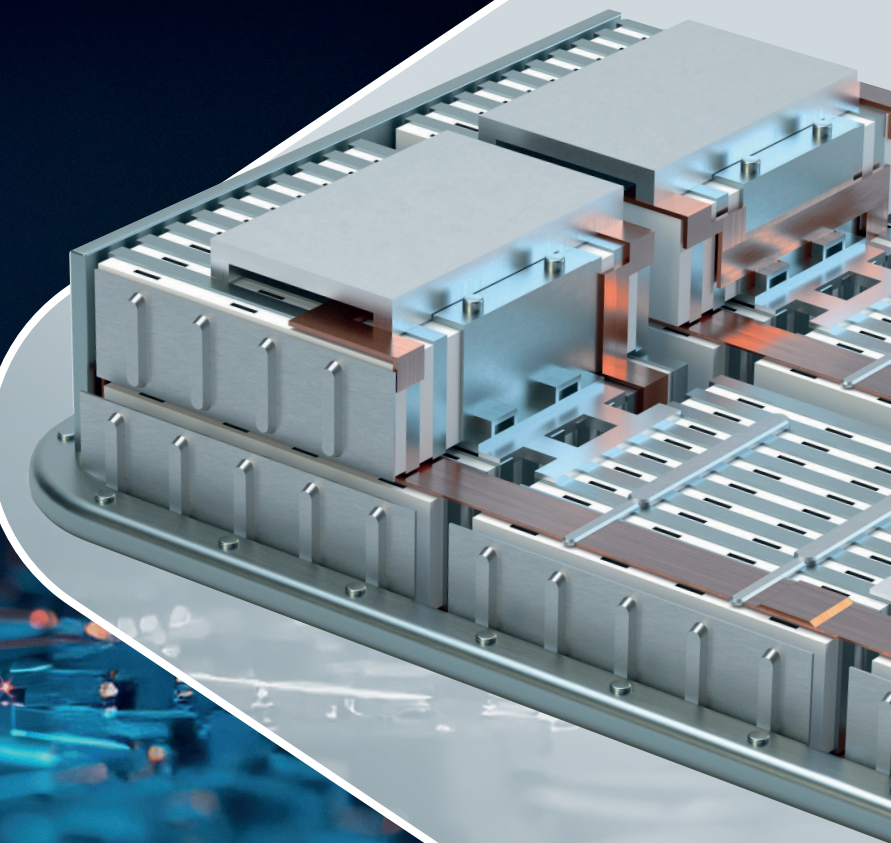




Electric Energy Storage

Innovation opportunity report 2025



Information correct at time of publication



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1 | Introduction



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Foreword

As global demand for clean mobility grows, innovation will be the key to maintaining competitiveness, securing jobs, and achieving net-zero ambitions. While academia and industrial research and development (R&D) have pushed boundaries for new technologies, commercialisation at scale, and at pace, remains an issue for the industry. Innovation in strategic technologies needs to align with the industrial supply chain's capabilities, strengths and weaknesses, to enable the automotive industry's transition.

Building on the key trends and drivers identified by the Automotive Council's Technology Roadmaps, our 'Industry challenges and Innovation Opportunities' reports examine key technology priorities and associated supply chain opportunities for the UK automotive industry. We highlight focus areas and strategic priorities, where targeted collaboration between industry, government, and research institutions can accelerate commercialisation and anchor value-add to future-proof the UK automotive industry.

Some of the innovation and R&D priorities identified in this report represent cross-sector opportunities and are equally relevant to other industrial sectors, such as aerospace, defence, and adjacent applications.

By focusing our collective efforts on the priorities outlined in the Roadmaps and associated industry challenges and innovation opportunities, we can secure the UK's leadership in the global clean mobility revolution.



Introduction

This report assesses the industry challenges and innovation opportunities for electrical energy storage (EES) and offers an in-depth review of all the themes and sub-themes identified in the Roadmaps and aligns them with UK automotive supply chain capabilities, at what is a pivotal time for the industry's transition to zero-emission vehicles.

With demand in 2024 for electric vehicles (EVs) slowing, coupled with geopolitical uncertainty arising from tariffs and export controls, the UK must develop its strategic direction in battery technologies to ensure a competitive edge over other competing countries. This report contributes to the UK government's objective of decarbonising the transport sector through supporting key elements of the broader UK Battery Strategy 2023.

Key issues for EV adoption in the UK are range, affordability, and fast-charging capabilities, according to the survey in the Transport and Environment study in 2024¹.

This report identifies points highlighted in the EES Roadmap and categorises them into themes to address these challenges:

Affordability

To increase cost competitiveness and market acceptance of innovative low-cost battery chemistries for increased EV adoption.

Range improvement

A spotlight on battery chemistries and innovations to improve overall vehicle range.

Fast-charging

A focus on improving vehicle performance via improvements for fast-charge capabilities.

Safety improvement

To improve thermal management, reduce risk of material failure, and improve cooling methods.

Life cycle impact

A view of sustainability and end-of-life issues, improved recycling of battery materials, and reduced wastage.

The report researched and analysed 120 different innovations identified in the Roadmap and has arrived at seven innovation categories that can accelerate the strategic approach to improve automotive battery capabilities in the UK. The seven categories cover the end-to-end value chain of the battery ecosystem; ranging from advanced materials that can improve the overall energy density of battery cells, to how we can recycle the end-of-life batteries to enable the circular economy supply chain.

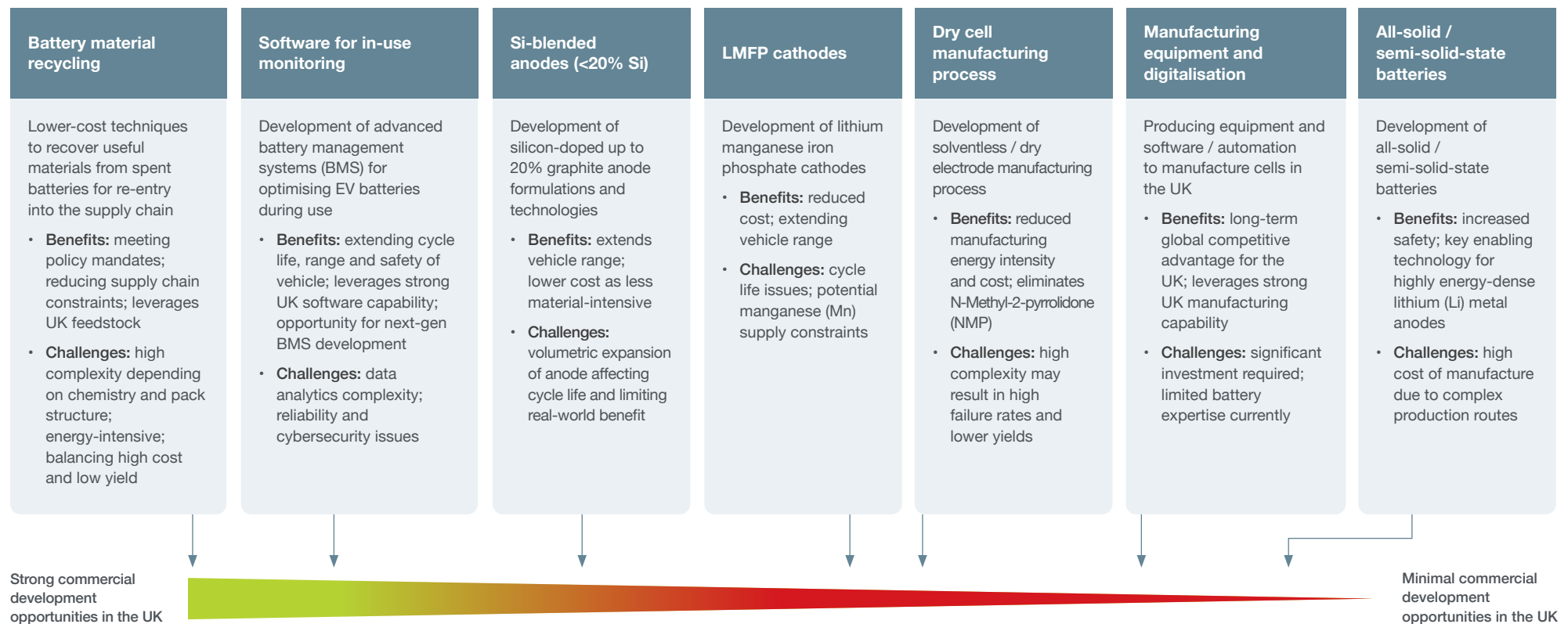
The report provides a detailed innovation profile for all the identified categories, with the significance of the opportunity to the UK, and the ease of implementation if the UK industry invests in the innovation theme. The report also provides a detailed strategic and technical rationale for selecting the prioritised list.

¹ Transport and Environment study

2 | Executive Summary

This report is part of the Automotive Council UK's Technology Roadmaps and specifically focuses on the priority innovations in the UK battery technology sector. It takes into account techno-economic, commercial, and other market factors.

The 120 innovations identified in the EES roadmap were analysed and filtered to seven priority innovation categories that hold strategic importance for the UK's battery capabilities over the next decade.



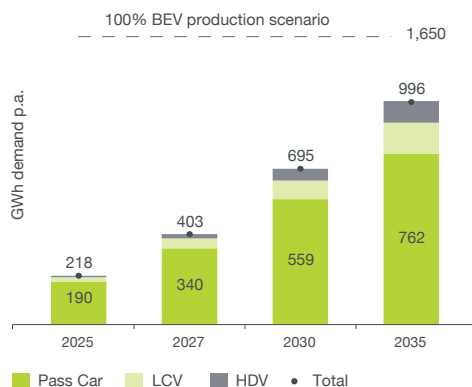
Market outlook for the UK battery sector

Development in battery technology is driven chiefly by industry requirements from a customer base poised to expand

Passenger EV uptake is a key driver of battery technology development

- According to the APC Demand Report², there will be 75 million BEVs (including plug-in vehicles) produced globally by 2035. Nearly 15 million plug-in EVs (passenger car and light commercial vehicle (LCV)) will be produced in Europe during the same period, which will result in an European battery demand of nearly 800 GWh.
- As the passenger EV consumer base grows, innovations are needed to meet key industry requirements such as range, safety, affordability, fast-charging capability, and battery life.

Figure 1: European³ battery demand (passenger and commercial vehicles)



² APC Q4 2024 Demand Report

³ European forecast includes non-EU countries such as Turkey

⁴ Department for Business and Trade UK Battery Strategy 2023

Landscape of automotive battery technology in the UK

- Developing the UK's battery sector has been identified as a strategic priority as outlined in the Department for Business and Trade's (DBT) UK Battery Strategy 2023⁴.
- The UK's battery sector capability has undergone significant growth in past years, supported by both committed government-funding and commercial investment from industry:

	Government commitments	• £1.6 billion via the APC to accelerate strategically important emerging vehicle technologies • £541 million to Faraday Battery Challenge (FBC) since 2017
	Industry investment	• AESC Group's gigafactory in Sunderland, initial capacity 12 GWh • Over £4 billion by Tata Group into new gigafactory, capacity 40 GWh • £2.5 billion by Bentley to produce EVs in Crewe by 2026

Future battery innovations for the automotive sector identified from research and stakeholder engagement



Innovations in battery cell chemistries

- Cathode and anode chemistries
- Electrolytes and separators
- Solvents, binders, and additives



Innovations in battery modules and packs

- Cooling systems
- Pack designs
- Thermal resistant housing
- BMS



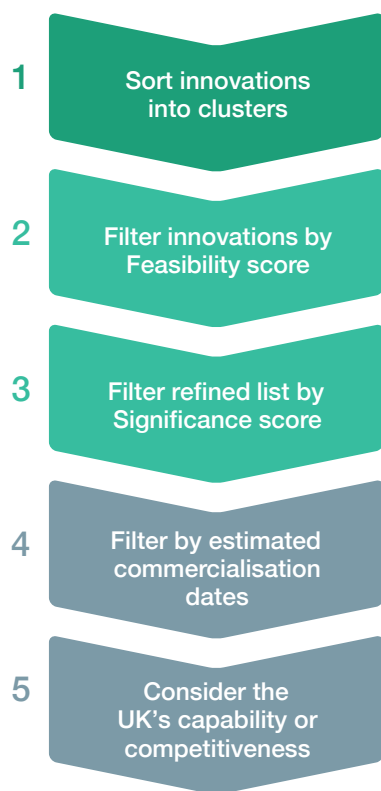
Innovations in manufacturing and implementation

- Circularity and recycling
- Critical minerals
- Transport and energy intensity
- Emissions and waste



3 | Methodology

Figure 2: Methodology overview

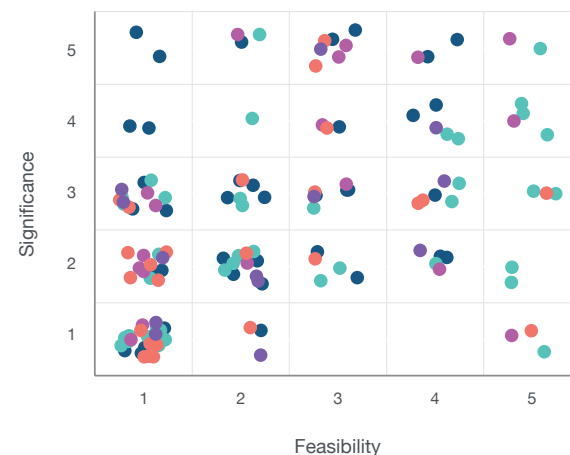


A five-step filtration process has been developed to identify the priority innovations.

- LCI considerations
- Range
- Fast charge
- Affordability
- Safety

- Five key clusters were identified for EES innovations, representing the key industry pull factors relevant to each of the innovations in the EES Roadmap.
- This was used to ensure that the innovations selected through this process directly address a key area of demand from the automotive industry.

Figure 3: Significance-feasibility matrix for the EES innovations



One-third of innovations score at least a 4 or above in one of the metrics.

- High-feasibility innovations fell into the 'Fast charge', 'Range' and 'Affordability' categories, indicating the trend that these industry pull factors have historically stimulated commercial development ahead of others.

Nearly two-thirds of the EES Roadmap innovations score a 3 or below for both Feasibility and Significance.

- Many of these come from the 'Life-cycle impact' (LCI) considerations category, reflecting the very low readiness-levels of many of the current innovations aimed towards increasing circularity of the battery value chain.
- The innovations in other categories such as 'Range' and 'Fast charge' in this zone may be subject to currently unsurmountable technical or economic challenges, limiting their commercial feasibility.

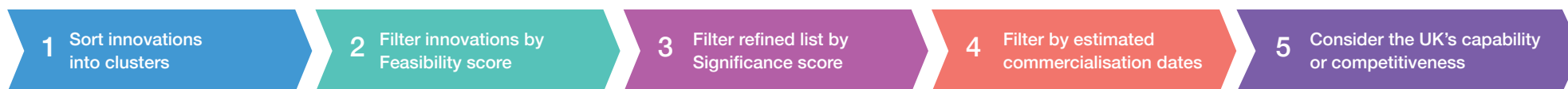
Further details can be found in the appendix of this report.

4 Results

Results of methodology for priority innovations

The identified seven innovations are listed below with their relevant tags for innovation cluster. The innovation opportunities may relate to more than one innovation cluster as they support the removal of barriers for EV adoption, for example, range and battery safety.

Methodology overview



Priority innovation (categories)	Primary innovation cluster	Secondary innovation clusters	Feasibility	Significance	Start date ⁵
Battery material recycling	LCI considerations	Affordability	4	4	2025
Software for in-use monitoring	Affordability	Safety; Range; Fast-Charge	3	5	2025
Silicon-blended anodes (<20% Si) for lithium-batteries	Range	Affordability	4	4	2025
Lithium manganese iron phosphate (LMFP) cathodes	Range	Affordability	4	4	2027
Dry manufacturing process for cell manufacturing	LCI considerations	Affordability	3	3	2031
Manufacturing equipment and digitalisation	Affordability	LCI	4	3	2025
All-solid (ASSB) and semi-solid-state batteries (SSSBs)	Range	Affordability; Safety; LCI	4	4	2026

⁵ Estimated commercialisation date as defined by APC Roadmaps



Battery material recycling

Significance and feasibility of this technology

Supporting evidence	
Significance	- Hydromet (water-based) and pyromet processes (heat-based) are currently the most viable battery recycling methods that exist. - Recycling will be essential and will enable some control over future materials supply. - Cost-reducing innovations in recycling processes or business models will be crucial as the industry develops over the coming years.
Feasibility	- Hydromet enables higher material recovery, lower energy consumption, and potentially reduced hazardous emissions. This is pertinent to the UK where pyromet is less feasible. - Battery recycling facilities using these methods have already been established in other countries with high recovery rates of cobalt, manganese, nickel, and lithium. Success factors include the cost of recycling, prices commanded for recycled materials and the status of local / regional markets. - The UK is likely to remain a net importer of batteries, providing a long-term source of recycling feedstock.

Key benefits and challenges

Given the increase in recycling mandates in the EU⁶ and UK, developing recycling capability is increasingly important for many countries:

Key benefit Meeting environmental targets, long-term critical mineral independence

Key challenge High transport and processing costs, high complexity

UK's current level of maturity for this technology

There is significant commercial interest in the UK for battery recycling at various steps in the process. Projects like ReLib⁷, a £18m research project led by major universities across the UK, aims to provide technological and circular economy solutions.

Level of UK capability for this innovation category

Strong commercial development opportunities in the UK



Minimal commercial development opportunities in the UK

Relevant UK entities include

UK companies	What they do
Altium	Processing of black mass using a hydromet process to produce battery metal salts, PCAM and CAM
RS Bruce	Pre-treatment and mineral recovery processes
Renewable Metals	Pilot-scale hydromet recycling for spent EV batteries
Cellcycle	Mechanical, chemical processes; direct recycling
Veolia Ecobat Recyclus	Pre-treatment (mechanical) processes for spent EV batteries

Companies are an example list and are not exhaustive

⁶ https://environment.ec.europa.eu/topics/waste-and-recycling/batteries_en

⁷ <https://relib.ac.uk/>

Strategic and technical context: Battery material recycling

Battery material recycling is determined by material volume, value-added, property retention, and process complexity. Due to the nascence of the sector, many steps are ripe for innovation to increase efficiency and cost-effectiveness.

Technical summary

Spent batteries first need to be gateway-triaged for their suitability for recycling. Integrated sensing has the potential to automate this manual process in the future. Proximity to feedstock sources is important to minimise transport costs and retain the value of recycled battery packs within the UK.

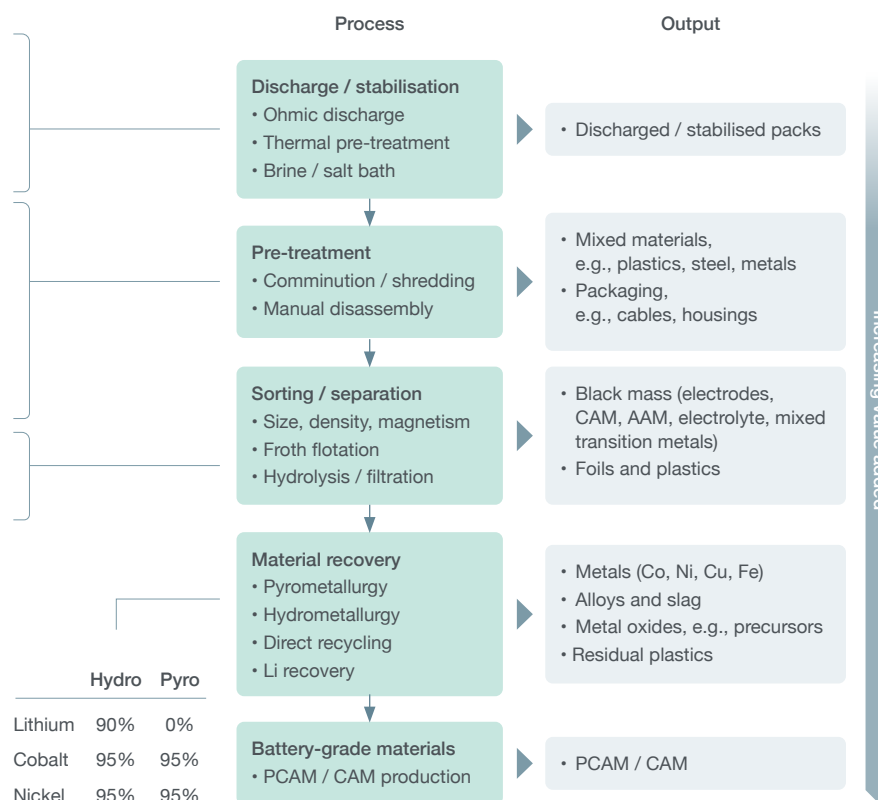
Shredding is a high-cost and low-yield step as it can comprise many processes depending on subsequent recycling processes. Safety risks include high voltage in packs, reactivity of lithium, and hydrogen fluoride (HF) gas emissions from LiPF_6 electrolytes.

Adhesives used in current pack designs make automation at this stage difficult. As black mass refining is costly, innovations to extract as many minerals as possible in the separation stage will be key to reducing recycling costs.

Pyromet is more mature, but is energy intensive due to high temperature. Sintering, leads to HF and CO_2 emissions and only recovers high-value metals⁸.

Hydromet requires less energy, enables higher material recovery rates, (see Figure 4) but is more complex and generates wastewater and HF emissions.

Figure 4: Battery recycling process and outputs



Strategic and market context

Battery material recycling is currently a high-cost process and will be increasingly sought after, particularly in Europe due to the EU battery regulation that mandates a minimum recycled content in batteries used⁹. There is the potential for secondary material to command a premium over virgin material if the recycling and refining costs are high.

Innovations that potentially bring recycling costs down will make UK companies more competitive. Feedstock availability will not be a critical challenge in the UK as domestic battery waste should be abundant, mainly from EVs coming to end of life, and partially from manufacturing scrap in British gigafactories.

⁸ Such as nickel and cobalt, while iron and lithium cannot be recovered.

⁹ https://environment.ec.europa.eu/topics/waste-and-recycling/batteries_en



Software for in-use monitoring

Significance and feasibility of this technology

Supporting evidence	
Significance	- Software for BMS is necessary for all EV battery systems and needs to vary depending on battery chemistry, pack structure and user requirements, such as charging speed and environmental temperature. - Developing more sophisticated methods of tracking and optimising EV batteries during use is critical for the safe and efficient use of EVs. - There is also a potential national security benefit in the UK developing its own software for EV management.
Feasibility	- Can leverage the UK's expertise in software development and the growing domestic EV sector. - Several UK companies and research groups are already engaged in implementing proprietary BMS software, sometimes in collaboration with other entities developing complementary software or hardware (such as installing in-situ sensors onto battery cells for real-time monitoring).

Key benefits and challenges

Improved BMS software is necessary to maximise EV performance while ensuring functional safety as far as possible.

Key benefit	Improved range, cycle life, and safety of the EV during operation
Key challenge	Data analytics, reliability, and integration

UK's current level of maturity for this technology

UK companies, research institutions, and funding bodies have shown considerable commercial interest in developing BMS software capabilities. There is a slew of FBC-funded projects related to improving BMS using new algorithms, including AI, machine learning, telemetry, sensor monitoring, and others. Some companies are already entering the market, partnering with large automakers, e.g., Breathe with Volvo Cars.

Level of UK capability for this innovation category

Strong commercial development opportunities in the UK



Minimal commercial development opportunities in the UK

Relevant UK entities include

UK companies	What they do
Breathe	Physics-based real-time BMS for either more range per minutes charging, or longer lifetime and range retention
Eatron Technologies	Physics and machine-learning-based approach in remaining useful life (RUL) estimation software for integration into BMS hardware
About:Energy	High-fidelity electrochemical battery models to achieve rapid and accurate calibration

Companies are an example list and are not exhaustive



Strategic and technical context: Software for in-use monitoring

BMS are critical to ensure the good performance and safety of EV batteries.

Technical summary

Battery cells have specified safe operating areas (SOAs) within which they are safer and effective from a performance perspective. If limits are exceeded for too long, the pack could enter thermal runaway conditions. BMS could play an important role in keeping the performance of the batteries optimised.

Electrical management

Current protection: cells have maximum continuous and peak charging and discharging current limits. A BMS can instantly respond to extreme current peaks, e.g., sudden acceleration.

Voltage protection: cells also have a safe voltage range. At the high voltage limit, a BMS induces the reduction of charging current. At the low voltage limit, a BMS reduces current from demand loads by reducing torque available to the traction motor.

Thermal management

Battery capacity diminishes at low temperatures due to slower chemical reaction rates. A BMS can control the heating and cooling of a pack for effective discharge of stored energy.

Capacity management

Different cells within a pack do not all charge and discharge simultaneously due to variable self-discharge rates. A BMS prevents overcharging of cells by detecting when one is about to reach its charge limit, re-routing excess current to the next cell instead. This maintains consistent performance and maximises battery life.

Strategic and market context

UK expertise in BMS could focus on new and sophisticated performance-improving software. Innovations in BMS need to be paired alongside new battery chemistries and technologies, such as SSSBs, LMFP, redox flow, etc., due to potential variations in self-discharge rates, internal resistance characteristics, operating temperatures, and fault detection methods. Physics-based models, AI, and machine learning can be leveraged here. There are opportunities for developing wireless BMS software for increased flexibility and convenience, as well as telemetry-enabled applications using cloud computing to monitor the health of many vehicles at once and identify outliers for earlier fault identification.

Additionally, data visualisation is becoming more important to handle large amounts of data being collected. A dedicated user-interface can help facilitate more harmony between operation and performance. Domestically-developed BMS companies can form part of a broader technology cluster in battery development, contributing to the advancement of UK battery technology and manufacturing. Proprietary BMS algorithms can also be licensed to other EV manufacturers outside of the UK.

To develop consumer confidence in the UK and drive the uptake of EVs in the mass-market, there needs to be good rigour and reliability of battery health and information. BMS can provide health and usage monitoring for consumers, and will be a key enabler for the EV second-hand market, supporting higher market values with a source-of-truth for battery health data.



Silicon-blended anodes (<20% Si) for lithium-ion batteries

Significance and feasibility of this technology

Supporting evidence	
Significance	- Si can increase the cell's gravimetric energy density significantly, increasing EV range by reducing anode mass, e.g., up to a theoretical 50% anode mass reduction for 10% Si-doping. - Si-blended anodes can access the entire existing and potential Li-ion transportation battery market that uses graphite anodes, regardless of application (including commercial flight).
Feasibility	- Low doping of silicon (3-5% by weight) into graphite anodes exists in the market. - However, higher doping levels present challenges due to the volumetric swelling and shrinking of silicon under charge / discharge, with a range of potential solutions to mitigate this. - The technology is more expensive today, but is likely to lead to lower-cost cells and packs in the longer term. - Theoretically, Si-blended anodes can alleviate supply chain constraints by enabling reduced graphite consumption. - It is likely that Si production is constrained if viable solutions require a supply of silane gas, which is heavily reliant on Korean and Chinese sources.

Key benefits and challenges

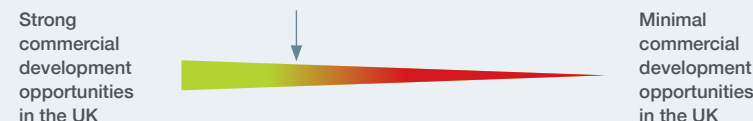
Silicon added to graphite anodes can increase vehicle range or reduce material costs of a standard battery pack made out of 100% graphite anode.

Key benefit	Improved energy density, therefore cost reductions
Key challenge	Volume expansion during charging reduces cycle life

UK's current level of maturity for this technology

Silicon-blended anodes (up to 20%) hold high potential in the UK automotive sector in the next 10 years given the growing adoption of higher-end EVs in the West. This area receives strong support from government-funded research grants across several UK universities. UK capability includes several international companies at mid-technology readiness levels (TRLs) with operations in the UK.

Level of UK capability for this innovation category



Relevant UK entities

UK companies	What they do
Nexeon	Development of Si-anode material (manufacturing is in Korea, close to silane production)
Alkegen	Manufacturing of proprietary silicon fibre material for Li-ion batteries
Talga	Development of Si-anode material

Companies are an example list and are not exhaustive

Strategic and technical context: Silicon-blended anodes (<20% Si) for lithium-ion batteries

Silicon-doping has high techno-economic feasibility and potential to improve overall range and energy density of batteries, despite some technical challenges. The UK must establish global competitiveness in this technology.

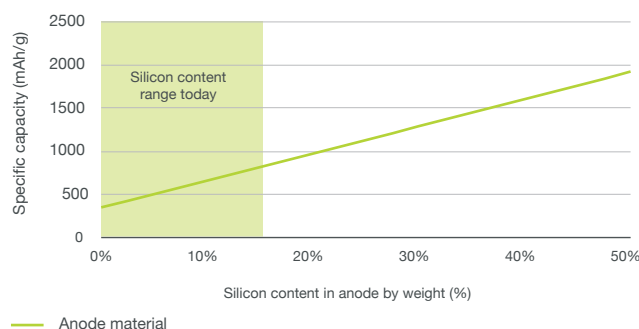
Technical summary

Si can increase the cell's gravimetric and volumetric energy density significantly, increasing EV range by storing more energy per weight or volume of anode. Si has a theoretical specific capacity of ~4,200 mAh/g, vs ~360 mAh/g for graphite.

Increasing the silicon-doping level beyond 20% gives diminishing returns on anode mass, anode material intensity, and, particularly, anode volume. This is from the barriers on volumetric expansion of the anodes with higher silicon content.

Si has a higher anode voltage than graphite, which reduces the overall cell voltage. This offsets some of the charge capacity benefits and may inhibit uptake in lower-capacity cells such as those based on lithium iron phosphate (LFP) and potentially LMFP. Currently, Si use is focused on nickel-manganese-cobalt batteries (NMC), which is better able to offset the voltage 'penalty' since it operates at a higher cathode voltage. Cost and cycle life are potential limitations, but manufacturers are working to enable silicon to be a 'drop-in' technology in conventional cell processes.

Figure 5: Silicon energy content by weight



Source: BNEF

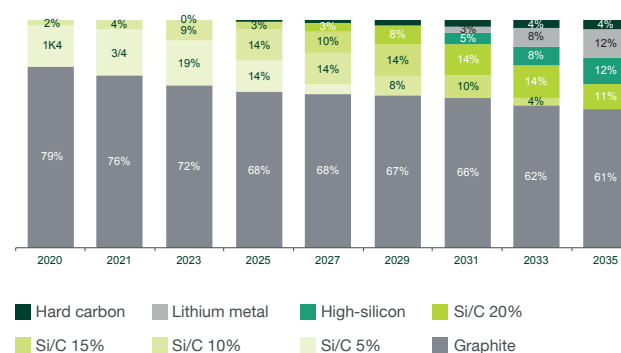
Strategic and market context

Silicon-doped anodes are likely to prevail globally due to energy advantages, so the UK automotive sector will need to either produce or buy silicon-doped anode materials to ensure its cells and vehicles are competitive. Currently, automakers are limiting silicon use to high-end vehicle segments given its initial price premium relative to the graphite-only alternative. By 2030, however, we expect up to 25% of the global BEV market to be using some variation of graphite and silicon-blended anodes (<20% Si).

Low doping of silicon into graphite anodes already exists in the market, e.g., LG Chem's MJ1 cell (3–5% by weight). The technology is more expensive today, but is likely to lead to lower-cost cells and packs in the longer term. Tesla is currently employing graphite composite anodes with 5–10 wt % Si anodes in the Model 3, achieving a driving range of about 500km.

The use of silicon significantly reduces the requirements for graphite and this could alleviate supply chain constraints from recent tariffs and export control constraints.

Figure 6: Anode chemistry split forecast until 2035



Source: BNEF

Lithium manganese iron phosphate (LMFP) cathodes

Significance and feasibility of this technology

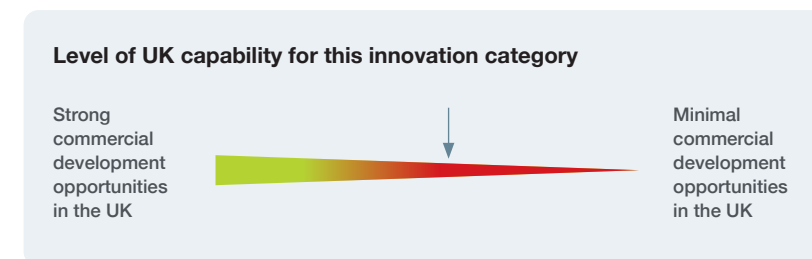
Supporting evidence	
Significance	- Can achieve a higher voltage than traditional LFP, thereby delivering higher cell and pack energy densities comparable to the more-expensive NMC 811 chemistry. - Can access the entire existing and potential Li-ion battery manufacturing market for EVs and, if cycle life can be improved sufficiently, for battery energy storage systems (BESS).
Feasibility	- Likely to gain traction globally within this decade. Based on the lead time for certification and development for new projects outside China, it is expected that there will be an acceleration in LMFP's market share post-2027. - LMFP batteries for EVs are being developed by many companies across the globe, including Integrals Power in the UK, and larger battery manufacturers including CATL, BYD and Gotion High-Tech from China, but have not yet been released to the EV mass market. - Mn is an inexpensive material with lower supply chain risk globally, but faces low intermediate processing rates outside China. China currently controls 95% of the market.

Key benefits and challenges

LMFP is a next-generation technology that is poised to achieve global market growth in the late 2020s	
Key benefit	Improved energy density, yielding cell / pack / EV cost reductions Volume expansion during charging reduces cycle life
Key challenge	Lower cycle life than NMC, potentially limited Mn supply

UK's current level of maturity for this technology

LMFP is still at the research stage in the UK, with no LMFP production currently at scale. UK capability in LMFP research is relatively advanced so it has the potential to scale-up with the appropriate funding.



Relevant UK entities include

UK companies	What they do
Integrals Power	LMFP cathode active material development and production
Redoxion	Development of methods for LMFP mass production

Companies are an example list and are not exhaustive

Strategic and technical context: Lithium manganese iron phosphate (LMFP) cathodes

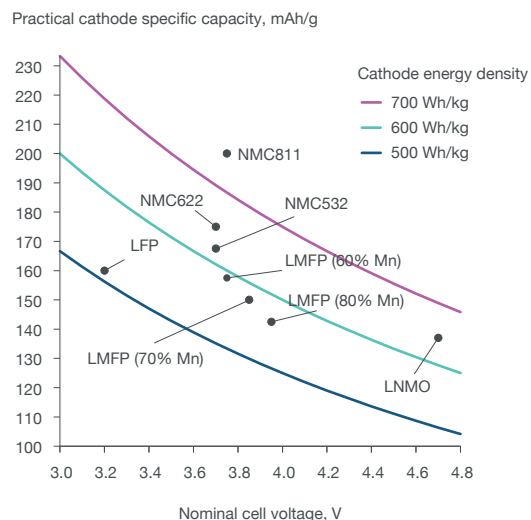
Adding Mn allows higher voltages to be achieved compared to LFP. The UK must establish its global competitiveness in this technology.

Technical summary

LMFP chemistries are based on replacing some of the iron in LFP cathodes with Mn. This offers significant pack energy density improvements over LFP due to higher cell voltages (see Figure 7).

Additionally, the resulting energy density advantage gives a lower cost per kWh for LMFP compared to NMC and LFP, as highlighted in the LFP cost competitive study report¹⁰ for the APC. The advantage lies in savings made from a smaller and efficient energy pack. However, the challenge lies in achieving a workable cycle life with pure LMFP, so it is currently almost always blended with NMC or LFP. LMFP offers advantages in specific capacity over LFP and affordability over NMC due to the much higher cost of nickel and cobalt compared to Mn.

Figure 7: Performance comparison of LMFP vs NMC cathode chemistries



¹⁰ APC LFP competitiveness study

¹¹ CRU research and analysis

Strategic and market context

LMFP, once developed, would be a logical replacement for medium-nickel NMC532/622 in mid-size vehicles. It is not yet being used in the EV mass market, but several companies are already developing LMFP for automotive use, including large Chinese companies like CATL, BYD and Gotion High Tech. Currently almost all LMFP is being blended with NMC due to cycle life challenges, but research is ongoing to achieve a workable, pure LMFP material.

A key challenge is the absence of Mn intermediate processing and LMFP cathode capacity outside China, meaning that western end-users will rely on supply from China. More than 90% of the refining capacity is currently stationed in China. The recent changes to export controls on critical technologies for the production of LMFP from China means the UK needs to develop capabilities for a local supply chain. This is an opportunity for countries like the UK to develop a Mn processing capability, reducing reliance on China and enabling an opportunity to become a key region for the LMFP supply chain (as highlighted in APC LFP competitiveness study¹⁰). CRU forecasts¹¹ that the market share for LMFP, including composites with NMC, will accelerate in the mid-to-late 2020s to make up about 15% of the global cathode usage in BEVs by 2030.



Dry manufacturing process for cell manufacturing

Significance and feasibility of this technology

Supporting evidence	
Significance	• If technologically mature, it has the potential to supersede wet electrode processing in all conventional batteries. • There is a significant reduction in chemical usage, notably NMP, combined with reduced energy consumption as drying processes are eliminated.
Feasibility	• Work in this area has been ongoing for many years, so far with limited evidence of success, especially in dry cathodes. • It should reduce material requirements, notably fluorinated compounds such as polyvinylidene fluoride (PVDF), which has a limited supply chain.

Key benefits and challenges

Dry manufacturing process for lithium-ion batteries involves electrode production without a solvent, which is needed for binding cathode active material to the electrodes.

Key benefit	Reduced environmental impact and cost in manufacturing
Key challenge	Manufacturing complexity might result in lower initial yields

UK's current level of maturity for this technology

The UK shows promising capability in dry electrode manufacturing. There is currently some UK participation in the dry electrode space at the feasibility trial stage, funded by government institutions.

Level of UK capability for this innovation category

Strong commercial development opportunities in the UK



Minimal commercial development opportunities in the UK

Relevant UK entities include

UK companies	What they do
Anaphite	Development of enhanced NMC and LFP composite cathodes for dry-coating
Global Nano Network	Current collectors to improve adhesion

Companies are an example list and are not exhaustive

Strategic and technical context: Dry manufacturing process for cell manufacturing

Dry electrodes can allow cell manufacturing to bypass some energy-intensive and environmentally harmful manufacturing steps.

Technical summary

Moving to dry electrodes in battery manufacturing requires solvent-free electrode coating processes. This provides environmental benefits by reducing the energy consumption from conventional drying equipment and eliminates the use of hazardous NMP solvents.

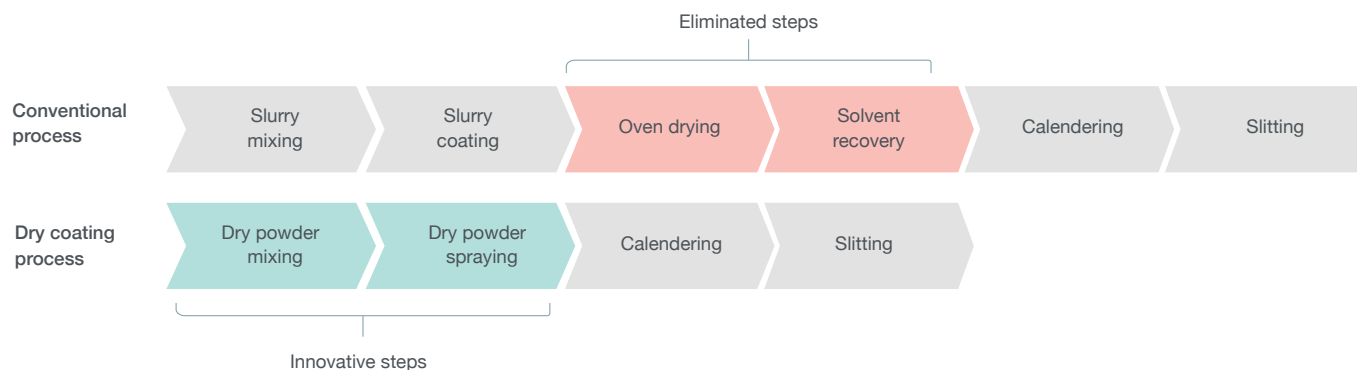
For conventional electrodes, NMP needs to be recovered and reprocessed and this can be environmentally complex and costly. This also, potentially, helps reduce manufacturing costs on energy for drying and NMP recovery, as well as capital costs on the building size and equipment required. However, yields may be negatively affected in this novel manufacturing process as new methods are being tested to ensure a homogenous electrode coating, using dry powder spraying. To achieve a uniform electrode coating on the metal foil, existing companies are pre-combining electrode feedstock materials with specialist polymer binders and conductive carbons, e.g., Anaphite (UK), DragonFly Energy (US).

Strategic and market context

There is considerable commercial interest in this technology. Research is underway to allow dry electrodes to achieve the performance seen in conventional wet electrode technology. Tesla has reportedly solved its technical challenges and is now preparing for production at scale for the new Cybercell 2.0 batteries as of the end of 2024. LG Energy Solution has announced it aims to start mass production by 2028. It has suggested that the energy savings from the dry-coating technology will amount to 17–30% of the overall energy consumption.

Dry electrodes are contingent on developments in other components such as binders, conductive agents, and current collectors. Given the higher energy costs and environmental complications of managing toxic NMP solvents, there is a strong rationale for the UK to manage and maintain a competitive advantage in the dry coating technology.

Figure 8: Electrode manufacturing process Conventional vs Dry



Manufacturing equipment and digitalisation

Significance and feasibility of this technology

Supporting evidence	
Significance	- Maximising manufacturing yield in gigafactories is the single most important factor to consider in battery manufacturing. - Digitalisation can help reduce labour costs and wastage through automation, allowing gigafactories to increase their competitiveness.
Feasibility	- Can leverage the UK's expertise in manufacturing equipment and software in adjacent sectors. - Would take time to reach a globally competitive level of maturity, but would aid the development of UK battery intellectual property (IP). - Opportunities for development lie in battery ecosystems, such as UK Battery Industrialisation Centre (UKBIC) and gigafactories: - UKBIC, funded by the FBC, the Industrial Strategy Challenge Fund from UK Research and innovation (UKRI), and West Midlands City Council. - AESC UK's Sunderland gigafactory in partnership with Nissan and Sunderland City Council.

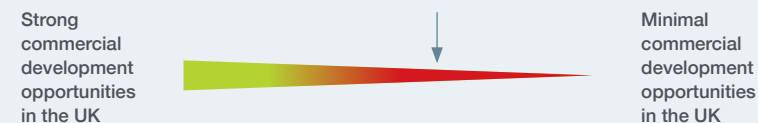
Key benefits and challenges

Making manufacturing equipment and developing software to optimise manufacturing goes hand-in-hand with developing a domestic gigafactory capacity.	
Key benefit	Global competitive resilience, affordability through increasing yields
Key challenge	Building a solid domestic expertise in manufacturing equipment may draw a higher initial cost owing to trial-and-error approach needed.

UK's current level of maturity for this technology

Current UK capability is low given the limited cell manufacturing facilities, but there is potential in software and digitalisation services. The UK has the opportunity to leverage existing experience in established industries such as food production and an established software development talent pool. Currently, there is limited knowledge in battery manufacturing equipment that is being produced in Europe, including in-line metrology for process control. UK capability in manufacturing software exists, but is at the feasibility study stage. There are some research projects funded by UK government.

Level of UK capability for this innovation category



Relevant UK entities include

UK companies	What they do
Waygate Technologies	Feasibility study of defect inspection for increasing battery yield using AI digital twinning
AMPLiFI-2	Scalable battery module and pilot production facility including digital twin testing software

Companies are an example list and are not exhaustive

Strategic and technical context: Manufacturing equipment and digitalisation

Optimising manufacturing processes through both equipment and digitalisation can help reduce manufacturing costs in the long run and aid the development of new battery technologies.

Technical summary

Achieving high yields is crucial for gigafactories to be cost-competitive on a global scale. Innovations in both hardware and software in battery manufacturing can include the following:

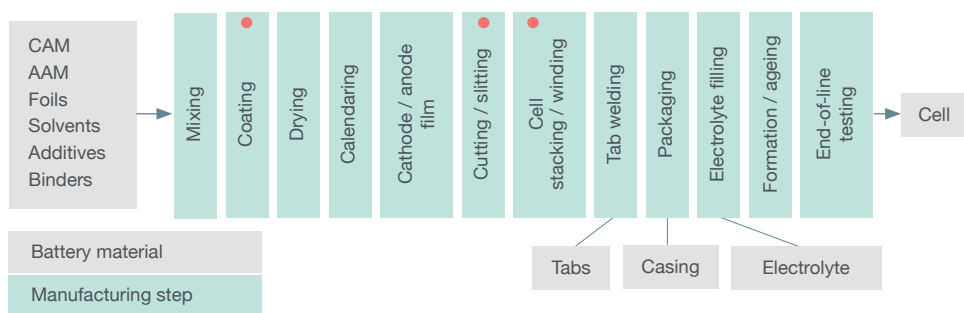
- In-line metrology: using characterisation techniques to monitor the conditions of battery cells and materials while they are being produced, by integrating sensors and detectors into the production line. This enables improvements in productivity at each process step, allowing for increases in gigafactory yield and reduced manufacturing costs.
- AI digital twin / physics-based models with machine learning: enabling real-time feedback on optimising the assembly process. It aims to offer insights on where hotspots for failure might arise, resulting in increased production efficiency without the need to interrupt the continuous manufacturing line, particularly for the formation, ageing, and testing steps of the process. Using AI also helps to reduce costs and avoid waste.

Strategic and market context

Domestic-made equipment would allow UK or European gigafactories to establish longevity and competitiveness among larger market players and protect the supply chain from geopolitical shocks.

While the implementation of efficiency mechanisms are conditional on having gigafactories in the first place, developing IP for software services to license to other manufacturing countries. This could be a strategic move for the UK given its current limited gigafactory capacity and low capex cost. Furthermore, the manufacturing of in-line metrology hardware, alongside other battery manufacturing equipment, may position the UK as a credible alternative for overseas equipment manufacturers.

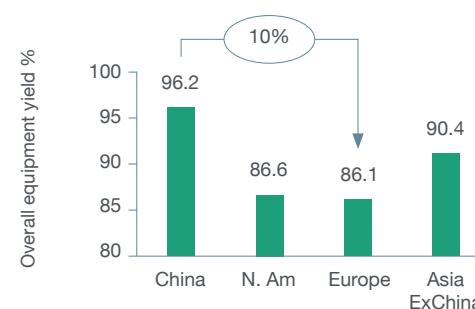
Figure 9: Cell manufacturing process and the competitiveness of Chinese suppliers



● Where China is more competitive compared to Rest of the World manufacturers

Source: CRU research and analysis

Figure 10: Overall equipment yield across listed manufacturing steps, %



Source: CRU research and analysis

All-solid and semi-solid-state batteries with high ionic conductivity

Significance and feasibility of this technology

Supporting evidence	
Significance	- Solid state batteries could provide a pathway for more advanced and safer battery technologies and could enable performance improvements associated with lithium metal anodes. - Volumetric energy density is increased compared to liquid electrolytes, allowing for a larger range for an EV with the same pack capacity.
Feasibility	- Several technology innovations are pursuing development of solid electrolytes to combine with lithium metal anodes. - Part of the production process for semi-solid state batteries is already used in the existing liquid electrolyte production line, providing a pathway to achieving commercial scale. - SSSBs are already in production in the EV-space by two major Chinese automakers, NIO and Dongfeng Motor. However, the space remains nascent and open to potential competition from other companies and countries. - A key development area for this technology is increasing ionic conductivity, which is lower compared to lithium-ion. - Much of this technology is tightly controlled and there is limited publicly available information. More research would be required.

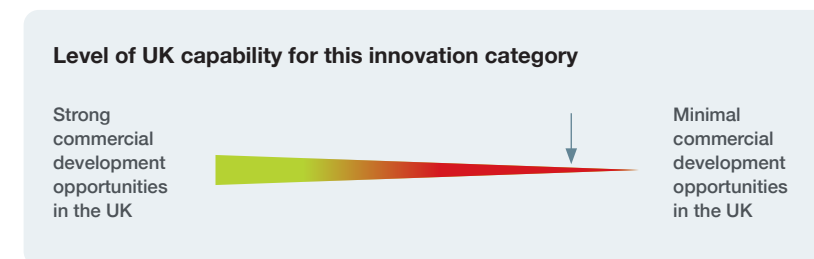
Key benefits and challenges

ASSB and SSSBs are an innovative improvement on traditional wet-electrolyte lithium-ion batteries, promising higher EV safety by reducing the overall flammability of electrolytes and cells.

Key benefit	Safety, improved energy density through enabling Li-metal anodes
Key challenge	Higher cost than liquid electrolyte (LE)

UK's current level of maturity for this technology

The UK's capability in ASSB and SSSBs for EVs is currently at the research stage, with some advancements in non-automotive applications. SSSBs can be a potential growth market for the UK owing to the relatively low number of market players.



Relevant UK entities include

UK companies	What they do
TaiSan	Proprietary polymer electrolyte with metal anode for sodium-ion (likely not applicable to automotive sector)
Ilika	Development of solid state battery technology designed to meet the specific demands of multi-sectoral applications

Companies are an example list and are not exhaustive

Strategic and technical context: All-solid and semi-solid-state batteries with high ionic conductivity

ASSB and SSSB have energy density, safety, and stability benefits over liquid electrolytes.

Technical summary

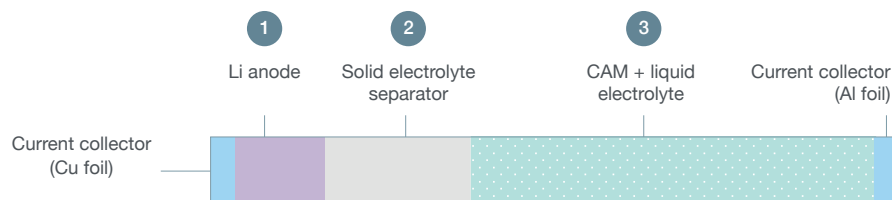
In all-solid state batteries a solid electrolyte is introduced as a media that conducts lithium ions. The solid electrolyte could be made of polymers, oxide, sulfide. The key challenge in ASSB is the mass production, and manufacturing difficulty in getting a fully scaled up plant.

SSSBs use a combination of liquid and solid electrolytes. They can offer significant improvements in energy density, safety, and stability compared to conventional liquid-electrolyte batteries, without the manufacturing complexity and high cost of all-solid-electrolyte batteries. They are seen as a more viable short-term option and as a stepping stone to full solid state batteries (SSBs), which are currently limited by their high cost and complexity.

Advantages of solid and semi-solid electrolytes over liquid

- 1 A solid electrolyte can enable the safe use of Li-metal anode to greatly enhance energy density due to its specific capacity being over 10x that of graphite (Synthetic graphite: 363 mAh/g; Li-metal: 3860 mAh/g).
- 2 Solid electrolyte eliminates the need for a separator. Corrosion and leakage is reduced, enhancing cycle life. SSBs have a higher temperature tolerance before thermal runaway¹², as well as slower temperature rise, vastly improving safety.
- 3 Liquid electrolytes for SSBs provide better contact with the electrode, whereas ASSB requires high pressure to establish contact, both during production, and in-use. 80–90% of SSSB manufacturing is compatible with the traditional Li-ion process, allowing easier implementation and much lower costs compared to ASSB.

Figure 11: Conceptual diagram of semi-solid state battery cell structure



Strategic and market context

SSSBs are a promising solution for EVs in the near-term, and are already in production by Chinese EV makers. Chinese auto-maker NIO launched its 150kWh EV using SSSBs supplied by WeLion in September 2024. Currently, SSSBs are manufactured at a modest but increasing scale. The UK has a narrowing window to become competitive. SSB innovations will also help in the parallel roadmap development of lithium metal anodes and the start-ups associated with it.

¹² Compared to traditional LE Li-ion battery.



Special mentions list

The special mentions category includes innovations that didn't make the priority list, but still have a high level of potential for the reasons listed in the table below.

Item	Reason why they did not make the priority list	Justification for special mention
Niobium anodes	• Constrained niobium supply chains • May reduce range and cycle life	• Fast-charging ability has real promise for niche applications, e.g., motor racing, high-performance off-highway vehicles • Existing UK commercial capability in Echion and Nyobolt
Sodium-ion cathodes	• Not suitable for most consumer automotive applications due to low energy density • Supply chain constraint resulting in high cost of hard carbon anodes	• Cheaper and more abundant cathode materials • Longer cycle life than lithium-ion • Wide temperature window • May be suitable for niche automotive applications, such as micromobility, e.g., e-scooters and boats
Lithium metal anodes	• Yet to be solved safety issues	• Potential for much higher-energy-density cells
Reduce cell material wastage / increased yield	• Not a technology innovation per se	• Critical for cost-competitiveness of gigafactories
Swappable battery support	• Requires collaboration with OEMs to be implemented; therefore, out of scope for this study	• Potential for reduced upfront cost of EVs (smaller packs)
Wireless / catenary charging for mass-transit systems	• Requires new government policy to enable establishment of infrastructure	• Potential for reduction in energy density / pack size requirements
Cell-to-chassis / structural batteries	• Requires collaboration with OEMs to be implemented, therefore, out of scope for this study	• Critical for increasing range of EVs and OEM competitiveness
Pack designs to enable easier EOL management, repair and flexible second-life usage	• Requires new government policy to enforce	• Important to enable full utilisation of battery SoH



5 | Conclusions

Conclusion and recommendations for the UK's automotive battery sector

To summarise, this report identifies key innovations in the UK battery technology sector, focusing on feasibility, significance, and commercial potential over the next decade. The analysis highlighted seven priority innovation categories that align with industry demands (significance) and UK capabilities (feasibility). The categories are crucial for addressing the automotive industry's evolving needs:

Battery chemistry innovations

Include silicon-blended anodes, LMFP cathodes, and hybrid / SSSBs.

Manufacturing Innovations

Manufacturing equipment and software digitalisation to enhance affordability and efficiency in battery production.

In-use monitoring

Operational monitoring for enhancing safety and performance management through software-enabled BMS.

End-of-life value chain

Battery recycling to enable sustainability and circular economy value chain.

The UK government and the automotive industry have already made significant investments in unlocking the pathway for some of the above opportunities as follows:

- Government commitments include £1.6 billion via the APC and £541 million for the FBC since 2017.
- Major industry investments like Tata Group's £4 billion investment for a new gigafactory.
- National Wealth Fund's initiative to secure £1 billion for AESC's Sunderland gigafactory

To build on this progress and unlock the full potential of the identified opportunities in the report, the following table highlights some potential initiatives that could be considered.

Innovation theme	Innovation category	Challenges	Potential recommendations
Battery chemistry innovations	Silicon-blended anodes	Volumetric expansion of anodes affecting cycle life	• Invest in R&D for new innovative silicon-carbon blends and encourage UK start-ups within this innovation area • Initiate pilot plants for trialling 20% and above silicon-blend chemistries
	LMFP cathodes	Potential Mn constraints	• Invest in supply chains for Mn near-shoring to UK / Europe.
	Hybrid / SSSBs	High cost of manufacturing and less mature	• Invest in early-stage TRL feasibility and R&D studies to further mature the solid electrolyte technologies
Manufacturing innovations	Manufacturing equipment and digitalisation	Limited battery expertise in the local region	• Invest in tier 1, tier 2 supply chain, e.g., CAM, AAM production for accelerating battery materials supply needed for upcoming gigafactories
	Dry electrode manufacturing	Manufacturing complexity and high costs	• Investing in pilot plants that can demonstrate the effectiveness of dry-coating technology
In-use monitoring	Software BMS	System integration and reliability	• Develop strong standards for interoperability and certification of the BMS • Encourage and grow the existing developed software ecosystem in the UK
End-of-life value chain	Recycling of batteries	High transport and processing costs	• To invest in R&D technologies that reduce the carbon intensity of separation and recycling • Investing in automation that reduces the costs of dismantling and shredding of battery systems



These recommendations and proposed initiatives should be integrated into the broader strategic assessment and current status of the UK automotive industry. The recent challenges seen in European battery manufacturing offer important lessons for the industry that extend beyond the technology and encompass complex issues such as supply chain constraints, geopolitical uncertainties, and workforce development.

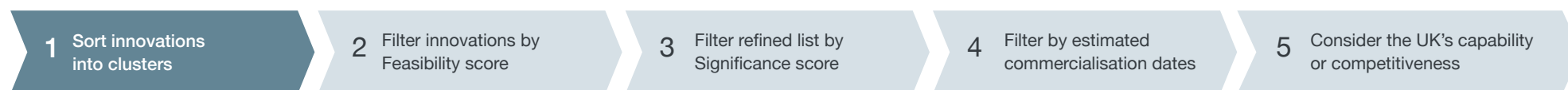
The wider review of the industry should focus on the following themes:

- competitiveness of the UK industries from an industrial energy cost perspective
- technology, including manufacturing know-how for making efficient battery cells in local regions
- regulatory landscape, incentive mechanisms and support for the industry in a rapidly evolving and dynamic market environment.

The innovation opportunities, proposed solutions, and broader strategic review outlined above are critical to maintaining the long-term vitality of the automotive industry as it navigates a once-in-a-generation transition from internal combustion engines to an electrified supply chain.

6 | Appendix

Overview of method of identifying priority innovations



Description of method

The APC's EES Roadmap¹³ were converted into 120+ innovations and assessed.

Six clusters were identified for EES innovations, representing the key industry pull factors relevant to each of the innovations in the EES Roadmap.

This was to ensure that the innovations selected through this process directly address a key area of demand from the automotive industry.

Note: As this report focuses on technologies, innovations categorised under the supply chain cluster will not be considered in the scope of this report.

LCI considerations (32%)

Innovations that primarily aim to reduce emissions, increase cycle life, increase use of sustainable materials, reduce use of harmful materials, improve recycling processes, or reduce wastage

Safety (10%)

Innovations that primarily aim to improve thermal management, reduce risk of failure of materials, facilitate efficient fire detection, or improve cooling methods

Fast-charge (10%)

Innovations that primarily aim to improve vehicle performance via increasing fast-charge capability

Range (28%)

Innovations that primarily aim to improve vehicle performance via increasing range

Affordability (17%)

Innovations that primarily aim to reduce cost to consumer through increasing cost-efficiency at manufacturing stage, using cheaper materials / chemistries, or increasing cost-efficiency at end-use stage

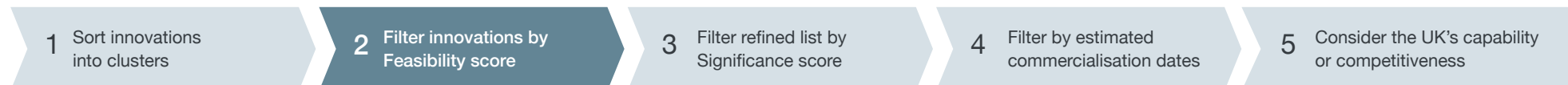
Supply chain (3%)

Innovations that primarily aim to strengthen the supply chain of materials used in automotive batteries, or increase production of existing technologies

¹³ Includes the APC's Cell Manufacturing Roadmap and the Module and Pack Manufacturing Roadmap, published in September 2024.



Overview of method of identifying priority innovations



Description of method

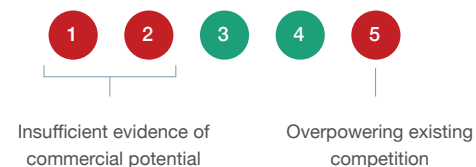
The innovations are scored according to their feasibility, which is defined as the (i) current or potential likelihood of scaling to commercial; (ii) success of technology at pilot scale and techno-economic analyses; and (iii) access to supply chains.

This methodology step factors in the likelihood of success for the innovation to reach a commercial scale if pursued in the UK. Also, it accounts for the potential for existing competition elsewhere in the world, that could leave little room for the UK to compete.

Scoring criteria for Feasibility

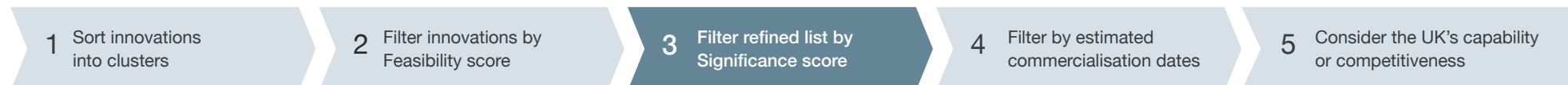
Description	Scoring				
	1	2	3	4	5
1 Current or potential likelihood of scaling to commercial	EITHER not yet proven at pilot stage; OR low technoeconomic scores; OR	Some success at pilot scale but no commercial-scale implementation due to inherent technology drawbacks	Proven success at pilot scale but limited commercial-scale implementation due to supply chain or cost barriers	Proven success at pilot scale AND commercial route-to-market tested, but weak cost-effectiveness compared to incumbent	Already implemented on a global commercial scale; AND proven cost-effectiveness, with robust supply chain established
2 Success of technology at pilot scale and technoeconomic analyses	highly dependent on vulnerable supply chains				
3 Access to supply chains					

Passing scores out of 5:





Overview of method of identifying priority innovations



Description of method

Progressed innovations were scored on their significance towards addressing their allocated automotive industry pull factor, as well as potential global market size.

This methodology step factors in the potential size of opportunity of the innovation being commercialised in the UK and its potential impact on the technological advancement of the automotive sector.

Scoring criteria for Significance

Description	Scoring				
	1	2	3	4	5
1 Potential global market size	EITHER small / fragmented potential global market size; OR limited / variable impact on industry pull factor	Small potential global market size; AND limited / variable positive impact on industry pull factor	EITHER large potential global market size; OR strong positive impact on industry pull factor	Large potential global market size; AND strong positive impact on industry pull factor	Very large potential global market size; AND game-changing impact on industry pull factor
2 Extent of impact on industry pull factor, i.e., LCI, Safety, Fast-Charge, Range or Affordability					

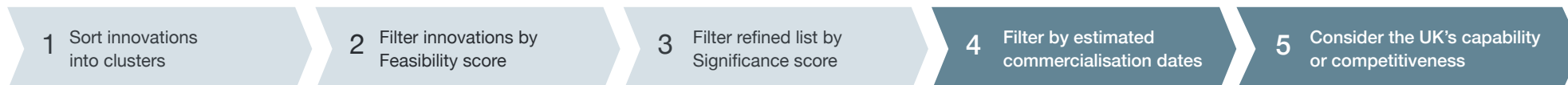
Passing scores out of 5:



Insignificant impact on automotive industry



Overview of method of identifying priority innovations



Description of method

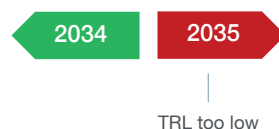
The next step defined priority innovations less than 10 years away from commercialisation, estimated based on the current trajectory of the automotive industry.

Consideration was given to innovations at technology readiness level (TRL) 6-8. This represents the short-medium term priorities for the UK with less focus on very low TRL technologies, which would likely not be integrated into industry any time soon.

The remaining innovations based on their viability of being developed within the UK for the automotive industry and includes the following factors:

- if it makes economical or technical sense to implement for the UK's automotive industry
- does the UK have, or could have, a competitive advantage over other market players
- if they pose direct conflicts with other priority innovations
- are they a distinct technology innovation that can be prioritised, or just a broader category

Passing estimated commercialisation dates:





EES 2024 Automotive Council Technology Roadmap innovations, grouped by industry pull factor and plotted by Significance and Feasibility score

Figure 12: Significance-feasibility matrix for EES innovations



Note: Detailed results for each roadmap item can be found in the accompanying datapack

One-third of innovations score at least 4 or above in one of the metrics.

- High-feasibility innovations fell into the 'Fast-charge', 'Range' and 'Affordability' category, indicating the trend that these industry pull factors have taken priority due to market and consumer conditions for EV adoption.

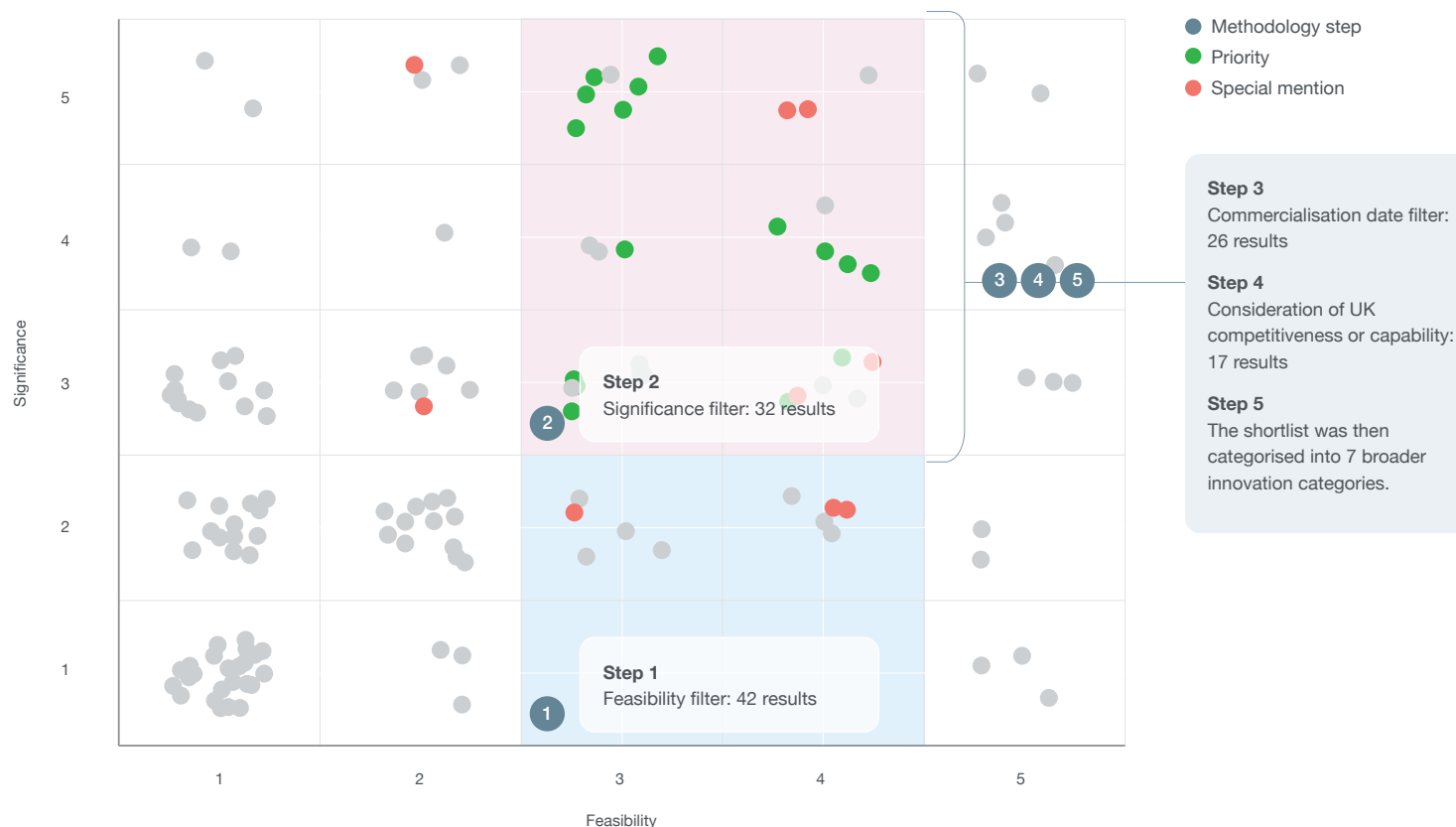
Nearly two-thirds of Feasibility and Significance innovations taken from the EES Roadmap score 3 or below for both:

- Many of these come from the 'LCI considerations' category, reflecting very low readiness levels of many of the current innovations aimed towards increasing circularity of the battery value chain.
- The innovations in other categories such as 'Range' and 'Fast-charge' may be subject to currently insurmountable technical or economic challenges, limiting their commercial feasibility.



Seven priority innovation categories were identified using the criteria described in the methodology steps

Figure 13: Methodology for arriving at seven innovation categories



As per the described study method, priority innovations fall within the Feasibility score of 3 and 4 and Significance score of >3. They are also filtered for UK capability and potential competitiveness.

The priority innovations each fall under either the 'Range', 'Affordability' or 'LCI considerations' categories.

- **Range:** This is one of the key concerns among UK EV consumers. While advancements in this category need to work together with charging infrastructure, range is crucial to enable wide-scale adoption of EVs in many countries.
- **Affordability:** This is also a key barrier as EVs have yet to reach cost parity with ICE vehicles globally. Reducing the cost of manufacturing, materials or wastage will help to improve this.
- **LCI considerations:** This will become increasingly important for the battery industry, which inherently aims to provide sustainable alternatives to fossil fuel energy.

Note: Detailed results for each roadmap item can be found in the accompanying datapack.



Glossary

AAM	Anode active material	LiPF ₆	Lithium hexafluorophosphate (type of electrolyte)
AI	Artificial Intelligence	LMFP	Lithium manganese iron phosphate (cathode material)
ASSB	All-solid-state battery	LNMO	Lithium nickel manganese oxide (cathode material)
BEV	Battery electric vehicle	mAh/g	Milliamp-hour per gram
BESS	Battery energy storage systems	Mn	Manganese
BMS	Battery management system	Na	Sodium
CAM	Cathode active material	NMC	Nickel manganese cobalt (cathode material)
CO ₂	Carbon dioxide	NMP	N-Methyl-2-pyrrolidone (solvent used in cell manufacturing)
EES	Electrical energy storage	OEM	Original equipment manufacturer
EOL	End-of-life	PCAM	Precursor cathode active material
EU	European Union	PVDF	Polyvinylidene fluoride
EV	Electric vehicle	Pyromet	Pyrometallurgical (recycling process)
FBC	Faraday Battery Challenge	R&D	Research and development
HF	Hydrogen fluoride (manufacturing air pollutant)	RUL	Remaining useful life
Hydromet	Hydrometallurgical (recycling process)	Si	Silicon
kg/kWh	Kilogram per kilowatt-hour	SOA	Safe operating area
km	Kilometre	SoH	State of health
LCI	Life Cycle Impact	SSSB	Semi-solid-state battery
LE	Liquid electrolyte	TRL	Technological readiness level
LFP	Lithium iron phosphate (cathode material)	UKRI	UK Research and Innovation (government organisation)
Li	Lithium	wt %	Percent by weight



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Further information

If you have any questions or would like more detail on any of the graphs or data, email info@apcuk.co.uk

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