FUEL CELLS

Roadmap Report

FLY ZERO

AEROSPACE TECHNOLOGY INSTITUTE

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CONTENTS

KEY & LIST OF ABBREVIATIONS

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.*

List of Abbreviations

APU - Auxiliary power unit
BoP - Balance of plant
BPP - Bipolar plate
GDL - Gas diffusion layer
H_2 - Hydrogen
HT-PEM - High-temperature proton exchange membrane
LH_2 - Liquid hydrogen
LHV - Lower heating value
LT-PEM - Low-temperature proton exchange membrane
MEA - Membrane electrode assembly
PGM - Platinum group metal
R&D - Research and development
TMS - Thermal management system
TRL - Technology readiness level
V&V - Verification and validation

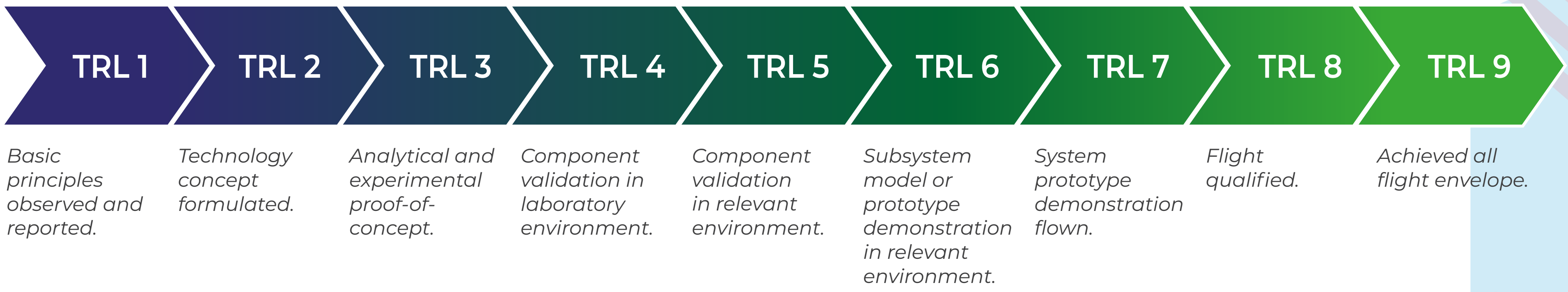


Figure 1 – Technology has been assessed against the NASA Technology Readiness Level (TRL) scale

OVERVIEW: REPORT CONTENT

The first primitive fuel cell was invented almost 200 years ago. Recently, however, major industrial organisations, research institutions and innovative start-ups are considering the technology for aviation applications.

Since the turn of the millennium, significant development has been achieved in fuel cell systems, whilst successfully being applied in a variety of use-cases. Worldwide, this technology is seen as a primary means of reducing carbon dioxide emissions. Once deployed, fuel cell systems could be applied across multiple aviation platforms. This includes new and retrofitting of sub-regional, regional and potentially larger aircraft, eVTOL airframes, long-range drones, and auxiliary power units for hydrogen-powered aircraft. To remain competitive in a fundamental sustainable technology, the UK must research, develop and commercialise next-generation, advanced fuel cell systems for aviation.

This document is an expansion of the Fuel Cells Roadmap and centres on the development of proton exchange membrane (PEM) fuel cells for aviation applications. Compared to other fuel cell types, PEM stacks have superior efficiency (50-60%) and specific power (4 kW/kg). They have been identified as a potential alternative powerplant for aircraft and offer the most viable, zero-carbon solution for minimising the environmental impact of aviation. Therefore, the aim is to provide strategic performance targets and, crucially, potential methods to realise aviation fuel cell systems.

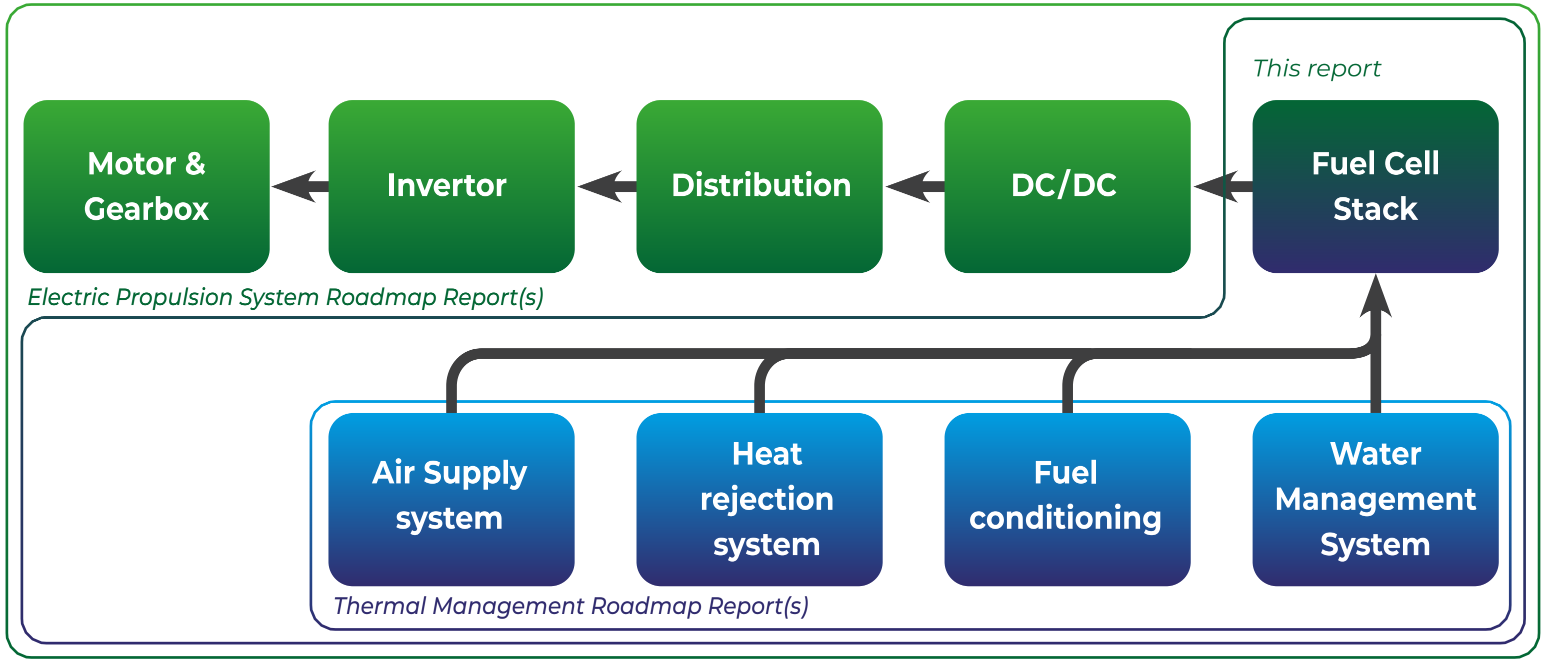
Near-term, low temperature proton exchange membrane (LT-PEM) fuel cells offer the most feasible solution for fuel cells in aviation. However, due to the low operating temperatures of 80°C or less, thermal management is challenging. To address this, high temperature proton exchange membrane (HT-PEMs) fuel cells with operating temperatures of at least 160 °C have also been identified as a strategic technology development stream. A greater difference between the operating and ambient temperatures allows for the easier rejection of heat. HT-PEM systems are in early-stage development, meaning there is significant uncertainty concerning the timeline for potential performance improvements at stack-level. Although, for the UK to be at the forefront, R&D on HT-PEM fuel cells needs to be launched immediately.

The focus in this document is placed upon the future development of high-power, lightweight fuel cell stacks. This is achieved by incorporating composite bipolar plates and endplates, with novel membrane electrode assemblies and higher platinum catalyst loading. Potential solutions for heat rejection, air supply, fuel conditioning and water management systems are also discussed. In particular, a suitable vapour compression cycle for heat management and the need for an exhaust water pre-conditioning system is considered.

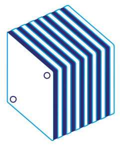
OVERVIEW: FUEL CELLS

Due to the interaction of multiple sub-systems and technologies, the electrical propulsion system is evaluated across three development roadmap reports: Electrical Propulsion System Roadmap Report, Fuel Cell Roadmap Report, and Thermal Management Roadmap Report.

- Both LT-PEM and HT-PEM system pathways are defined within this document.
- The fuel cell, as well as the system and sub-system balance of plant roadmap, are covered in this Fuel Cell Roadmap Report.
- The heat exchanger sub-systems required to enable the balance of plant system functionality is covered in the Thermal Management Roadmap Report.
- The complete electrical powertrain is covered in the Electrical Propulsion System Roadmap Report.



FUEL CELL ROADMAP TECHNOLOGY INDICATORS



		2026 TRL6	2030	2035	2050*
Fuel cell aircraft - LT-PEM	LT-PEM stack (kW/kg)	7+	9	11	16
	LT-PEM stack + BoP (kW/kg)	1.5 to 2.0	2.0 to 2.5	2.5 to 3.0	3.0 to 3.5
	Stack peak efficiency (%)	60	65	70	75
	Durability target (hr)	5,000	10,000	15,000	25,000
	Operating temperature (°C)	80	90	100	100
	Cost - stack ($/kW)	920	600	320	160
	Cost - system ($/kW)	1,560	1,100	640	500

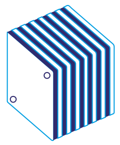
* *Transition to HT-PEM.*

\+ *Value determined from industrial product currently in development.*

Notes and Commentary

- Power density and efficiency provided from industrial partner and internal assessment.
- Durability target is extrapolated from heavy-duty and automotive projections in literature.
- Cost is eight times the cost of heavy-duty automotive fuel cell projections. However, total cost of ownership must also be considered.
- High cost is due to low volume production and manual assembly. Cost reductions can be achieved by economies of scale with the implementation of narrowbody-type fuel cell aircraft, APUs, retrofitting, eVTOLs and automation of fuel cell manufacturing.

FUEL CELL ROADMAP TECHNOLOGY INDICATORS



		2030 TRL6	2035	2050*
Fuel cell aircraft - HT-PEM	HT-PEM stack (kW/kg)	≤3	≤5	**16**
	HT-PEM stack + BoP (kW/kg)	1.5 to 2.0	2.5 to 3.0	**5.0 to 6.0**
	Operating temperature (°C)	120	160	**≥160**

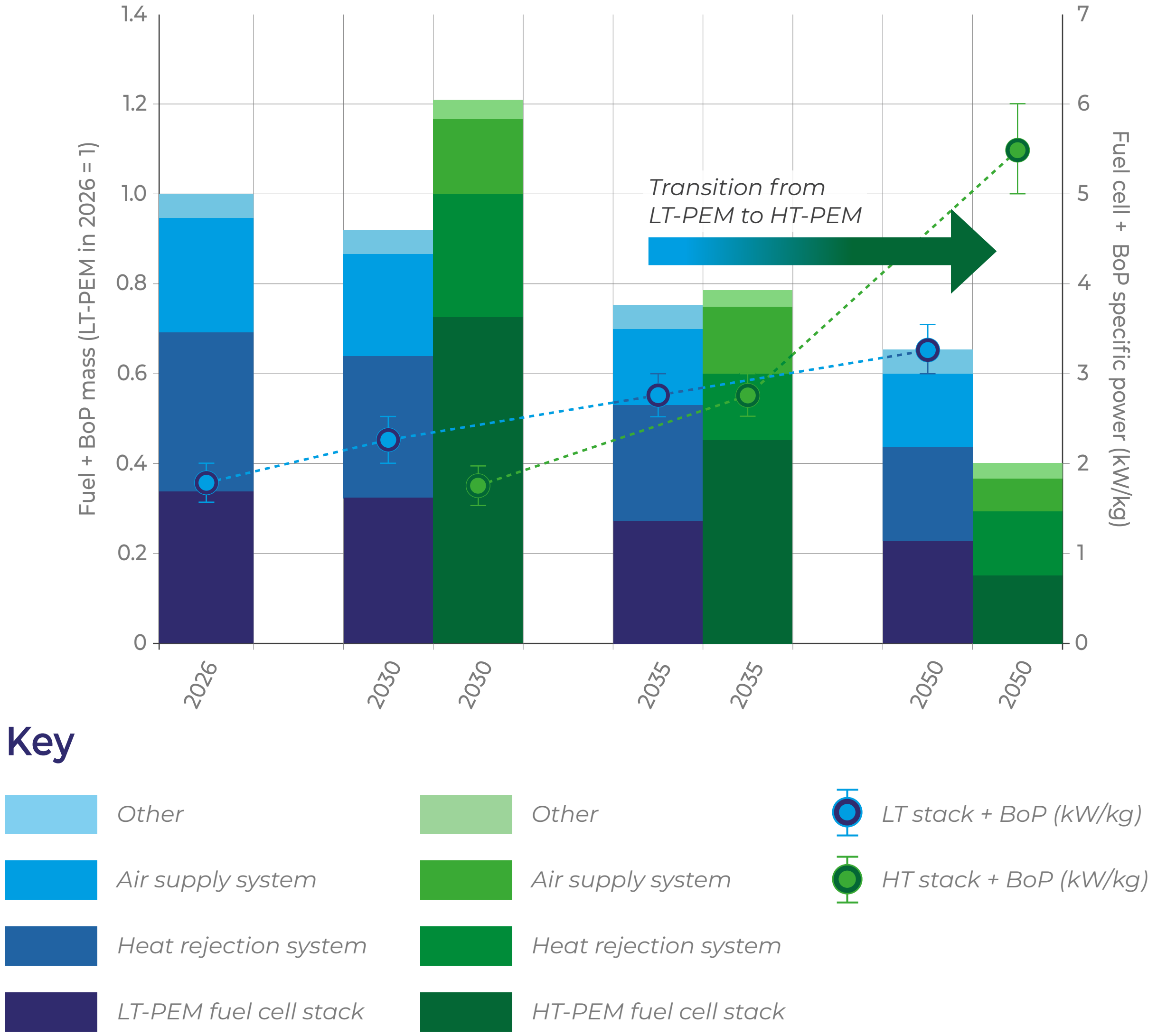
** Transition from LT-PEM.*

Notes and Commentary

- Power densities are provided from internal assessment.
- The current low technology readiness level (TRL) status of HT-PEM stacks means the rate of specific power development is uncertain. Although, with sufficient material development, these targets could be surpassed.
- Transition from LT-PEM to HT-PEM is driven by fuel cell + BoP specific power.
- Internal assessment has determined the necessity of higher operating temperatures. However, the upper limit of the operating temperature depends upon material development and performance.
- The aim is for HT-PEM and LT-PEM durability, efficiency and cost targets to align by 2050.

TRANSITION TO HT-PEM FUEL CELLS

An expansion of the fuel cell stack + BoP specific power technology indicators and breakdown of mass.

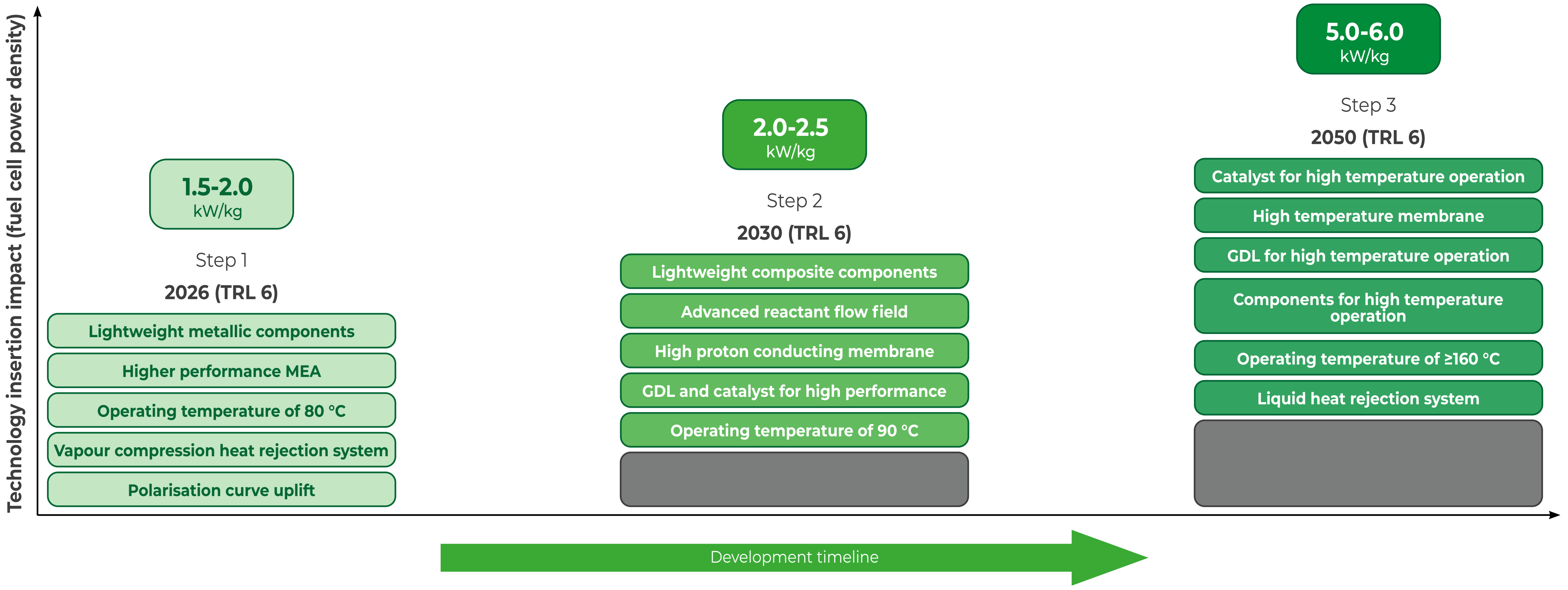


- HT-PEM fuel cell stacks at TRL 6 are expected to be available in 2030.
- Low specific power stacks and heat rejection system are the biggest mass contributors for LT-PEM systems between 2025 and 2035.
- To improve the specific power of the air supply and heat rejection systems, higher operating temperatures are necessary.
- For HT-PEM fuel cells in 2030, mass contributions from the heat rejection and air supply systems are significantly reduced.
- Minimal improvement of LT-PEM fuel cell system specific power is expected post-2035.
- LT-PEM fuel cell stack is oversized to improve efficiency and reduce thermal challenge – this is not the case for HT-PEM.
- As HT-PEM technology matures, fuel cell system specific power dramatically increases, resulting in a transition from LT-PEM to HT-PEM between 2035 and 2050.

TECHNOLOGY STAIRCASE

The chart below shows essential development of technologies, their potential insertion at specific points in time and the overall impact this could have on fuel cell system power density. Please note these power density numbers need to be considered with opportunities of novel airframe designs, which are possible due to the flexibility of the electric propulsion system. Although FlyZero has not explored designs such as blended wing or wing mounted pods, it is a strong recommendation to evaluate these in conjunction with an electrical propulsion system.

The 2050 target refers to a step change due to the implementation of HT-PEM fuel cell technology. However, there is significant uncertainty on the development timeline for these technologies.



EXPANSION OF TECHNOLOGY INDICATORS

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* *Transition to HT-PEM.*

[+] *Value determined from industrial product currently in development.*

1

LT-PEM stack specific power

Aviation brings an added importance to specific power of fuel cell stacks. The stacks must be as light and powerful as possible. Significant development of specific power for LT-PEM stacks has been realised, with values of 4 kW/kg being achieved. Projections have been calculated using historical trends and future development of stack mass and power per cm^2 of fuel cell active area.

2

LT-PEM stack + BoP specific power

Lightweight propulsion systems are imperative for aviation. The fuel cell system consists of the stacks, heat rejection, air supply, fuel conditioning and water management systems. To capture the development of fuel cell system specific power, an in-house tool was developed to assess the interactions between the sub-systems. A range is provided due to the variety of development opportunities for multiple sub-systems.

3

Stack peak efficiency

The peak efficiency is at partially loaded power. The exact percentage of power at peak efficiency is subject to fuel cell design. It can be generally estimated as 10-30% rated power and utilises the LHV of H_2. Owing to the difference between fuel cell and gas turbine, it is critical to have the system optimised based on fuel cell efficiency curve. The cruise efficiency should be close to peak efficiency to suit the percentage load demand.

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** Transition to HT-PEM.*

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1 Durability target

It is acknowledged that improving specific power while simultaneously improving durability and reducing costs is extremely challenging. However, the improvement in durability is critical if fuel cells are to offer an alternative to gas turbines. This can also be achieved by alternative approaches such as mid-life refurbishment and sealed disposable units. Durability target projections are based on heavy-duty vehicle fuel cells. Although, aviation-specific duty cycles must be considered.

2 Operating temperature

Increasing the fuel cell operating temperature is fundamental for the long-term successful application of fuel cells in aviation. Higher operating temperatures improve the electrochemical process kinetics and efficiency, increases the MEA's resistance to impurities, and reduces the balance of plant complexity. Furthermore, temperatures up to 100 °C reduce the heat rejection challenge, as well as balance of plant mass and cost.

EXPANSION OF TECHNOLOGY INDICATORS

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1

Stack cost

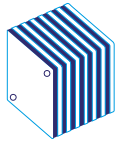
Aviation stacks are highly optimised for high specific power by utilising high strength, lightweight materials. Therefore, costs are calculated as eight times the projections for heavy-duty vehicle fuel cells and adapted from current literature. Current fuel cell stacks are labour intensive, due to the manual assembly process. Future stack development requires automation within the manufacturing and assembly process to reduce costs and improve quality.

2

System cost

The fuel cell system includes fuel cell stacks and balance of plant (BoP) only. Aviation systems are highly optimised for high specific power with novel thermal and lightweight air supply systems. As the stack matures, the BoP becomes the biggest cost contributor. Additionally, HT-PEM fuel cells would minimise system complexity due to a reduction in size and removal of humidification requirements, thus, reducing cost.

EXPANSION OF TECHNOLOGY INDICATORS



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** Transition to LT-PEM.*

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1

HT-PEM stack power density

Aviation brings an added importance to specific power of fuel cell stacks. HT-PEM fuel cells are less susceptible to impurities and able to utilise lower purity fuel. There is limited data for industrialised HT-PEM stack specific power, resulting in greater uncertainty in the achievable capability. The technology is in early-stage development, with specific power targets projected for 2030 onwards.

2

HT-PEM stack + BoP

Lightweight propulsion systems are imperative for aviation. Here, the fuel cell system consists of the stacks, heat rejection, air supply, fuel conditioning and water management systems. To capture the development of fuel cell system specific power, an in-house tool was developed to assess the interactions between the subsystems. A range is provided due to the variety of development opportunities for multiple subsystems. Significantly higher system specific powers for 2050 can be attained with HT-PEM when compared to LT-PEM due to the simplified rejection system.

3

Operating temperature

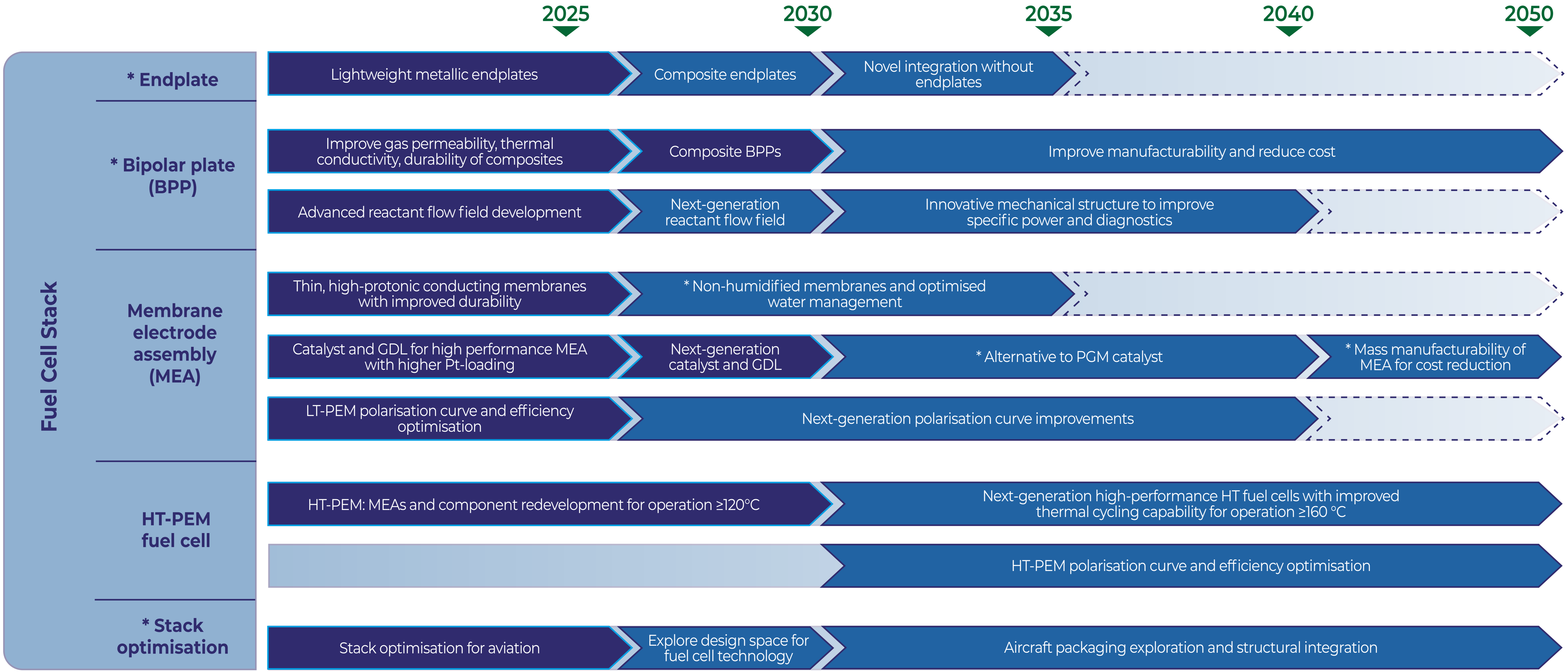
Increasing the fuel cell operating temperature is fundamental for the long-term successful application of fuel cells in aviation. Higher operating temperatures improve the electrochemical process kinetics and efficiency, increases the MEA's resistance to impurities, and reduces the balance of plant complexity. Furthermore, temperatures >120 °C reduces the heat rejection challenge, as well as balance of plant mass and cost.

FUEL CELL STACK COMPONENT

Fuel Cell Stack

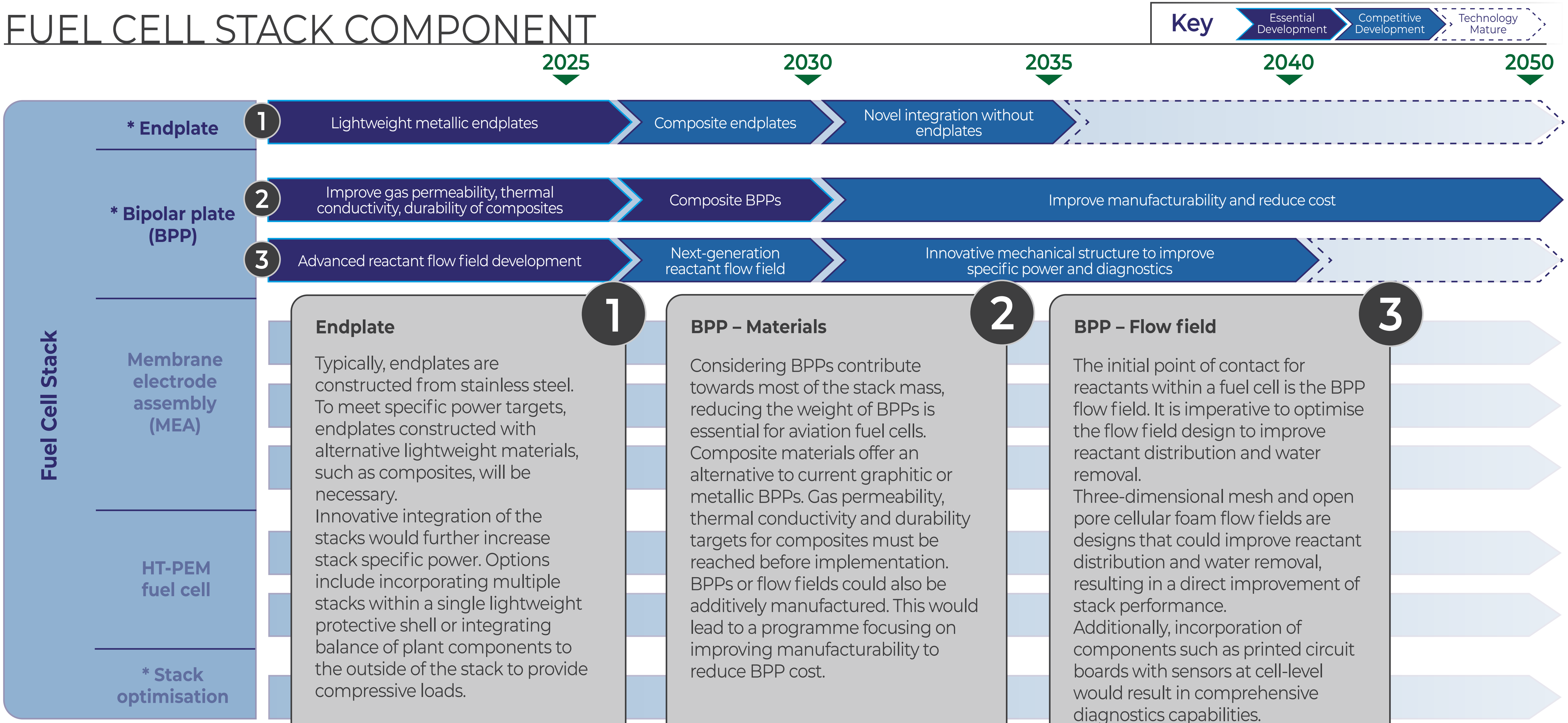
Component	Description
Endplate	**Endplate**: Details the material development and future integration of endplates. Endplates are passive components that apply compression forces on the stack and can contribute 15-45% of the stack mass.
Bipolar plate (BPP)	**Bipolar plate (BPP)**: Details the material development and reactant flow field optimisation of the BPPs. Reducing mass and optimising performance is imperative, as BPPs are multi-functional components that can contribute 60-80% of the stack mass.
Membrane electrode assembly (MEA)	**Membrane electrode assembly (MEA)**: This section of the roadmap discusses the development required on the fuel cell membrane electrode assembly (MEA) for LT-PEM fuel cells. The constituent parts of the MEA and their required improvements are presented. The gas diffusion layer (GDL) is also reviewed. Other performance related factors such as improvements in polarisation curve, efficiency, and the impurity resistance of the membrane and electrode are also highlighted.
HT-PEM fuel cell	**HT-PEM fuel cell**: Covers the development of HT-PEM fuel cells, with an operating temperature of ≥160 °C. HT-PEM fuel cells require a lighter thermal management system due to the increased delta between the fuel cell operating temperature and ambient temperature. This is necessary for fuel cell systems to have competitive specific powers.
Stack optimisation	**Stack optimisation**: Discusses the performance characteristics of fuel cell stack and how it opens opportunity for unique packaging space and aircraft structure integration optimisation.

FUEL CELL STACK COMPONENT ROADMAP



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

FUEL CELL STACK COMPONENT



1 Endplate

Typically, endplates are constructed from stainless steel. To meet specific power targets, endplates constructed with alternative lightweight materials, such as composites, will be necessary.
Innovative integration of the stacks would further increase stack specific power. Options include incorporating multiple stacks within a single lightweight protective shell or integrating balance of plant components to the outside of the stack to provide compressive loads.

2 BPP – Materials

Considering BPPs contribute towards most of the stack mass, reducing the weight of BPPs is essential for aviation fuel cells. Composite materials offer an alternative to current graphitic or metallic BPPs. Gas permeability, thermal conductivity and durability targets for composites must be reached before implementation. BPPs or flow fields could also be additively manufactured. This would lead to a programme focusing on improving manufacturability to reduce BPP cost.

3 BPP – Flow field

The initial point of contact for reactants within a fuel cell is the BPP flow field. It is imperative to optimise the flow field design to improve reactant distribution and water removal.
Three-dimensional mesh and open pore cellular foam flow fields are designs that could improve reactant distribution and water removal, resulting in a direct improvement of stack performance.
Additionally, incorporation of components such as printed circuit boards with sensors at cell-level would result in comprehensive diagnostics capabilities.

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

FUEL CELL STACK COMPONENT

Key: Essential Development | Competitive Development | Technology Mature

2025 | 2030 | 2035 | 2040 | 2050

Fuel Cell Stack

- * Endplate
- * Bipolar plate (BPP)
- Membrane electrode assembly (MEA)
- HT-PEM fuel cell
- * Stack optimisation

Membrane electrode assembly (MEA)

1. Thin, high-protonic conducting membranes with improved durability → * Non-humidified membranes and optimised water management
2. Catalyst and GDL for high performance MEA with higher Pt-loading → Next-generation catalyst and GDL → * Alternative to PGM catalyst → * Mass manufacturability of MEA for cost reduction
3. LT-PEM polarisation curve and efficiency optimisation → Next-generation polarisation curve improvements

1 MEA – Membrane

Membranes with high proton conductivity, lower gas permeability, reduced gas crossover, and improved durability at gradually increasing temperatures are essential for high performance fuel cells. Composite membranes utilising organic and/or non-organic filler is seen as a promising means to achieving higher proton conductivity, low electron conductivity and good water retention. Reducing membrane thickness would result in increased performance, although a focus on durability is essential.

Non-humidified membranes which can retain water without the need for external support would significantly reduce system complexity, weight, and cost.

2 MEA – Catalyst and GDL

Development of advanced electrodes utilising a higher concentration of platinum group metals (PGM) and shape control improves performance. Gas diffusion layers (GDL) that increase the removal of product water at the cathode electrode would significantly improve high current performance. Catalysts and GDLs must also be corrosion resistant at operating temperatures above 80 °C. High performing, non-PGM based catalysts for electrodes would reduce cost and improve manufacturability. Subject to achieving aviation performance requirements, non-PGM based catalysts would result in economies of scale. Furthermore, there is potential for improved electrode performance from non-PGM catalysts.

3 MEA – Polarisation curve

Uplift in power density and efficiency are key for high performance LT-PEM fuel cells. Targeting a higher open circuit voltage, along with higher voltage and current at any given load. The higher voltages are also accompanied by an increase in current produced over the active area, with industry targets of 3-4 A/cm^2 at 0.8 V.

The uplift also increases fuel cell efficiency, reduces heat generated from the stack, and therefore the overall heat rejection challenge.

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

FUEL CELL STACK COMPONENT

Key: Essential Development | Competitive Development | Technology Mature

2025 | 2030 | 2035 | 2040 | 2050

Fuel Cell Stack

- * Endplate
- * Bipolar plate (BPP)
- Membrane electrode assembly (MEA)
- HT-PEM fuel cell
- * Stack optimisation

1 HT-PEM fuel cell

Higher operating temperatures improve electrochemistry kinetics, reduce susceptibilities to impurities, potential for higher efficiencies and a simpler balance of plant. Higher operating temperatures would lead to an increase in system-level specific power due to the reduction in balance of plant mass. Current LT-PEM components, such as MEAs and BPPs, are not suitable for high temperature operation. In order to operate in a high temperature environment, component redevelopment is required to prevent corrosion. Improved thermal cycling of components is necessary to increase stack lifetime and efficiency. A polarisation curve uplift is also expected for HT-PEM fuel cells once higher temperature membranes and electrodes are established. TRL 6 HT-PEM stacks are only expected to be available from 2030, due to the extensive component redevelopment required.

2 Stack optimisation

Fuel cell features include modular design, high efficiency and low operating temperature. This opens more unique packaging options that can be explored such as pod design and utilising external surfaces.
To design a fuel cell powered aircraft, novel structural integration of BoP should be evaluated. The development process should consider how to design an aircraft and assign a suitable mission profile which is optimised for fuel cell technology. Redesigning and optimising for an aviation specific stack considering durability, geometry and cell configuration.

HT-PEM fuel cell

1. HT-PEM: MEAs and component redevelopment for operation ≥120 °C → Next-generation high-performance HT fuel cells with improved thermal cycling capability for operation ≥160 °C

HT-PEM polarisation curve and efficiency optimisation

*** Stack optimisation**

2. Stack optimisation for aviation → Explore design space for fuel cell technology → Aircraft packaging exploration and structural integration

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

FUEL CELL SYSTEM

Fuel Cell Balance of Plant

- Stack heat rejection system
- Stack air supply system
- Stack fuel conditioning
- Water management

Stack heat rejection system: Stack heat rejection system ensures stack operation within the specific temperature range and manage the means to dissipate the waste heat.

Stack air supply system: Stack air supply system ensures sufficient air is delivered to the stack to react H_2 gas at catalyst sites. It typically consists of an air precooler, compressor, air filter and humidifier.

Stack fuel conditioning: Stack fuel conditioning system heats the H_2 fuel from cryogenic to ambient temperatures for entry to the fuel cells stacks.

Water management: Water management system includes a water exhaust conditioning and processing system for contrail management.

Fuel Cell System

- Aviation fuel cell system
- Monitoring
- Sustainability

Aviation fuel cell system: Aviation fuel cell system discusses the potential opportunities to optimise the performance of a fuel cell system for aviation.

Monitoring: Monitoring and diagnostic covers the capability of monitoring and detecting faults in the aircraft and how the fuel cell system can be integrated to the aircraft monitoring and diagnostic system.

Sustainability: Sustainability covers the aspects of a fuel cell aircraft regarding environmental impact, focusing on contrails and sustainable materials.

FUEL CELL SYSTEM ROADMAP

Key: Essential Development | Competitive Development | Technology Mature

2025 — 2030 — 2035 — 2040 — 2050

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

FUEL CELL SYSTEM

Key: Essential Development | Competitive Development | Technology Mature

Fuel Cell Balance of Plant

		2025	2030	2035 – 2040 – 2050
Stack heat rejection system	1	Vapour compression heat rejection cycle for LT-PEM fuel cell	Major focus liquid heat rejection cycle for HT-PEM	Continued evolution of HT-PEM fuel cell liquid heat rejection cycle
	2	High performance sub-systems for LT-PEM fuel cell heat rejection cycle	Sub-systems for LT & HT-PEM fuel cell heat rejection cycle	Continued evolution of sub-systems for HT-PEM fuel cell heat rejection cycle
Stack air supply system	3	Air system for LT-PEM fuel cell	Air system for LT & HT-PEM fuel cell	Continued evolution of HT-PEM fuel cell air system
	4	High performance sub-systems for LT-PEM fuel cell air system	Sub-systems for LT & HT-PEM fuel cell air system	Continued evolution of sub-systems for HT-PEM fuel cell air system
Stack fuel conditioning				
Water management				

Fuel Cell System

Aviation fuel cell system			
Monitoring			
Sustainability			

1 Fuel cell stack heat rejection - System

The combination of specified ISA day requirements and thermal loads with LT-PEM fuel cell technology leads to the development of vapor compression refrigeration technology to manage fuel cell stacks heat rejection needs. For HT-PEM, higher operation temperatures allow to simplify the TMS. Pressurized liquid cooling and smaller equipment would be sufficient for HT-PEM, particularly lighter and lower drag air radiators.

2 Fuel cell stack heat rejection - Subsystem

A variety of heat exchanger technology is required with heat transfer between different fluids, including air, refrigerant and potentially coolant.
LT-PEM fuel cells will require air-refrigerant condensers, refrigerant compressors and expansion valves.
For HT-PEM fuel cells, the technology focus will be air-liquid coolant heat transfer technology.

3 Air supply system - System

A new air system able to deliver the feed pressure requirements to the fuel cell at different power conditions and altitudes is required. For LT-PEM fuel cells, air pre-cooling technology will be required to deliver the air at adequate temperatures. Depending on the operating temperatures of the HT-PEM fuel cells, the air system could be simplified with no pre-cooling required.

4 Air supply system - Subsystem

New compressor technology is required plus turbine technology for exhaust power recuperation. For LT-PEM fuel cells specific cooling technology should aim to explore opportunities, such as the use of LH_2 as a thermal sink to pre-cool air to the appropriate temperatures. Filtration technology is also required minimising mass and parasitic power loss. Exploration of oxygen concentration technologies should be considered.

FUEL CELL SYSTEM

Key: Essential Development | Competitive Development | Technology Mature

2025 | 2030 | 2035 | 2040 | 2050

Fuel Cell Balance of Plant

- Stack heat rejection system
- Stack air supply system
- **Stack fuel conditioning**
  - 1 Fuel conditioning system for LT-PEM fuel cell → Fuel conditioning system for LT & HT-PEM fuel cell → Continued evolution of HT-PEM fuel conditioning system
  - 2 High performance sub-systems for LT-PEM fuel conditioning system → Sub-systems for LT & HT-PEM fuel conditioning System → Continued evolution of sub-systems for HT-PEM fuel conditioning system
- **Water management**
  - 3 Water exhaust management system → Exhaust water conditioning and processing system further optimisation based on contrail impact assessment

Fuel Cell System

- Aviation fuel cell system
- Monitoring
- Sustainability

1 Fuel conditioning - system

Optimised technologies are required in areas such as filtration, pressurisation and temperature pre-conditioning. Filtration risks are partially mitigated using LH_2. Adequate H_2 filtration technologies will be necessary to ensure minimisation of fuel cell contamination. H_2 will be pressurised to be taken to supercritical conditions to allow for more manageable heat transfer processes. The temperature of H_2 will require pre-conditioning, as H_2 will have to be delivered to the fuel cell stacks at adequate temperatures to avoid problems such as water congealing.

2 Fuel conditioning – sub-system

Fuel conditioning components will interact with H_2 at different pressures and temperatures. Therefore, H_2 embrittlement and management of external surface temperatures should be considered. Equipment such as H_2 filters to remove internal contamination, LH_2 pump technology compatible with the range of operating conditions, and heat exchanger technology to precondition temperatures of H_2 will be required.

3 Water management

Although it is not considered essential for the technology indicators, exhausted water would be a contributor to climate impact for H_2 aircraft. It is critical that this is assessed. A significant amount of water would be produced as a mixture of liquid and vapour at low temperature by a H_2 fuel cell aircraft. Water generated by the fuel cell stack can be captured easily. This allows far greater flexibility in controlling the water exhaust than a gas turbine. Pre-conditioning the water prior to release to the atmosphere could play an important role in contrail prevention.

FUEL CELL SYSTEM

Key: Essential Development | Competitive Development | Technology Mature

2025 | 2030 | 2035 | 2040 | 2050

Fuel Cell Balance of Plant

- Stack heat rejection system
- Stack air supply system
- Stack fuel conditioning
- Water management

1 Aero FC system

It is critical to consider the difference of efficiency curve between a fuel cell and a gas turbine. The mission profile and control strategy can be adjusted to optimise the fuel cell performance. Peak take-off power, climb phase power, take-off to cruise power ratio and cruise duration should be considered. Hybridisation should be re-assessed for improved performance with technologies available post-2035.

2 Monitoring

Monitoring system and diagnostic system are both related to aircraft health checks and fault reporting. Monitoring of the polarisation curve, temperature and humidity of the stacks must be integrated to the aircraft existing monitoring system. An integrated monitoring function that focuses on raising fuel cell alerts to an aircraft centralised monitoring system and reports fuel cell failures to the on-board maintenance system is proposed.

3 Sustainability – contrail

The production of contrails and impact of H_2 must be assessed as they also determine how much climate impact is associated with H_2 technology. The exact implication and long-term impact of a H_2-powered aircraft, is not fully understood. Low temperature water exhaust offers more flexibility on controlling the exhaust water via a water processing system.

4 Sustainability – material

Sustainable manufacturing and maximising the recyclability of future fuel cell stacks is essential. This is ensured by: utilising sustainably sourced energy for manufacturing; minimising material wastage in manufacturing; prioritising recyclability and re-use of components at end of life and; usage of alternative natural fibres in composites.

Fuel Cell System

Area	#	Essential Development	Competitive Development	Competitive Development / Technology Mature
Aviation fuel cell system	1	Explore the capability of fuel cell technology in aviation (Study + V&V)	Aircraft mission profile and control strategy for fuel cell propulsion system	Explore energy efficient configuration, such as hybridisation and oversizing
Monitoring	2	Integrated sensors to enable remote diagnostics and maintenance	Next generation diagnostics and maintenance	(Technology Mature)
Sustainability	3	Assess environment impact of current fuel cell system	Long-term environmental impact of H_2-powered aircraft assessment and evaluation	
Sustainability	4	Manufacture process for low environmental impact with focus on system recyclability and re-manufacturing	Net zero production capability	

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

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

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

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

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

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.

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FUEL CELLS

Roadmap Report

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