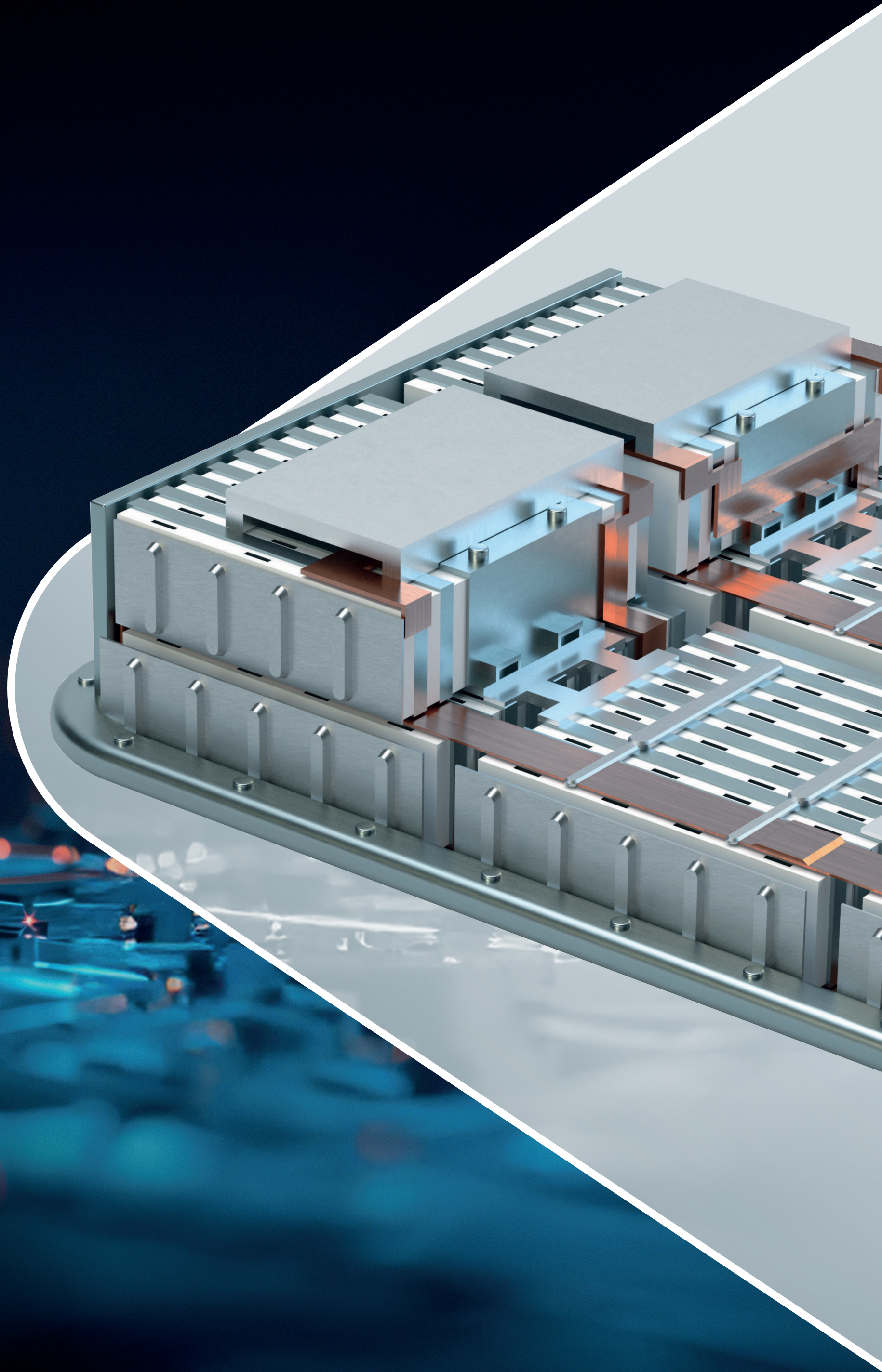
Electric Energy Storage

Narrative Report

2024



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Information correct at time of publication

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1 | Introduction

1.1 | Foreword to the 2024 roadmaps

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Chair, Automotive Council Strategy Group

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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.

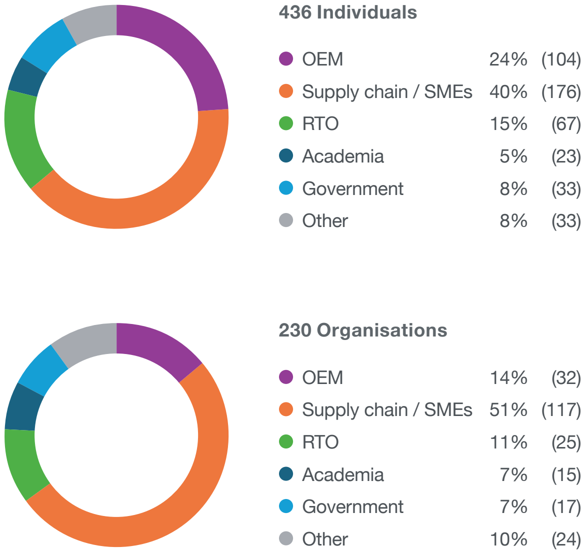
1.3 Building a consensus

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



Professor Dave Greenwood
CEO
WMG HVM Catapult

Since 2017, the UK has had a focussed strategy on growing an indigenous battery industry to serve its automotive sector, and then to diversify into a range of other energy storage applications. Through the Faraday Battery Challenge we have built a world-class battery R&D capability, and through the UK Government's Automotive Transformation Fund that is delivered through the Advanced Propulsion Centre UK, we have anchored two large-scale cell assembly plants (gigafactories) in the UK, with others under discussion.

During that time, we have built a more granular understanding of the future needs of the automotive sector – being characterised by three types of batteries – low-cost 'good enough' chemistries for low-cost suburban vehicles, 'higher cost, higher energy density' batteries for long-range and premium vehicles, and 'high-power' batteries for high-performance and hybridised applications.

The opportunity now is for industry, with support from government, to step into the multi-billion pound opportunities around the upstream and downstream supply chain. This latest iteration of the Electrical Energy Storage Roadmap shows where those opportunities lie, and should help de-risk both public and private investment in the sector.

Tony Harper
Director
Faraday Battery Challenge

The first Automotive Council Technology roadmap was published in the New Automotive Innovation and Growth Team (NAIGT) report of 2009. From an energy storage point of view, there was simply an arrow labelled 'Energy Storage Breakthrough' somewhere in the region of 2024-5 as an enabler for Mass Market EV adoption. Given this was some 3 years before the launch of the Nissan Leaf, it was a common view at the time that battery electric vehicles would not be viable without a transformation in performance and cost.

I would argue this 'Breakthrough' has at least partially occurred and a lot earlier than 2024. Not through any single transformational invention but through numerous improvements large and small in chemistry, cell design, manufacturing processes, module and pack integration, battery management systems, etc. The EES roadmaps over the years have evolved to reflect this, each time increasing in sophistication and reflecting the best consensus view of industry and academia of the technical enablers required to achieve the required targets.

As well as arguing that significant progress has been made, it is also clear that much more needs to be done particularly in regard to performance and cost to enable full mass market adoption. This significant 2024 update to the roadmaps refreshes the performance and cost targets to achieve this at cell and pack level out to 2035, places these targets in the wider context of batteries for electrification and takes a whole system approach to describing the enablers required. My hope is that this document continues to be the common touch-stone for policymakers, industry and academia as we continue our journey to ensure UK Automotive thrives though the transition in the design and manufacture of truly sustainable vehicles.

Jeff Pratt
Vice President Manufacturing and SCM Europe
AESC

Battery technology and electrification will be pivotal in achieving the UK's net-zero targets by 2050. As the global automotive industry transitions towards sustainable mobility, batteries are emerging as the key enabler of this shift, driving innovation across electric vehicles (EVs), energy storage, and circular economy initiatives.

Electrification of transport will extend beyond passenger vehicles to commercial fleets, buses, and heavy-duty vehicles, necessitating continued innovation in energy density, charging infrastructure, and grid integration. The upstream materials supply chain will require strategic investments to ensure resilience and sustainability.

A key trend through to 2050 is the advancements in battery chemistry, with a focus on diversifying beyond lithium-ion technologies. Alongside chemistry advancements, battery recycling plays an essential role in creating a circular economy, minimising waste and ensuring resource efficiency.

As we look to 2050, cross-sector collaboration between industry, academia, and government will be critical to foster a cleaner, more resilient automotive ecosystem. The Automotive Council UK Electrical Energy Storage Roadmap lays a comprehensive foundation for such collaboration and provides invaluable insights into the key trends and drivers for the battery industry.

Julian Hetherington
Automotive Transformation Director
APC UK

On-vehicle energy storage is the key challenge for electrification of transport, and batteries are a vital element – either as primary storage or in combination with hydrogen fuel cells or engines in the case of hybrids.

The updated Automotive Council UK Technology Roadmap for Electrical Energy Storage (Batteries) reflects on the latest trends and drivers in the rapidly evolving field of battery technology. This refreshed roadmap highlights the critical role of diversity in battery chemistries and formats in meeting the varied demands of the automotive industry, from high-performance applications to cost-effective solutions for mass-market vehicles.

Equally important is the focus on low-impact materials production, including secondary reprocessing and recycling, which is essential to move towards a circular economy. Through efficient recovery and reuse of valuable materials, we can reduce waste, lower costs, and minimise the environmental impact of battery production in our pathway to net-zero emissions.

This roadmap also recognises the need for resilient and ethical supply of primary upstream raw materials as the industry grows. As new supply chains are established, greater transparency and knowledge of embodied impacts is vital. These supply chain considerations and the application of battery technologies across other sectors such as grid-connected storage will be key factors in where and how process elements of the value chains are executed.

We hope this roadmap gives greater precision to decision-makers, to shape the foundation of a resilient, sustainable future for automotive energy storage in the UK.

1.4 | Electrical Energy Storage – overview

The development of lithium-ion batteries has accelerated over recent years and this is reflected in a revised roadmap with many previously forecasted developments happening sooner than was initially considered feasible.

Overview: The current market

In the UK there are now over a million electric cars on the road with electric vehicles accounting for over 20% of sales. The number of models available to consumers continues to grow, with over 100 available[1], which in turn is improving the availability of vehicles at different price points. This has led to a rapid maturing of lower cost lithium iron phosphate (LFP) battery technology as well as growing interest in sodium-ion batteries.

Despite this growth, uncertainty remains around price parity with internal combustion engine (ICE) vehicles. This could, in part, be driven by a continuing period of economic uncertainty and changing legislation. Since 2020, 35 countries have introduced nearly 200 pieces of legislation relating to securing or profiting from critical minerals, with 100 pieces of legislation launched in the last two years alone[2].

The role of critical minerals features strongly, particularly in relation to the recycling of end-of-life batteries, with many countries seeking to secure material in a turbulent global landscape.

Technology advances have been rapid with consumer concerns around 'range anxiety' reducing significantly thanks to higher energy densities and lighter batteries owing to advancements in pack integration.

The 2024 roadmap focuses on high-volume, cost-sensitive applications and is split into two parts:

- Battery cell
* Battery modules and packs

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[1] At the time of writing – Sept 2024

[2] Introducing the Critical Minerals Policy Tracker – Analysis – IEA

Overview – Cell materials and manufacturing roadmap

As the market share of BEVs increases, the retail price point is an important factor to drive adoption with the focus on reducing battery cost.

Low-cost cathodes

Lithium Iron (Manganese) Phosphate (LF(M)P) battery chemistries have been growing in market share and will continue to do so. Continual improvements to performance are making LF(M)P a versatile and cost-effective chemistry with many automotive manufacturers announcing LF(M)P as part of their plans in both passenger and commercial vehicles.

Sodium-ion chemistry is also receiving considerable investment and vehicles with sodium-ion batteries are already on the market in China with a growing number of models available. There is uncertainty in its adoption for mainstream automotive applications in the West as LF(M)P is likely to remain cost-competitive with sodium-ion chemistries for some time.

Charging rate

With much of the cathode developments focusing on cost, there are still significant improvements possible in charging rate (C-rate), and capacity with research in novel structures and engineering of cathodes at the particle level. Already, artificial intelligence (AI) is being implemented in the selection and optimisation of candidate structures.

Anodes

With anodes, there is a greater focus on optimising C-rate and capacity with a push towards greater silicon content already evident and some claims of 100%-silicon anodes as soon as 2027. Challenges in implementing 100%-silicon anodes will be overcome through particle engineering and pre-lithiation techniques to improve lifetime issues.

Other anode materials with the potential to disrupt include niobium. Anodes containing niobium are expected to gain market share in off-highway applications where very high power and very short downtime are a necessity. Niobium enables both. The headline figures of C-rates beyond 10°C would make niobium anodes seem very attractive to all industries.

Electrolytes

There is significant uncertainty around different electrolytes and the varying market shares they will take. This is still an emerging technology with very well-documented technical and economic challenges. It is expected that new liquid electrolytes will continue to be developed, which will provide improved safety and performance while reducing cost. It is not until mid-2030s that the benefits of solid-state batteries will be realised at a cost-competitive price point. Alongside this, semi-solid or hybrid electrolytes will offer some of the benefits of solid-state electrolytes, such as safety, e.g. non-flammability and leakage prevention, efficiency, e.g. higher energy density, and performance, at some of the cost increase.

Safety and sustainability

Across the other materials, including binders and separators, safety and sustainability will be key considerations with safer electrolytes and separators being developed to reduce fire risks. In the future, bio-derived separators could reduce the environmental impact of separator materials and the toxicity of electrolytes is likely to be reduced. The timing of these developments is uncertain, but it estimated they would happen from 2035. There is expectation that either of these could be driven more rapidly by regulation which may well be introduced as more holistic life cycle analysis (LCA) regulations come into place.

Life cycle impact is a major feature of these roadmaps and for cell manufacturing there are significant areas that can be improved. Manufacturing of cells is energy intensive and there is currently significant innovation looking to reduce the energy and chemical usage for it. In-line metrology and digital twins are starting to aid in this optimisation with an expectation that AI will be used in cell manufacture by 2030.

Overview – Battery modules and packs roadmap

In the 2020 roadmaps, the consensus was that there would be a shift towards homologated cell design. This was anticipated as a number of chemistries were being trialled and tested with different cell designs to deliver highly-optimised solutions to help improve packaging and safety whilst driving down cost. Now, a divergence of cell designs with homologation being difficult to envisage in the next decade is occurring. This reflects the scale of innovation continuing in battery design at cell, module and pack level.

Smarter battery management

Smart cells with built-in sensors are expected to communicate directly with the battery management system (BMS) in the future. This would enable smarter management of the lifetime of individual cells with dynamic charge and discharge profiles governed through trained algorithms and, eventually, AI.

Consumer expectations for faster charging and more convenience could see, not just increased charging speeds, but battery swapping and wireless charging models. These models are expected to be applied more in public transport, but could gain traction in other sectors. As of January 2024, there were 1,400 battery-swap stations operating in China, this is expected to increase significantly to at least 5,000 by 2025. It is uncertain if this technology will gain popularity outside of China. Additionally, improvements in fast-charging and the accompanying infrastructure may render it unnecessary for passenger cars.

Whichever charging protocols emerge, BMS developments will need to keep in-step, as well as support vehicle-to-everything (V2X), vehicle-to-home (V2H), vehicle-to-load (V2L), vehicle-to-grid (V2G) which are expected to become widely adopted. Consumers will soon expect vehicles to be capable of load balancing for their home energy. V2G is expected to take time to mature in some countries due to the complexity of energy markets in some regions.

Thermal management

Thermal management of batteries continues to see innovation, especially in managing potential thermal events. Chinese and US national standards stipulate that a warning is given to the driver in the case of a thermal event. This requires the monitoring of certain characteristics of a battery in real-time. Currently, this is predominantly carried out at a module level. Methods for detecting thermal events earlier are in development and include various sensing techniques between and in cells to provide cell-level data, which can be monitored in real time by a wireless BMS.

Alongside continuing advancements in lightweight structures for battery packs and modules, research into fire resistant and retardant materials will start to be adopted in mass production improving battery safety.

Designs

Cell-to-pack and cell-to-chassis designs are already on the market. Structural batteries, where the battery is an integral part of the vehicle structure, are anticipated to be widely adopted in EVs in the 2030s. Not every manufacturer is following the route of further integration into the vehicle. Whilst weight and performance advantages can be gained, there are concerns around repairability and applicability, particularly in markets such as bus and coach, where the vehicle would be expected to outlast a battery, with module replacements a more viable option. To enable further integration, some manufacturers are looking to crash modelling, applying machine learning (ML) to predict outcomes of collisions and monitor integrity of battery cells in the event of a collision, reducing and avoiding the need for costly repairs.

With the expected introduction of the European Union's (EU) Battery Directive, batteries entering the EU for sale will need a passport to track the CO_2 emissions associated with the battery and the recycled material contained therein. With targets set for minimum recycled content accelerating the need to develop efficient and cost-effective recycling of batteries is heightened. As such, significant investment and innovation are expected to both reduce the carbon footprint of battery manufacturing and increase the efficacy of battery recycling.

2 | Cross-cutting themes

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.

2.1 | Policy and regulations

The EU Battery Directive (see Figure 2) is the world's most ambitious legislation covering the marketing, recycling and carbon intensity of batteries. It aims to regulate the entire life cycle of batteries placed on the market within the EU.

Beyond emissions and recycling, further regulation is anticipated that considers the entire life cycle impact of batteries, including the impact of harmful chemicals. As a result, companies are investing in research on water-based solvents for cathodes.

New regulations may emerge to govern design for repair and disassembly. Additionally, the growing second-life market could incentivise original equipment manufacturers (OEMs) to create batteries that are easier to re-manufacture.

Regions globally aim to accelerate the introduction of zero-emission vehicles through legislation. While the methods and definitions vary, the end result is a clear acceleration of demand for batteries and battery materials.

Figure 2: Timeline of the EU Battery Directive

However, current recycling regulations are aimed at the recycler, requiring them to innovate to improve efficiencies and produce more recycled material for the supply chain. Recent drops in raw material pricing are disincentivising the development of novel recycling methods. This could come to a difficult point if OEMs pursue highly integrated designs to maximise energy density and recyclers are unable to innovate quickly enough to recycle such designs at scale. This would mean recycling targets are missed, therefore driving new regulations to be introduced governing design for repair and design for disassembly.

A growing second-life market could incentivise OEMs to design for second-life by including features that make batteries easier to re-manufacture through physical design and information recorded by the BMS. This creates its own challenges and could see regulation introduced to define standards for second-life, especially around safety standards.

As well as CO_2, other materials could be designated for reduction or elimination. For example, a potential polyvinylidene fluoride (PVDF) regulation or a ban in the EU could force innovation for new electrolyte and binder materials (see Figure 3).

Global targets for vehicle sales

Around the world, many regions are introducing legislation for zero-emission vehicles. The definition varies from region to region with some regions designating zero emissions of any tailpipe emissions and others specifying only CO_2. In China new energy vehicles (NEVs) include plug-in hybrid vehicles (PHEVs), BEVs and fuel cell electric vehicles (FCEVs), with a commitment that by 2030 60% of sales will be NEVs (see Figure 4).

Global targets show that there will be a substantial increase requiring supply chains across the world to be scaled-up at pace. For some materials, such as lithium, there is concern that this is simply not possible, for other materials there are concerns over geopolitical stability of supply chains, e.g. colbalt. As a result, there is and will continue to be, increased attention to the development of alternative chemistries that can reduce or remove such materials.

Figure 3:
Recycled material content

Recycled material content target	2027 targets (%)	2030 targets (%)	2035 targets (%)
Cobalt	Declare Amount	12	20
Lithium	Declare Amount	4	10
Nickel	Declare Amount	4	12

Figure 4
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

Energy

Since the publication of the 2020 roadmap, the cost of energy has risen creating a renewed focus on energy-efficient manufacturing processes to reduce costs. Battery manufacturing is particularly energy intensive and so focus has been given to rapidly reducing the most energy intensive aspects (see Figure 5).[3]

Reducing energy consumption during manufacturing lowers both costs and environmental impact, with the latter being more significant when clean energy is unavailable. This is of particular importance in serving the European market where battery passports dictate the requirements for transparent carbon accounting. The choice of future gigafactory sites will consider access to low-cost, low-carbon energy as part of the decision-making process, and this will drive investment in infrastructure to deliver the required energy to the sites that need it.

Cost and cleanliness of energy do not just impact the battery manufacturing, but also the extraction and production of the necessary materials. Throughout the supply chain, targets to decarbonise are being put in place, from mining through to the production of active materials.

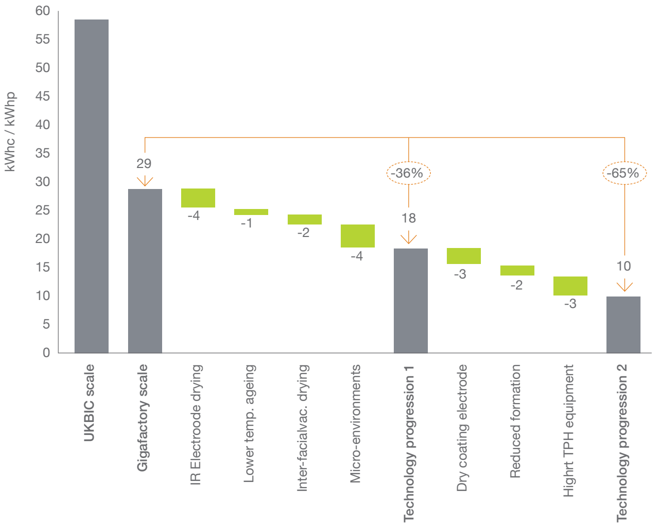
The global mining industry currently has approximately 30,000 large mine hauling trucks in service, with the majority diesel-powered. These trucks emit about 70 million tonnes of CO_2 per year, accounting for almost half the industry's total emissions. Note that these figures are for the mining of all materials and battery materials are a relatively small part of this total[4].

The world's top mining companies, making up one third of the industry, have committed to achieving net-zero emissions by 2050, which will be achieved if the energy used at the mine is clean energy. This involves both building the required infrastructure onsite and the delivery of energy to site. In addition, there is the consideration of vehicle-fleet decarbonisation, some of which can be challenging owing to the demanding duty cycles required. However, with the application of a number of solutions, such as material circularity and the use of clean energy, it is possible to achieve net zero by the 2050 deadline.

The cost of energy also impacts the buyer's choice of vehicle. A more efficient vehicle can achieve a better total cost of ownership and this is, in part, driving increased energy density chemistry choices alongside cell-to-pack and cell-to-chassis trends. However, these trends have other consequences in safety and repairability, which impact insurance prices and resale value.

While some manufacturers are pursuing higher energy densities, not all manufacturers will as they prioritise or consider safety, repairability and recyclability as important factors, particularly depending on use-case. For example, in heavy-duty applications such as trucks and buses, the battery will be expected to be safe and last much longer. Therefore, cell-to-chassis would not be suitable as repairability is a key factor. Extracting value at end-of-life through recycling could also become a key factor.

Figure 5: Potential impact of technology implementation for reduced energy consumption



The three largest energy consuming areas are electrode drying, formation and ageing, and the use of dry rooms to create low-humidity environments.

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[3] ref: Pathways to Reduce Energy Consumption in Li-ion Battery Cell Manufacturing (ukbic.co.uk)

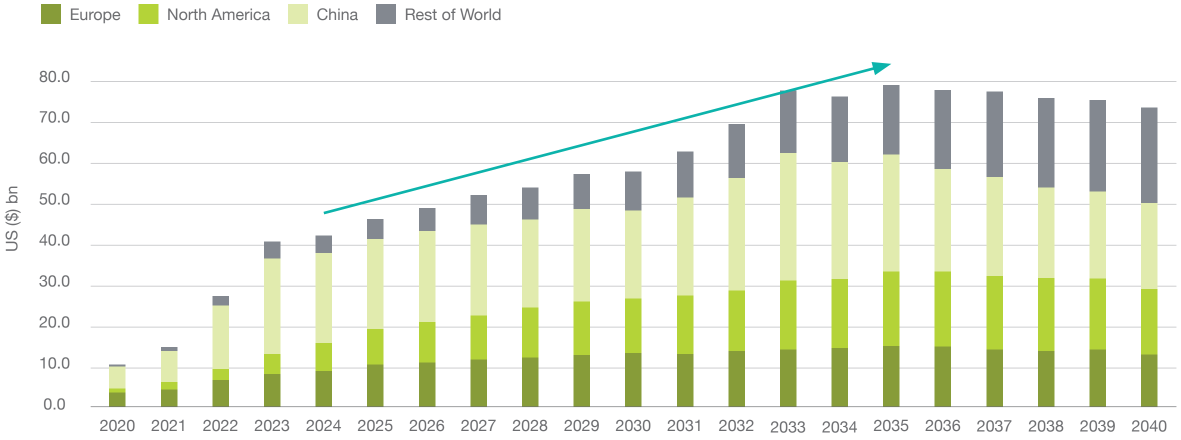
[4] rmi-pulling-the-weight-of-heavy-truck-decarbonization.pdf

Infrastructure

Another important factor in customer choice is availability of charging infrastructure, with range anxiety and availability of simple-to-use charge points being a key concern in many countries. As with driving efficiency, this propels vehicle designs towards higher energy density chemistries and cell-to-pack or cell-to-chassis designs to optimise vehicle range. However, as charging infrastructure continues to be rolled out, these concerns are likely to reduce and more cost-effective, but lower energy density chemistries could see a boost in popularity.

Annual BEV charging investment is expected to hit $57 billion by 2030 (see Figure 6), and significant investment for EV charging infrastructure is already being committed across the UK and Europe.

Figure 6: Annual BEV charging investment



BNEF Economic transition scenario

UK

UK Government has invested in increasing the availability of public charging points through the deployment of various investment funds and grants. In December 2023, UK Government launched the £70 million rapid-charging fund pilot that will facilitate the roll-out of ultra-rapid charge points at motorway service areas. The UK aims to have 30,000 public charge points by 2030.

UK Government is currently delivering £381 million to local councils through the Local Electric Vehicle Infrastructure (LEVI) fund. Local councils can choose where best to install charge points in their area.

Europe

As part of the EU's alternative fuel infrastructure regulation, more EV charging stations will be deployed. Some key highlights from the proposal include:

- From 2025 onwards, fast recharging stations of at least 150 kW for cars and vans need to be installed every 60 km along the EU's main transport corridors (TEN-T network)
- Recharging stations for heavy-duty vehicles (HDVs) with a minimum output of 350 kW need to be deployed every 60 km along the TEN-T network. This initiative is supposed to start deployment in 2025, with full network coverage by 2030.

A further interesting development in infrastructure will be in the support for V2X bi-directional charging. V2H and V2L are already advertised features.

V2H is where a vehicle's battery can be used to balance load during the day at a house with its own energy generation, e.g. solar. V2L is where a vehicle battery can be used to charge another device, e.g. camping equipment.

V2G is another part of V2X but is currently difficult to utilise. V2G is where a vehicle's battery is connected to the grid, which could be via any charge point, and can be used to dynamically balance grid load. This has the potential to generate revenue for the vehicle owner and completely change how energy storage is seen in the energy generation system. However, it requires new infrastructure development to optimise the potential benefits.

2.3 Materials and manufacturing

Pricing and investment

Potential price fluctuations and shortages of various materials used in batteries will drive development in innovations that reduce material usage or look to swap them out entirely. For example, LFxP is seeing a growth in investment as it provides a lower cost alternative to nickel manganese cobalt (NMC), since the cathode does not contain nickel and cobalt, and when combined with other innovations can deliver competitive pack-level performance. When a full LCA is done on the cost of NMC, it could actually be lower than that of LFP-based cathodes if the recycling potential of cobalt and nickel are considered. Sodium-ion chemistries remove the need for lithium and can offer a cost-competitive option where energy density is less critical. Copper thrifting can be achieved by moving to 800 V (and higher) architectures.

Investment in new material supply chains, such as direct lithium extraction in Europe and the UK, is supporting the drive towards localisation. Similar strategies can be expected for other critical materials with potential for innovation in extraction and processing methods to reduce costs and environmental impact of material supply chains.

Recycled materials

Recycling of batteries is expected to create a new supply chain for battery materials. While in its infancy, the integration of recycled materials is perceived as challenging owing to potential contamination. However, this concern is expected to diminish as innovative recycling methods emerge. These advancements in recycling technology will not only decrease costs and increase yield, but also lessen the environmental impact. This is achieved by reducing energy consumption and minimising the use of hazardous chemicals in the recycling process.

The integration of recycled materials into manufacturing processes is just one of several large changes expected in manufacturing over the coming years. Currently, the focus for manufacturing is primarily in reducing cost; innovations that achieve this also typically reduce material waste and energy consumption and offer additional positive environmental benefits.

An example is where dry electrode manufacturing eliminates the need for capital, energy and time-intensive drying steps while reducing the use of solvents. Tesla has estimated that dry electrode manufacturing will require 86% less capital investment.

Environmental footprint

Solvent and water-free processes are being developed that will reduce the environmental footprint of manufacturing with reduced water use and the elimination of hazardous waste materials.

New coating techniques, e.g. optimised slot-dies for improved coating thickness, along with learnings adapted from other industries, can improve the battery-cell characteristics while improving control and reducing material usage and costs.

Clean and dry room facilities are being optimised to reduce the amount of space and energy they use, bringing down costs and improving the environmental impact of battery manufacturing.

New metrology techniques are being incorporated to monitor and control quality at each step of the process leading to smarter manufacturing methods that can predict the outcome of final testing and reduce the need for lengthy and expensive testing processes.

2.4 Digitalisation

Digital twins

Digitalisation is set to revolutionise manufacturing through the use of digital twins, which can be physical simulations of a manufacturing process or AI models derived from measurements of material inputs, in-line metrology and final manufacturing test outcomes.

However derived, the intention of these digital twins is to aid in developing closed-loop process control that can monitor production processes and adjust in real-time for deviations from control parameters. Digital twins can also be used to correlate battery performance to input material and production parameters offering a solution to reduce costly final performance testing.

Data

Enabling this comes with significant implementation challenges, most significant is the interoperability of large amounts of data amongst devices, often from different vendors. Here, the developments of standards for data, interfaces and protocols from communication between different systems will need to be developed and adopted. Potential large data pools require their own support systems and if data are to be pooled across equipment vendors or manufacturers then data security will be a key issue that needs addressing. However, the potential gains are also significant, by controlling and optimising quality across the process costs can be reduced and performance of cells and packs can be improved.

Digital tools

Digital tools, such as physics-based simulations or AI models, are used before manufacturing even begins. Digital tools are being used to accelerate material discovery, develop new chemistries for anodes, cathodes and electrolytes and even new ways of making a cell are being employed to create lower cost and higher performance batteries.

When battery cells are in use, digital tools can be deployed on the BMS to monitor and optimise the charging and discharging of cells, improving both performance and battery life. New ways of monitoring individual cells are being developed to improve battery safety and provide insight into battery failures. Such tools can be used to indicate which cells need replacing to rejuvenate a battery pack ready for a second life. The same improved information can offer confidence to insurers and consumers, both for monitoring the health state of batteries involved in incidents, and for greater confidence in buying a second-hand vehicle.

3 | Narrative to roadmap

3.1 | Electrical Energy Storage – technology indicators

These technology indicators have been developed for energy-focused, cost-sensitive applications. These are technology indicators that industry is likely to achieve in a mass-market competitive environment.

1 Energy density applies to both cell and pack, and is measured volumetrically (Wh/l) and gravimetrically (Wh/kg). Volumetric energy density governs how much space a battery pack takes up and gravimetric energy density how heavy it is.

2 Charge acceptance continuous C-rate, often referred to as charge rate or C-rate, is a measure of the rate at which a battery pack is being charged and discharged. A 4 C rating means battery packs are expected to be fully charged in 15 minutes.

Cost has been omitted due to the transient nature of costs for the chemistries described.[5]

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[5] Cost is linked to cost of materials, production scale and design. Therefore, different applications will have very different costs and the volatile nature of material costs makes forecasting future costs challenging.

3.2 | Cell materials and manufacturing – technology themes

The next few pages of this report will look in-depth at each section of the Electrical Energy Storage Technology Roadmap. It is recommended you have the document to hand. However, for ease of reference the relevant page is pictured.

Roadmap technology themes

(Click underlined links to jump to sections)

Electrodes

Anode development for lithium-ion and sodium-ion cells are detailed in this section. In the medium term, there is a focus on increasing silicon content in anodes to improve energy density.

Cathodes continue to represent the highest cost in a cell. Innovations to reduce cost and increase energy density are featured here. Sodium-ion cathodes offer the potential to reduce cost and the use of critical minerals.

Other cell materials

Electrolytes provide the matrix through which ions travel between the electrodes. Liquid electrolytes continue to see incremental improvements. The step-change innovation comes with semi-solid and solid electrolytes with the former likely to hit mass market sooner.

Separators provide insulation between layers of the cell. As separators get increasingly thinner and are asked to handle higher current densities, new materials and coatings are needed.

Current collectors are typically made from copper or aluminium foil. New materials and structures are being developed to optimise flow of charge, thus optimising power density and longevity of the cell.

Solvents, binders and additives

Solvents, binders and additives enhance the conductivity and adhesive properties in the active materials. Continued improvement in conductivity through new additives is expected alongside innovation in improving the safety and environmental impact of solvents and binders. As dry electrode processes are introduced, these will need new binders.

Manufacturing and processing

The manufacturing and processing section captures the improvements expected in cell manufacturing. Digital tools will play a key role in reducing costs and energy usage. Dry manufacturing processes, which eliminate solvents, will further reduce the environmental impact of battery manufacturing and, in turn, reduce the cost.

Life cycle

Life cycle impact includes not only carbon intensity but also broader environmental impact, resource consumption, and developments relating to reuse and re-manufacturing of cells, and material supply chains.

Material recovery captures the recycling of cell materials at the cell-manufacturing stage and the required development to enable that recycling.

▸ **Electrodes**
- Anodes
- Cathodes

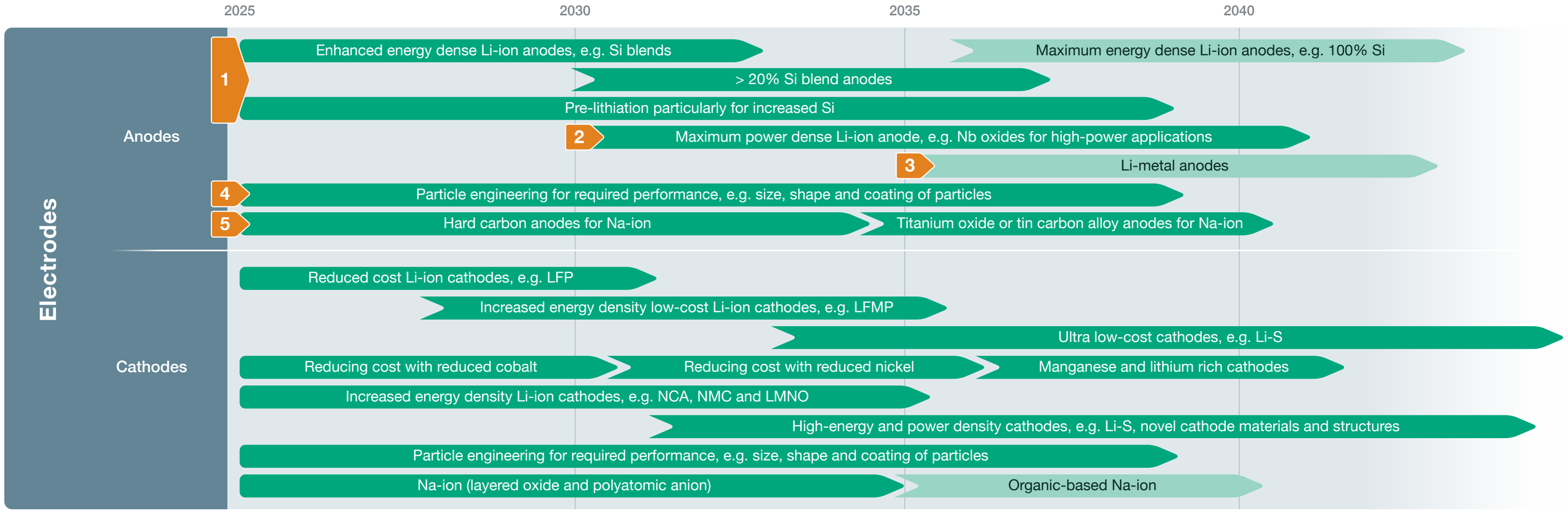
▸ **Other active materials**
- Electrolyte materials
- Separators
- Current collectors

▸ **Solvents, binders and additives**

▸ **Manufacturing and processing**

▸ **Life cycle**
- Life cycle impact
- Material recovery

This section looks in detail at the line-by-line activity on the Electrical Energy Storage Roadmap. The numbers will direct you to the line being discussed here in detail.



Cell materials and manufacturing

Electrodes

1 Increasing silicon content in graphite anodes for lithium-ion cells increases the energy density. Silicon anodes experience volume expansion during use leading to mechanical degradation. To enable > 20% and eventually 100%, silicon anodes pre-lithiation techniques are needed, potentially alongside other techniques, like particle engineering. Pre-lithiation can compensate for the lithium losses caused by expansion and maintain battery life for longer.

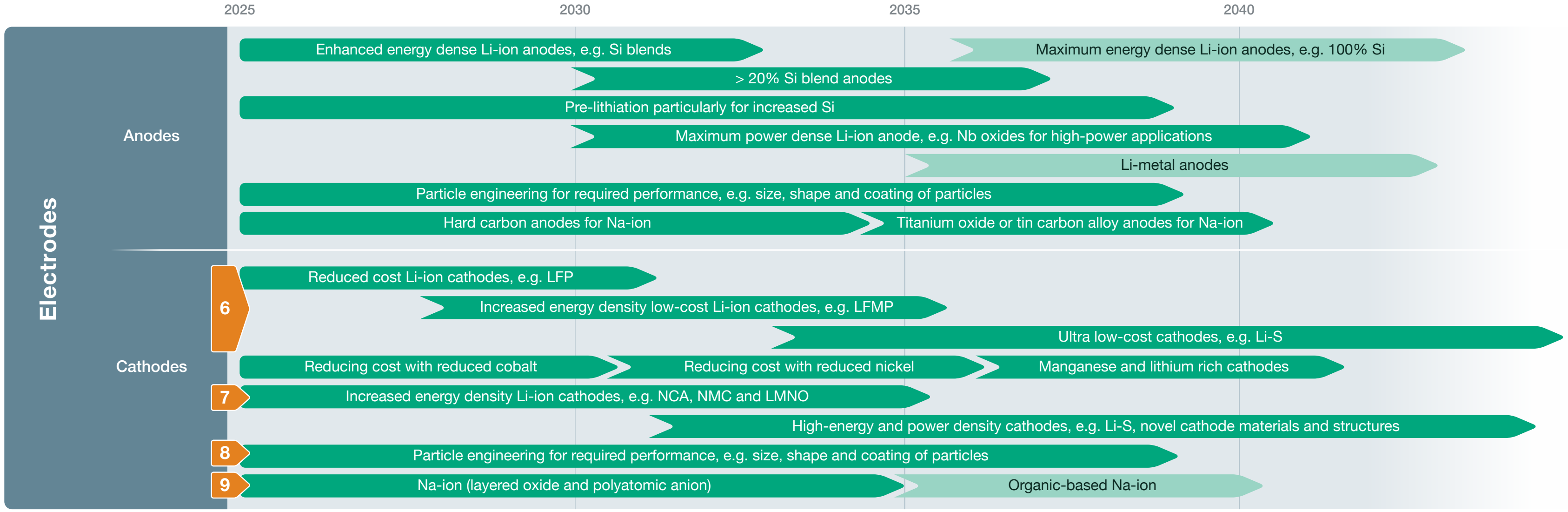
In general, pre-lithiation is used to account for lithium losses particular during factory acceptance test (FAT) process and increase the battery energy density.

2 Despite increasing silicon content, high-power applications could make use of alternative materials. In the near term, other promising anode materials for high-power include niobium-based anodes, which could provide higher voltages and power densities without dramatically increasing costs. By 2025, niobium-based anodes will be commercially available for some applications.

3 One novel anode is lithium metal, providing a step-change in capacity and cell construction. However, producing lithium metal cost-effectively and reducing dendrite growth to ensure adequate battery life remain significant challenges.

4 Whatever the material, particle engineering can be employed to optimise the required characteristics, such as electrochemical performance, mechanical stability, and overall lifespan of batteries, through the control of particle size, shape, porosity and via the application of coatings. Digitalisation, e.g. predictive modelling, can help optimise particle engineering.

5 Sodium-ion is beginning to see commercial use in vehicles in China and it offers a potential cost reduction alongside the opportunity to move away from high-risk supply chains. Consequently, improving anodes specifically for sodium-ion cells will enable higher energy densities than currently achievable and further increase the potential densities available to the automotive-based market.



Cell materials and manufacturing

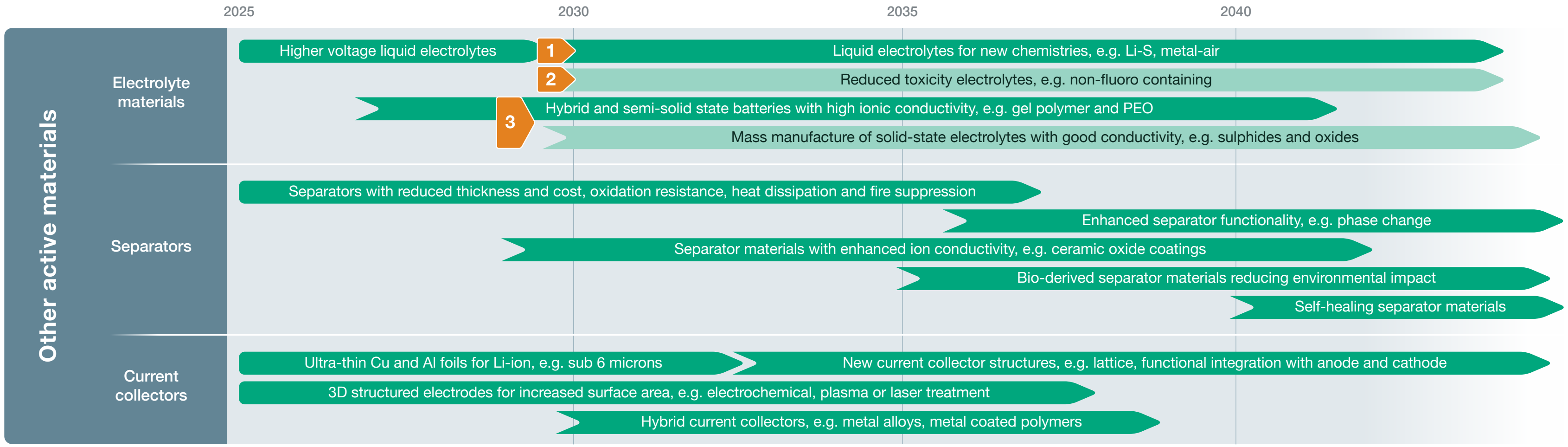
Electrodes (continued)

6 For some high-volume automotive applications, reducing the cost of cathodes, by removing high-purity nickel and cobalt, is seen as a promising route. Cathodes such as LFP are being deployed in the immediate term, by 2025 some cell manufacturers will be adding manganese to LFP, increasing energy density. In Europe and other markets, other ultra-low-cost cathode materials are expected to enter the market alongside LFP / LFMP. These include manganese-rich NMCs, which eliminate cobalt and drastically reduce nickel content.

7 NMC and nickel cobalt aluminium oxide (NCA) are the dominant energy dense lithium-ion cathode materials used by the automotive industry. For NMC in particular, the trend is for increasing energy density by increasing nickel content. Other high energy and power density cathodes, such as lithium sulphur, are attracting investment and may reach mass market in the next decade.

8 As with anode materials, particle engineering can be employed to optimise the required characteristics through the control of particle size, shape, porosity and using coatings.

9 Over the past 10 years, there has been significant industry activity around sodium-ion chemistry cells with Chinese manufacturers announcing new cells and ramping-up supply chains. These new cells are being deployed in small vehicle segments in China, while in Europe OEMs have expressed interest in bringing sodium-ion chemistry to market to reduce both cost and reliance on the critical mineral supply chain.



Cell materials and manufacturing

Other active materials

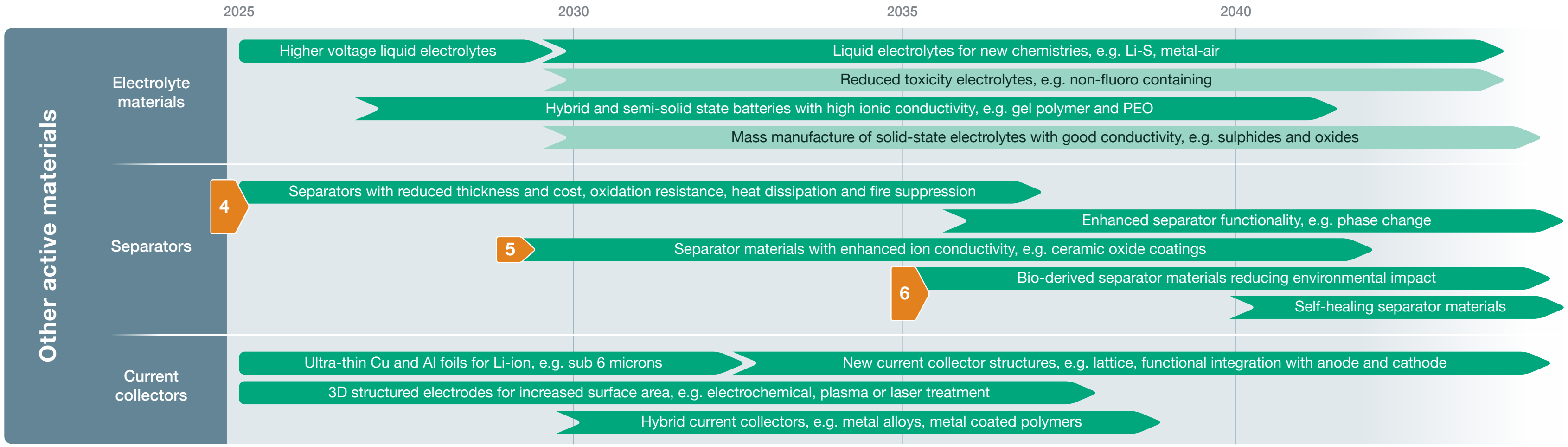
1 Incremental improvements in chemical composition have enabled liquid electrolytes to evolve with improved cathode and anode materials. Electrolytes that can tolerate higher voltages and faster charging for energy-dense electrodes have been a key focus of research. Recent innovation has focused on blending lithium salts, solvents and additives that improve ionic conductivity and reduce the thickness of the solid electrolyte interphase on the electrodes.

Higher nickel content in NMC-based cathodes and higher silicon in the anode can cause traditional electrolyte solutions to degrade more rapidly. New electrode materials, like sodium-ion and lithium sulphur, all require electrolytes tailored to their properties.

2 Electrolytes can contain hazardous chemicals. These are likely to be replaced with alternatives in a bid to reduce the environmental impact of batteries and improve the recycling safety.

3 Hybrid or semi-solid electrolytes and solid-state electrolytes offer enhanced safety, improved energy density and faster charging capability. Hybrid electrolytes can reduce the use of binders and other active materials as well as removing or reducing costly processing steps like drying, solvent recovery and electrolyte filling. Solid-state electrolytes can remove the need for a separator and reduce the likelihood of dendrite growth, a key cause of thermal runaway, thus enabling the use of anode materials like lithium-metal anodes. Two main types of solid-state electrolyte are sulfides and oxides, each with inherent strengths and weaknesses. Oxides are environmentally more benign but harder to manufacture, while sulfides contain more hazardous materials.

There is still significant process improvement required to achieve mass production for high energy-dense applications. Semi-solid or hybrid electrolytes entering mass market in the next couple of years are likely to offer many of the benefits of solid-state chemistry. Hence, there remains a significant lack of consensus on when true solid-state chemistry will be available for mass-market use.



Cell materials and manufacturing

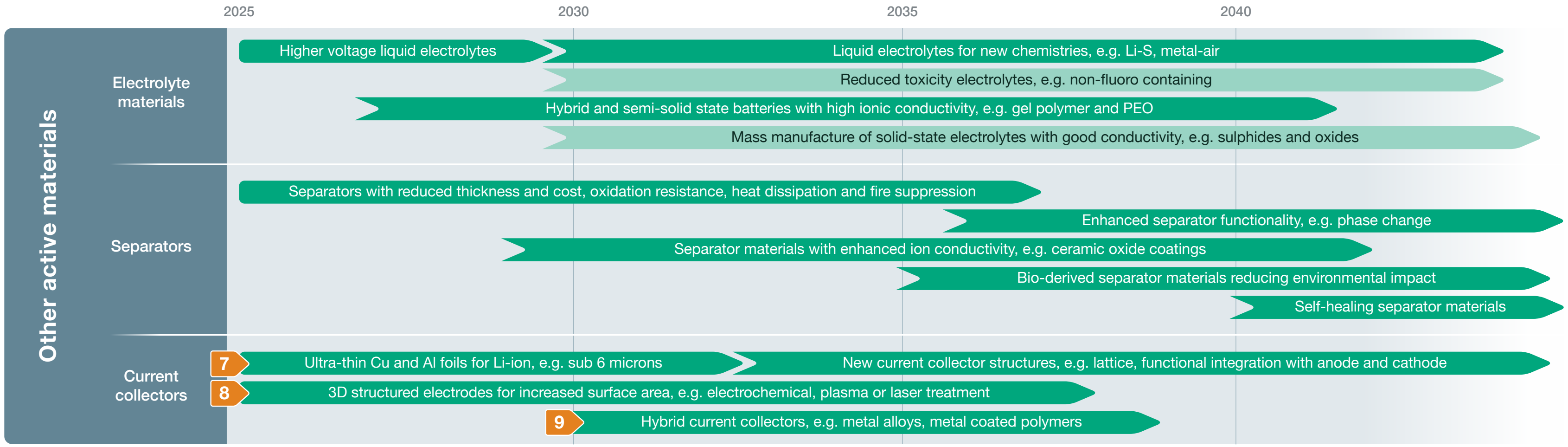
Other active materials (continued)

4 Separators in Li-ion batteries are typically made from polyethylene (PE). However, it is common to see polypropylene (PP)/PE/PP tri-layer separators, consisting of a middle layer of PE sandwiched by outer PP layers. As the C-rate of cells increases, more thermally robust separators will be needed to reduce the likelihood of internal propagation. Maintaining capacity at higher current densities is also essential to commercialise high-powered cells.

In the medium to long term, enhanced functionality is likely to include separators with advanced thermal management (phase-change materials) or fire-resistant materials.

5 Novel materials are being developed for both separator coatings and the membrane material. Ceramic materials that can operate under high temperatures are candidates to improve conductivity and reduce degradation.

6 New materials are being developed to reduce the environmental impact of separator materials, which are generally polyethylene-based. These include bio-derived alternatives that can be industrially composted. Other novel materials likely to emerge in the future could include advanced sensing and self-healing properties to reduce the occurrence of thermal runaway. For example, polymeric gel separators with micro-capsules are self-healing materials. Companies developing advanced battery technologies are exploring self-healing separators to enhance the safety and durability of their battery packs.



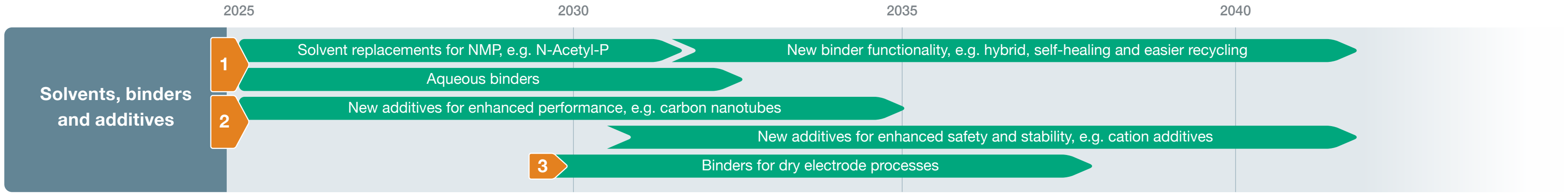
Cell materials and manufacturing

Other cell materials (continued)

7 Cost-effective foils for high-volume applications are currently around 6-10 µm thick. For high-performance applications, achieving below 6 µm is desirable. In the long term, cathodes and anodes could be functionally integrated with current collectors via lattice structures, where the cathode material is embedded into the foil rather than coated on top of it.

8 Surface treatment of electrodes takes place in order to optimise porosity, increase surface area and enhance adhesion. Further development of more novel 3D structured electrodes, for example using 3D-printing techniques, will further improve charging speeds and battery capacity.

9 New hybrid, multi-material, current collectors will enter mass market in the short to medium term. Using tailored metal alloys to enhance conductivity and tensile strength is one innovation route. Other methods include ‘sandwich’ materials, where polymers or graphene are encased in copper or aluminium.



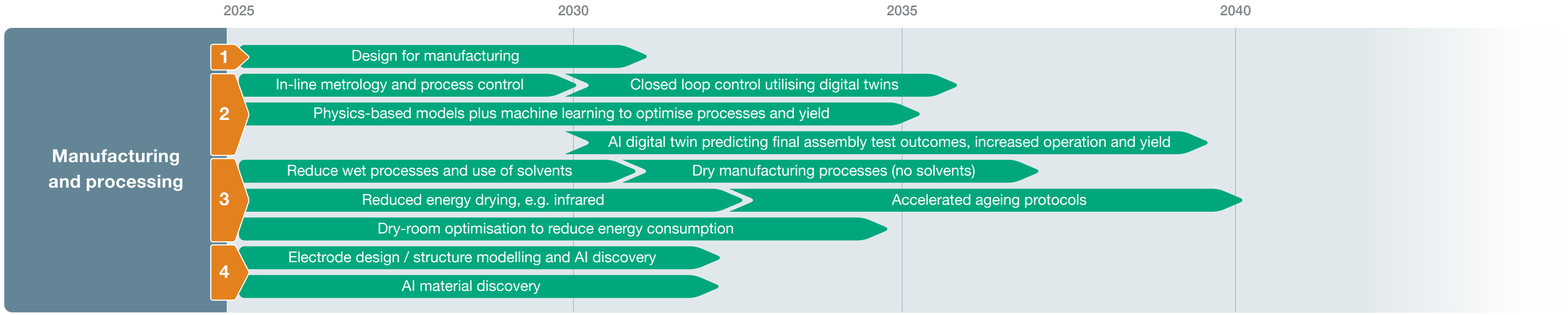
Cell materials and manufacturing

Solvents, binders and additives

1 Eliminating N-methyl-2-pyrrolidone (NMP) will reduce manufacturing costs and improve environmental impact and safety. NMP is both toxic and flammable. Aqueous binders are the preferred alternative where possible. As new binders are developed, new functionality is added with self-healing binders that accommodate anode expansion and improved ease of recycling, with aqueous binders being attractive functionality to add.

2 Additives are one of the key elements used in batteries. Unknown or undisclosed quantities of additives can make recycling more challenging and create a safety concern. New additives can improve the safety of the battery both during use and at end-of-life, as well as improve the battery life.

3 Dry manufacturing processes are starting to be adopted, in particular for anodes although cathodes remain more challenging. These dry manufacturing processes require new binders. In the long term, binders may be eliminated entirely in fully dry manufacturing processes.



Cell materials and manufacturing

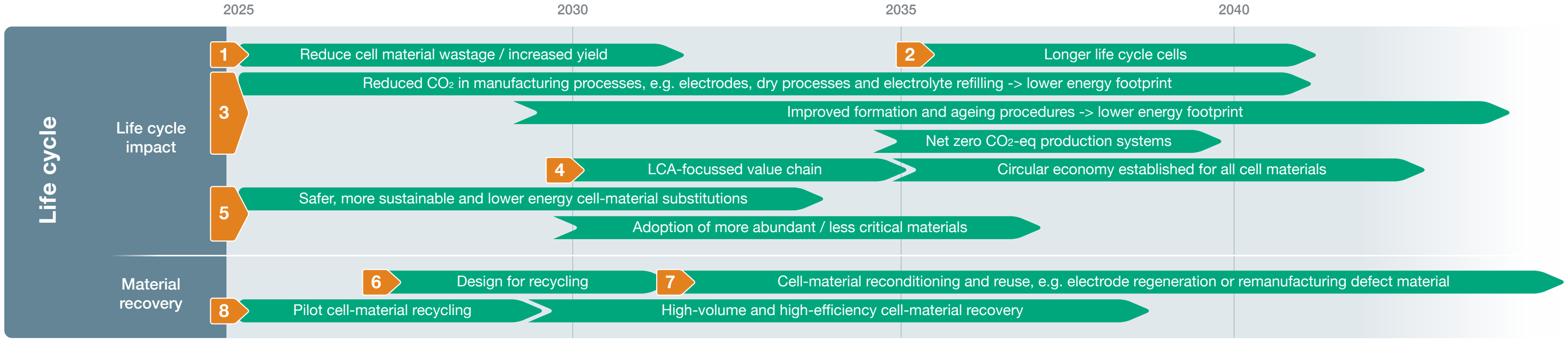
Manufacturing and processing

1 To optimise throughput and cost, manufacturers will be looking to design manufacturing principles and utilising digital tools in the design phase. The potential unintended consequence is that design for manufacturing does not always equate well to the design for repair or recycling.

2 Digital tools will play a greater role in improving manufacturing processes through the application of sensors to provide real-time metrology data from imaging of defects in electrodes, through to particle-size measurement of input materials. This data, combined with digital twins based on physical models and, in the future AI, can provide closed-loop control, predict outcomes of formation, aging and test steps resulting in increased yield and reduced costs.

3 Use of energy and hazardous chemicals will be reduced by moving closer to full dry manufacturing processes, reducing energy consumption of manufacturing steps like drying, accelerating energy intensive aging protocols and optimising dry-room energy usage.

4 AI-tools are being used to develop new materials for all parts of a cell. These materials may offer advantages but require new manufacturing processes to be developed.



Cell materials and manufacturing

Life cycle

1 Reducing cell-material waste and faulty cells are top priorities to minimise cost and life cycle impact of cell manufacturing. Digital tools and AI are expected to play a big role in the optimisation of manufacturing processes and in doing so will increase yield and reduce waste / scrap.

2 Whilst some chemistry developments chase energy density at the potential expense of lifetime, future developments may look to improve the life cycle of cells with good enough energy density, thereby improving the life cycle impact.

3 The cost of energy and a desire to achieve net-zero CO_2 emissions are driving innovation to reduce the manufacturing carbon footprint. Combined with access to low-cost, low-carbon energy, net-zero production is achievable within the next decade.

4 The supply chain has its own environmental footprint and while cost is a key driver, life cycle assessments are to become an important element when assessing a material supply chain. Along with the recycling of waste material, cell-material supply chains will significantly reduce their life cycle impact in the coming decade and move towards circularity.

5 Safety and cost are key considerations meaning cell-chemistry choices will be seen moving where possible to safer and more sustainable materials with the adoption of more abundant materials becoming more of a consideration. This could increase the adoption of LFP based lithium-ion cells and sodium-ion cells.

6 While the design for manufacturing is the current focus, the need to make good use of waste material will see the design for recycling feature more prominently in cell manufacturing. The cell designs themselves may not change, but some change could be seen in the manufacturing of the electrodes that, for example, facilitates recycling.

7 Current techniques to recover material involve hydrometallurgy, which recovers salts of the required materials needing further processing. For cell manufacturing, direct recycling or regeneration of electrode material from defect material, offcuts and defect cells could provide a higher efficiency recycling pathway.

8 Outside of China, cell-material recycling is still happening on a relatively small scale and it is expected that collocated cell recycling will be initiated with many cell manufacturers leading to high-volume, high-efficiency material recovery for a particular cell type and chemistry manufacturing at that site.

3.3 | Module and pack – technology themes

The next few pages of this report will look in-depth at each section of the Electrical Energy Storage Technology Roadmap. It is recommended you have the document to hand. However, for ease of reference the relevant page is pictured.

Roadmap technology themes

(Click underlined links to jump to sections)

Cell format and design

Cell formats and design are diverging based on requirements of each OEM with optimisation based on balancing packaging, economics and safety being different for varying end-use cases.

Module and pack innovations

Electrical distribution systems (EDS) enable power from battery cells to be intelligently distributed and monitored. New requirements for improved safety, longevity and improved features will drive innovation.

Thermal management systems are essential to maintain the health of a battery pack and can increase its lifetime. Cells can be heated or cooled to mitigate issues relating to high and low temperatures. Avoidance of safety issues related to thermal events is a key area of research focus.

Mechanical elements include the housing and joining techniques that contribute to the integrity of modules and packs. Battery casings and structures offer significant opportunities to reduce weight, while new joining processes ensure cell-to-cell contacts are robust.

Pack integration and manufacturing explore ways of integrating energy storage and management into the vehicle. Embedding energy storage into the wider vehicle structure and converging thermal management systems are key trends for this section.

Life cycle

Life cycle impact includes, not only carbon intensity, but also the broader environmental impact, resource consumption, and developments relating to reuse and re-manufacturing of cells, modules and whole packs.

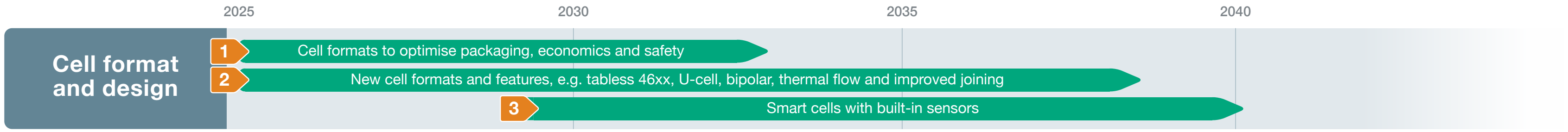
Material recovery captures the recycling of cell, module and pack materials at the end of the useful life and the required development to enable that recycling.

▸ **Cell format and design**

▸ **Module and pack innovations**
- Electrical distribution system
- Thermal
- Mechanical
- Pack integration and manufacturing

▸ **Life cycle**
- Life cycle impact
- Material recovery

Modules and packs roadmap



Module and pack

Cell format and design

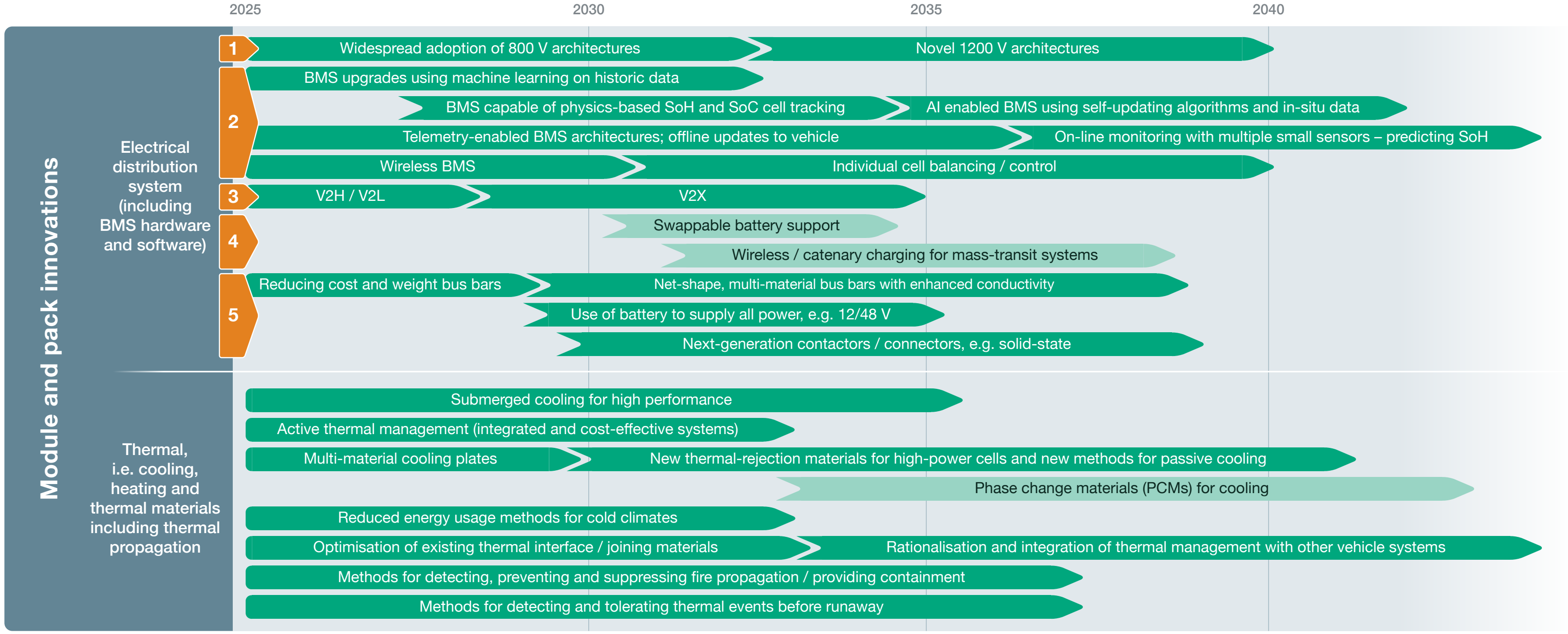
1 In 2020, the roadmap stated an expectation that battery-cell formats would converge around some standard formats.

In 2024, a wide variety is seen to support cell-to-pack and cell-to-chassis for differing OEM designs. The development of different chemistries supports different formats and, whilst there is some standardisation at the OEM level, innovation continues at pace and that necessitates flexibility in new cell formats.

2 As cell chemistries continue to evolve, new formats can improve manufacturing efficiency, energy and power density, as well as safety.

3 Not every cell in a battery pack is the same. It is the job of the BMS to monitor, control and optimise the pack but this is done with limited to no information at the cell level.

Smart cells can include non-invasive sensors used during manufacturing to optimise the FAT process. Sensors attached to cells are already in use in some cases, but sensors are being further integrated directly inside the cell to provide the most accurate and real-time information. As these capabilities are further developed, wireless communication with the BMS from each cell would allow optimisation of the battery at the cell level along with increased safety through the monitoring of abnormal behaviour in individual cells, providing a step-change in health management.



Module and pack

Module and pack innovations

1 800 V architecture is being widely adopted, including in mass-market applications. 400 V architecture will remain in use alongside that of 800 V where cost is critical or in micromobility and similar applications.

2 Improvements to BMS are enabling better state-of-charge (SOC) and state-of-health (SOH) information leading to improved management of a battery life and performance, including optimising charging speeds.

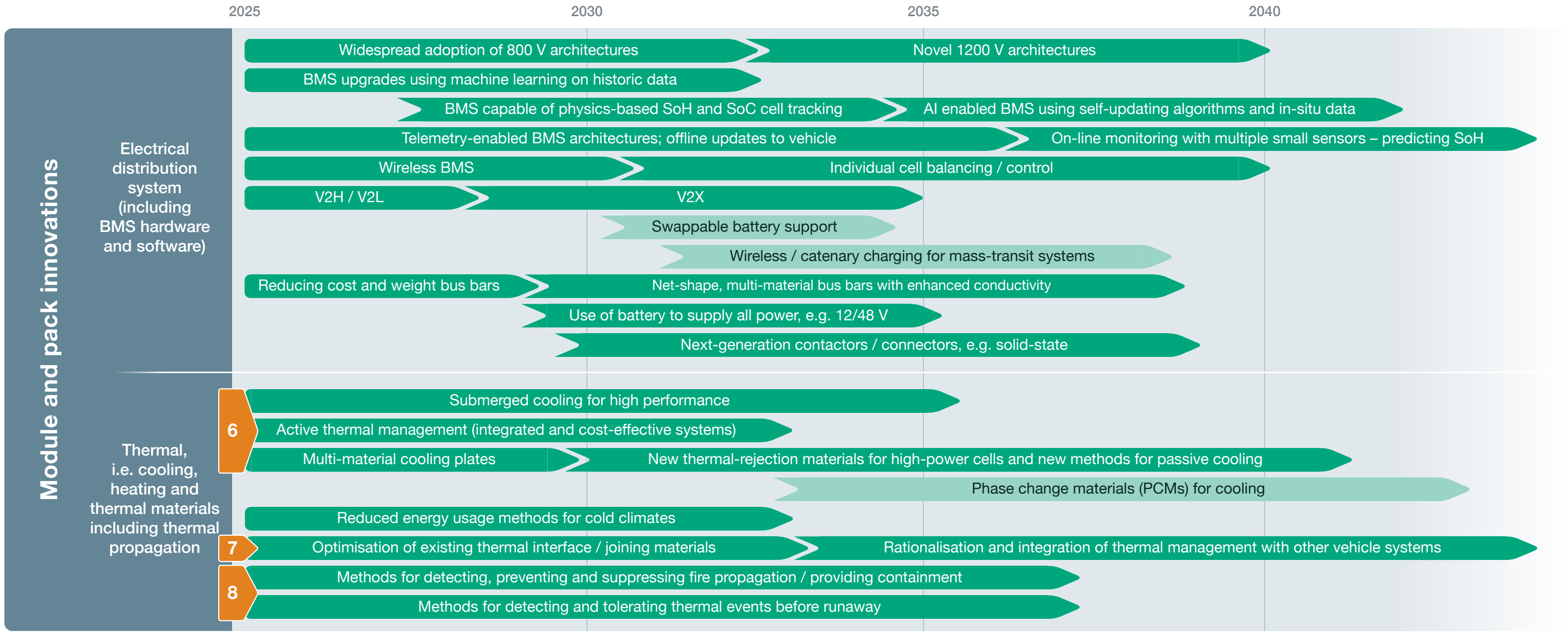
In the near term, real-world historic data is used to inform algorithms with more sophisticated methods based on multi-physics modelling being deployed in other applications making their way to the automotive industry. AI could enable battery models to self-update using real-time data from smart cells. An advanced BMS could isolate cells, enabling a degree of self-healing, extending the life of cells and highlighting which cells need replacing in fault scenarios.

3 For homeowners who generate power, for example with solar panels, V2H creates an opportunity for load balancing, using the car as energy storage while not in use, but ensuring it is ready to use when needed.

V2X, vehicle to anything, for example the energy grid (V2G), enables the same load balancing but at a potentially national level. This would require investment in enabling infrastructure and some incentives for the vehicle owner, but has the potential to change how energy as a system is managed.

4 New methods of charging, such as wireless charging, or avoiding charging by swapping batteries will need developments in BMS software to enable and optimise performance. While trials are being carried out in the near term, it is still uncertain whether these technologies will reach mass-market applications.

5 Bus bars and connectors are essential for efficient electrical-power distribution and safety. Reducing the size and weight improves the vehicle efficiency allowing for greater range. Developments include using alternative materials and developing next-generation devices, which can be equipped with sensors and communication capabilities for diagnostics and predictive maintenance. Solid-state connectors, unlike traditional ones with moving parts, rely on semiconductor technology. They have no wear or corrosion due to a lack of physical contacts and minimal resistance with no contact bounce.



Module and pack

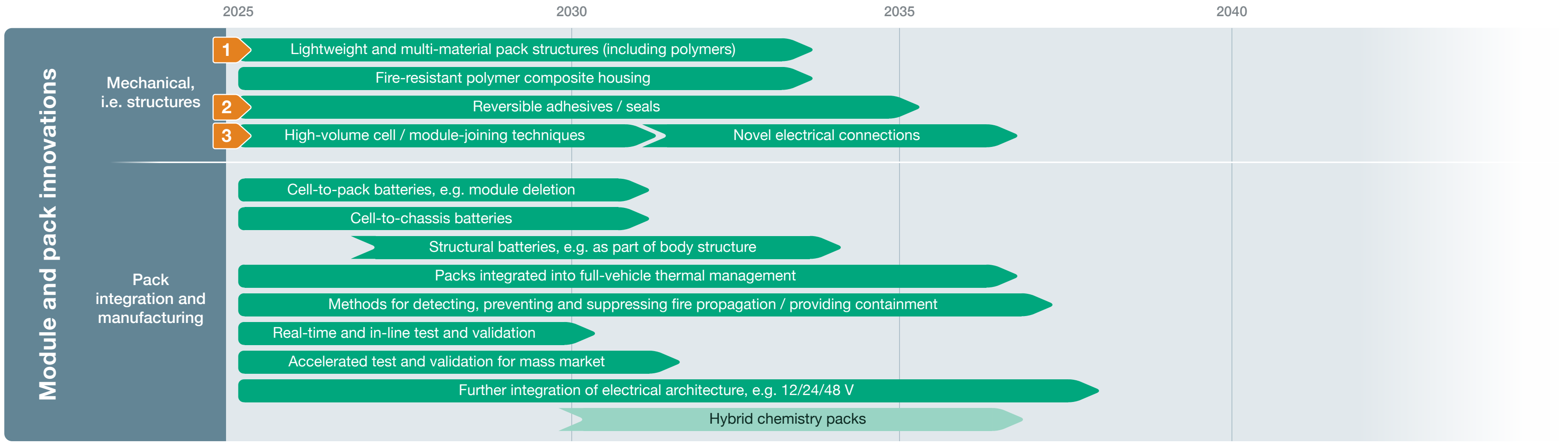
Module and pack innovations (continued)

6 As higher C-rate-allowing fast-charging is becoming more prevalent, along with high-energy and high-power battery packs, enhanced cooling methods are required to keep batteries at an optimal temperature. The most pronounced thermal events occur during rapid charging > 150 kW, pre-cooling the battery and enabling active cooling during charging are potential strategies to mitigate this risk.

7 To optimise thermal management, improvements in thermal interfaces are needed to allow for the most rapid transfer of heat. As the active systems become more complex, integration with other thermal management systems on the vehicle is a growing trend.

8 Chinese and US national standards require the driver is given a warning in case of a thermal event. Certain battery characteristics are recommended for the measurement. These characteristics indicate a thermal event is happening. Methods for detecting thermal events earlier are in development and include various sensing techniques between and in cells.

Beyond warning of thermal events, much attention is paid to preventing them occurring and preventing spread to other cells.



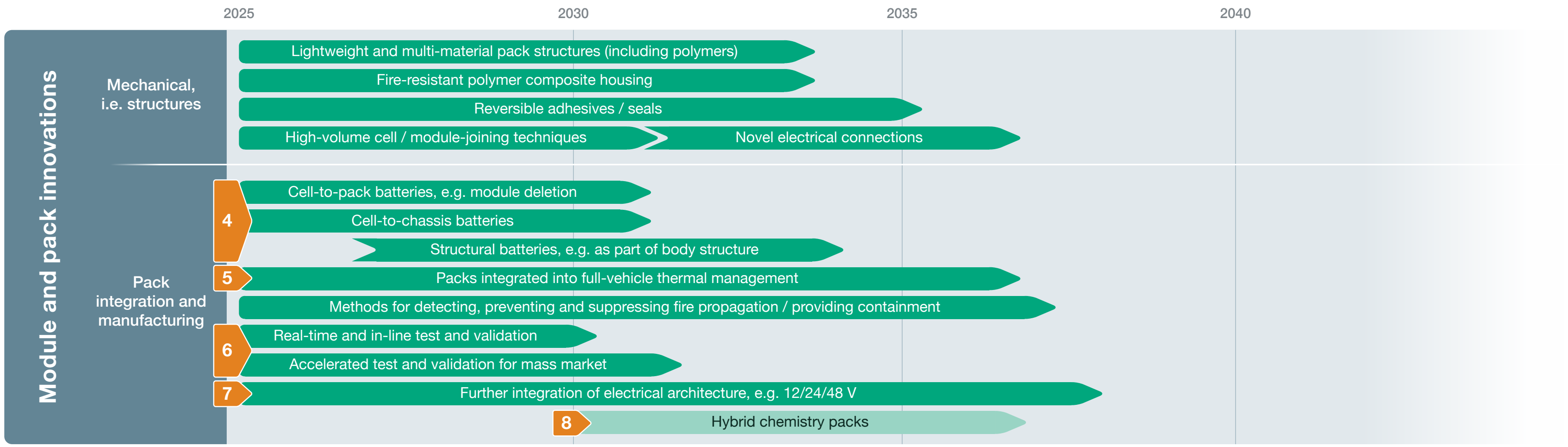
Module and pack

Module and pack innovations

1 Polymers and composites are offering replacements to metals to reduce the weight of battery casing and support structures. Polymer-composite housing can also offer additional safety in the case of fire.

2 Battery packs and modules are sealed to provide environmental protection, optimise cooling efficiency and provide safety in the event of a failure. However, when non-reversible adhesives are used, this presents a challenge to reuse, remanufacture and recycle modules and packs. Therefore, reversible adhesives and seals are increasingly important.

3 Achieving robust joining of different materials at high speed is essential for durability, performance and cost. New joining technologies are being developed along with real-time closed-loop production testing to capture defects early. New electrical connection techniques that reduce the need for high-precision equipment and improve quality while also promoting easier reuse, remanufacture and recycling are needed.



Module and pack

Module and pack innovations (continued)

4 Cell-to-chassis batteries are being used on a number of models to reduce the battery weight and therefore increase the vehicle range or reduce the battery size to achieve acceptable range.

Further integration of cells into the vehicle structure reduces weight and increases the potential driving range or enabling less cells to provide similar range. To optimise this integration, it requires a greater understanding of the crash performance of cells. The ability to simulate crash performance improves safety for first responders, therefore the state-of-health of a battery in a crash incident is better understood. For example, a minor crash that would not damage a cell can be predicted as well as a potentially dangerous crash situation.

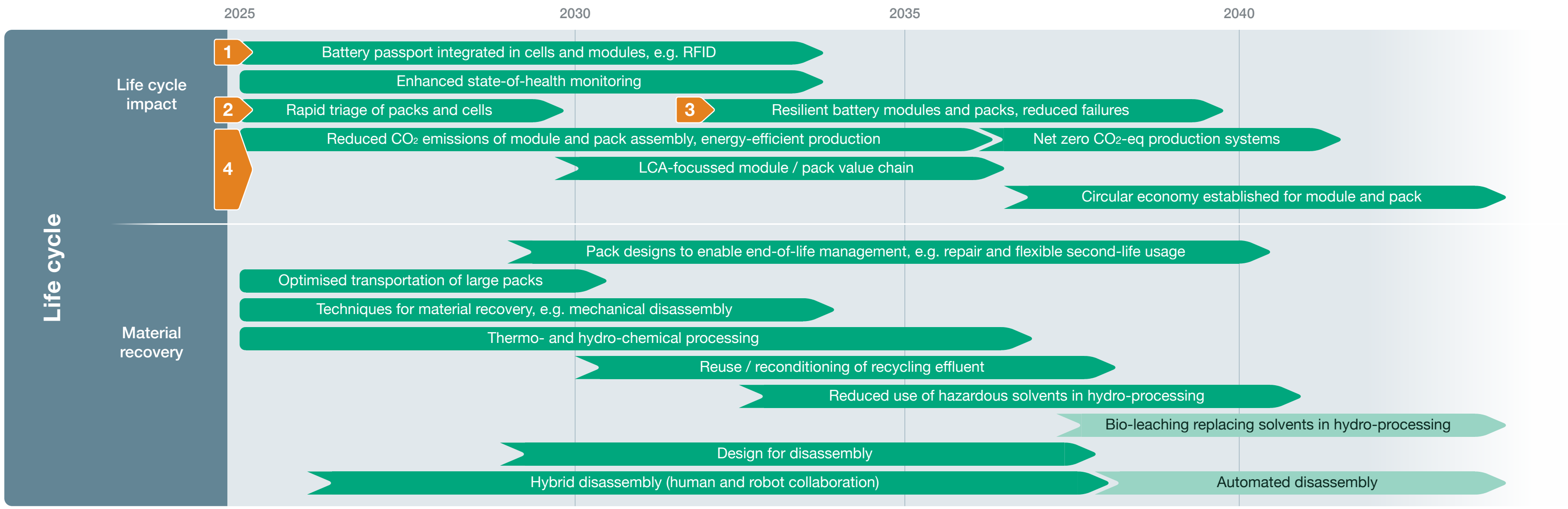
Not all OEMs will pursue further integration as repairability is seen as a key feature. For instance, HDVs such as heavy-goods vehicles (HGVs) and buses, need long lifetimes and there will be an expectation that cells and modules can be replaced.

5 Thermal management systems of batteries are seeing integration with motors and power electronics reducing the mass of the system and increasing efficiency at a vehicle level.

6 Real-time in-line cell and module testing can reduce manufacturing failures and remove end-of-line testing. In-line testing offers the possibility of inspecting areas that would otherwise be impossible to inspect when a pack is fully assembled.

7 As vehicles become more complex with auxiliary features, such as advanced driver-assistance systems (ADAS) requiring high power, there is a requirement to provide higher system voltages. To date, these have been provided by a separate battery but, increasingly, this is being integrated with the propulsion battery, which may then need to be bigger depending on the chemistry and packaging used. Additionally, the energy demands from the ADAS could potentially affect the battery performance. The integration with the propulsion battery can enable cost savings by reducing wiring complexity and weight; reducing wiring width, and therefore weight, and enabling features such as brake by wire and steer by wire.

8 A couple of hybrid packs combining NMC and LFP exist on the market. Theoretically, hybrid packs could reduce cost but add complexity elsewhere. Using mixed chemistries can enable the best of both; high power when needed, along with long life, for instance. It is possible that some more novel mixed chemistry packs will enter the market but the added complexities of both managing the cells and end-of-life management may deter adoption.



Module and pack

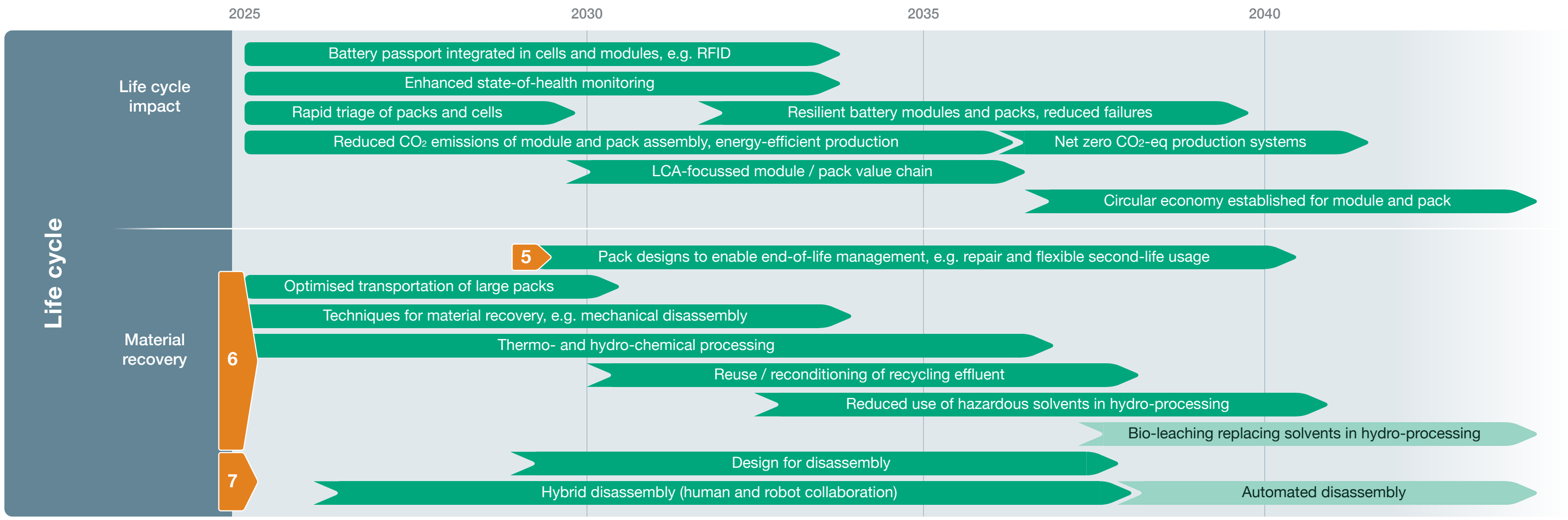
Life cycle

1 The EU Battery Directive requires a battery passport to track carbon intensities and report on the make-up of the cells. It is expected that battery passports will be widely adopted and integrated, not just at pack level but, into modules and cells to enable easier tracking during second life.

2 Triaging packs to decide on repair, remanufacture, reuse or recycle is currently complicated due to lack of standardisation. Enhanced state-of-health monitoring occurring through innovation and enforced by regulation will help. At the same time, companies are innovating to create their own rapid triage methods to identify cells and modules, which can be repaired or reused and those needing to be recycled.

3 Combining many of the technologies highlighted in the roadmap will lead to more robust modules and packs. While there is a trend of cell-to-pack and cell-to-chassis, it is possible this will change in the future with resilience becoming an important feature particularly in heavy-duty use-cases. For example, cell-level monitoring and redundancy can keep a pack running until a repair can be enacted.

4 As with manufacturing cells, the manufacturing of modules and packs is transitioning to a net-zero CO_2 production system and this requires efficiency improvements across the value chain. Establishing a closed loop is expected to take longer due to the complexities in recycling divergent pack design with greater levels of integration.



Module and pack

Life cycle (continued)

5 Some OEMs are already beginning to highlight the potential value of battery second-life, either as a spare part for their customers or for an alternative use such as stationary storage. If this value chain is to be realised, it will require designs that enable that end-of-life management, which could mean stepping away from further integration or finding reversible ways to achieve the same goal.

6 Hydrometallurgy is one of the technologies which will increasingly become more prominent for recycling lithium-ion batteries. Hydrometallurgy is a highly technical chemical process requiring multiple steps and multiple solvents to extract cobalt, nickel and lithium. Therefore, to improve the safety and environmental impact of recycling, the use of hazardous solvents is likely to be reduced before eventually being replaced, ensuring effluent from the process can be reconditioned and reused.

7 The EU Battery Directive calls for minimum recycling efficiencies and with minimum recycled content targets being potentially challenging, it will be important to maximise efficiency. One way is to disassembly a battery down to its cells. However, with limited standardisation, design complexity and potential safety concerns from unknown end-of-life conditions of batteries, disassemble to maximise material recovery is challenging. This is additionally compounded with a current trend for further integration of battery cells into packs and chassis. Human robot co-operation, for example via telerobotics, can improve disassembly times and mitigate safety hazards. In the future, some level of standardisation in battery pack design may be imposed, via regulation, which enables automation. Advanced robotics and AI may solve these challenges independent of regulation. Whilst designs are currently aiming for further integration, there is an expectation that design for some level of disassembly will be needed, driven by value from recycled material or, more likely, enforced by regulation.

Glossary

ADAS	Advanced driver-assistance system
AI	Artificial intelligence
BEV	Battery electric vehicles
BMS	Battery management system
CO_2-eq	Carbon dioxide equivalent greenhouse gas effect
CO_2	Carbon dioxide
EDS	Electrical distribution system
EU	European Union
EV	Electric vehicle
FAT	Factory acceptance test
FCEV	Fuel cell electric vehicle
HDV	Heavy-duty vehicle
HGV	Heavy goods vehicle
LCA	Life cycle analysis
LCV	Light commercial vehicle
LDV	Light-duty vehicle
LEVI	Local electric vehicle infrastructure
LFMP	Lithium manganese iron phosphate
LFxP	Lithium iron phosphate
Li-S	Lithium sulfur
LMNO	Lithium manganese nickel oxide
ML	Machine learning
NCA	Lithium nickel cobalt aluminum oxide
NEV	New energy vehicle
NIB	Sodium-ion batteries
NMC	Nickel manganese cobalt
NMC(A)	Lithium nickel manganese cobalt aluminum
NMP	N-methyl-2-pyrrolidone
OEM	Original equipment manufacturer
PE	Polyethylene
PHEVs	Plug-in hybrid electric vehicle
PP	Polypropylene
PVDF	Polyvinylidene fluoride / polyvinylidene difluoride
R&D	Research and Development
Si	Silicon
SOC	State-of-charge
SOH	State-of-health
TEN-T	Trans-European Transport Network
UK	United Kingdom
V2G	Vehicle-to-grid
V2H	Vehicle-to-home
V2L	Vehicle-to-load
V2X	Vehicle-to-everything
xEV	Electrified powertrain vehicle including hybrids
ZEV	Zero-emissions vehicle

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

automotive council UK

ADVANCED
PROPULSION
CENTRE UK

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.

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