperator airside pressure drop is critical to maximising the achievable fuel delivery temperature and careful design of installation ducting will be required to guide the flow into and out of the heat exchanger. Should wall temperature management or heating the hydrogen directly in the exhaust path challenge operability and safety management, an intermediate fluid can be used at the expense of increased system mass. Generation 2 recuperator indicates an improvement on mass and pressure drop. Generation 3 recuperator would need to be designed for much higher operating pressures for compatibility with the generation 3 hydrogen gas turbine expander cycle.

3 Cooled-cooling air heat exchanger

An additional heat exchanger can be used to cool down the cooling air used for the turbine blades, using the hydrogen fuel as the heat sink. The air flow is typically taken from the high-pressure compressor exit and can still be at a temperature over 900 K during take-off. If this temperature can be reduced then less cooling air is required, which has significant specific fuel consumption benefits. However, the heat exchanger needs to have a low-pressure loss to maintain a healthy film pressure margin across the blade cooling holes. The addition of a cooled-cooling air heat exchanger adds further cycle complexity and is therefore considered a second-generation technology. A generation 3 cooled-cooling air heat exchanger would need to be designed for the much higher operating pressures of a hydrogen expansion cycle. As the hydrogen will be warm entering the cooled-cooling air heat exchanger, managing wall surface temperature is no longer a problem. However, the heat exchanger will need to operate in both a hydrogen environment and at hot temperatures, posing a significant challenge to material strength and life.

HEAT EXCHANGER TECHNOLOGIES

Key: Essential Development | Competitive Development | Technology Mature



2025 | 2030 | 2040 | 2050

Hydrogen Gas Turbine

- Fuel & Control System

Fuel Cell Balance of Plant

- **Stack Heat Rejection System** ①: 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** ②: Low drag air precooler for LT-PEM FC → Low drag air precooler for LT-PEM FC
- **Water Management** ③: 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

Fuel Storage & Distribution

- Tank Pressurisation System

① **Low drag air radiator**

LT-PEM fuel cells drive up the size of air radiators due to small temperature differences between the heat cycle and the ambient air. Vapour compression cycles can help increase this temperature difference, requiring a vapour condensing radiator. If HT-PEM fuel cells can be established, simpler single phase coolant loops can be adopted and the size of the air radiators significantly reduced. Air radiators could be situated behind the propellers such that active coolant is available from take-off. The aerodynamic design of the installation ducting, together with novel heat exchanger architectures, will be key to minimising the drag of the installed air radiators.

② **Low drag air precooler**

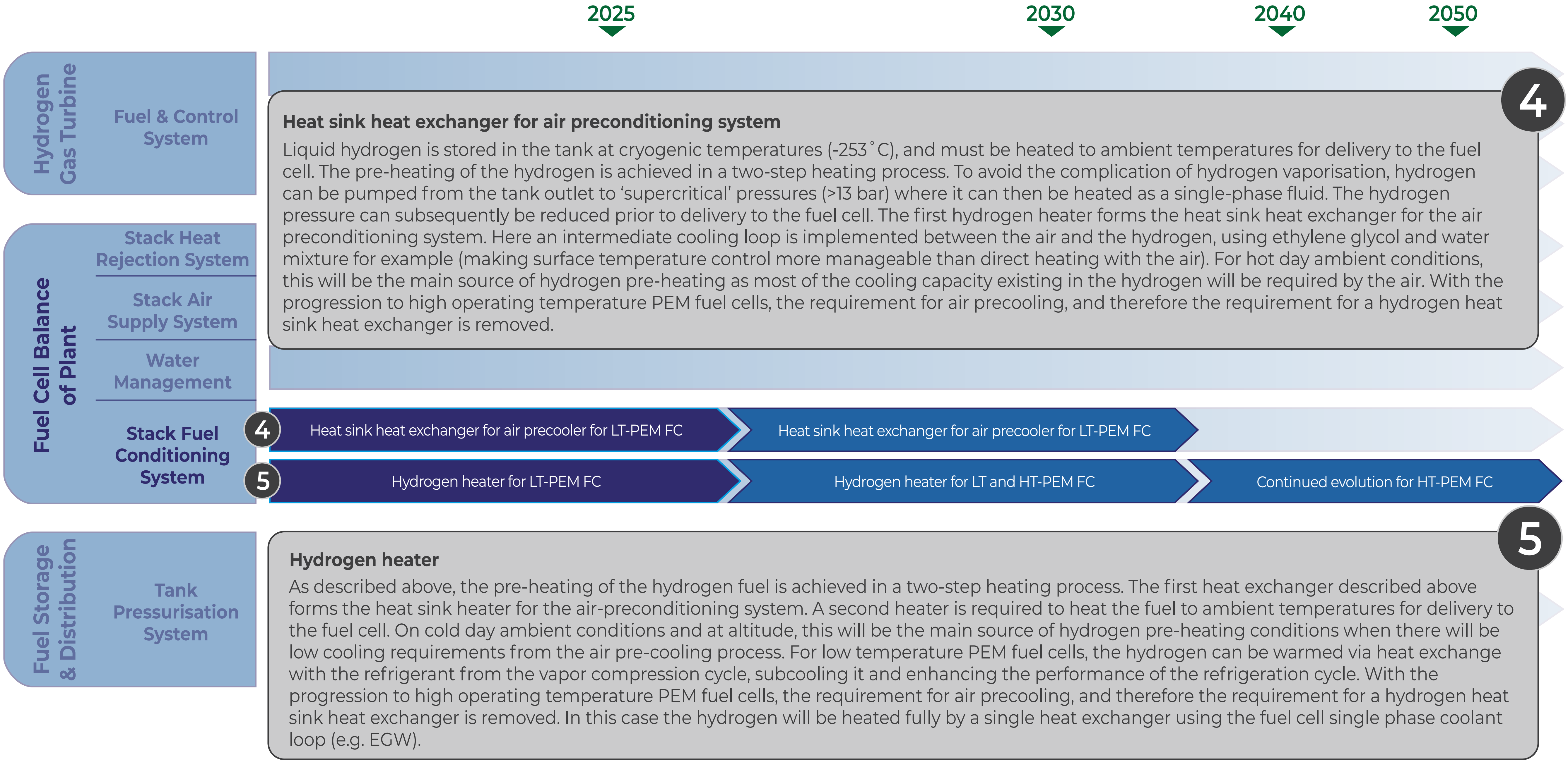
The combination of air ambient temperatures and feed pressures required by the fuel cell stack impose the need for air precooling for a significant range of operating conditions, especially at take-off. In order to minimise the amount of compression power required, the air will be pre-cooled before being compressed. The direct cooling of the ambient air with the cryogenic hydrogen fuel yields unfeasible heat exchanger dimensions (to avoid surface frost). Therefore, an intermediate cooling loop can be implemented between the air and the hydrogen, with the air precooler using, for example, ethylene glycol and water mixture (EGW) as coolant. The air precooler presents an additional source of drag to the aircraft and therefore airside pressure drop should be minimised. With the progression to high operating temperature PEM fuel cells, the requirement for air precooler can be removed.

③ **Water management**

Hydrogen fuel cell aircraft will produce a significant amount of water exhaust as a mixture of liquid and vapour. Conditioning the water exhaust prior to release to the atmosphere could play an important role in the avoidance of persistent contrails. Detailed studies are required to understand the impact of a range of water exhaust conditions and inform any additional requirements on the thermal management to enable the optimal pre-conditioning of the water exhaust.

HEAT EXCHANGER TECHNOLOGIES

Key: Essential Development | Competitive Development | Technology Mature



4

Heat sink heat exchanger for air preconditioning system

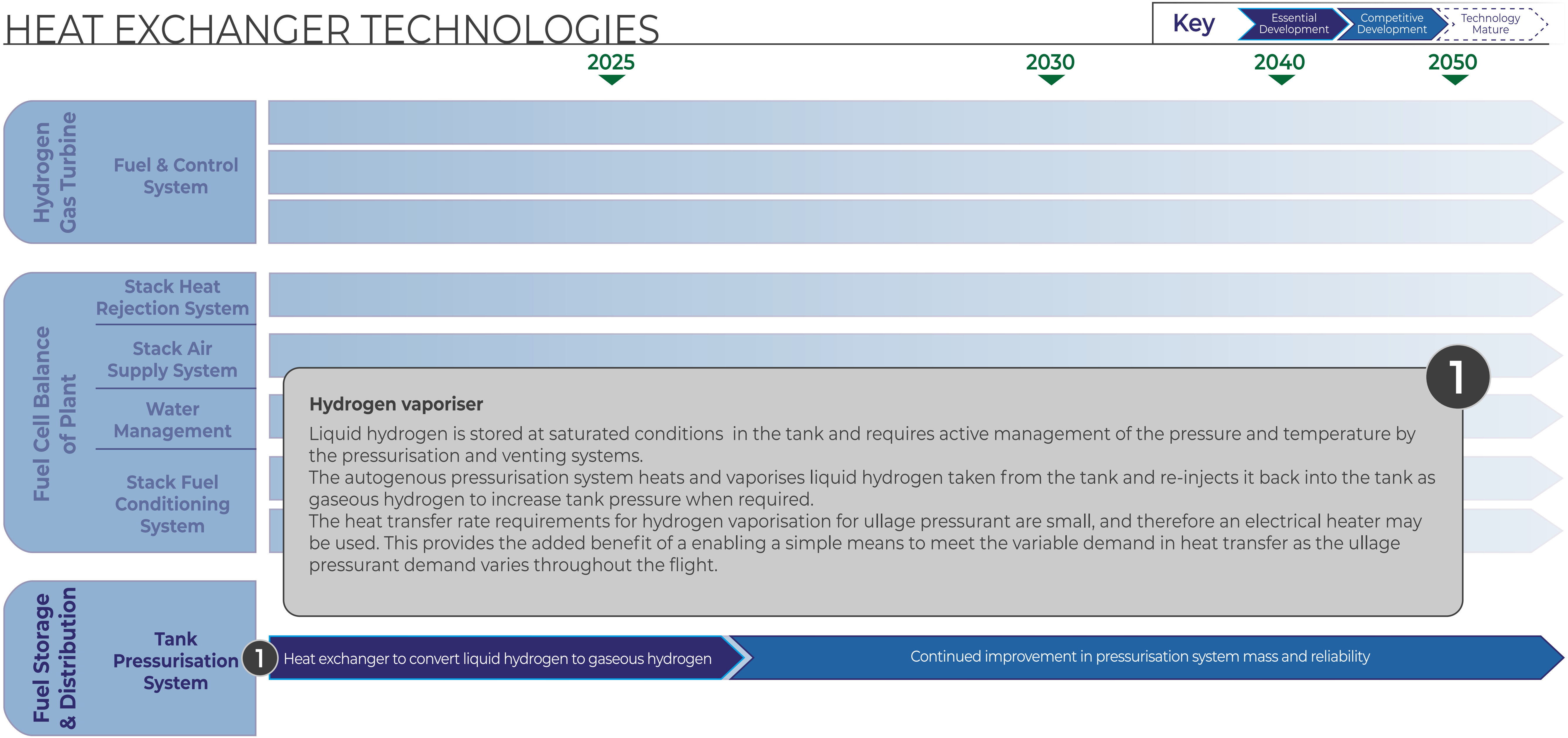
Liquid hydrogen is stored in the tank at cryogenic temperatures (-253 ˚C), and must be heated to ambient temperatures for delivery to the fuel cell. The pre-heating of the hydrogen is achieved in a two-step heating process. To avoid the complication of hydrogen vaporisation, hydrogen can be pumped from the tank outlet to 'supercritical' pressures (>13 bar) where it can then be heated as a single-phase fluid. The hydrogen pressure can subsequently be reduced prior to delivery to the fuel cell. The first hydrogen heater forms the heat sink heat exchanger for the air preconditioning system. Here an intermediate cooling loop is implemented between the air and the hydrogen, using ethylene glycol and water mixture for example (making surface temperature control more manageable than direct heating with the air). For hot day ambient conditions, this will be the main source of hydrogen pre-heating as most of the cooling capacity existing in the hydrogen will be required by the air. With the progression to high operating temperature PEM fuel cells, the requirement for air precooling, and therefore the requirement for a hydrogen heat sink heat exchanger is removed.

5

Hydrogen heater

As described above, the pre-heating of the hydrogen fuel is achieved in a two-step heating process. The first heat exchanger described above forms the heat sink heater for the air-preconditioning system. A second heater is required to heat the fuel to ambient temperatures for delivery to the fuel cell. On cold day ambient conditions and at altitude, this will be the main source of hydrogen pre-heating conditions when there will be low cooling requirements from the air pre-cooling process. For low temperature PEM fuel cells, the hydrogen can be warmed via heat exchange with the refrigerant from the vapor compression cycle, subcooling it and enhancing the performance of the refrigeration cycle. With the progression to high operating temperature PEM fuel cells, the requirement for air precooling, and therefore the requirement for a hydrogen heat sink heat exchanger is removed. In this case the hydrogen will be heated fully by a single heat exchanger using the fuel cell single phase coolant loop (e.g. EGW).

HEAT EXCHANGER TECHNOLOGIES



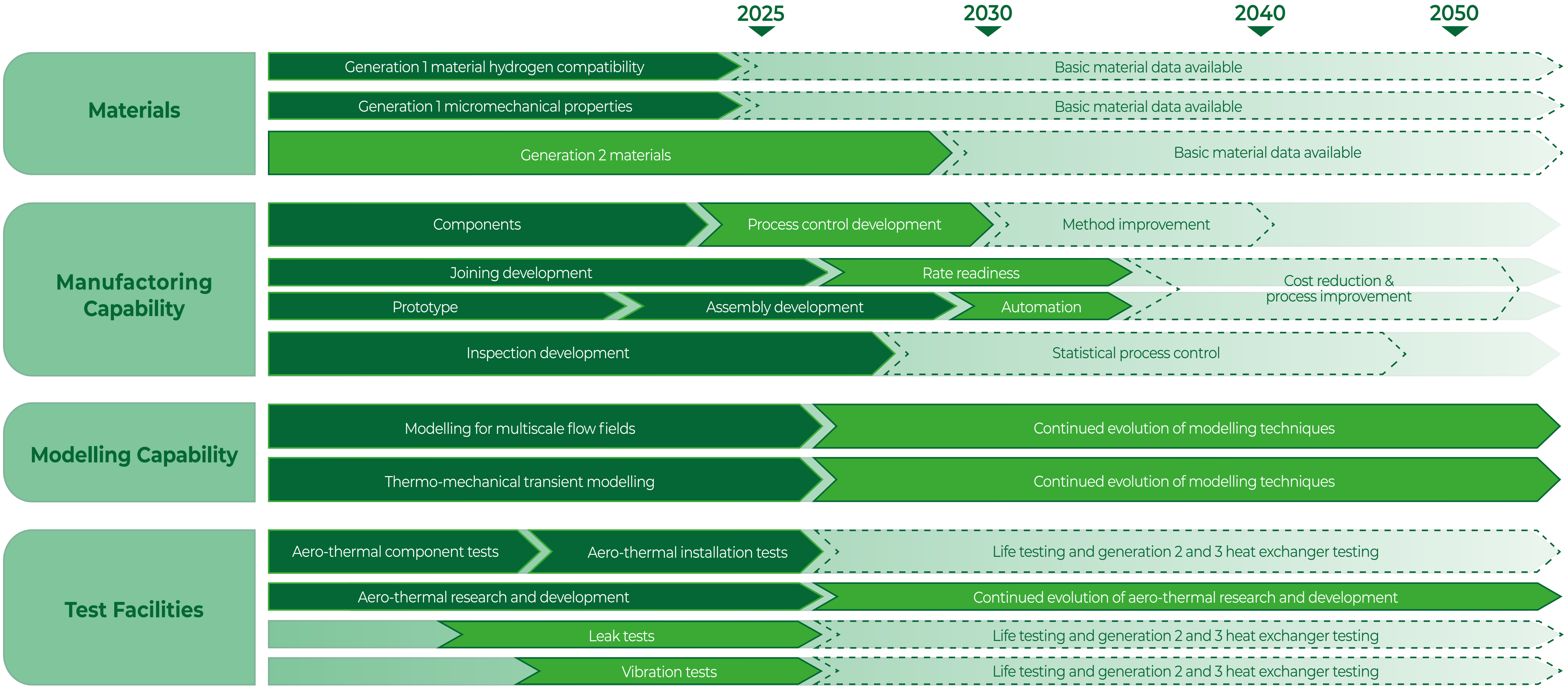
Hydrogen vaporiser

Liquid hydrogen is stored at saturated conditions in the tank and requires active management of the pressure and temperature by the pressurisation and venting systems.
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.
The heat transfer rate requirements for hydrogen vaporisation for ullage pressurant are small, and therefore an electrical heater may be used. This provides the added benefit of a enabling a simple means to meet the variable demand in heat transfer as the ullage pressurant demand varies throughout the flight.

Note: Fuel storage - tank active refrigeration
Active cooling systems are seen as a means to maintain cryogenic temperatures or minimise boil-off during flight, for dormancy periods on the ground or in any emergent heat rise condition. A survey of current technologies for active cooling systems shows this science is too immature for on-board flight due to power consumption and system mass. Further research should be made to realise any opportunity for active cooling systems.

HEAT EXCHANGER ENABLERS ROADMAP

Key
- Essential Enabler
- Competitive Enabler
- Technology Mature



2025 **2030** **2040** **2050**

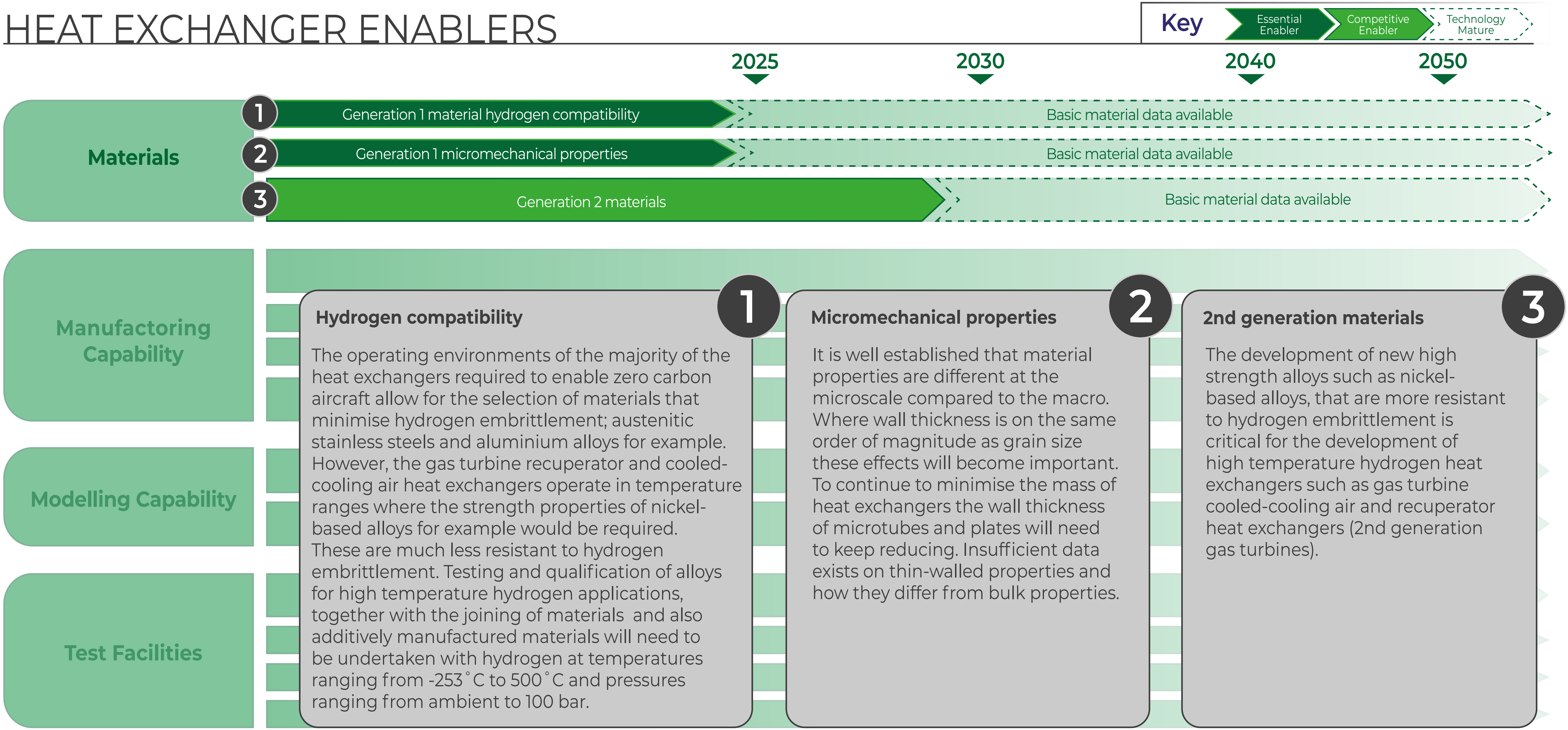
Materials
- Generation 1 material hydrogen compatibility → Basic material data available
- Generation 1 micromechanical properties → Basic material data available
- Generation 2 materials → Basic material data available

Manufactoring 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

HEAT EXCHANGER ENABLERS



1 Hydrogen compatibility

The operating environments of the majority of the heat exchangers required to enable zero carbon aircraft allow for the selection of materials that minimise hydrogen embrittlement; austenitic stainless steels and aluminium alloys for example. However, the gas turbine recuperator and cooled-cooling air heat exchangers operate in temperature ranges where the strength properties of nickel-based alloys for example would be required. These are much less resistant to hydrogen embrittlement. Testing and qualification of alloys for high temperature hydrogen applications, together with the joining of materials and also additively manufactured materials will need to be undertaken with hydrogen at temperatures ranging from -253˚C to 500˚C and pressures ranging from ambient to 100 bar.

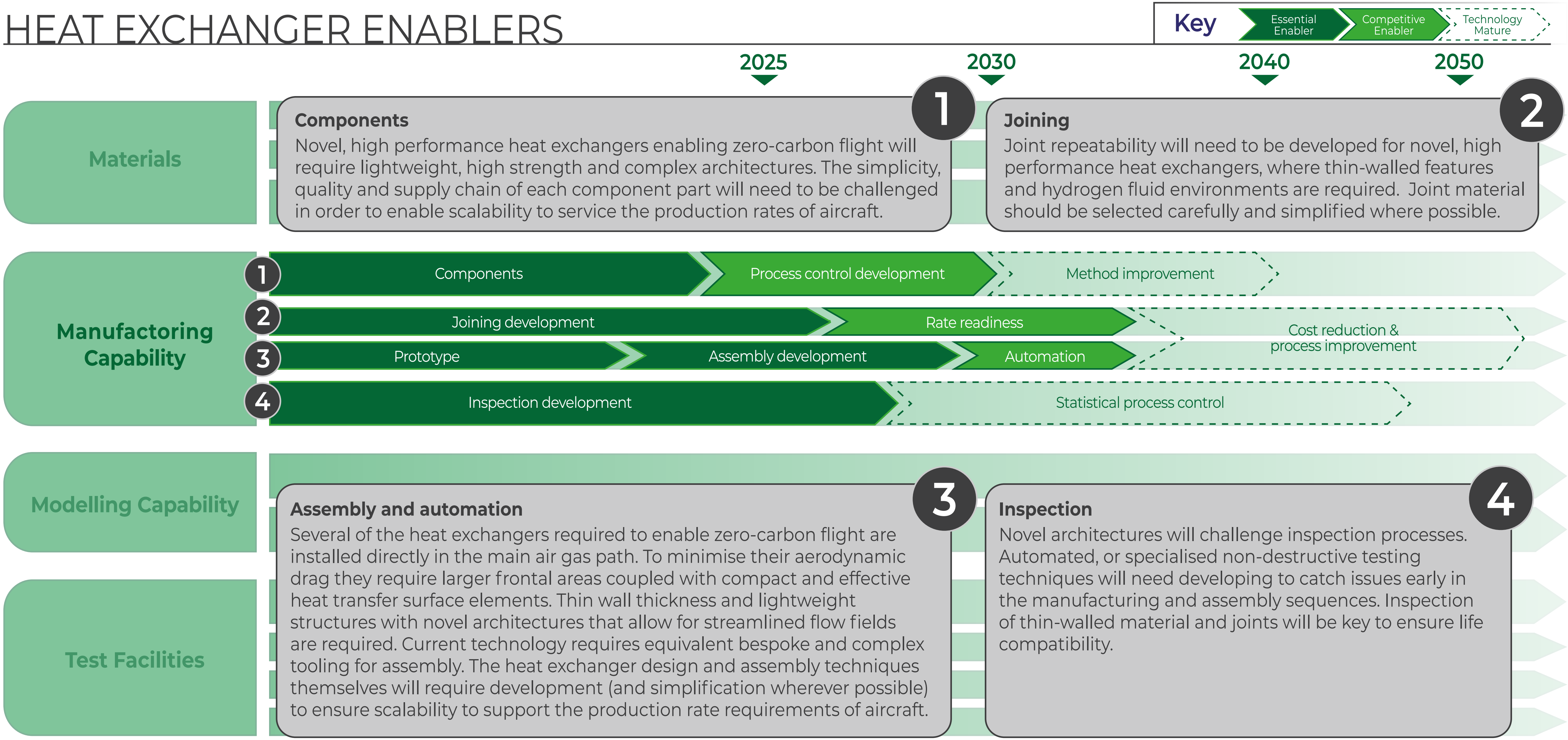
2 Micromechanical properties

It is well established that material properties are different at the microscale compared to the macro. Where wall thickness is on the same order of magnitude as grain size these effects will become important. To continue to minimise the mass of heat exchangers the wall thickness of microtubes and plates will need to keep reducing. Insufficient data exists on thin-walled properties and how they differ from bulk properties.

3 2nd generation materials

The development of new high strength alloys such as nickel-based alloys, that are more resistant to hydrogen embrittlement is critical for the development of high temperature hydrogen heat exchangers such as gas turbine cooled-cooling air and recuperator heat exchangers (2nd generation gas turbines).

HEAT EXCHANGER ENABLERS



1

Components

Novel, high performance heat exchangers enabling zero-carbon flight will require lightweight, high strength and complex architectures. The simplicity, quality and supply chain of each component part will need to be challenged in order to enable scalability to service the production rates of aircraft.

2

Joining

Joint repeatability will need to be developed for novel, high performance heat exchangers, where thin-walled features and hydrogen fluid environments are required. Joint material should be selected carefully and simplified where possible.

3

Assembly and automation

Several of the heat exchangers required to enable zero-carbon flight are installed directly in the main air gas path. To minimise their aerodynamic drag they require larger frontal areas coupled with compact and effective heat transfer surface elements. Thin wall thickness and lightweight structures with novel architectures that allow for streamlined flow fields are required. Current technology requires equivalent bespoke and complex tooling for assembly. The heat exchanger design and assembly techniques themselves will require development (and simplification wherever possible) to ensure scalability to support the production rate requirements of aircraft.

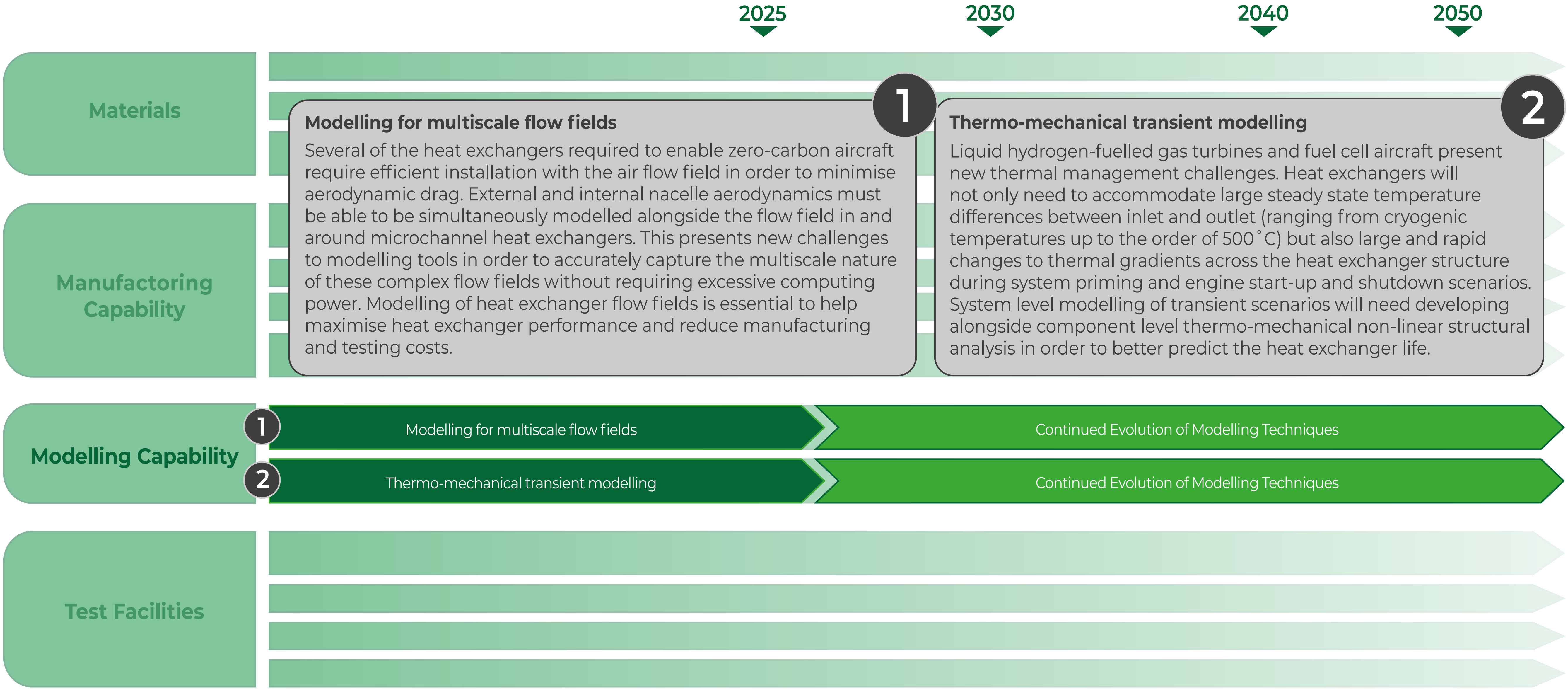
4

Inspection

Novel architectures will challenge inspection processes. Automated, or specialised non-destructive testing techniques will need developing to catch issues early in the manufacturing and assembly sequences. Inspection of thin-walled material and joints will be key to ensure life compatibility.

HEAT EXCHANGER ENABLERS

Key Essential Enabler | Competitive Enabler | Technology Mature



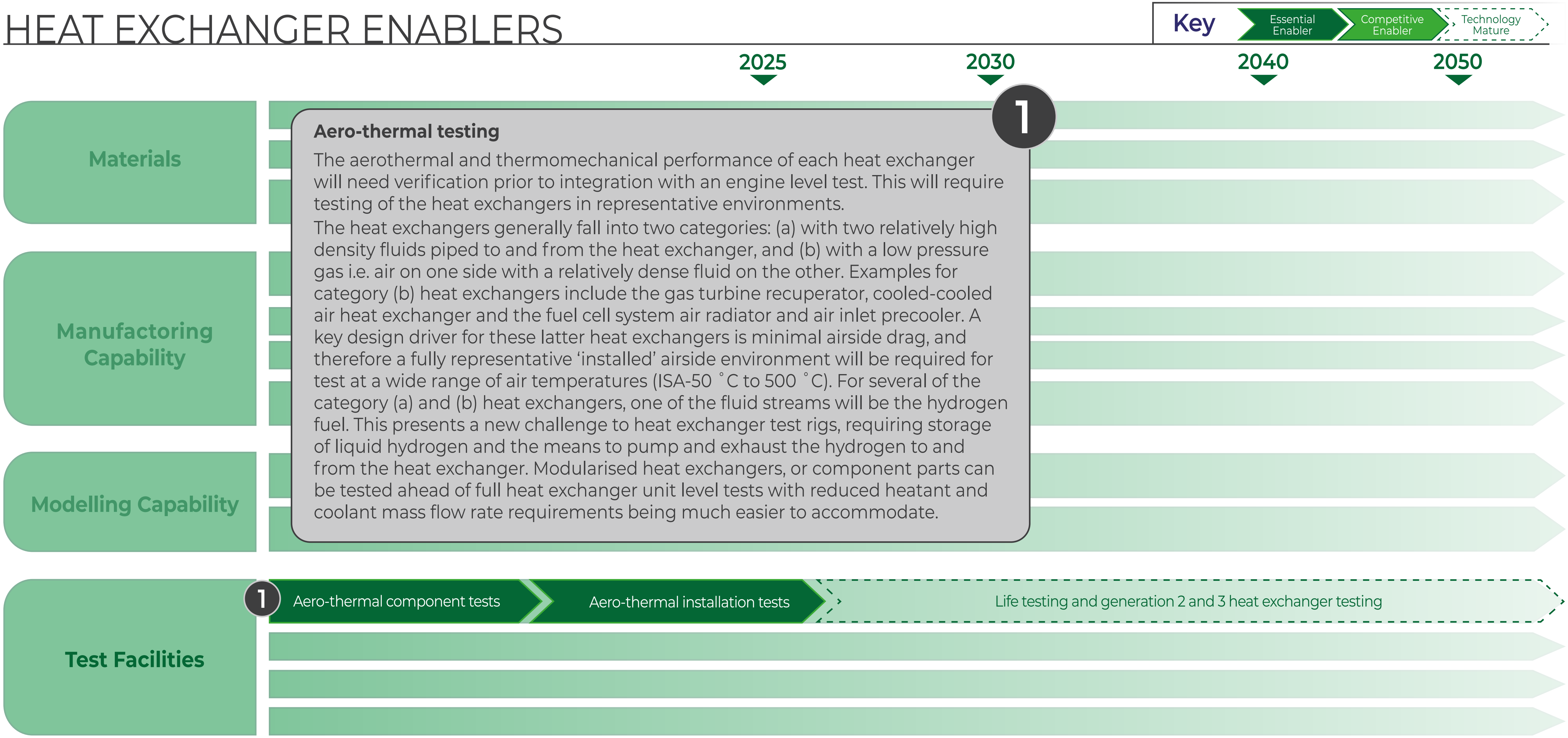
① **Modelling for multiscale flow fields**

Several of the heat exchangers required to enable zero-carbon aircraft require efficient installation with the air flow field in order to minimise aerodynamic drag. External and internal nacelle aerodynamics must be able to be simultaneously modelled alongside the flow field in and around microchannel heat exchangers. This presents new challenges to modelling tools in order to accurately capture the multiscale nature of these complex flow fields without requiring excessive computing power. Modelling of heat exchanger flow fields is essential to help maximise heat exchanger performance and reduce manufacturing and testing costs.

② **Thermo-mechanical transient modelling**

Liquid hydrogen-fuelled gas turbines and fuel cell aircraft present new thermal management challenges. Heat exchangers will not only need to accommodate large steady state temperature differences between inlet and outlet (ranging from cryogenic temperatures up to the order of 500 °C) but also large and rapid changes to thermal gradients across the heat exchanger structure during system priming and engine start-up and shutdown scenarios. System level modelling of transient scenarios will need developing alongside component level thermo-mechanical non-linear structural analysis in order to better predict the heat exchanger life.

HEAT EXCHANGER ENABLERS



1

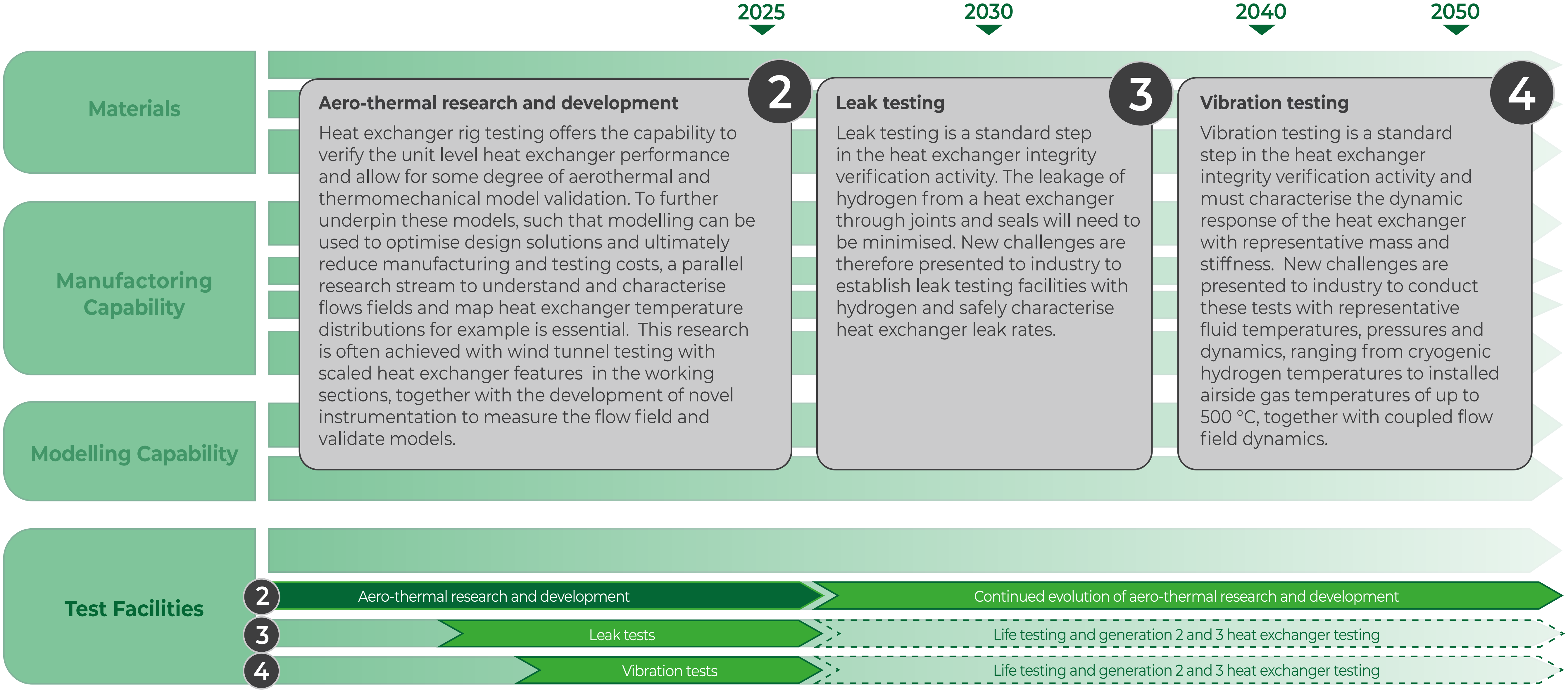
Aero-thermal testing

The aerothermal and thermomechanical performance of each heat exchanger will need verification prior to integration with an engine level test. This will require testing of the heat exchangers in representative environments.

The heat exchangers generally fall into two categories: (a) with two relatively high density fluids piped to and from the heat exchanger, and (b) with a low pressure gas i.e. air on one side with a relatively dense fluid on the other. Examples for category (b) heat exchangers include the gas turbine recuperator, cooled-cooled air heat exchanger and the fuel cell system air radiator and air inlet precooler. A key design driver for these latter heat exchangers is minimal airside drag, and therefore a fully representative 'installed' airside environment will be required for test at a wide range of air temperatures (ISA-50 ˚C to 500 ˚C). For several of the category (a) and (b) heat exchangers, one of the fluid streams will be the hydrogen fuel. This presents a new challenge to heat exchanger test rigs, requiring storage of liquid hydrogen and the means to pump and exhaust the hydrogen to and from the heat exchanger. Modularised heat exchangers, or component parts can be tested ahead of full heat exchanger unit level tests with reduced heatant and coolant mass flow rate requirements being much easier to accommodate.

HEAT EXCHANGER ENABLERS

Key: Essential Enabler | Competitive Enabler | Technology Mature



2025 | 2030 | 2040 | 2050

Materials

Manufactoring Capability

Modelling Capability

2 **Aero-thermal research and development**

Heat exchanger rig testing offers the capability to verify the unit level heat exchanger performance and allow for some degree of aerothermal and thermomechanical model validation. To further underpin these models, such that modelling can be used to optimise design solutions and ultimately reduce manufacturing and testing costs, a parallel research stream to understand and characterise flows fields and map heat exchanger temperature distributions for example is essential. This research is often achieved with wind tunnel testing with scaled heat exchanger features in the working sections, together with the development of novel instrumentation to measure the flow field and validate models.

3 **Leak testing**

Leak testing is a standard step in the heat exchanger integrity verification activity. The leakage of hydrogen from a heat exchanger through joints and seals will need to be minimised. New challenges are therefore presented to industry to establish leak testing facilities with hydrogen and safely characterise heat exchanger leak rates.

4 **Vibration testing**

Vibration testing is a standard step in the heat exchanger integrity verification activity and must characterise the dynamic response of the heat exchanger with representative mass and stiffness. New challenges are presented to industry to conduct these tests with representative fluid temperatures, pressures and dynamics, ranging from cryogenic hydrogen temperatures to installed airside gas temperatures of up to 500 °C, together with coupled flow field dynamics.

Test Facilities

2 Aero-thermal research and development → Continued evolution of aero-thermal research and development

3 Leak tests → Life testing and generation 2 and 3 heat exchanger testing

4 Vibration tests → Life testing and generation 2 and 3 heat exchanger testing

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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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
Business, Energy
& Industrial Strategy

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THERMAL MANAGEMENT

Roadmap Report

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