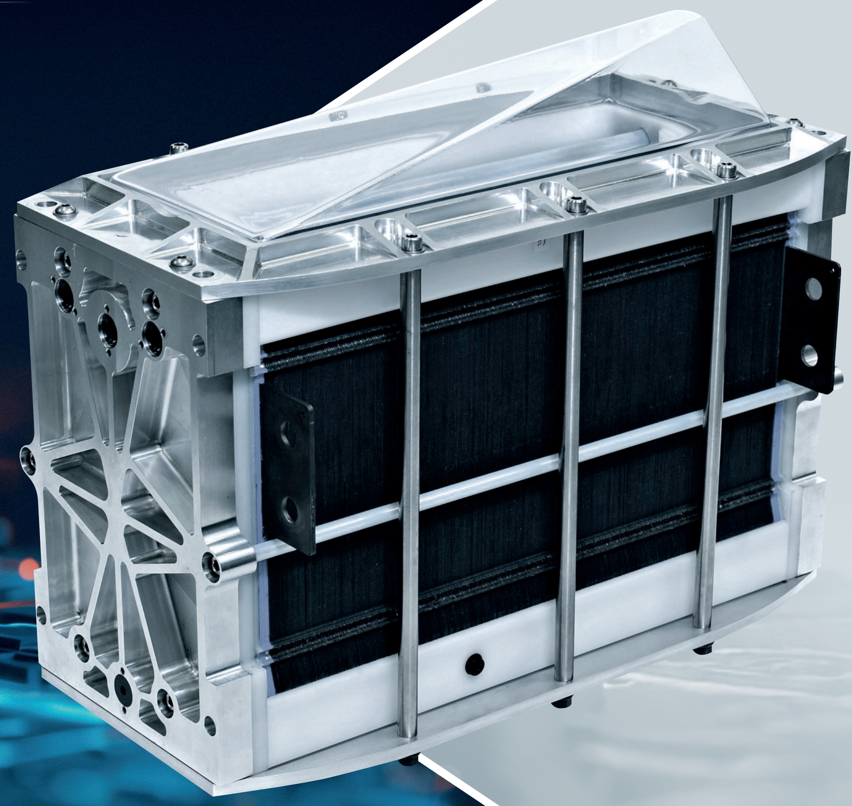
Hydrogen Fuel Cell System and Hydrogen Storage

Narrative Report

2024



Produced by the Advanced Propulsion Centre UK on behalf of the Automotive Council UK

Information correct at time of publication

Contents

1 Introduction

1.1 Foreword to the 2024 roadmaps

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The UK Automotive Council is well known for producing robust and detailed technology roadmaps that define potential routes for Automotive including Commercial Vehicles and Off-Road machinery and related products to achieve our UK environmental and societal goals. Roadmaps are a function of current knowledge and as new ideas and technologies emerge, must be regularly renewed. This exercise, led by the Advanced Propulsion Centre UK, has generated the fourth generation of these roadmaps.

Whilst many organisations develop roadmaps as part of their product planning process, the Automotive Council roadmaps are unique in providing a consented view from the Automotive sector including Commercial Vehicle and Off-Road Machinery, in the UK. This enables us to define common future challenges and where to focus collaborative R&D and capital resources in developing successful, sustainable, net-zero solutions.

These solutions must also meet future consumer needs and not introduce challenges in experience or limitations in operation. Often, more than one technical approach appears viable to meet future needs. It is important that all of these approaches are explored and introduced to market as the carbon reduction goal becomes more urgent. Ultimately, it is possible that one approach may dominate but we cannot afford to wait for this to emerge.

1.2 | The purpose of the 2024 roadmaps

The Automotive Council UK roadmaps outline key themes, trends and drivers in the global automotive industry. This narrative report explains and provides insights to support the roadmap's themes. It helps clarify the reasons behind the roadmap's content and how it should be used.

The report aims to guide research and development (R&D), innovation, and cross-sector collaboration. A list of recommendations for how industry, academia, and government can use this information is shown opposite:

Industry

- Compare in-house R&D priorities with industry trends and drivers in the automotive sector.
- Evaluate supply chain risks and develop strategies for sustainable and circular business models in automotive products.
- Help start-ups by guiding their technology focus, investment choices, and collaboration plans.

Academia

- Address long-term research challenges that need to be solved.
- Align university research, education, and skills development with the automotive industry's needs.
- Strengthen partnerships between academia and industry to apply research to real-world solutions.

Government and policymakers

- Understand key themes and trends in automotive technologies.
- Direct policy and funding to support R&D priorities and innovation for reaching net zero.
- Promote cross-sector collaboration and trade policies that benefit the automotive industry and broader industrial sectors.

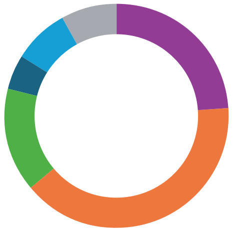
1.3 Building a consensus

This consensus roadmap has been developed through the facilitation of the Advanced Propulsion Centre UK (APC), with contributions from 436 individuals representing 230 organisations, which include government, industry and academia.

Collating the information required for the 2024 roadmaps has only been possible due to the breadth of contribution and valuable feedback from those who have fed into the process, which began in early 2023. The APC would like to thank everyone who gave their time and input across the various webinars, workshops, and surveys conducted.

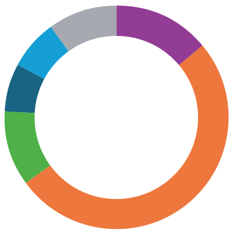
As a result of this consultation across industry and academia the 2024 roadmaps build on previous versions and demonstrate the significant change that is happening across the automotive sector and its supporting industries.

Figure 1: Representation by individual and organisation



436 Individuals

OEM	24%	(104)
Supply chain / SMEs	40%	(176)
RTO	15%	(67)
Academia	5%	(23)
Government	8%	(33)
Other	8%	(33)



230 Organisations

OEM	14%	(32)
Supply chain / SMEs	51%	(117)
RTO	11%	(25)
Academia	7%	(15)
Government	7%	(17)
Other	10%	(24)

Dr Christopher Dufield
Chief Technology Officer
Intelligent Energy

This timely release of these latest fuel cell and hydrogen storage roadmaps provides the necessary focus for both academia and industry to address the needs of the automotive sector in terms of meeting the Net Zero targets. The updated format of the separate roadmaps for both PEM fuel cell technology and hydrogen storage technologies allows for the distinct range of technology development needs and the timebound KPIs for the range of automotive applications to be clearly and concisely presented.

Professor Nigel Brandon
Imperial College London

There is increasing recognition of the important role that fuel cell and hydrogen technologies will play in supporting decarbonisation within and across many sectors, including the transport sector. These fuel cell and hydrogen storage roadmaps help prioritise the research and innovation that will be needed for a wide range of vehicle types, and also address important cross-cutting topics such as policy, infrastructure and life cycle impact.

1.4 Hydrogen Fuel Cell System and Hydrogen Storage – overview

The advancement of hydrogen fuel cells and hydrogen storage technologies has progressed rapidly in recent years, with policy and environment concerns driving the automotive industry to decarbonise. Fuel cell applications and hydrogen storage (also required to support combustion technologies) have been targeted as vital technologies to assist in the drive to reduce carbon.

Overview: Fuel cells and storage

A continuous rise to mainstream

In 2022 and 2023, approximately 35,000 new fuel cell electric vehicles (FCEVs) were sold worldwide with the 2023 figure more than three times the sales recorded in 2017. In 2022, there were more than 72,000 FCEVs on the road globally, a 40% growth compared to 2021. The sale and production of these vehicles have been primarily dominated by a select few brands, with the Hyundai Nexo and Toyota Mirai leading the charge for passenger vehicles.

FCEVs offer a low compromise alternative to battery electric vehicles (BEVs), with comparable range and refuelling to existing combustion engine vehicles, and can support the global automotive industry's push towards decarbonisation with a system efficiency that rivals internal combustion engines (ICEs) in specific use-cases.

There are two primary fuel cell technologies that are considered on the global scale for automotive applications:

- proton-exchange membranes fuel cells (PEMFCs)
- solid oxide fuel cells (SOFCs).

However, since the 2020 roadmap update, the automotive industry has focussed primarily on PEMFCs. This is reflected in this fuel cell roadmap refresh, with PEMFCs the key technology focus throughout, and SOFCs highlighted if / when it is the preferred technology for certain applications and areas.

Increase of global activity

Global OEMs are becoming increasingly interested in hydrogen fuel cells, with some manufacturers doubling down on their portfolio, such as Toyota with its latest fuel-cell-powered Hilux. European OEMs have taken their previous trials forward to production concepts, such as the BMW i Hydrogen NEXT concept transitioning into the iX5 Hydrogen. Further development has been made on concepts and product trials, such as the Toyota GR Yaris H_2, Hyundai N Vision 74 and Honda CR-V FCEV, to name just a few.

The heavy goods transport sector, as well as rail, maritime and aviation sectors, are all promising hydrogen fuel cell applications to compliment BEV technology as the transport sector moves to decarbonisation. Prototype vehicles and project trials are in high demand for the industry.

The uptake of hydrogen fuel cell vehicles in most use-cases remains hindered by the high purchase price, lack of refuelling infrastructure, systems efficiency and overall robustness of the systems.

The challenge of storing hydrogen onboard

FCEVs require consistent hydrogen delivery from an onboard storage source for its operation. How this should be stored onboard is actively being researched and developed. Currently, the most popular method of onboard storage is in pressurised tanks, either Type 3 or Type 4, with plans to develop Type 5 tanks in the future.

Alternative methods are still in the scope. However, technologies, such as cryogenic / liquid hydrogen and solid-state storage, are being considered for some niche applications with product trials underway.

In the 2020 roadmap, hydrogen storage and management were included as sub-technologies of the fuel cell iteration. However, hydrogen is not limited to just fuel cell applications, with technologies such as hydrogen internal combustion engines (ICE) becoming more widely considered as part of the ongoing transition to net zero. In this 2024 roadmap, hydrogen storage has its own sub-roadmap referencing both fuel cell and hydrogen-ICE technologies.

This is a new section for the 2024 roadmaps and aims to provide a comprehensive context for issues and drivers that extend beyond vehicular systems and technologies.

Four overarching themes or micro-level drivers that influence all aspects of the technology roadmaps have been pinpointed. The drivers identified are multifaceted, ranging from global to local scales. Global drivers encompass changes and challenges that transcend national boundaries, often beyond the direct influence of UK suppliers. National drivers are those that are unique to the UK's socio-economic and regulatory environment, while local drivers affect specific regions or communities within the UK. The interplay between these cross-cutting themes and drivers impacts the evolution and development of forecasted technology solutions. These drivers interact with each other and with the technology roadmaps – expediting the advancement of certain technologies, while simultaneously necessitating change in others. In this section, we delve into four pivotal drivers that are reshaping the landscape of technology and innovation:

1. Policy and regulations: examining the influence of legislative frameworks on technological progress.
2. Energy and infrastructure: assessing the role of energy availability and infrastructural support in driving innovation.
3. Materials and manufacturing: understanding the impact of manufacturing capabilities and constraints on technology development.
4. Digitalisation: exploring the transformative power of digital technologies across the automotive sector.

2 | Cross-cutting themes

2.1 | Policy and regulations

The use of fluoropolymers in hydrogen fuel cells and storage

One of the key regulatory focuses affecting the technological development of fuel cells is the removal of fluoropolymers and per- and polyfluoroalkyl substances (PFAS) from the entirety of the fuel cell system, including the stack, balance-of-plant and ancillary components. These substances can be found within the membrane and catalyst layers of the stack, and have raised widespread environmental concerns as they are 'persistent'. This means they may not break down in the environment, potentially contaminating soils and drinking water at end-of-life disposal if not repurposed or recycled, which is detrimental to both human health and animal welfare.

Over the past decade, PFAS derivatives have had restrictions placed on them, including perfluorooctanesulfonic acid (PFOS), perfluorooctanoic acid (PFOA) and perfluorohexanesulfonic acid (PFHxS), primarily by the Stockholm Convention and the EU's Persistent Organic Pollutants (POPs). Additionally, PFCAs have been restricted for use in the EU / EEA since February 2023 by REACH (Registration, Evaluation, Authorisation and Restriction of Chemicals), further signifying the importance of reducing fluorinated material content across all manufacturing.

The regulatory push for their removal is driving innovation in the development of alternative materials across the fuel cell system and hydrogen storage that remove harmful PFAS chemicals. They are not only efficient and environmentally-friendly, but additionally will not negatively impact the performance or safety of the components. This shift is expected to drive the creation of more sustainable and eco-friendly fuel cells, which could significantly contribute to the future adoption of hydrogen fuel cell technology.

The Hydrogen Europe Association believes that rather than having an 'outright ban' on the use of fluoropolymers in key fuel cell components and applications, there should instead be a focus on 'substances that present an unacceptable risk', from the REACH regulation as there are currently no suitable alternatives to fluoropolymers that would not directly affect the H_2 sector KPIs (related to quality, durability, efficiency and economic viability).

Fuel cell passports and recycling safety

For both the fuel cell and storage, there is an expectation that new policies and regulations will come into effect regarding the disassembly and reuse of components within the technology, similar to what now exists for battery recycling and end-of-life. This is in line with the broader global movement towards a circular economy where resources are kept in-use for as long as possible.

The concept of component passports is currently of interest to the sector and is being actively proposed by industry bodies. These passports would provide detailed information about each component's origin, material composition and potential for reuse or recycling. This could be based around the EU Battery Directive's passport requirements, which are due to come into effect from 1 February 2027.

Fuel cell passports could also support the recycling safety and efficiency at end-of-life, particularly in relation to storage tanks. Further measures for design for recycling include reducing part counts, and moving towards the use of less carbon fibre reinforced plastic (CFRP) tanks beyond 2035.

Global targets for vehicle sales

Fuel cell technologies are becoming a viable option in the global quest to decarbonise the automotive sector, with new legislation coming into place targeting both tailpipe and CO_2 emissions (see Figure 2 below).

Where a region may struggle to implement electric vehicle (EV) recharging networks due to grid requirements, hydrogen could provide a suitable alternative to help meet targets. In many cases, meeting these targets will involve a combination of net-zero applications. For example, FCEVs could prove to be the preferred powertrain for long distance heavy-duty vehicles (HDVs).

Figure 2:
Zero-emission vehicle sales commitments

	2025	2030	2035	2040
EU	• 15% CO_2 reduction across car fleet • 15% CO_2 reduction across HDV fleet	• 55% CO_2 reduction across car fleet (50% for LCV) • 45% CO_2 reduction across HDV fleet	• All new cars zero CO_2 emissions • HDV 65% fleet CO_2 reduction	• HDV 90% fleet CO_2 reduction
UK	• ZEV sales targets 22% cars and 10% vans	• ZEV sales targets 80% cars and 70% vans	• All sales ZEV for cars and vans • All HDV <26 tonnes ZEV	• All HDV ZEV
Rest of the world	• **Canada** 20% ZEV for light and heavy-duty sales (2026)	• **USA** 50% of vehicle sales to be electric • **China** NEV 60% of sales • **Japan** 20% BEV and PHEV passenger car sales • **India** 30% car sales ZEV, 70% commercial vehicles ad 80% two / three-wheelers • **Australia** 30% LDV sales to be ZEV	• **Canada** 100% ZEV for light- and heavy-duty sales • **Japan** 100% EV passenger car sales • **Australia** 100% LDV sales to be ZEV	• **China** 100% NEV for light- and heavy-duty sales

Dates correct at time of publication

2.2 | Energy and infrastructure

Continued growth in the hydrogen refuelling infrastructure is critical for the growth of hydrogen fuel cell applications and adoption. The lack of infrastructure could pose substantial challenges to the deployment of hydrogen fuel cells.

The existing infrastructure in most countries is still in early development, although China, Germany and the USA are investing in hydrogen refuelling. In 2023 alone, 37 new hydrogen stations opened in Europe, 12 in Japan, 29 in South Korea and 7 in North America[1]. Several projects have been introduced globally, such as the Hydrogen Mobility Europe initiative which deployed over 45 stations in the EU from 2015-2022 and was co-funded by the Clean Hydrogen Partnership[2]. Additionally, as part of the EU's 'Fit for 55' package, the Alternative Fuel Infrastructure Regulation (AFIR) plays an important role in shaping the future of hydrogen refuelling across the EU, setting specific targets for the deployment of these stations. The key target in this directive is that publicly available hydrogen refuelling stations, serving both cars and lorries, must be deployed from 2030 onwards in all urban nodes and every 200 km along the Trans-European Transport Network (TEN-T).

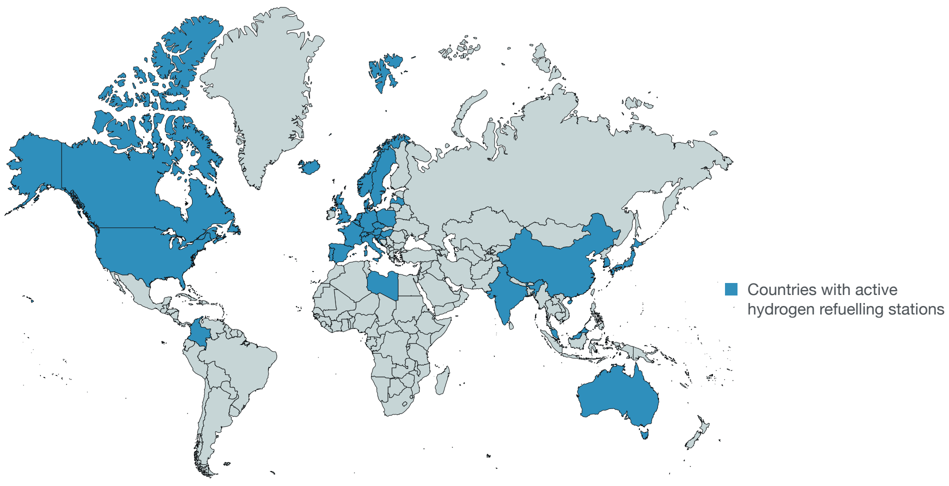
The map pictured (Figure 3) shows the spread of active hydrogen refuelling stations in operation as of December 2023[1].

Additionally, the energy landscape, or electricity grid's capacity to handle the load from electrolysis plants for hydrogen production, or conversely, to integrate electricity produced by fuel cells, is another infrastructure-related aspect that can affect these technologies. The energy landscape plays a pivotal role in shaping the development and adoption of the hydrogen fuel cell technologies. There is need for a significant increase in availability of renewable energy sources, such as wind and solar power, which is crucial for the sustainable production of hydrogen through water electrolysis. The refuelling infrastructure could also make demands on the UK's energy as highlighted by the National Grid. It has reported that if all heavy-goods vehicles (HGVs) in England and Wales were powered by hydrogen fuel cells, with hydrogen production via electrolysis, the annual energy demand would be around 98 TWh / year, representing around 30% of the total amount of electricity generated in 2019[3].

There is a risk of grid instability and to counter this there needs to be significant investment for the sustainable production of hydrogen, thus enabling net-zero transport[3]. Additionally, there is a requirement for hydrogen purity requirements to be met, primarily for PEMFC applications, which must conform to the ISO 14687 requirements[4]. This means the purer the hydrogen, the better it can be utilised in the fuel cell.

Hydrogen combustion engines will have separate purity requirements to fuel cells, however the challenges around energy and infrastructure remain. The Internal Combustion Engines Roadmap provides further detail about these challenges.

Figure 3: Active hydrogen refuelling stations[1]



1 h2stations.org
2 https://www.clean-hydrogen.europa.eu/index_en
3 https://www.nationalgrid.com/document/146441/download
4 This specifies the minimum quality characteristics of hydrogen fuel as distributed for utilisation in vehicular and stationary applications

2.3 Materials and manufacturing

Reliability and durability

One key trend seen in manufacturing is the enhancement of reliability and durability. In particular, this is observed within the manufacturing process of fuel cell stacks, balance-of-plant and storage systems as there is a focus on boosting the operational lifespan of the fuel cell before requiring a replacement or rebuild. Additionally, the membrane electrode assembly, bipolar plating, and catalysts are manufactured to be more durable for resilience against lower purity hydrogen and poisoning from chemicals other than the intended hydrogen.

Improving the reliability and increasing the durability of balance-of-plant components is crucial for scaling-up production. These components are exposed to the acidic environments of hydrogen and oxygen mixtures so once resilience has increased there can be a focus on reducing part counts and addressing vulnerabilities through simplifying the balance-of-plant design.

Simplification of integrated design

Other key trends in manufacture, directly affecting the development of fuel cells and storage, are cost and lightweighting. These can primarily be achieved by simplifying the design and integrating components wherever possible to reduce the complexity of the fuel cell and storage design. With these new designs, fuel cell, balance-of-plant and hydrogen storage components will benefit from significantly lower costs, making production scale-up much easier.

The manufacturing trend of simplification not only occurs on the design level, but also at the production level, with new streamlined manufacturing processes coming into place to aid integration and enabling high-volume manufacturing. A key example of this is the introduction of automation into the manufacturing process to reduce the tolerances in sealing and compression phase of the fuel cell. This not only speeds up the process but also reduces the chance of error, enabling scaled-up production.

Circularity and material recovery

Circularity and material recovery are a high-level focus of industry with new directives being introduced across a multitude of technologies, including batteries, which will inevitably also come to play in the hydrogen fuel cell and storage space. A priority on designing for disassembly and component passports becomes commonplace. The primary purpose for this is to encourage significant waste reduction across the manufacturing process as well as promoting the reuse and recycling of materials, rather than disposal at end-of-life. Overall, this contributes to a more sustainable and efficient manufacturing process.

A key enabler of circularity within the supply chain is introducing material recovery at a much higher volume. This is critical for end-of-life recycling, particularly when the components include platinum group metals (PGMs), carbon fibres and polymers, which are either increasing in rarity, high in price, or a combination of both. The demand for virgin material in the production process is not only reduced, but the environmental impact of fuel cell and storage production is also greatly decreased.

2.4 | Digitalisation

Control system optimisation

Through digitalisation, across the system there is a trend in the introduction of artificial intelligence (AI) tools and machine-learning implementations, primarily for increased efficiency of the stack operation. As the system grows and there are more fuel cell vehicles introduced to market, data generated will inform operational improvements to real-time fuel cell stacks.

An example is predictive analytics, particularly on regular routes (potentially for a HDV), where there is constant communication between onboard sensors and software, anticipating and preventing any potential issues. This will reduce downtime and maintenance costs. This could prove to be critical to operations, especially in the near future, as mass amounts of fleet data is used and applied to refine the control systems for each fleet vehicle, maximising efficiency.

Smart sensors and tags across systems

An example of digitalisation inside the fuel cell is the introduction of integrated sensors added on a cell-by-cell basis, which monitor voltage data and can predict any errors or performance issues on a micro scale in real-time. These are power-consuming devices, requiring constant monitoring and are costly to implement as there can be hundreds of fuel cells within a single stack, with each cell needing an individual loom for monitoring. With technology advancements, we could see manifolds in place of individual wiring looms, leading to a more simplified and cost-effective solution of safety monitoring via sensors.

Sensors across the fuel cell and the storage system are beneficial for not only durability and performance through optimisation, but safety. For example, particularly in the balance-of-plant and hydrogen storage, sensors monitor for pressure build-up, leakage, impact or penetration. The data from these sensors feeds into the overall control system, with the algorithmic, binary checks in the nearer term or machine-learning and AI control systems in the longer term, to quickly predict and solve issues, rather than react.

At the end-of-life of fuel cell and storage components, for recycling, there is a requirement for safety, particularly around tanks. Additionally, with battery passports becoming mandated from 2027 onwards in the EU, there is speculation a similar approach could be taken for fuel cells and storage shortly after. In preparation, there would need to be an influx of radio frequency identification (RFID) / near field communication (NFC) implementation, enabling easy allocation of each component for recycling, reuse or safe disposal, with full accountability of origins and ownership.

Automation in manufacturing

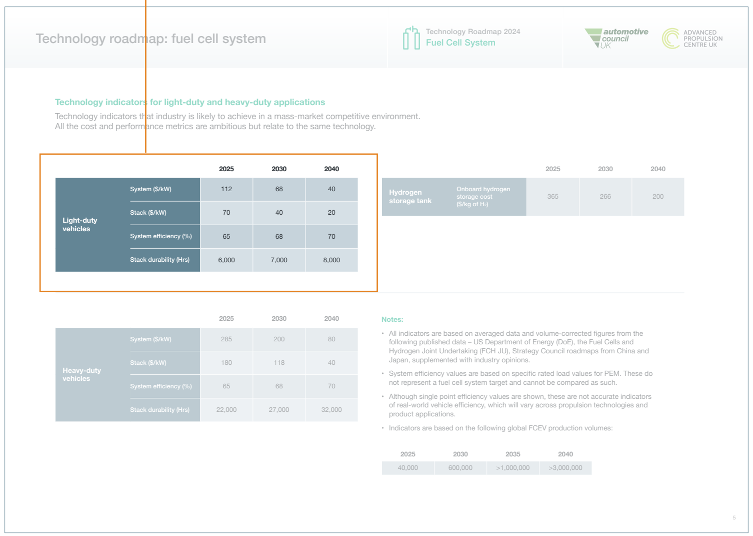
Digitalisation can be used in the automation of manufacturing fuel cells and storage, particularly when relating to tolerances and ensuring tight fits on seals for compression. Moving to an automated manufacturing process impacts the production rate for the hydrogen fuel cells and reduces the costs significantly. It offers a direct contribution enabling high-volume manufacturing of hydrogen fuel cells and storage tanks.

3 | Narrative to roadmap

3.1 | Hydrogen Fuel Cell System and Hydrogen Storage – technology indicators

Costs, system efficiency and durability have remained as the key metrics for fuel cell mass-market adoption, as highlighted in the 2020 Fuel Cell Roadmap. The indicators refer to the same technology across all fields of cost and performance.

		2025	2030	2040
Light-duty vehicles	System ($/kW)	112	68	40
	Stack ($/kW)	70	40	20
	System efficiency (%)	65	68	70
	Stack durability (Hrs)	6,000	7,000	8,000



Fuel cell system – light-duty vehicles metrics

System ($/kW)

This refers to the cost of the complete fuel cell system, including stacks, ancillary components and balance-of-plant, but does not include the fuel storage and delivery system.

The pricing directly correlates with the market adoption, so by reducing these costs it can be assumed there is increased adoption, and vice-versa.

Stack ($/kW)

The stack costs will vary from the system costs because the stack focuses more on the core electrochemical components rather than the entire system costs. This means they cannot map linearly to the stack costs. Additionally, the stack costs will be closely related to the stack performance and durability, whereas the system costs will account for the overall system efficiency, safety and reliability.

System efficiency (%)

The system efficiency and overall performance of a fuel cell will be affected by real-world drive cycles and driveline efficiency. Although they are capable of high-system efficiencies, this should not be taken as a fuel economy reference. The values covered in this section are for rated loads (typical torque demand relative to maximum output capability). For PEM, this is at 25% rated load.

Stack durability (Hrs)

This figure is to provide an estimate for the number of hours the fuel cell can perform reliably without exceeding the service wear limits for overhaul. This metric is common for engines, often referred to as time between overhaul (TBO).

Fuel cell system – heavy-duty vehicle metrics

System ($/kW)

The heavy-duty metrics, because of system and design, are quite different to light-duty vehicles. Often, the duty cycle, use-case and balance-of-plant are unique with intensive requirements for regular operations. Similarly to light-duty, however, there is still a significant cost reduction needed to achieve mass-market adoption.

Stack ($/kW)

The duty cycle and power demands for a heavy-duty application, whether on-road or off-road, require a unique fuel cell design for HDVs. As a result, the indicators remain higher than for light-duty. However, a similar trend in cost reduction is expected as interest grows in fuel cells for the HDV sector.

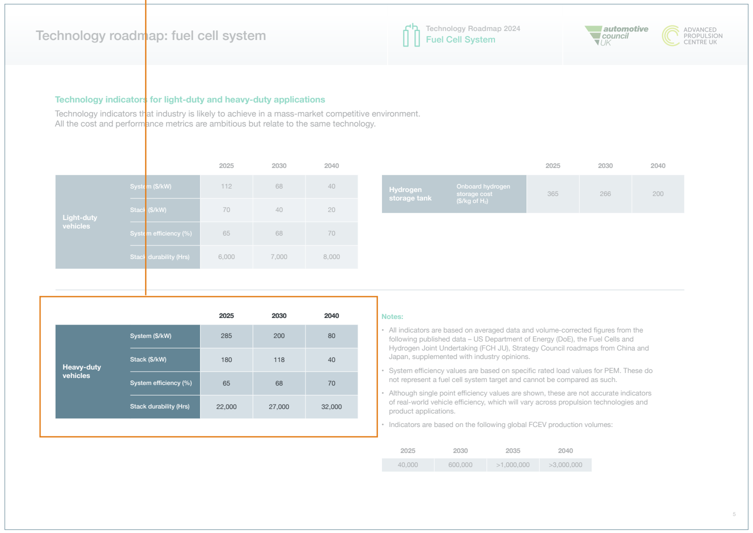
System efficiency (%)

The system efficiency and overall performance of a fuel cell will be affected by real-world drive cycles and driveline efficiency. Although they are capable high-system efficiencies, this should not be taken as a fuel economy reference. The values covered in this section are for rated loads (typical torque demand relative to maximum output capability). For PEM, this is at 25% rated load. The efficiency for heavy-duty applications remains the same as for light-duty, as it is not expected that scaling should affect this.

Stack durability (Hrs)

This figure is to provide an estimate for the number of hours that the fuel cell can perform reliably without exceeding the service wear limits for overhaul. The values for heavy-duty applications are higher than for light-duty ones as fleets are driven to higher utilisation rates and need to be total cost of ownership (TCO) competitive. This metric is common for engines, often referred to as TBO.

		2025	2030	2040
Heavy-duty vehicles	System ($/kW)	285	200	80
	Stack ($/kW)	180	118	40
	System efficiency (%)	65	68	70
	Stack durability (Hrs)	22,000	27,000	32,000


Technology roadmap: fuel cell system
Technology Roadmap 2024
Fuel Cell System

Technology indicators for light-duty and heavy-duty applications

Technology indicators that industry is likely to achieve in a mass-market competitive environment. All the cost and performance metrics are ambitious but relate to the same technology.

		2025	2030	2040
Light-duty vehicles	System ($/kW)	112	68	40
	Stack ($/kW)	70	40	20
	System efficiency (%)	65	68	70
	Stack durability (Hrs)	6,000	7,000	8,000

		2025	2030	2040
Hydrogen storage tank	Onboard hydrogen storage cost ($/kg of H_2)	365	266	200

		2025	2030	2040
Heavy-duty vehicles	System ($/kW)	285	200	80
	Stack ($/kW)	180	118	40
	System efficiency (%)	65	68	70
	Stack durability (Hrs)	22,000	27,000	32,000

Notes:
- All indicators are based on averaged data and volume-corrected figures from the following published data – US Department of Energy (DoE), the Fuel Cells and Hydrogen Joint Undertaking (FCH JU), Strategy Council roadmaps from China and Japan, supplemented with industry opinions.
- System efficiency values are based on specific rated load values for PEM. These do not represent a fuel cell system target and cannot be compared as such.
- Although single point efficiency values are shown, these are not accurate indicators of real-world vehicle efficiency, which will vary across propulsion technologies and product applications.
- Indicators are based on the following global FCEV production volumes:

2025	2030	2035	2040
40,000	600,000	>1,000,000	>3,000,000

5

2025	2030	2035	2040
40,000	600,000	>1,000,000	>3,000,000

Setting indicator values

Fuel cells are a maturing technology for automotive applications, but there is currently still limited vehicle benchmark data. The approach continues to use key performance indicators from existing, extensive work carried out by the US Department of Energy (DoE), the EU Fuel Cells and Hydrogen Joint Undertaking (FCH JU), and the Strategy Council roadmaps from China and Japan (Figure 4).

To keep the values reliable for comparison, this 2024 update includes the same sources used in the 2020 roadmap, using updated versions of the studies as well as industry reviews to provide more recent and accurate values.

Each report varies in its assumptions for fuel cell demand or production. As such, a volume-adjusted approach has been taken to determine values for this report.

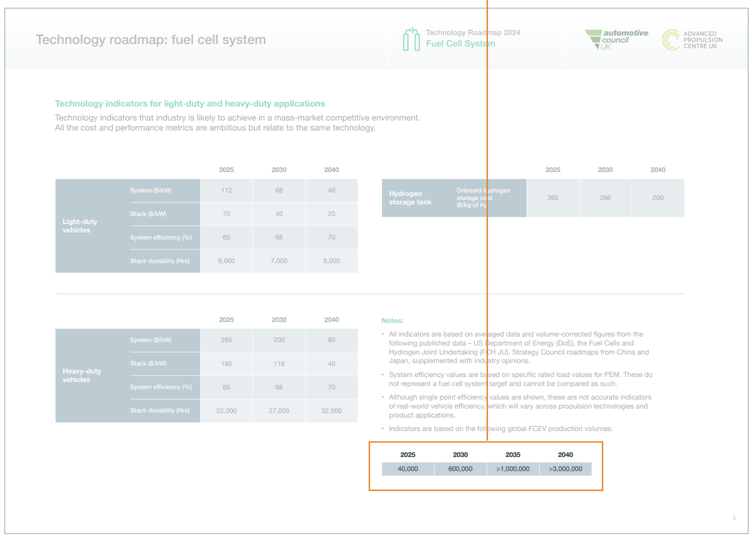
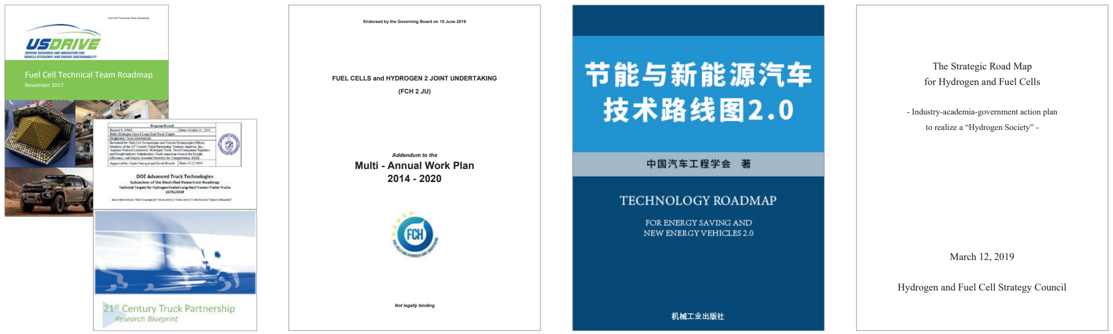


Figure 4: Images of DoE, FCH JU and Strategy Council roadmap documents



US Department of Energy | EU Fuel Cells and Hydrogen Joint Undertaking | China | Japan

Hydrogen storage tanks

The challenge of hydrogen storage set out in the 2020 roadmap remains owing to the low volumetric energy density. Compared to natural gas, hydrogen is 3.2 times less energy dense. This means efficiently storing hydrogen at large quantities is challenging. Industry continues to use both 350 bar (5,000 psi) and 700 bar (10,000 psi) tanks in FCEVs, which use extremely high-strength materials, like CFRPs, and significant reinforcements for pressurised tanks are required. Not only does this come with a mass and cost penalty, it also raises safety concerns of issues such as penetration from impact, leakage from impact or leakage from wear, to name a few.

Onboard hydrogen storage costs

The cost of storing hydrogen remains a significant part of the complete PEM fuel cell system. Similarly to the fuel cell key performance indicators, the values provided are primarily taken from the US DoE US-Drive and EU FCH JU publications. However, the figures have been fed through multiple industry reviews and workshops to refine and align them with current industry thinking for increased accuracy, albeit still with an optimistic uptake of FCEVs in mind.

Different storage technologies, such as absorbent systems, metal hydrides and chemical regeneration systems, were also considered in the benchmark reports. The cost of the storage systems is provided in $ per kg of hydrogen required.

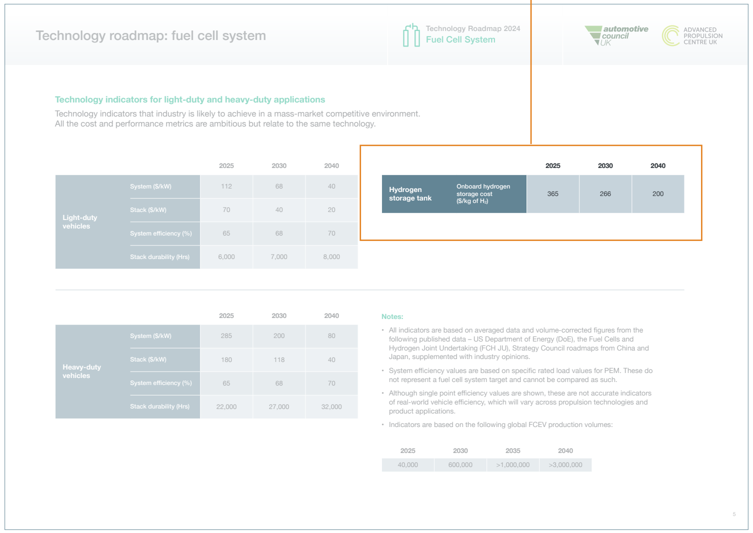
It should be noted that hydrogen storage onboard costs do not just affect the FCEV landscape, but also hydrogen ICE applications, which offer the opportunity for alternative technologies helping to decarbonise the automotive sector to be developed.

Price of hydrogen (fuel supply)

The price of hydrogen (per kg in 2024) continues to evolve and change with supply, infrastructure investments and development. These are driven by the market and local authority incentives, therefore are not included in the roadmap indicators list.

Current estimates remain close to the figures in 2020, at around $14/kg average (with California still around $16/kg), However, there is still a significant amount of market fluctuation, with refuelling sites closing down in popular locations due to lack of use. The estimates for 2035 remain, although with optimism that uptake and increase will allow pricing to reduce to, on average, $4/kg by 2035. This could be lower in some environments depending on infrastructure development.

		2025	2030	2040
Hydrogen storage tank	Onboard hydrogen storage cost ($/kg of H_2)	365	266	200



Technology roadmap: fuel cell system

Technology Roadmap 2024
Fuel Cell System

Technology indicators for light-duty and heavy-duty applications

Technology indicators that industry is likely to achieve in a mass-market competitive environment. All the cost and performance metrics are ambitious but relate to the same technology.

		2025	2030	2040
Light-duty vehicles	System ($/kW)	112	68	40
	Stack ($/kW)	70	40	20
	System efficiency (%)	65	68	70
	Stack durability (Hrs)	6,000	7,000	8,000

		2025	2030	2040
Hydrogen storage tank	Onboard hydrogen storage cost ($/kg of H_2)	365	266	200

		2025	2030	2040
Heavy-duty vehicles	System ($/kW)	285	200	80
	Stack ($/kW)	180	118	40
	System efficiency (%)	65	68	70
	Stack durability (Hrs)	22,000	27,000	32,000

Notes:

- All indicators are based on averaged data and volume-corrected figures from the following published data – US Department of Energy (DoE), the Fuel Cells and Hydrogen Joint Undertaking (FCH JU), Strategy Council roadmaps from China and Japan, supplemented with industry opinions.
- System efficiency values are based on specific rated load values for PEM. These do not represent a fuel cell system target and cannot be compared as such.
- Although single point efficiency values are shown, these are not accurate indicators of real-world vehicle efficiency, which will vary across propulsion technologies and product applications.
- Indicators are based on the following global FCEV production volumes:

2025	2030	2035	2040
40,000	600,000	>1,000,000	>3,000,000

5

3.2 | Hydrogen fuel cell system – technology themes

The next few pages of this narrative report will take an in-depth look at each section of the Hydrogen Fuel Cell and Storage Executive Roadmap document. It is recommended that you have the executive roadmap to hand, however, for ease of reference, the relevant page is pictured here.

Roadmap technology themes

(Click underlined links to jump to sections)

Fuel cell stack

A fuel cell stack is composed of many key components. Considering the PEMFC technology, the key focus areas are the bi-polar plates (the electrodes), membrane electrode assembly (MEA) – comprising of membranes, coatings, gas diffusion layers (GDLs) and catalysts) – insulation and end plates. These form the primary technology themes for the fuel cell stack section of the roadmap with five key focus areas: membranes and ionomers, catalyst layers, gas diffusion layers, bipolar plates, and power management and manufacturing.

Balance-of-plant

The balance-of-plant relates to all additional supporting components and auxiliary systems that are required for delivery and management of energy to and from the fuel cell stack in automotive applications.

Thermal management includes heat exchangers and integrated thermal management systems that can increase system efficiencies by allowing for higher temperature operations.

Air, H_2 and fluid handling refers to the ancillary components which are reliable for transporting vital gases and fluids between various components and the fuel cell stack, such as recirculation blowers of excess hydrogen, water ejectors and filtration systems.

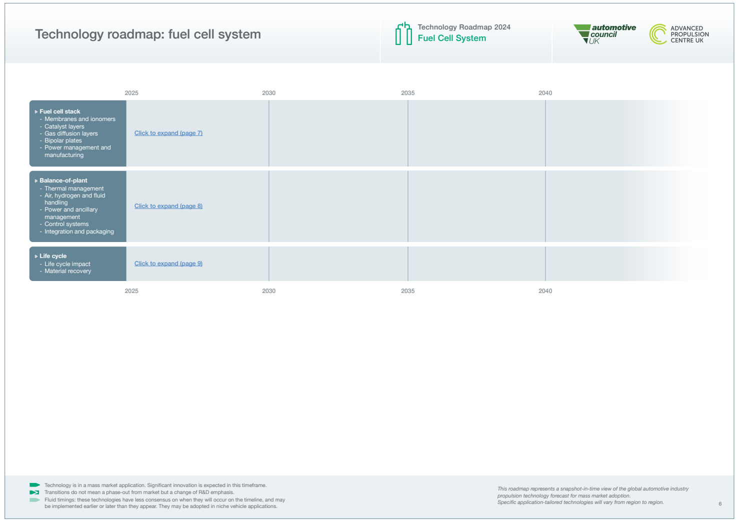
Power and ancillary management covers power and ancillary architecture, component requirements and efficiency measures.

Control systems represent the onboard control measures in place for diagnostics related to efficiency, durability and performance as well as discussions on emerging technologies that could be used, such as AI.

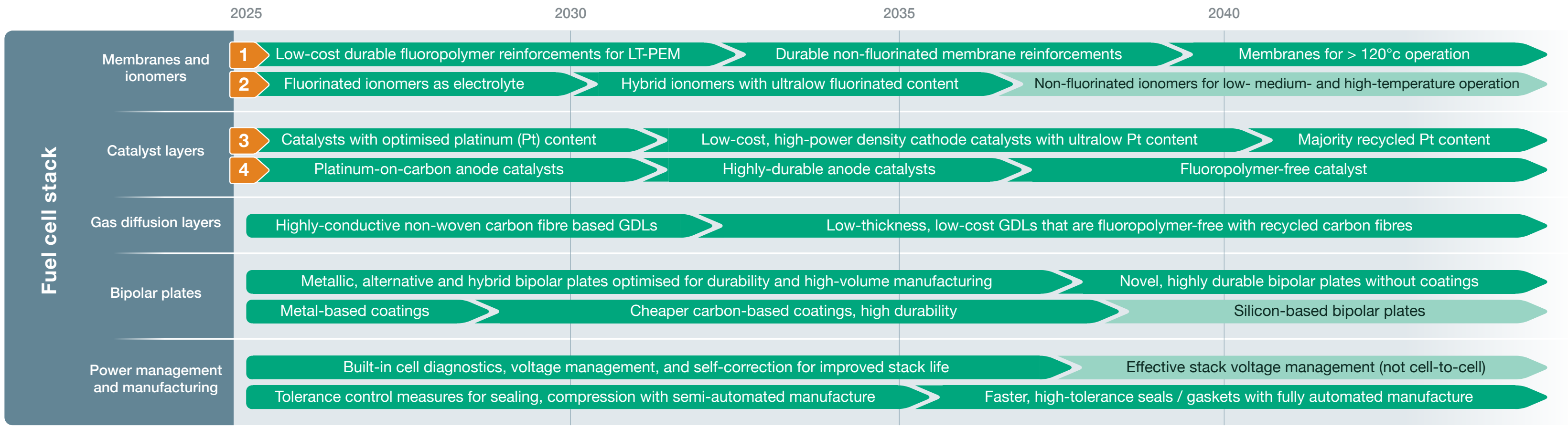
Integration / packaging covers the cell management, DC boost technologies and power architecture of the entire system, with focus around integration across the system.

Life cycle

This includes the impact across the full life cycle of the fuel cell, including the resource consumption, recyclability and circularity supply chain requirements for fuel cell components as well as the manufacturing process. Additionally, there is a new focus on material recovery, which is a key step in closing the loop on circularity in the supply chain.



This section looks in detail at the line-by-line activity on the Hydrogen Fuel Cell System and Hydrogen Storage Roadmap. The numbers will direct you to the line being discussed here in detail.



Hydrogen fuel cell system

Fuel cell stack

Material developments in all parts of the fuel cell stack are vital for cost, efficiency and durability improvements of the fuel cell.

1 Membranes for higher temperature operations

The operating temperatures for PEMFCs, usually run at around 60-80°C, which limits the energy conversion rate and directly affects the performance and efficiency of the fuel cell stack. At levels of above 120°C, these fluoropolymer membranes face limitations with proton conductivity, thermal stability and water management.

At a higher temperature, fluoropolymers may degrade or lose stability. Reducing the content within the membrane is one of the keys to achieving high temperature (HT) PEMFC operations. Currently, a barrier to mass-market HT-PEMFC is cost reduction as alternatives to fluoropolymers can be expensive, proving a potential barrier for research and development (R&D).

2 Ionomers for higher temperature operations

Fluoropolymers also directly affect the capability of the ionomers in the fuel cell stack to run at a higher temperature, creating another barrier for HT-PEMFC operations. The same principle applies, of reducing fluoropolymer content to achieve above 120°C operation in the fuel cell.

In the fuel cell stack, there are two types of ionomers: the PEM ionomers used in the membrane, and the electrode ionomers used in the catalyst layers. Hence, this technology focus affects two key components of the fuel cell. The developments in this space should aim to reduce the limits of proton conductivity, increasing overall performance.

3 Platinum group metals (PGMs) in catalyst layers

PGMs are used within the catalyst layers due to the exceptional catalytic activity, stability and efficient charge transfer characteristics. However, there is considerable focus on reducing the amount of platinum content due to environmental, supply and cost concerns.

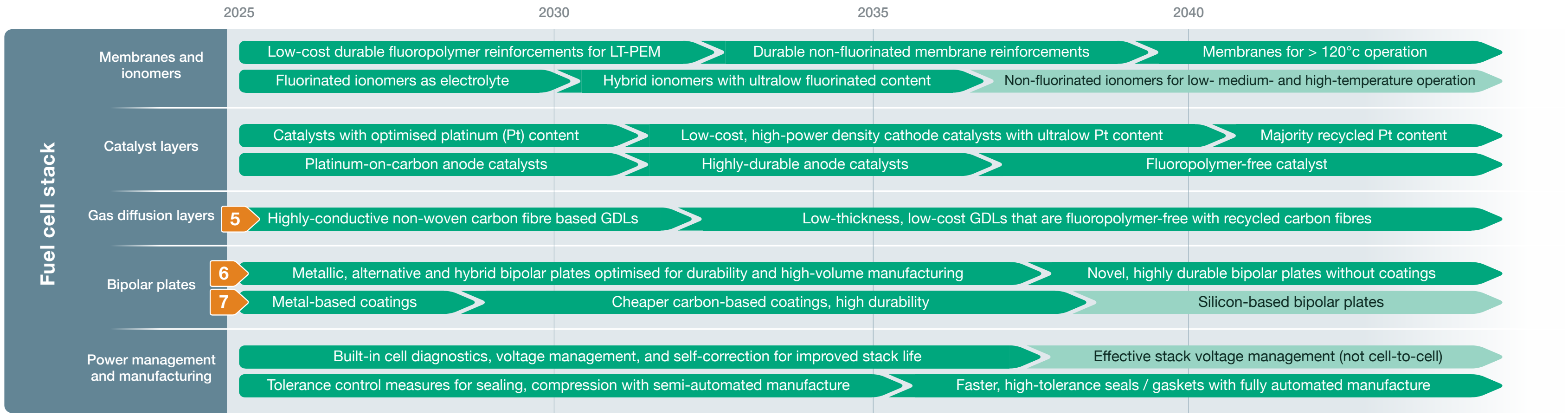
Platinium (Pt) is used in both the anode and cathode layer, facilitating the splitting of hydrogen gas into protons and electrons as well as catalysing the reaction of oxygen with protons and electrons to form water vapour.

Alongside the push for recyclability of Pt content, there are alternatives being widely considered for Pt-based catalysts, such as Metal-Nitrogen-Carbon structures, e.g. iron-based catalysts, Fe-N-C, single-atom catalysts and non-precious metal catalysts (NPMCs).

4 Catalyst fluoropolymer reduction and durability

There is also a move to reduce fluoropolymer content within the catalyst to achieve operating temperatures greater than 120°C, as well as a focus on increasing the durability of the anode catalysts to satisfy longevity and stability by minimising the amount of degradation and poisoning of the catalyst layers.

Again, enhancing the material content of the catalyst layers, allows for uninhibited higher temperature operation in the fuel cell, improving the efficiency of energy conversion.



Hydrogen fuel cell system

Fuel cell stack (continued)

5 Gas diffusion layer innovations

The GDLs, as part of the membrane electrode assembly (MEA), are a porous material, typically composed of a dense array of carbon fibres, providing an electrically conductive pathway for current collection. They also perform the function of reactant transport, heat / water removal, mechanical support and corrosion protection.

In a similar trend to the membranes, ionomers and catalyst layers, the industry focus is to reduce the materials used and fluoropolymer content to improve higher temperature capability within the fuel cell, and to also reduce costs. This is further supported by the focus on using recycled carbon fibres.

6 Bipolar plate material innovations

Bipolar plates are a key component in the fuel cell, with the responsibility of distributing gas and air uniformly, conducting electrical current from cell-to-cell, removing heat from the active area and preventing leakage of gases and coolant.

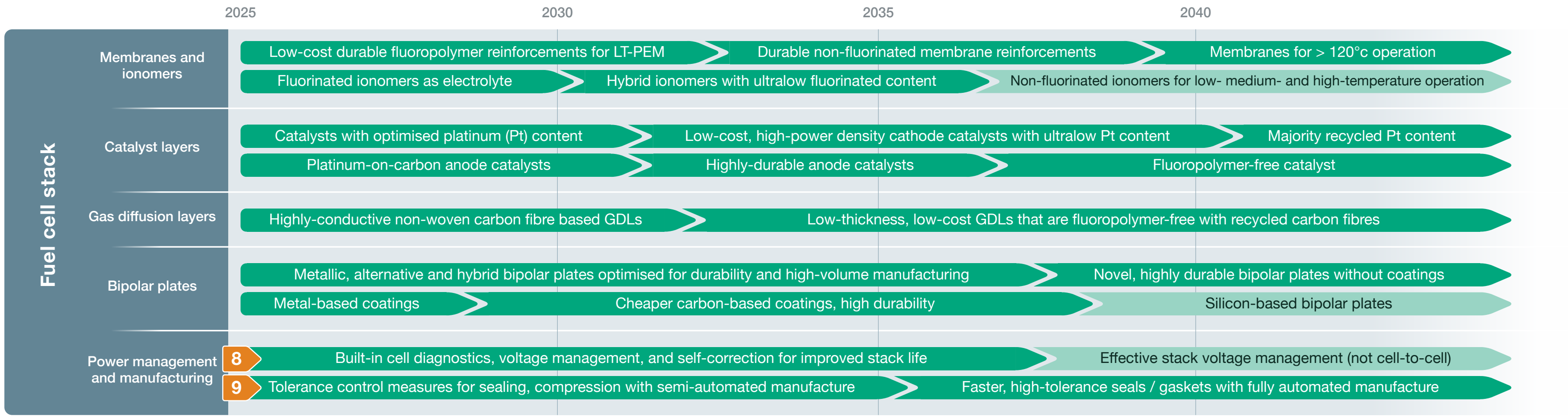
Material development is required for bipolar plates as well as optimisation in high-volume manufacturing techniques to bring down costs and to optimise durability, so that the fuel cell is more resistant to degradation and has an increased lifespan.

Importantly, as of 2024, there is currently development and product-testing underway with carbon-based bipolar plates.

7 Bipolar plate coatings innovations

The coating of the bipolar plates is crucial to provide the plates with corrosion resistance during their exposure to the acidic environment within the fuel cell. The coating prolongs the plate lifespan and provides a smoother and more conductive surface to assist with reducing the contact resistance and any resulting impact on the power output of the fuel cell.

The future of the bipolar plate could follow the trend of moving to carbon-based coatings from metallic. This would enable a high durability for longevity, and would support the long-term aim for silicon-based bipolar plates which do not require coatings, reducing costs of the bipolar plates, and therefore the entire fuel cell.



Hydrogen fuel cell system

Fuel cell stack (continued)

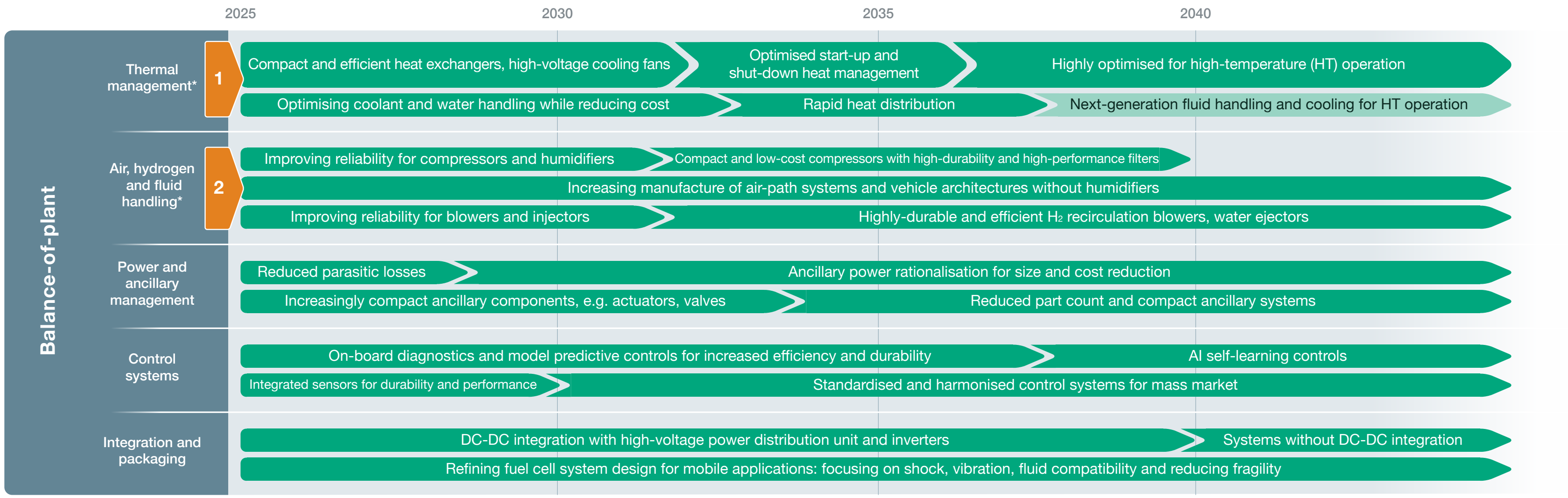
8 Cell management in the stack

There is a requirement for high-detail cell management within the fuel cell in order to inform design decisions to increase cell health as well as built-in cell management paired with software-controlled systems. This would allow prolonged cell life by managing the fuel cell components on a micro-scale, with a view to having wider stack voltage management to manage systems on a less focused scale.

Industry opinion is that there must be an advancement in technology allowing for cell voltage monitoring (CVM) so that cell-to-cell diagnostics are not required or, at least, an external wiring loom is not required for monitoring.

9 Manufacturing tolerances

Within the manufacturing process, fuel cell systems are usually constructed via a semi-automated manufacture, with some manual handling in the process. Because of this, tolerance control measures are required, especially during sealing / compression. The technology push for manufacturing is to move towards more automated processes when working with seals / gaskets to ensure more control on tolerance and enabling faster manufacture for high-volume production.



Hydrogen fuel cell system

Balance-of-plant

1 Thermal management through optimisation and cooling

Ensuring the fuel cell remains at the optimal temperature for efficiency is crucial, and this is achieved through various thermal management components within the balance-of-plant, including heat exchangers and fan systems to dissipate heat. The optimal temperature currently for a PEMFC is around 80°C. A higher temperature than this can affect performance and could potentially cause irreversible damage to fuel cell components, such as the membrane.

Compact and efficient heat exchangers with high-voltage fan systems are key technologies to reduce costs and improve the efficiency of the entire system, as well as enabling the higher temperature PEMFC technology to be seen in future.

There is also a requirement for rapid heat distribution so any excess heat can be removed from vital areas of the fuel cell system without causing damage. In the future, this will be supported by advancements in fluid cooling enabling higher temperature PEMFC technology.

Non-road mobile machinery (NRMM) applications are often stationary for a high amount of their operating time and cannot benefit from natural airflow to assist in thermal management and heat rejection. For a mobile fuel cell application, the size of the required cooling system is much larger than for on-highway or other off-highway applications, and in most current vehicle designs are difficult to package.

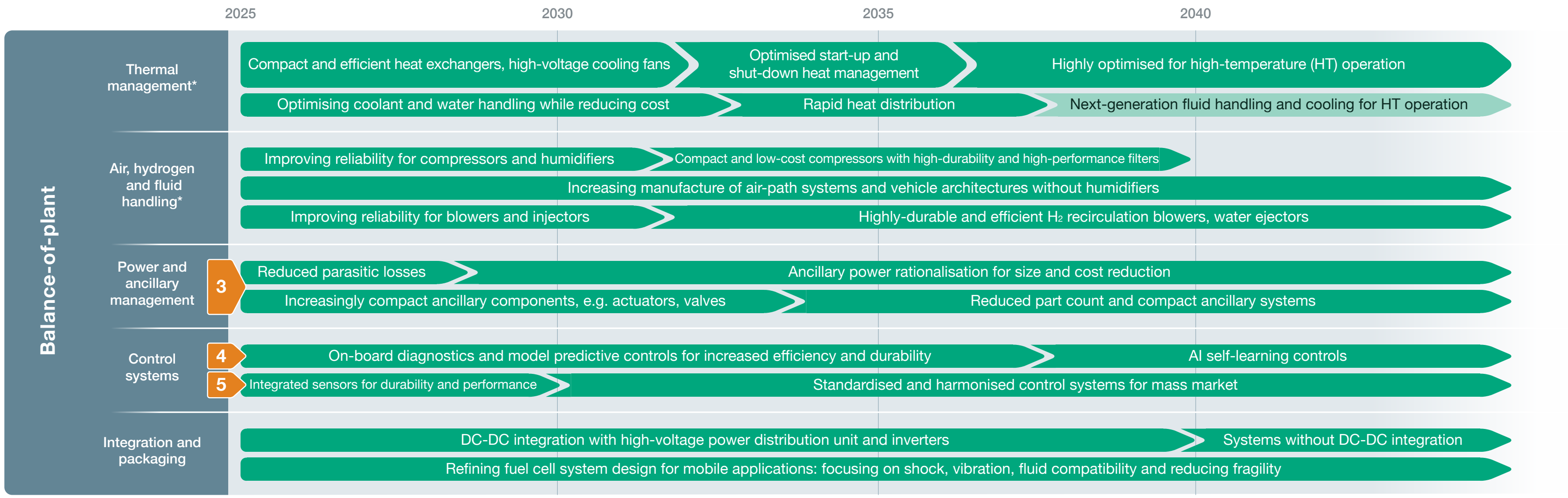
2 Air, H_2 and fluid handling

In a PEMFC, the membrane requires hydration and for this the water must be evaporated at the same rate it is produced. Without this, the membrane can dry out or become flooded, which would damage the PEMFC, affecting efficiency and performance.

A key component of the balance-of-plant is the componentry that controls the flow, path and characteristics of the vital gases such as air, H_2 and fluids across the system to where they need to be. The components include compressors, humidifiers, blowers, injectors and filters with improvements in durability and reliability to ensure these components can last beyond the expected life of the fuel cell to reduce costs and increase recyclability / reuse.

Reducing the costs of the balance-of-plant and compactness is important for compressors and humidifiers. Therefore, integration is more seamless and manufacture can be scaled-up to greater volumes, offering the potential to remove humidifiers from the system entirely. In some automotive applications available today, there are systems operating without humidifiers as a design choice, with direct water injection offering an alternative for the next generation of fluid management.

In NRMM applications, air supply can be an issue, particularly when machinery is stationary in a dust particle rich environment. There is a need for high-performing, large-scale filtration systems, as well as a dedicated air supply, pulling in air from the atmosphere to counter the lack of natural airflow.



Hydrogen fuel cell system

Balance-of-plant (continued)

3 Power and ancillary management

The fuel cell requires numerous ancillary components and systems for monitoring and operation, such as blowers, compressors, filtration systems, water management, heat exchangers, tank conditioning systems, etc., which consume power continuously for safety and management of the entire system. Therefore, a focus is placed on reducing the parasitic losses to increase overall system efficiency.

Compactness continues in the ancillary components, decreasing the total part count of the systems to enable a reduction in the cost of manufacturing, and increased volume capacity. Some examples of simplification and wider improvements in the system could be seen with the implementation of end-to-end zonal architectures in design, and fault tolerances built into the power electronics at a modular level.

4 Model predictive controls and artificial intelligence (AI)

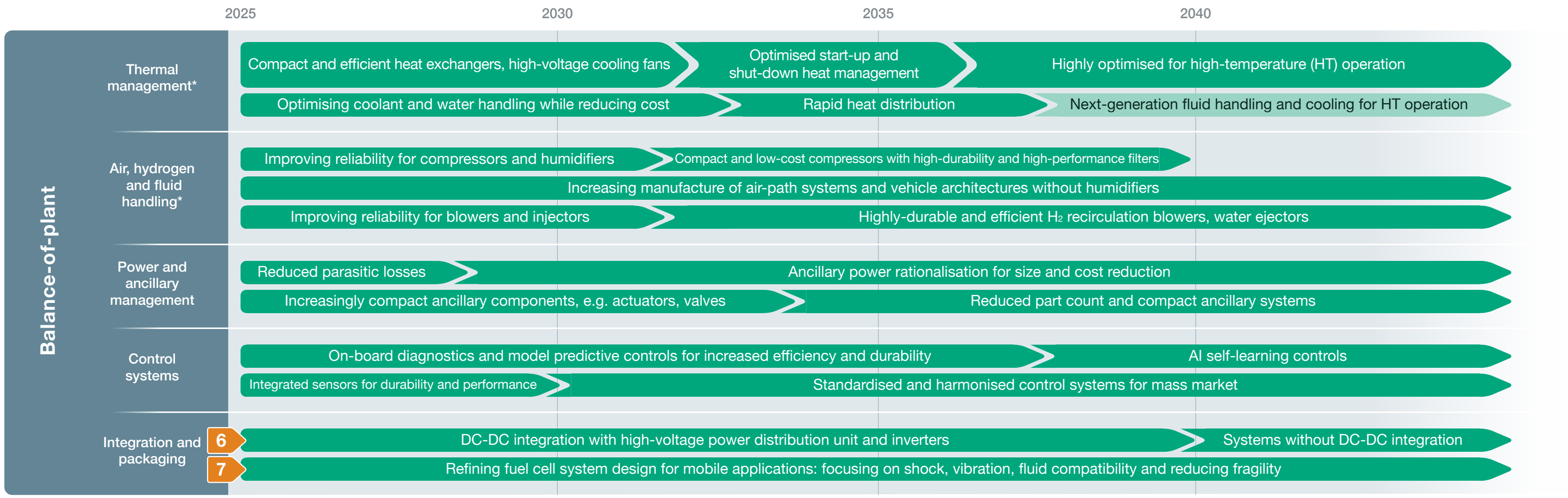
Onboard diagnostics (supported by sensors) are already commonplace in industry within PEMFC automotive applications, with predictive controls (providing advanced warnings or planning service schedules) and complex model-based control (considering multiple system factors), enabled through smart software onboard applying algorithms and metrics to measure against.

In the future, it is possible AI implementation will enable self-learning capabilities within the fuel cell control system. Predictive and machine-learning technologies could permit decision-making without user input required to improve the stack performance and health. Pilot trials within AI automotive control are already happening. The potential for this to be applied to PEMFC applications, particularly for safety and longevity, is growing.

5 Sensors and software

Integrated sensors and software enhance durability and performance and are present in fuel cell automotive applications today. They exist in several forms including optical and chemical sensors placed throughout the balance-of-plant for monitoring safety and optimal operations, as well as enabling software to control components of the fuel cell to extend its life.

Standardised and harmonised control systems remain a necessity for realising the mass-market potential for FCEVs. They promote affordability through cost reduction, safety and reliability through regulatory compliance and uniformity, and global adoption of, not only the vehicles themselves, but also the technology, via interoperability and compatibility amongst all FCEV components.



Hydrogen fuel cell system

Balance-of-plant (continued)

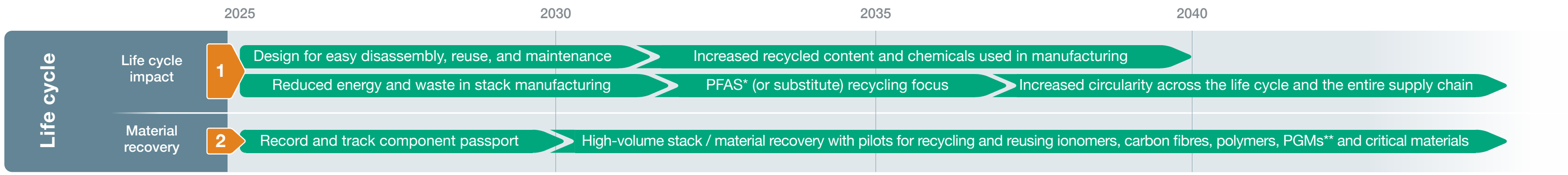
6 DC-DC integration

In the fuel cell system, the DC-DC converter ensures seamless integration of the fuel cell into the entire DC microgrid, which involves other components such as batteries and power electronics. The DC microgrid often operates at much higher voltage than a fuel cell outputs, so the converter is required to align the fuel cell voltage output with the reference voltage of the DC microgrid.

Integration can also be used across components such as the DC-DC converter with the propulsion system High-Voltage Power Distribution Unit to reduce the part and system count, improving cost management and energy losses resulting in a greater system efficiency.

7 Designing for mobile applications

Fuel cell systems have been used for decades to generate power in stationary applications. With a focus on mobile applications, there are specific design considerations that are vital, such as increased resistance to shock and vibrations and reducing fragility. The overall aim is to ensure that vehicle motion is not detrimental to fuel cell operation.



Hydrogen fuel cell system

Life cycle

1 Life cycle impact

The entire life cycle impact is important for fuel cell manufacturing for cost-effectiveness and mass adoption. This starts with design, ensuring disassembly of the fuel cell systems at end-of-life is considered. Component reuse and ease of maintenance throughout the life of the fuel cell are also included, with options to prolong life by repairing or replacing subcomponents or cells within the fuel cell stack.

There is a requirement for circularity, in part, for recycled content and chemicals, either from fuel cells or similar components, to be reused in the manufacture of new fuel cells, to bring the recyclability on a par with ICE and battery materials.

At present, there is a focus to reduce the energy and waste within the stack manufacturing process resulting in increased energy efficiency. This has a direct link to the carbon footprint of each fuel cell produced, enabling true net-zero production processes. This must become a goal for manufacturers with a focus on recycling PFAS materials and chemicals for circularity and life cycle compliance targets to be fully achieved.

2 Material recovery

Recovering materials at a fuel cell end-of-life is important to enable their circular economy. Designers, manufacturers and recyclers all have a shared responsibility of ensuring the fuel cell components can be, and are, fully disassembled for reuse, reconditioning or eco-friendly disposal.

The fuel cell system component passport is a necessity for this to be achieved. At end-of-life, each part can be identified and recycled / repurposed with full accountability across the supply chain. As the fuel cell ecosystem grows, there is the expectation that critical materials, PGMs and high-value components are recovered / recycled at a high volume as a key enabler for high-volume manufacturing.

3.3 | Hydrogen storage – technology themes

Roadmap technology themes

Hydrogen storage

In the 2024 Hydrogen Fuel Cell System and Hydrogen Storage Roadmap, compressed gas covers the key approaches to PEMFC fuel storage for compressed gas routes, including different tank types, technologies to achieve recyclability, manufacturing for compressed gas pressures and technologies related to cost-reduction without compromising performance.

Other storage forms refer to the alternative technologies being researched and developed for automotive applications, including cryogenic / liquid hydrogen storage and solid-state storage, such as metal hydrides and carbon-based.

Structural integration refers to the technologies associated with combining tanks or alternatives to vehicle chassis across car and van, and truck and bus routes.

Balance-of-plant

Refuelling focuses on the options along a timeline to different pressure norms in the automotive application, the flow rate of hydrogen into the storage system, either gaseous or liquid, as well as a cost target for compressing hydrogen, future hybrid technologies, such as liquid to gas refuelling.

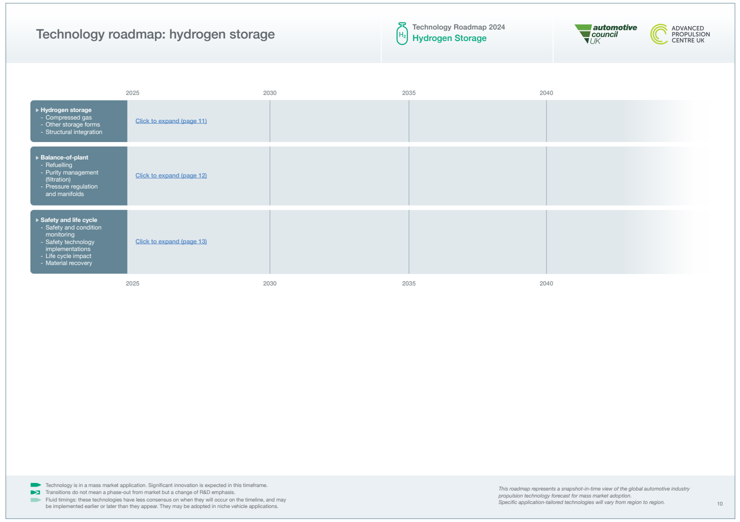
Purity management is considered across two main technologies, fuel cell and combustion engine. The requirements for each technology vary due to their nature, with fuel cells requiring a higher level of purity than combustion engines.

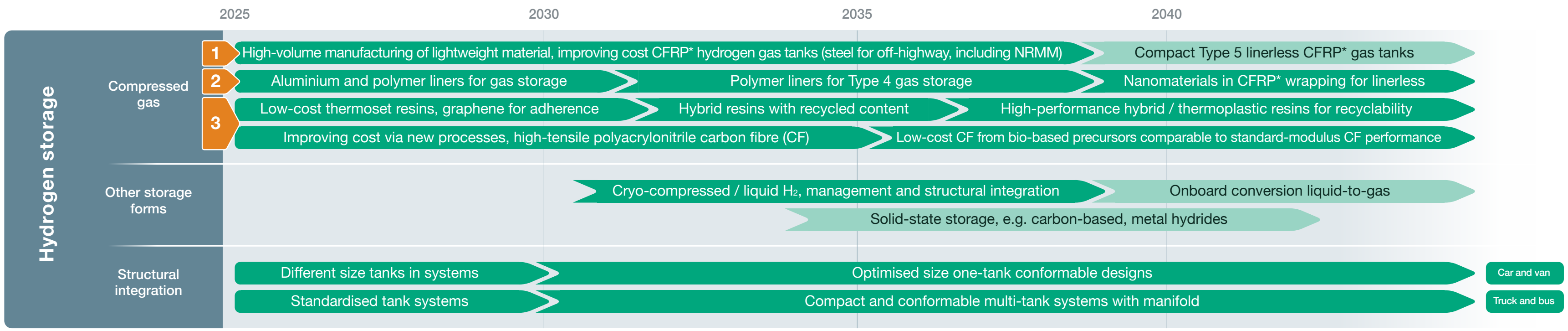
Pressure regulation and manifolds comprises the supporting architecture and componentry that allows for safe and efficient pressure regulation, with developing technologies for integration and cost-optimisation.

Safety and life cycle

Safety includes condition monitoring for leak prevention and safety control, including sensors, fatigue and predictive monitoring using software and technology advancements. Safety also refers to the new technology implementations such as safety bypasses, ventilation and material improvements to help reduce the effects of leakage and increase the level of impact protection.

Life cycle refers to the impact across the service life cycle of the hydrogen storage system, the recyclability and circularity supply chain requirements for hydrogen storage components and the manufacturing process. The 2024 Hydrogen Fuel Cell System and Hydrogen Storage Roadmap sees a new focus on material recovery, a key step in closing the loop on circularity in the supply chain.





Hydrogen storage

Hydrogen storage

1 Type 3, to Type 4 and Type 5 hydrogen tanks

PEMFC requires specialist hydrogen tanks for compressed gas storage, which are built to withstand high pressures of hydrogen, usually 350 bar (5,000 psi) and 700 bar (10,000 psi). However, materials and manufacture is costly.

Type 3 tanks are constructed with composite materials, either glass or carbon fibres and have an internal liner made from aluminium. These tanks can support pressures of up to 350 bar, and density is approximately 25 grams per litre.

Type 4 tanks are also constructed with composite materials, but primarily carbon fibres, with a polymer liner on the inside to seal in the hydrogen. These are more suitable for 700 bar applications, with a density of approximately 40 grams per litre.

Type 5 tanks are similar to Type 4, however they do not have a liner, and instead rely on an all-composite shell which acts as the liner. This allows a greater reduction of material costs, manufacturing complexity and the introduction of lightweight design, but at the cost of a lower usable hydrogen capacity.

2 Enablers for Type 4 and Type 5 hydrogen tanks

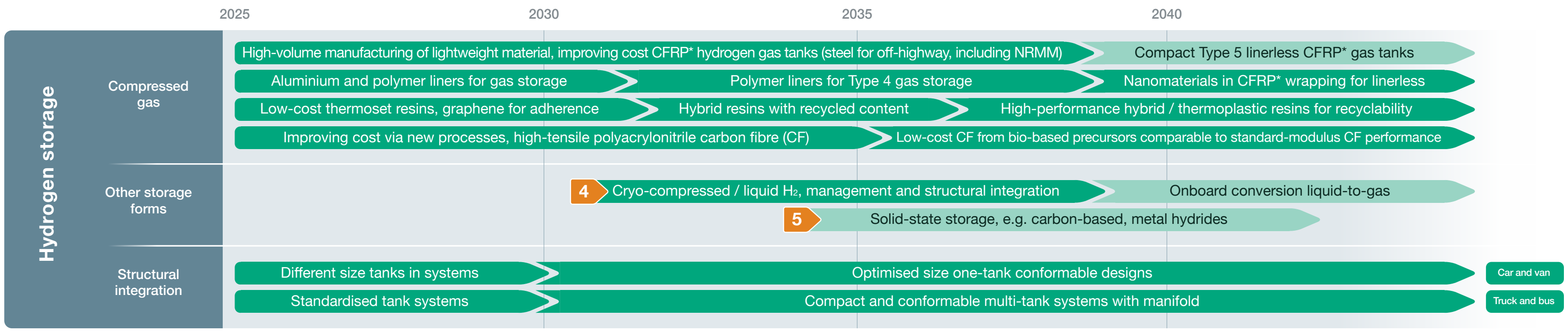
In the current market, there is a focus on improving the high-volume capability of hydrogen tanks with both aluminium and polymer liners (Types 3 and 4), by reducing the cost and increasing the durability of these tanks.

Throughout the development of hydrogen tanks, the common choice of material remains to be CFRP for the shell. However, the key difference between each tank type lies with the way the hydrogen is contained. The aluminium and polymer liners are currently the mass-market approach in industries. However, a Type 5 tank is possible, with a CFRP shell manufactured with nano-materials which have certain properties that remove the need for any form of liner.

3 Manufacturing costs and recycled content

Thermoset resins are used in compressed-gas storage, primarily for the barrier properties, safety and durability capability offered. The current barrier to mass adoption is high material requirement costs, and bringing these down will greatly increase the amount of high-volume manufacturing. A supporting enabler for high-volume manufacturing is the recyclability factor. By increasing the use of recovered thermoset resin (monomer) and designing for manufacture, storage tanks can benefit from high-quality, recycled materials, reducing the overall cost and closing the supply chain loop for circularity.

Additionally, using bio-based precursors for carbon fibre while maintaining performance and durability, paired with cost reductions via new production processes, will allow for a more cost-effective manufacturing process enabling high-volume manufacturing.



Hydrogen storage

Hydrogen storage (continued)

4 Liquid hydrogen

Liquid hydrogen, as an alternative to compressed-gas storage, is a promising and well-researched area, being more widely considered for specific applications in the automotive space, such as long-haul transportation. Hydrogen stored in a liquid form offers a much higher energy density than in a compressed gas form. However, it does need to be stored at very low temperatures under 250°C (-420°F), which poses an additional integration and maintenance challenge. Raising the temperature from this nominal operating temperature causes hydrogen boil-off, reducing the amount of hydrogen stored onboard. In the longer term, if cryogenic storage is to be achieved, there needs to be an onboard controlled conversion to avoid losses between liquid hydrogen to gas hydrogen.

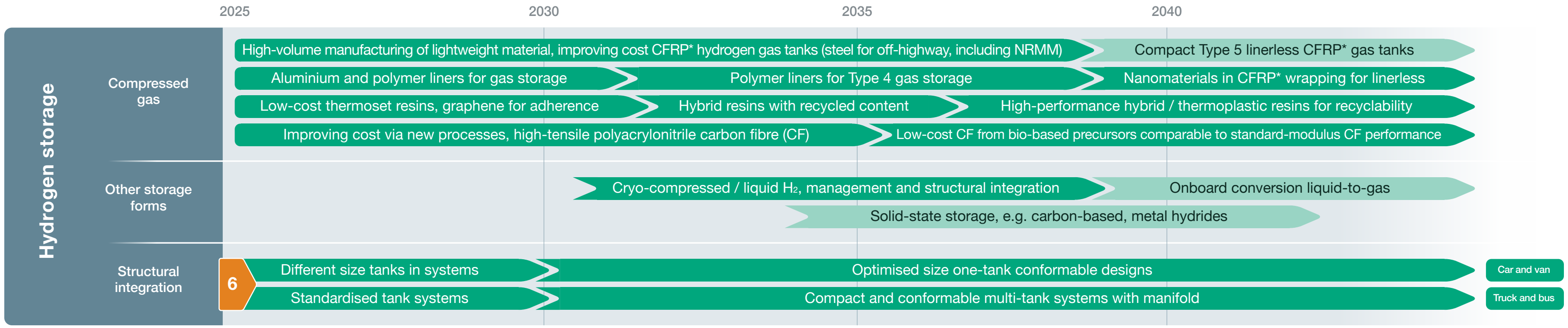
5 Solid-state hydrogen

Another alternative to both compressed gas and liquid hydrogen storage, is solid-state storage, which comes in a few different forms such as; metal hydrides, metal-organic frameworks (MOF) and carbon-based (such as nano-tubes). Solid-state storage can offer a more environmentally-friendly and efficient storage method compared to gaseous or liquid, as well as being renewable and sustainable in most cases. However, it is still not as competitive for gravimetric and volumetric densities, with difficulty achieving high numbers.

Mixed metal hydrides are formed by reactions of hydrogen in gas form, with a parent hydride forming metal, alloy, or intermetallic compound, and can store significant amounts of hydrogen in a stable environment. However, the absorption and desorption rates of hydrogen into these systems are currently quite slow and impractical for the automotive use-case.

Carbon nano-tubes have a nano-porous structure that can absorb hydrogen with their large surface area and offer lightweight storage. They are very expensive to produce and are significantly challenging to scale at the rate required for PEMFC technology to grow.

MOFs are porous materials with tuneable structures so they can be designed specifically for various applications due to this unique flexibility. However, they can be sensitive to moisture and are subject to degradation over time, posing further challenges for production scale-up, raising the question of return on investment for onboard applications.



Hydrogen storage

Hydrogen storage (continued)

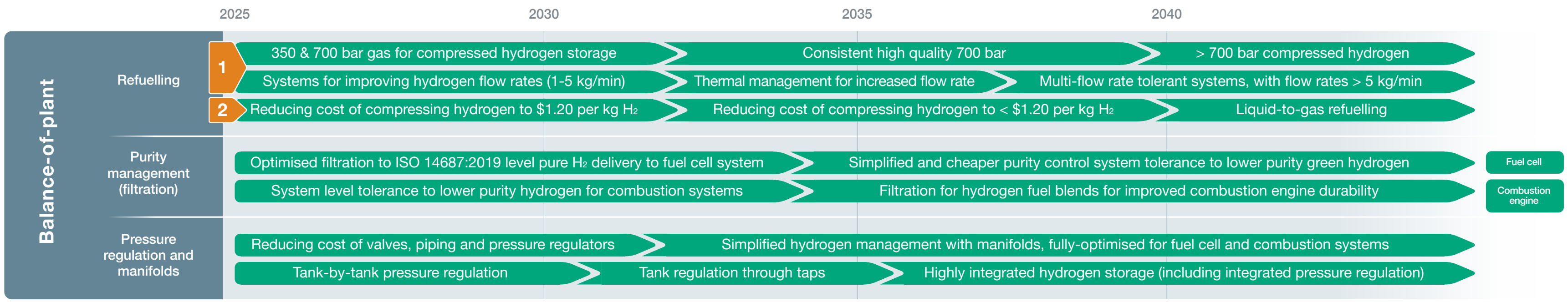
6 Structural integration

Hydrogen gas tanks, primarily Types 3 and 4, are the most common method to store hydrogen, but the challenge is around how they are integrated into the structure of a vehicle. Many original equipment manufacturers (OEMs) are taking different approaches and creating bespoke tank designs and sizes to conform to the structure of the chassis. This approach makes sense for smaller scale manufacturing and ease of production. However, for high-volume production, there is a significant cost to manufacturing bespoke tanks for different vehicle models.

For cars and vans, there is a smaller chassis area to work with so development is needed to move towards one-size conformable tanks to form the centre of vehicle design. OEMs could potentially use the same tank architecture across all models to greatly reduce production costs. Ideally, there would be one large tank per vehicle to reduce the amount of material used in production, to drive down costs for high-volume manufacturing.

For trucks, buses and other heavy-duty applications, chassis sizes are larger. This means it is easier to begin with standardised tank sizes to replace existing fuel containers. These are commonly side-mounted, or placed in a vertical stack format behind the driver's cabin in HGV trucks.

In the future, a similar trend would be ideal but with more compact and comfortable tank designs and multiple tanks for increased hydrogen storage enabling longer range.



Hydrogen storage
Balance-of-plant

1 Pressurisation and refuelling flow rate

In the current market, 350 and 700 bar applications are common for compressed hydrogen storage, dependent on the use-case of the automotive application. 350-bar application is well-established, with 700-bar pressure capability commonplace at lower production volumes. The onboard refuelling capability should match that of the storage capability, and there is an industry push to allow for consistent high-quality 700-bar refuelling in most applications.

There is a marginal energy requirement increase when compressing hydrogen to 700 bar, over a 350-bar application. Compressing hydrogen from 20 bar to 350 bar takes approximately 1.05 kWh per kilogram of H_2, whereas for 700 bar the energy requirement is closer to 1.35 kWh per kilogram of H_2.

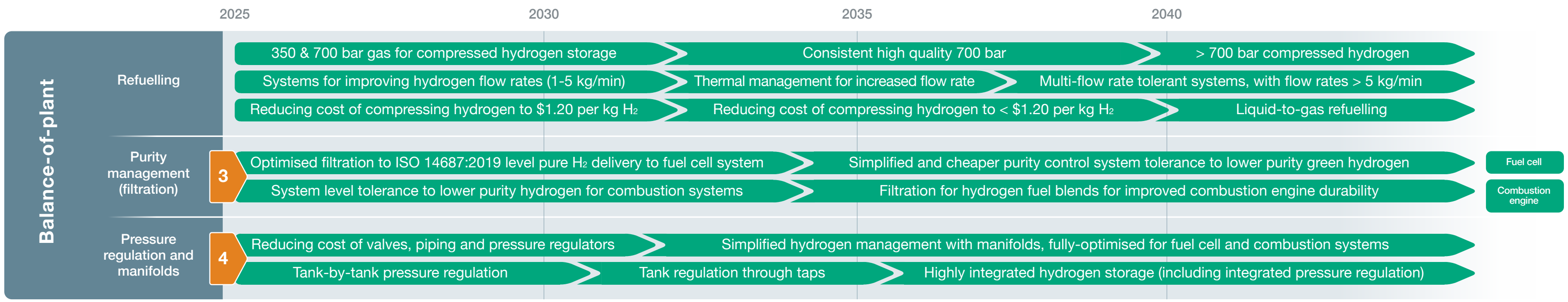
There is the potential for pressure requirements above 700 bar for longer range heavy-duty applications. However, in most cases, the costs of R&D far outweigh the potential benefits, when hydrogen refuelling times are taken into consideration. Currently, the hydrogen flow rates remain between 1-5 kg/min, for both 350 and 700 bar, taking between three to six minutes to refuel a FCEV passenger car. Heavy-duty applications take longer, however there are targets to increase flow rates to above 5 kg/min, with potential targets of heavy-duty fast-fills of 10 kg/min averages (US Hydrogen Program).

2 Hydrogen compression costs

To make hydrogen applications in automotive cost-effective, for both fuel cell and hydrogen ICE, there needs to be a significant cost reduction in compressing hydrogen.

This will directly affect the popularity, and therefore high-volume manufacturing capability. The aim is to initially reduce the cost of compressing hydrogen to $1.20 per kilogram, with further reductions once automotive hydrogen storage becomes more commonplace in the industry.

As an alternative, liquid refuelling is usually as convenient and comparable to diesel refuelling, and is ideal for heavy-duty applications, seeing refuel times reduce to 10-15 minutes with approximately 30 times less energy than gaseous hydrogen refuelling. However, most PEMFC applications rely on gaseous hydrogen for operation, and hydrogen ICE also combusts gaseous hydrogen. Therefore, there must be future developments in the onboard conversion of liquid to gas hydrogen.



Hydrogen storage

Balance-of-plant (continued)

3 Hydrogen purity management

There are specific requirements that must be met for the purity level of hydrogen used in automotive applications, primarily for PEMFC. Any impurities in the hydrogen supply can cause short-term issues with the performance of the fuel cell, and will affect efficiency. Additionally, prolonged use of low-quality hydrogen can accelerate the degradation of the fuel cell components, such as the membrane or contaminants, poisoning the catalyst layers.

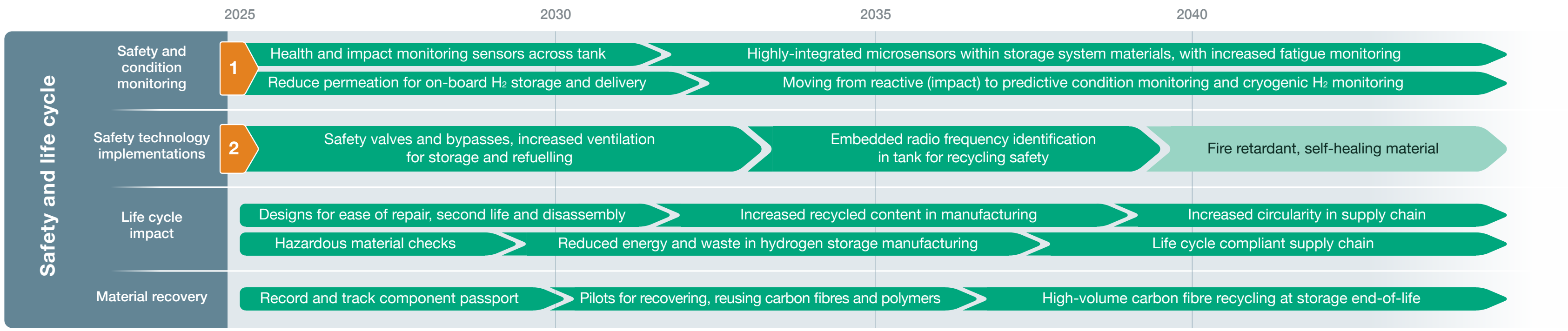
Fuel cells operate most efficiently when supplied with the purest hydrogen. There are standards in place, such as ISO 14687, which specify the maximum amount of impurity that can be present in specific applications for fuel cells, and this must be met at the minimum. However, in the long term, there could be filtration systems and tolerances built into the fuel cell to allow for lower purity green hydrogen to be used without causing much harm or damage.

The purity requirements for hydrogen ICE differ from fuel cells as there should be a tolerance built in to handle impurities in the hydrogen supply. By its nature, the hydrogen in the engine is designed to be combusted, which can be offered in a broad range of fuel-air mixtures, allowing the engines to continue running efficiently with low-purity hydrogen. Nevertheless, there still must be advancement made in filtration to prolong engine durability.

4 Pressure regulation systems

Current hydrogen storage technology involves pressure regulation on a tank-by-tank basis, with a wide array of valves, pipes and pressure regulators spread across the balance-of-plant to modulate and relieve any pressure build-up before it becomes a safety concern. There is a focus to reduce the costs of these associated ancillary components so, in turn, there is a cost reduction in both the production of each hydrogen storage system and its part counts, enabling a smoother transition to high-volume manufacturing.

The focus for technology improvements is to achieve a simplification at a system level for balance-of-plant, which extends to pressure regulation, with simplified hydrogen management through manifolds in place of individual piping and pressure regulators. This requires a more standardised approach, and by moving to highly integrated hydrogen storage, such as integrating pressure regulators into the tank, part counts and manufacturing complexity can be reduced as well as costs, which will directly make high-volume manufacturing easily achievable.



Hydrogen storage

Safety and life cycle

1 Safety and condition monitoring

Safety within hydrogen storage tanks is important to prevent the risk of hydrogen leaking in to the atmosphere or penetration causing ignition through spark. Preventative measures could include highly detailed and concentrated sensors placed across the tank and supporting components. They would allow the monitoring of key components, such as the composite shell or liner in critical areas, the ancillary components, and within piping.

As well as health monitoring, sensors currently are focused on impact monitoring so that, when detected, control systems can dissipate any hydrogen safely and isolate the system to avoid spread to additional tanks.

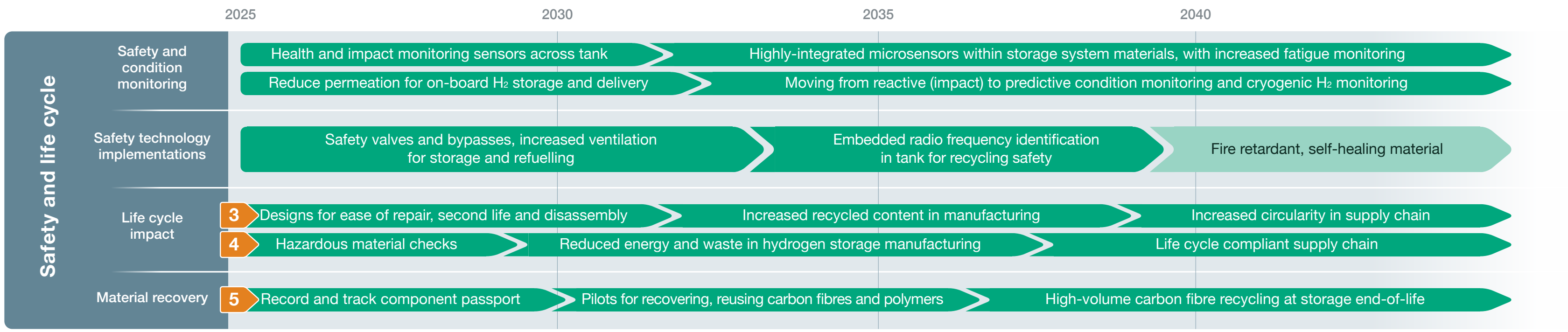
Additionally, a current concern is the permeation with natural wear on the tank and supporting components increasing the risk of hydrogen leaks at a level that causes a safety concern.

Looking to the future, the technology evolves to more integrated micro-sensors embedded in the storage system materials, monitoring fatigue and becoming more predictive. With current technology, safety and condition-monitoring happens on a reactive basis. However, there is room for improvement here with a move towards more predictive conditioning using these micro-sensors, which have the ability to work with the onboard control system identifying potential failures before they occur.

2 Safety technology implementations

A key enabler for safety improvement in the hydrogen storage space is the implementation of fresh and innovative solutions to safety. Currently, there is still significant space for improvement in the onboard safety bypass systems to ensure that there is a fail-safe in place for most eventualities, especially in the dynamic environment of hydrogen storage with multiple active characteristics. In the future, having materials with fire-retardant and self-healing properties used across the storage system would further reduce the impact of any ignition or damage to the components.

Safety also extends beyond the normal life of the hydrogen storage system to the recycling stage. Sensors and RFID in the tank would allow for safer recycling and, in many cases, a tank may be suitable for reuse. However, some fatigue may be not visible and, in these cases, RFID can keep a track of the usage of the tank enabling a suitable end-of-life recycling decision. The RFID in tank is also critical for potential reuse with new owners understanding the current condition and life of the storage tank.



Hydrogen storage

Safety and life cycle (continued)

3 Circularity through design and recycling

The life cycle impact of hydrogen storage tanks aligns with the actions required in the fuel cell roadmaps, to enable high-volume manufacturing and mass adoption for both fuel cell and hydrogen ICE applications.

The circularity must come from design phases, through to end-of-life, and begins with hydrogen tanks which are designed to be disassembled with ease, for either repair, second life / reuse or recycling for other applications.

Once this is achieved in most tank designs, there can be an influx of recycled content from other hydrogen storage tanks in the new manufacturing process, in turn increasing the circularity across the supply chain.

4 Manufacturing actions for reducing life cycle impact

To support circularity in reducing the life cycle impact of hydrogen tanks, there are some actions to be completed within manufacturing, primarily focusing on reducing the energy and waste in hydrogen storage manufacturing and becoming a more environmentally-friendly process enabling a life cycle-compliant supply chain.

There should also be increased commitment to using the recycled content and checking for hazardous material across all tank manufacture. A closed-loop value chain for key stack materials, like CFRP, is still critical to enable a more economically-viable, high-volume manufacturing process.

5 Material recovery

Recovering the materials at the end-of-life of hydrogen storage is necessary to enable the closed-loop value chain and one of the key enablers to achieving this is the component passport. The passport ensures that each part can be identified and recycled and repurposed with full accountability across the hydrogen storage supply chain.

There is also an increasing focus for more recovery of carbon fibres and polymers at the end-of-life as these are the highest value components of the hydrogen storage system. If carbon fibres can be recovered and recycled at a high volume, the costs of the hydrogen storage system will decrease significantly.

Glossary

AFIR	Alternative fuels infrastructure regulation
AI	Artificial intelligence
BEV	Battery electric vehicle
CFRP	Carbon fibre reinforced plastic
CO_2	Carbon dioxide
CVM	Cell voltage monitoring
DoE	Department of Energy
EEA	European Environment Agency
EU	European Union
EV	Electric vehicle
FCEV	Fuel cell electric vehicle
FCH JU	Fuel Cells and Hydrogen Joint Undertaking
GDL	Gas diffusion layer
H_2	Hydrogen
HDV	Heavy-duty vehicle
HGV	Heavy goods vehicle
HT	High temperature
ICE	Internal combustion engine
MEA	Membrane electrode assembly
MOF	Metal-organic frameworks
NFC	Near field communication
NRMM	Non-road mobile machinery
OEM	Original equipment manufacturer
PEMFC	Proton exchange membrane fuel cell (or polymer electrolyte membrane fuel cell)
PFAS	Perfluoroalkyl substances
PFHxS	Perfluorohexanesulfonic acid
PFOA	Perfluorooctanoic acid
PFOS	Perfluorooctanesulfonic acid
PGM	Platinum group metals
POP	Persistent organic pollutants
Pt	Platinum
R&D	Research and Development
REACH	Registration, Evaluation, Authorisation and Restriction of Chemicals
RFID	Radio frequency identification
SOFC	Solid oxide fuel cell
TBO	Time between overhaul
TCO	Total cost of ownership
TEN-T	Trans-European Transport Network
UK	United Kingdom

System-Level Roadmaps

Mobility of People

Mobility of Goods

Technology Roadmaps

Electric Machines

Power Electronics

Electrical Energy Storage

Lightweight Vehicle and Powertrain Structures

Internal Combustion Engines

Hydrogen Fuel Cell System and Storage

Find all the roadmaps at

www.apcuk.co.uk/technology-roadmaps

Established in 2013, the Advanced Propulsion Centre UK (APC), with the backing of the UK Government's Department for Business and Trade (DBT), has facilitated funding for 304 low-carbon and zero-emission projects involving 538 partners. Working with companies of all sizes, this funding is estimated to have helped to create or safeguard over 59,000 jobs in the UK. The technologies and products that result from these projects are projected to save over 425 million tonnes of CO_2.

The APC would like to acknowledge the extensive support provided by industry and academia in developing and publishing the roadmaps.

V01 09/24