Electrical Energy Storage Roadmap 2020

Narrative Report

February 2021 | Version 1.0

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Overview: Electrical Energy Storage

Li-ion batteries are fast approaching automotive market maturity. Aggressive cost reductions in batteries have underscored a transformative decade in the automotive industry's history. This maturity is reflected in the topics at the top of industry expert's minds: sustainable and ethical supply of batteries and raw materials, and finding cost effective ways to reuse, recycle and dispose of batteries.

Almost 80% of industry experts believe that battery electric vehicles will cost the same to produce as ICE vehicles by 2035, or even earlier. To achieve this, high-volume vehicle manufacturers are demanding their supply chains deliver ever lower costs while maintaining pack-level energy density. No optimum battery strategy or technology exists – each vehicle segment requires engineers to strike a balance between the various attributes and decide the appropriate trade-offs. Providing a multitude of research and manufacturing options for future transport applications is vital.

The 2020 roadmap primarily focuses on high-volume, cost-sensitive applications and is split into two parts – the battery cell (materials and manufacturing) and battery modules and packs. However certain technology themes identified in the roadmap are more applicable to high power, or, performance applications.

Cell materials and manufacturing roadmap

- The push to increase energy density is likely to spur on further developments in graphite anodes, and the increasing use of silicon or completely new materials for higher-power applications.
- Lithium-iron phosphate (LFP) has re-emerged during the past few years as a suitable material for lower-cost cathodes whilst high nickel batteries (e.g., NCA, NMC, eLNO) can support higher energy density and faster charging.
- In other materials:
  - electrolytes will continue to evolve, but solid-state electrolytes offer a step change in energy density and safety when combined with lithium metal anodes, albeit with complex manufacturing challenges
  - as the capacity of cells increases, enhanced separators will be needed for thermal management
  - demand for ever thinner foils could see functional integration of cathodes and anodes.
- The drive for sustainable manufacturing will progress on many fronts: reducing and eliminating solvents and binders, phasing out the use of scarce materials, as well as hazardous chemicals, reducing energy-intensive cell manufacturing processes and making efforts to minimise waste and reuse / recycle materials.
- Looking ahead, sodium-ion is emerging as an ultra low-cost battery chemistry with supply benefits as sodium is the sixth most abundant element on the earth.

A full glossary is provided at the end of this report

Overview: Electrical Energy Storage

Battery modules and packs roadmap

- With the proliferation of Li-ion cells, manufacturers are consolidating on a number of cell formats. Cylindrical, pouch and prismatic are the three main options. A clear winner is difficult to predict as each have unique advantages. New cell formats that are optimised for new chemistries are also likely to emerge.
- Within electrical distribution systems, battery management system software will become more sophisticated, not only improving performance and health, but optimising the decision to repurpose a battery. Improvements to busbars and connectors/contactors will be needed as vehicle architectures adopt higher voltages.
- With higher-power applications and fast charging, thermal management becomes more important. New methods to keep batteries at their optimum operating temperature, including new passive and active cooling strategies, will be needed.
- In addition to further lightweighting and increasing cell-to-pack ratios, greater integration of battery packs with the rest of the vehicle is envisaged; as primary structural elements, potentially distributed throughout the vehicle; and using converged thermal management systems.
- Meeting legislative pressure on net-zero CO_2 emissions and life cycle will require effort on a number of fronts:
  - enhancing traceability, monitoring battery health and creating a battery passport will deliver gains in performance and further re-use opportunities
  - designing battery packs to enable a second life – particularly understanding degradation rates more fully and enabling battery cells to be extracted from packs using automated tools; this is particularly challenging given increased integration and use of polymers and mixed materials
  - decarbonising manufacturing – modules and packs assembly is a comparatively low-energy process compared to cell manufacture and thus presents an early candidate to be net zero.

Foreword and Acknowledgements

The APC would like to acknowledge the extensive support provided by industry and academia in development and publishing this roadmap.

We are grateful to the Automotive Council for entrusting us with the product and technology roadmaps refresh and their continued support.

This work has received significant support from BEIS (Department for Business, Energy and Industrial Strategy).

Neville Jackson
On behalf of the
UK Automotive Council

I am delighted to share the 2020 automotive propulsion technology roadmaps developed closely in collaboration with industry by the Advanced Propulsion Centre. These roadmaps define critical future targets and the most promising pathways to achieve a decarbonised and more sustainable future vehicle parc. They are an essential tool in developing a focused R&D agenda, particularly relevant for collaborative innovation.

The roadmaps build on the foundations of original UK Automotive Council roadmaps and developed further by the APC in 2017. These have been refreshed to reflect the urgency in transitioning to the UK target of net-zero emissions by 2050. The rate of change in propulsion technologies has accelerated rapidly in recent years; electrified vehicle adoption is on the rise, battery prices have come down faster than previously forecast, alternative zero-emission technologies like fuel cells are maturing at significant pace and clean fuels for combustion, including hydrogen, are emerging to replace existing fossil fuels.

However, there are significant challenges to overcome as the rate of change must increase further, requiring more intensive R&D and commercialisation that will deliver affordable products to market that are even more attractive for consumers. The 2020 technology roadmaps have been developed by industry expert surveys and panels, delivering a consensed view of future automotive propulsion targets, technologies and timescales.

Our aim with this report is to support the automotive sector with insights and a common technology focus to accelerate and deliver world-class solutions. The roadmaps are an important source of information in building collaborative R&D opportunities to address future mobility challenges, goods transport and off-highway vehicle research and development.

Prof David Greenwood
WMG,
APC Spoke for Electric Energy Storage

Battery technology is the key to decarbonisation of transport – whether used solely for battery electric vehicles, or in combination with an engine or fuel cell. It is a unique component that sets the pace of transport electrification. In the last decade, costs have fallen dramatically, and energy density has increased significantly, making electric vehicles practical and affordable in most vehicle segments.

At the same time, the UK has also become far more active in battery development and has plans for gigafactory scale production with supply chain companies stepping up to provide the valuable constituent parts and materials.

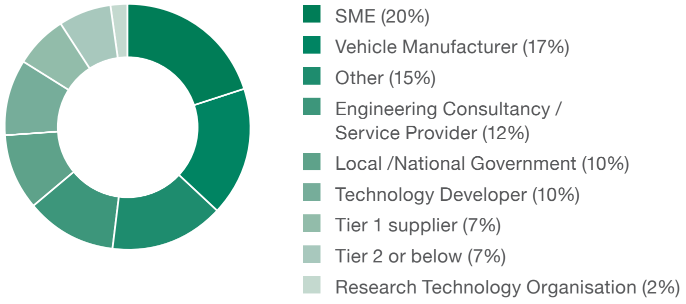
Improvements have come from strides in technology, manufacturing innovation and economies of scale – all of which are rapidly increasing, leading to a more complex landscape than previously seen.

As a result, the 2020 EES technology roadmap is much more detailed than the 2017 version, considering unique requirements of the increasing number of battery applications for transport and technology solutions that can meet these demands, delivering cost and performance fit-for-purpose. Whilst this makes for a more complex view of the future, it is more robust and targets critical factors than previous roadmaps. We hope this roadmap gives greater precision to decision makers.

Insights from the 2020 Industry Experts Online Survey

The main challenges are a high dependency on raw material supply from Asia, and responsible and ecological end-of-life battery disposal, combined with a rapidly growing demand.

A spread of industry specialists responded to the online technology survey carried out in September 2020:



Top three hot topics from the experts

1 Sustainable, ethical and commercially competitive battery supply

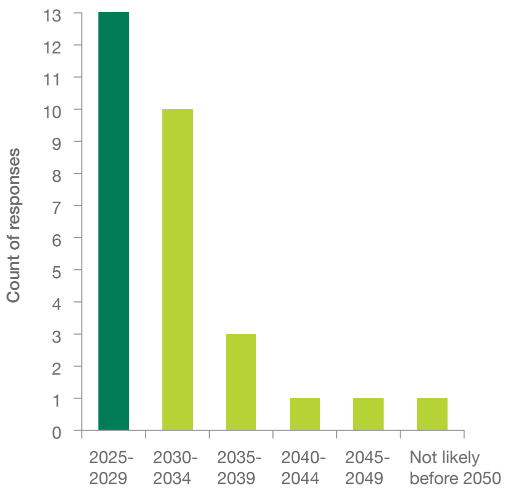
2 Increased reuse applications, efficient recycling and end-of-life ecologically responsible disposal

3 Raw material extraction and refinement that is environmentally and LCA focused

When will BEV achieve cost parity with ICE vehicles?

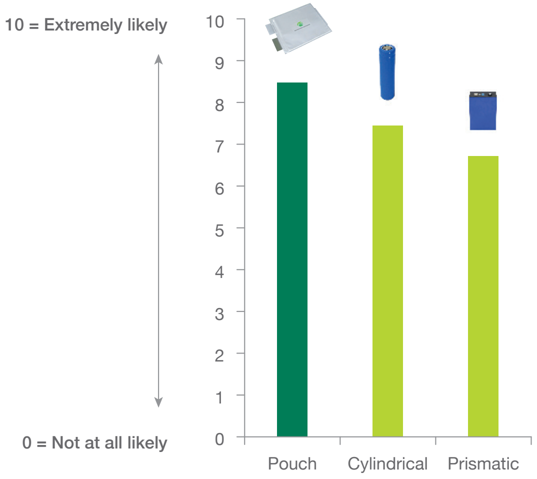
Almost 80% of the experts believe that battery electric vehicles will cost the same as ICE vehicles by 2035.

NB: With battery pack costs forecast to reach $100/kWh by 2025, BEV is likely to achieve cost parity with ICE vehicles much earlier.



In the long term, which cell format is likely to dominate the EV battery market?

There is no clear winner here as each have individual strengths and benefits, and a related supply chain dependency.



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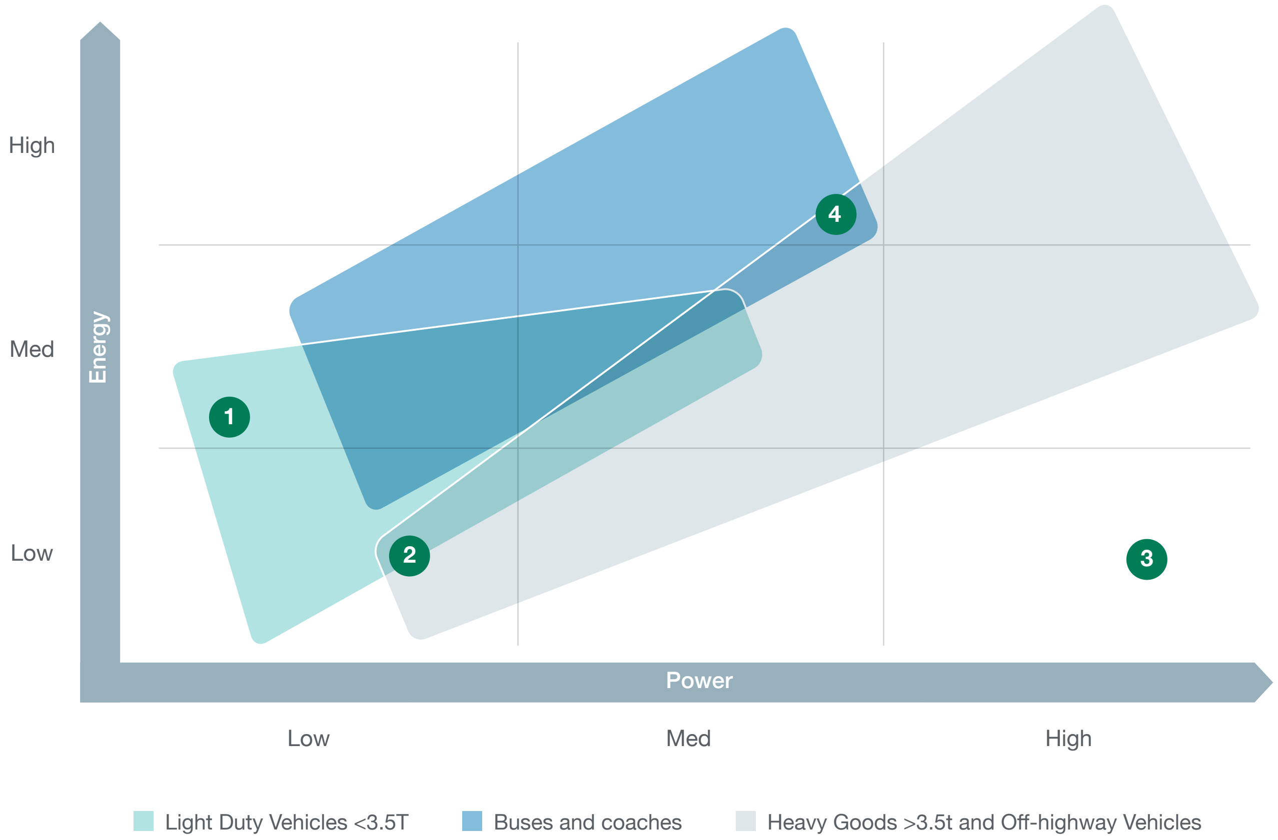
Energy-power spectrum across applications

Propulsion systems are tailored to specific power and energy demands, based on their use case and duty cycle. The graph below presents an outline of principle mass-market products.



The 2020 roadmap provides values for (1) Energy focused, cost sensitive indicators.

Other values are available from the KTN Cross-sector Battery Systems (CSBS) Innovation Network.

1. **Energy focused, cost sensitive**
   The key strategic drivers are for lower pack level costs and better continuous charge acceptance whilst maintaining or improving energy density levels. This is because a large capacity and faster charging are required to meet attribute requirements.

2. **Power focused, cost sensitive**
   The key strategic driver for this cluster is transient power handling at an affordable price, the applications would benefit from increased power and energy density but not at the expense of cost.

3. **Power focused weight sensitive**
   The key strategic driver for this cluster is power handling with minimal weight impact with a range of energy density requirements. Cost is less of a consideration than volume automotive.

4. **Energy focused, weight and power sensitive**
   The key strategic drivers are better gravimetric energy density and achieving better continuous discharge power density for more repeatable performance with greater range or reduced vehicle weight.

Technology indicators for energy focused, cost sensitive applications

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

		2020	2025	2030	2035
Cell Indicators	Transient Discharge Power Density (W/kg)	1100	1180	1260	1340
	Gravimetric Cell Energy Density (Wh/kg)	280	300	320	340
	Volumetric Cell Energy Density (Wh/l)	720	770	850	900
	Cell Cost ($/kWh)	85	70	58	48

		2020	2025	2030	2035
Pack Indicators	Transient Discharge Power Density (W/kg)	715	825	945	1070
	Charge Acceptance (Continuous C Rate)	1.5	2.5	3.5	4
	Gravimetric Pack Energy Density (Wh/kg)	185	210	240	275
	Volumetric Pack Energy Density (Wh/l)	470	540	640	720
	Pack Cost ($/kWh)	125	97	77	63

Notes:

- Two roadmaps have been created, giving equal weighting to both cell and pack innovations. This reflects that developments in both are needed to achieve the future performance indicators.
- These indicators align with the 1 **Energy focused, cost sensitive** category developed by Warwick Manufacturing Group (WMG) and the Faraday Battery Challenge as part of the KTN Cross-sector Battery Systems (CSBS) Innovation Network.
- The lowest costs of the CSBS Innovation Network targets have been adopted for this roadmap. This is to emphasise that low costs are prioritised for this technology.
- Assumed cell-to-pack ratios for energy and power density are: 65% for 2020, 70% for 2025 and 75% for 2030 and 80% 2035.
- C-rate has been added this year to reflect that cost effective chemistries, in addition to others, are expected to accept faster charging rates in the future.
- For specific product applications you will need to refer to page 1 on the energy-power map and find your relevant indicators on the KTN CSBS Innovation Network targets.

Technology indicators
In 2020, these replace targets in the roadmaps, providing a direction of travel and an approach to measuring best-in-class performance for this technology.

The indicators refers to the same technology across all the fields of cost and performance.

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Transient power density indicates the peak power the pack or cell can draw out. For the purpose of this roadmap, ‘transient’ is defined as <10 seconds 25°C and 50% SoC.

C-rate is a measure of the rate at which a battery pack is being charged and discharged. A 4C rating in 2035 means battery packs are expected to be fully charged in 15 minutes.

Energy density applies to both cell and pack, and is measured volumetrically and gravimetrically. Energy density governs how much space a battery pack takes up and how heavy it is.

Cost for these targets refers to OEM purchase prices for cells and packs. For energy-focused, cost-sensitive applications, cost is all-important.

Roadmap 2020

Electrical Energy Storage

Cell Materials and Manufacturing Roadmap

Technology indicators for 2020-2035 can be seen on page 2

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This roadmap represents a snapshot-in-time view of the global automotive industry propulsion technology forecast for mass market adoption. Specific application-tailored technologies will vary from region to region.

Dark bar: *Technology is in a mass market application. Significant innovation is expected in this time frame*

Transition: *Transitions do not mean a phase out from market but a change of R&D emphasis*

Dotted line bar: *Market Mature – technology has reached maturity. Likely to remain in mass market until it fades out where it's superseded*

Electrodes	Anodes	Enhanced energy dense Li-ion anodes (e.g. graphite, Si blends) → Maximum energy dense Li-ion anodes (e.g. 100% Si) → (market mature)
		Enhanced power dense Li-ion anodes (e.g. LTO) → Maximum power dense Li-ion anodes (e.g. Nb oxides) → (market mature)
		Next gen. anodes for new chemistries (e.g. Li metal anodes, hard carbon for Na-ion)
	Cathodes	Reduced cost Li-ion cathodes (e.g. LFP) → Ultra low cost cathodes (e.g. manganese rich, Li-S, Na-ion)
		Increased energy density Li-ion cathodes (e.g. NCA, NMC, eLNO, NFA, LMNO) → Localized particle optimization, cathode blending (e.g. colloidal cathodes)
		High powered Li-ion cathodes (e.g. nano-phosphates, thinner cathodes, smaller particle sizes) → (market mature)
		High energy and power density cathodes (e.g. Li-S, multi-valent chemistries, novel cathode materials and structures)
Other Cell Materials	Electrolyte Materials	Higher voltage liquid electrolytes → Liquid electrolytes for new chemistries (e.g. Na-ion, Li-S, metal-air)
		Hybrid and semi-solid state batteries with high ionic conductivity (e.g. gel polymer, PEO)
		Mass manufacture of solid state electrolytes with good conductivity (e.g. sulphides and oxides)
	Separators	Separators with reduced thickness and cost, oxidation resistance, heat dissipation → Enhanced separator functionality (e.g. phase change, fire suppression)
		Separator materials with enhanced ion conductivity and current density (e.g. PVDF, alumina) → (market mature)
	Current Collectors	Ultra-thin Cu and Al foils for Li-ion (e.g. sub 6 microns) → New current collector structures (e.g. lattice, functional integration with anode and cathode)
		Collector surface preparation (e.g. Plasma, laser) → Hybrid current collectors (e.g. metal alloys, metal coated polymers) → (market mature)
Solvents, Binders and Additives		Solvent replacements for NMP (e.g. N-Acetyl-P and water) → New binder functionality (e.g. hybrid, self-healing) → (market mature)
		Reduce wet processes and use of solvents → Dry manufacturing processes (no solvents) → Binderless electrodes and electrolytes
Life Cycle and End-of-Life for Cell Materials		Reduced CO_2 in manufacturing processes (e.g. electrodes, dry processes) → lower energy footprint → Net zero CO_2 production systems
		Safer and more sustainable cell material substitutions → Adoption of more abundant / less critical materials → LCA focussed value chain
		Reduce cell material wastage / increased yield → Cell material reconditioning and reuse (e.g. electrode regeneration or remanufacturing defect material)
		Pilot cell materials recycling → High volume, high efficiency cell materials recovery → Circular economy established for all cell materials

2020 · 2025 · 2030 · 2035 · 2040 · ...

Primary Technology Themes

Theme	Sub-themes
Electrodes	Anodes Cathodes
Other Cell Materials	Electrolyte Materials Separators Current Collectors
Solvents, Binders and Additives	
Life Cycle and End-of-Life for Cell Materials	

Electrodes

Li-ion-based **anodes** for both high-energy and high-power applications are detailed in this section. In the medium term, anodes for new chemistries and high-performance transition metal anodes are expected to reach the market.

Cathodes represent the highest cost in a battery cell and have been the subject of extensive R&D efforts. Innovation routes for low-cost, high-energy and high-power Li-ion cathodes are detailed here, together with next-generation cathode materials that go beyond Li-ion.

Other Cell Materials

Electrolytes are needed to help shuttle lithium ions to and from the electrodes. Liquid electrolytes are being incrementally improved to work alongside enhanced Li-ion chemistries. The step-change innovation comes with solid- and semi-solid-state electrolytes, which improve both energy density and safety when combined with lithium metal anodes but present complex manufacturing challenges.

Separators should be excellent isolators with no electrical conductivity. As separators get increasingly thinner and handle higher current densities, new membrane materials and coatings are needed.

Current collectors are typically made from aluminium or copper foil. Thinner foils are being demanded by cell manufacturers, with scope for new manufacturing processes and functional integration between electrode and current collector.

Solvents, binders and additives enhance the conductivity or adhesive properties of the active materials. The use of solvents, binders and additives is expected to decrease, improving both costs and the environmental performance of batteries.

Life cycle includes the carbon intensity, environmental impact, resource consumption and recyclability of the battery cell and material supply chains. Only by improving all of these elements can electric vehicles be a truly sustainable solution.

Electrode developments

Although there is scope for further development of graphite, silicon is expected to be increasingly incorporated to enhance cell energy density. There are several promising new anode materials for the highest power applications.

Roadmap 2020

Electrical Energy Storage

Cell Materials and Manufacturing Roadmap

Electrodes
- Anodes
- Cathodes

Other Cell Materials
- Electrolyte Materials
- Separators
- Current Collectors

Solvents, Binders and Additives

Life Cycle and End-of-Life for Cell Materials

1. Enhanced energy dense Li-ion anodes (e.g. graphite, Si blends) → Maximum energy dense Li-ion anodes (e.g. 100% Si)
2. Enhanced power dense Li-ion anodes (e.g. LTO) → Maximum power dense Li-ion anodes (e.g. Nb oxides)
3. Next gen. anodes for new chemistries (e.g. Li metal anodes, hard carbon for Na-ion)

1

Enhancing cell energy density

For cost-effective, energy-dense cells, graphite will remain the dominant anode material due to its stability and lower costs. A current trend is to blend more synthetic graphite with natural graphite to improve cycle life and stability. Other manufacturing innovations include reducing particle sizes and dispersing particles uniformly on the copper foil to increase cell capacity.

Another route to increasing energy density is introducing silicon alongside graphite. 3–5% silicon anodes are already commonplace, with 30% silicon anodes expected to reach the market in the next 5 years.

Longer term, 100% silicon anodes could be commercialised to maximise the energy density of existing Li-ion cells. The historic challenge with using silicon is it can expand up to three times in size when charging, causing the battery cell to swell up and capacity to fade. Many methods are being trialled by industry to prevent this, for example using ‘graphene shells’ to encase the silicon particles. This minimises the expansion and improves the cycling, but may increase the costs. This approach may therefore be suited to applications where high energy density is a priority.

2

Increasing power density

Despite the dominance of graphite and the emergence of silicon-based anodes, high-power applications still use a variety of anode materials including Lithium titanite oxide (LTO), which is typically used in buses, motorsport and some high-powered hybrids. The benefits of LTO are rapid charge and discharge capability, enhanced temperature performance and enhanced safety.

In the medium term, other promising anode materials for high power include niobium-based anodes, which could provide higher voltages and power densities without dramatically increasing costs. These are currently in late-stage development, with many companies close to commercialisation.

3

Next generation anode materials

Next-generation anodes can include both novel concepts and anodes developed to work alongside new cathode materials and electrolytes. The time frame for market application of these anodes is in the next 7 to 10 years.

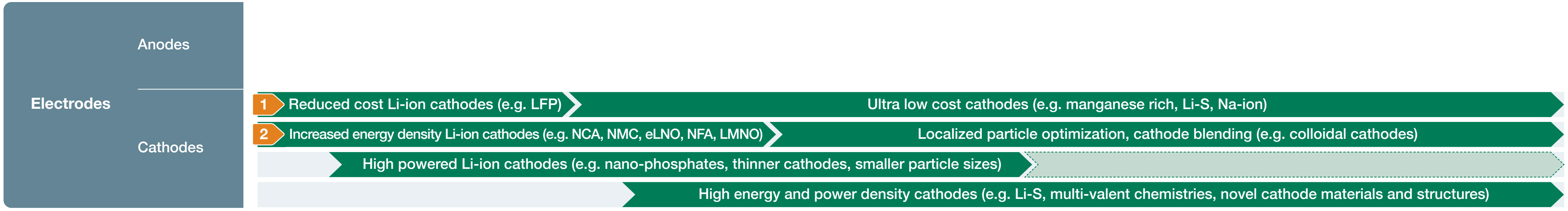
One novel anode is lithium metal, providing a step change in capacity and cell construction. However, producing lithium metal cost effectively and reducing dendrite growth to ensure adequate battery life are significant challenges.

Other possible routes are anode materials that enable new cell chemistries. For example, Na-ion batteries need new anode technologies such as hard carbon or antimony to be competitive in the automotive industry.

2020 | 2025 | 2030 | 2035 | 2040 | ...

Electrodes

High-power cathodes can be realised through new cell designs, while changes to the composition of LFP cathodes and new materials will help lower costs.



Other Cell Materials

Electrolyte Materials

Separators

Current Collectors

Solvents, Binders and Additives

Life Cycle and End-of-Life for Cell Materials

1

Low-cost cathodes

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, and in the next 2 to 3 years, some cell manufacturers will be adding manganese to LFP, increasing energy density without raising costs.

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.

In the medium term, other cost-effective cathodes materials are likely to be adopted, such as Li-S and Na-ion-based cathodes. Na-ion is one promising low-cost cathode material with fast charging capabilities, achieving lower costs because sodium is cheaper than lithium, and aluminum current collectors can be used in the anode instead of copper.

However, the cost reduction requires a performance trade-off. Currently Na-ion batteries are three times heavier than existing Li-ion and have poor cycle life. For stationary energy storage, however, Na-ion are already competitive with lead-acid batteries. Na-ion is likely to be first adopted by smaller, urban vehicles, which have limited range and need faster charging rates.

2

High-energy cathodes

NMC and NCA are the dominant energy-dense Li-ion cathode materials used by the automotive industry. The trend for both cathode chemistries is to increase energy density by transitioning to high nickel blends.

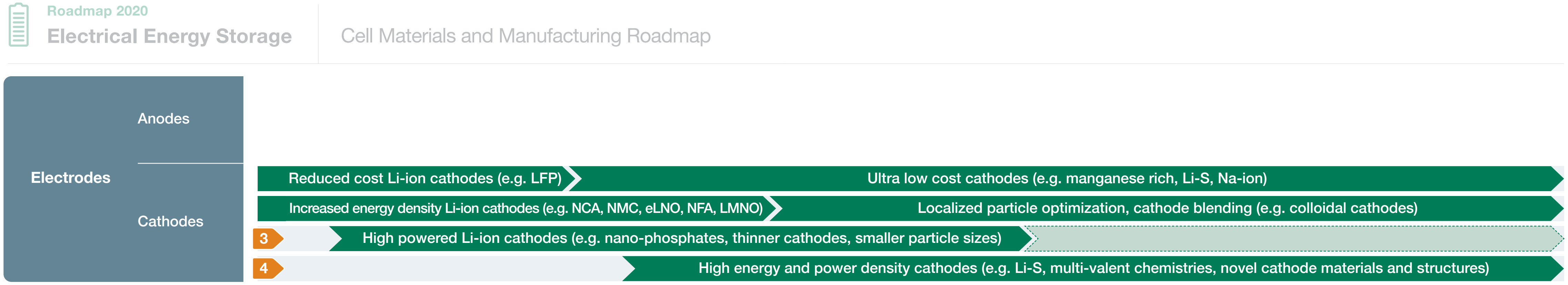
For NMC, the trend is transitioning to NMC811, or even NMC9.5.5. Similarly, NCA is moving from 7% cobalt to 3% cobalt, with Panasonic aiming for cobalt-free cathodes by 2025. Other high-energy-dense cathodes are also being developed for commercial release in the next few years. For example, Johnson Matthey has accelerated its plans to supply eLNO and Nissan are working on a Ni-Fe-Al cathode.

To sustain improvements in energy-dense Li-ion cathodes, innovative structures and manufacturing methods are needed to enhance the material's performance. Localised particle optimisation and blending of different cathode materials could offer significant improvements in energy density.

2020 2025 2030 2035 2040 ...

Electrodes

A number of companies are developing energy dense cathode materials, adjusting blends and evaluating new materials. Lithium sulfur offers a step-change in energy density and is likely to be increasingly used in the longer term.



3

High-power cathodes

Power-dense Li-ion cathodes use the same materials as energy-dense cathodes but place a greater emphasis on cell design. Higher power densities can be achieved through lower coating weights, lower areal capacities, smaller active particles and higher cathode porosities. High-powered cathodes also tend to be heavily calendared compared to energy-dense cathodes.

Enhanced types of LFP, known as nano-phosphates, have been tailored to achieve up to 35C while achieving better thermal stability and longer battery life. These types of chemistries have found a market in the bus market and motorsport sector where high C-rates are crucial.

4

Next-generation cathodes

To achieve both higher power and higher energy densities, new cathode materials are needed. Li-S batteries offer the potential to lower costs and a step change in energy density; initial deployment will be in small aerospace applications like drones before transitioning to automotive applications. Early automotive adopters for Li-S could be performance-passenger cars, double-decker buses and heavy goods vehicles, where low weight and high energy density are essential.

Other promising next generation cathodes include multi-valent batteries (e.g. Mg- and Ca-ion), sulfur and fluorophosphate-based cathodes. These materials offer a dramatic improvement in energy density, cycle life and power densities. While it is uncertain whether these chemistries will be commercialised for automotive applications, there is enough potential to justify continued R&D in material science and pilot manufacturing.

Other cell materials

Traditional electrolytes continue to evolve incrementally for Li-ion chemistries, while new electrolytes will need to be tailored for other cell chemistries. Solid- and semi-solid-state electrolytes offer a step change in both energy density and safety, but present complex manufacturing challenges.

Electrodes: Anodes, Cathodes

Other Cell Materials: Electrolyte Materials, Separators, Current Collectors

Solvents, Binders and Additives

Life Cycle and End-of-Life for Cell Materials

1

Liquid electrolytes

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- and NCA-based cathodes and higher silicon in the anode can cause traditional electrolyte solutions to degrade more rapidly. A potential solution offered by companies like Solvay are fluorinated liquid electrolytes that can operate at higher voltages and have longer cycle life. Due to their higher cost, fluorinated electrolytes are likely to be introduced in applications tolerant to higher cell costs. New electrode materials for Na-ion, Li-S, multivalent chemistries and metal-air batteries all require electrolytes tailored to their properties.

1. Higher voltage liquid electrolytes → Liquid electrolytes for new chemistries (e.g. Na-ion, Li-S, metal-air)
2. Hybrid and semi-solid state batteries with high ionic conductivity (e.g. gel polymer, PEO)
3. Mass manufacture of solid state electrolytes with good conductivity (e.g. sulphides and oxides)

2

Hybrid solid-state electrolytes

Hybrid solid-state electrolytes contain both solid and liquid materials, offering a practical compromise that could deliver safer batteries while enhancing cell performance compared to liquid electrolytes. Typically, the approach is to integrate polymer and inorganic electrolytes, or to encase liquid electrolytes in a solid, porous shell.

Hybrid solid-state batteries can reduce the use of binders and other inactive materials, as well as removing or significantly reducing other costly processing steps such as drying, solvent recovery, calendaring and electrolyte filling.

3

Solid-state electrolytes

Compared to liquid electrolytes, solid-state electrolytes offer enhanced safety, improved energy density and faster charging capability. They remove the need for a separator and reduce the likelihood of dendrite growth, a key cause of thermal runaway.

The two main types of solid-state electrolytes are sulfides and oxides, which both have their inherent strengths and weaknesses: oxides are environmentally more benign and offer greater stability at higher voltages, but require high temperature sintering or other complex manufacturing routes; sulfides offer greater ionic conductivity, but contain more hazardous materials in the chemical processing. However, both types require significant process improvement before they are mature enough for high-performance and high-energy-dense applications.

2020 | 2025 | 2030 | 2035 | 2040 | …

Other cell materials

Separators with enhanced functionality are needed to provide advanced thermal management. As they get thinner and handle higher current densities, new membrane materials and coatings will be needed.

1

Improving functionality of existing separators

Separators in Li-ion are typically made from polyethylene (PE). However, it is common to see PP/PE/PP tri-layer separators, consisting of a middle layer of PE sandwiched by outer polypropylene (PP) layers. As the present Ah 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; and separators that can pre-empt failures via enhanced sensing, or self-heal to reduce the occurrence of thermal runaway.

2

New materials for advanced separators

Novel materials are being developed for both separator coatings and the membrane material. One promising separator material is polyvinylidene fluoride (PVDF), which provides a step change in performance compared to polyethylene and polypropylene. PVDF separators tend to demonstrate better thermal performance, exhibiting minimal shrinkage under higher temperatures. They also show increased porosity by allowing ions through without the electrolyte degrading the membrane.

It is becoming increasingly common to coat separators with ceramic material, due to high-power charge and discharge events. A popular choice is high-purity aluminium oxide, which can operate under high temperatures.

2020 2025 2030 2035 2040 ...

Other cell materials

Cell manufacturers are demanding thinner foils, with scope for new manufacturing processes and functional integration between electrode and current collector.

Electrodes: Anodes, Cathodes

Other Cell Materials: Electrolyte Materials, Separators, Current Collectors

Solvents, Binders and Additives

Life Cycle and End-of-Life for Cell Materials

1

Optimising existing current collectors

Battery cell manufacturers are demanding thinner copper and aluminium foils to reduce weight and cost. Cost-effective foils that are suitable for high-volume applications are 6–10µm thick.

For high-performance application, reducing the thickness below 6µm is desirable, but this is expected to be limited by conventional rolling, annealing or electrodeposition processes. Improved annealing processes or new current collector designs (such as nanowire foil) therefore need to be developed to produce foils under 6µm.

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.

2

New processes and current collector concepts

The adhesion of cathode and anode slurries to the foils can be enhanced by using different surface preparation techniques (e.g. altering the roughness and surface tension of foils). Potential treatment methods are plasma treatment, UV radiation or laser structuring to aid mechanical and thermodynamic adhesion. This could promote the reduction of binders in the slurry, thereby increasing the active material.

In addition to surface preparation, new multi-material hybrid current collectors are in advanced stages of development. 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.

1 Ultra-thin Cu and Al foils for Li-ion (e.g. sub 6 microns) → New current collector structures (e.g. lattice, functional integration with anode and cathode)

2 Collector surface preparation (e.g. Plasma, laser) → Hybrid current collectors (e.g. metal alloys, metal coated polymers)

2020 | 2025 | 2030 | 2035 | 2040 | ...

Solvents, binders and additives

Reducing reliance on ‘wet’ manufacturing processes offers not only improved performance and cost, but the potential for increased safety and reduced environmental impact.

Electrodes
Anodes
Cathodes
Other Cell Materials
Electrolyte Materials
Separators
Current Collectors

1

Substituting harmful solvents

Eliminating the solvent N-methyl-2-pyrrolidone (NMP) will reduce manufacturing costs and improve safety due to its toxicity and flammability. Potential substitutes are N-acetyl-P and water.

Enhancing binder functionality

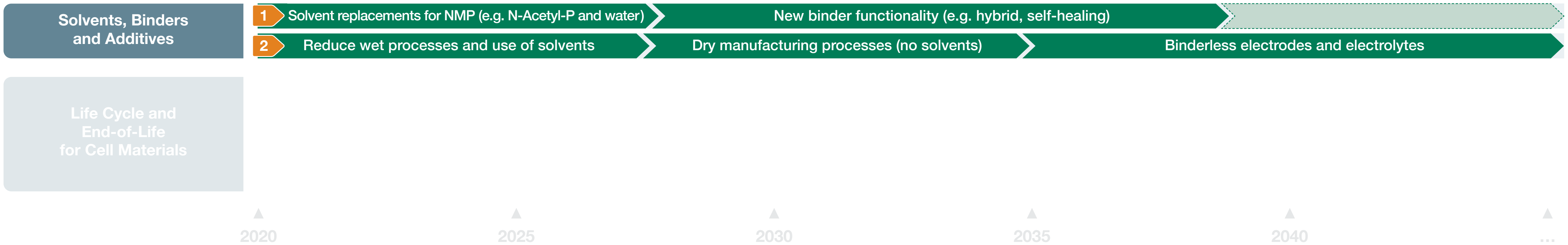
While binders are classed as inactive material, materials that enhance the functionality of the electrode slurry could be used. Attractive properties include self-healing polymers or binders that can accommodate expansion of anode materials such as silicon.

2

Reducing and eliminating solvent and binder use

Since the 1990s, Li-ion batteries have been manufactured using ‘wet’ processes: liquid slurries are mixed in batches and coated on current collector foils. Reducing the amount of solvents and using binder and additives only where necessary are first steps to improving the percentage of active materials that enhance energy and power densities.

In the long term, however, there are opportunities to completely alter how battery cells are manufactured. Many research organisations are investigating fully ‘dry’ manufacturing processes, which do not require solvents and binders. This would remove harmful chemicals that are expensive to manufacture with and improve the safety of the cell assembly process. Potential innovation routes to achieve this include powder coating anode and cathode materials on foils, or using flexible electrode films.



Life Cycle and End-of-Life for Cell Materials

Life cycle

Improvements across all aspects of materials use and manufacturing are needed to build an ethical, safe and sustainable battery supply chain.

Roadmap 2020

Electrical Energy Storage

Cell Materials and Manufacturing Roadmap

Electrodes: Anodes, Cathodes

Other Cell Materials: Electrolyte Materials, Separators, Current Collectors

Solvents, Binders and Additives

1

CO_2 and LCA impact of cell manufacturing and materials

The dual burden of net-zero CO_2 emissions and vehicles being legislated on a life-cycle basis has put increasing pressure on cell manufacturing and its value chain. The short-term focus is on reducing the CO_2 intensity of cell assembly and cathode production through energy-efficient manufacturing processes or low-carbon energy sources.

In the longer term, the full environmental impact of the cell and chemical supply chain will come under further scrutiny. This will incorporate the energy intensity of anode, cathode, electrolyte and separator production, as well as environmental impacts like VOCs and water consumption. This could stimulate the commercialisation of new energy- and resource-efficient ways of making battery chemicals.

2

Safer and more sustainable battery materials

Materials and chemicals used in battery manufacturing are not only strategically critical but can be harmful for human health and raise ethical concerns.

Cobalt and nickel are expected to run into a shortage of supply in the next few years. Chemical refiners are expecting the demand for high-purity nickel, cobalt and lithium to outstrip supply in the next 3 to 5 years. Using more abundant materials such as manganese, iron, aluminium and sodium could help reduce the risk of over-reliance on key materials.

Existing cell manufacturing methods use many hazardous and carcinogenic chemicals. Their reduction not only lowers handling and manufacturing costs but also helps at end of life. For example, battery recycling releases volatile flammable compounds from the electrolyte solvent and generates hydrogen fluoride (HF) from the electrolyte.

Finally, there are ethical concerns surrounding battery materials: most of the world's cobalt is mined in Democratic Republic of Congo where child labour is still used; lithium deposits in South America are in areas where there is water scarcity. Understanding and mitigating against these concerns is vital in creating a safer and more sustainable battery supply chain.

Life Cycle and End-of-Life for Cell Materials

- 1 Reduced CO_2 in manufacturing processes (e.g. electrodes, dry processes) → lower energy footprint → Net zero CO_2 production systems
- 2 Safer and more sustainable cell material substitutions → Adoption of more abundant / less critical materials → LCA focussed value chain
- Reduce cell material wastage / increased yield → Cell material reconditioning and reuse (e.g. electrode regeneration or remanufacturing defect material)
- Pilot cell materials recycling → High volume, high efficiency cell materials recovery → Circular economy established for all cell materials

2020 | 2025 | 2030 | 2035 | 2040 | ...

Life cycle

As production rises, and regulatory pressure to recycle increases, it will become ever more important to increase yields, reuse materials more effectively and ultimately build a fully circular economy.

Electrodes: Anodes, Cathodes

Other Cell Materials: Electrolyte Materials, Separators, Current Collectors

Solvents, Binders and Additives

3

Maximising the efficiency of cell materials

Although increasing yield rates from gigafactories is a top priority, reducing faulty cells and improving plant waste management must be addressed. In the longer term, creating on-site recycling facilities to take faulty cells and create a feedstock for, is seen as one potential route.

Another route being explored is reconditioning existing battery cells to maximise the asset. Argonne National Lab is exploring reconditioning electrode materials to help sustain performance into second life.

4

Recycling and circular economy

As vehicles become increasingly electrified, high-volume solutions for recycling battery cells and materials are needed. EU legislation will require battery cells made or imported into the EU to include an increasing level of recycled nickel, cobalt and lithium. This is the first step to encourage the development of a circular economy.

The challenge increases with the proliferation of different cell chemistries to suit different applications. The current situation is either high-volume cell-agnostic recycling routes with poor recovery rates or specialised recycling routes with high recovery rates that attract a cost premium.

Current hydrometallurgical and pyrometallurgical processes are still relatively low volume compared to the expected demand in the next 5 to 7 years. When these processes are scaled up, they need to minimise environmental impact (using no harmful chemicals or energy-intensive processes) and have high recovery rates of both critical and non-critical materials. The challenge is to achieve this in an economically viable way.

The ideal solution would be high-volume cell-agnostic recycling systems that could accept all types of cells, producing a range of high-purity battery grade chemicals that could feed back into cell manufacturers or other industries – a full circular economy with a level of resource independence in key critical materials.

Life Cycle and End-of-Life for Cell Materials

- Reduced CO_2 in manufacturing processes (e.g. electrodes, dry processes) → lower energy footprint → Net zero CO_2 production systems
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2020 | 2025 | 2030 | 2035 | 2040 | ...

Roadmap 2020

Electrical Energy Storage

Modules and Pack Roadmap

Technology indicators for 2020-2035 can be seen on page 2

automotive council UK

ADVANCED PROPULSION CENTRE UK

This roadmap represents a snapshot-in-time view of the global automotive industry propulsion technology forecast for mass market adoption. Specific application-tailored technologies will vary from region to region.

Dark bar: *Technology is in a mass market application. Significant innovation is expected in this time frame*

Transition: *Transitions do not mean a phase out from market but a change of R&D emphasis*

Dotted line bar: *Market Mature – technology has reached maturity. Likely to remain in mass market until it fades out where it's superseded*

Cell Formats and Design

- Consolidated cell formats for high volume manufacture
- New cell formats and features (e.g. Tabless, in-situ instrumentation, thermal flow and improved joining)

Electrical Distribution System (including BMS hardware and software)

- 400V architectures → Widespread adoption of 800V architectures → Novel 1200V architectures
- BMS upgrades using historic data → BMS capable of physics-based SoH and SoC cell tracking → AI enabled BMS using self-updating algorithms, in-situ data
- Telemetry enabled BMS architectures. Off-line updates to vehicle and live monitoring
- Next generation contactors / connectors (e.g. solid state)
- Reducing cost and weight bus bars → Net-shape, multi-material bus bars with enhanced conductivity

Thermal (i.e. cooling, heating and thermal materials including thermal propagation)

- Active thermal management (integrated, cost effective systems) → Submerged cooling for high volume
- Multi-material cooling plates → New thermal-rejection materials for high power cells and methods for passive cooling
- Reduced energy usage methods for cold climates → Thermal energy storage to maintain battery temperature in cold climates
- Optimisation of existing thermal interface / joining materials → Rationalisation and integration of thermal materials
- Methods for detecting, preventing and suppressing fire propagation / providing containment

Mechanical (i.e. Structures)

- Lightweight battery carriers → Lightweight, multi-material pack structures (inc. polymers)
- High volume cell / module joining techniques → Novel electrical connections

Pack Integration and Manufacturing

- Cell-to-pack batteries (e.g. module deletion) → Cell-to-chassis batteries → Structural batteries (e.g. as part of body structure)
- Packs integrated into full vehicle thermal management
- Real-time, in-line test and validation → Accelerated test and validation for mass market

Life Cycle and End-of-Life for Modules and Packs

- Health passport integrated in cells and modules (e.g. RFID) → Resilient battery modules and packs, reduced failures
- Reduced CO_2 emissions of module and pack assembly, energy-efficient production → Net zero CO_2 production systems
- Pack designs to enable end-of-life management and flexible 2nd life usage → LCA focussed module / pack value chain
- Design for disassembly → Techniques for material recovery (e.g. mechanical disassembly, processing) → Circular economy established for module and pack

Primary Technology Themes

Cell Formats and Design	**Cell formats and design** will become either increasingly standardised to support economies of scale, or specialised to accommodate different vehicle requirements.
Electrical Distribution System (including BMS hardware and software)	**Electrical distribution systems** enable power from the battery cells and modules to be intelligently distributed with minimal losses. This can be achieved via better battery management systems, busbars and connectors/contactors.
Thermal (i.e. cooling, heating and thermal materials including thermal propagation)	**Thermal** management systems are essential to maintain a battery pack's health. Battery cells can be heated and cooled through better active cooling systems or enhanced materials to manage heat and mitigate cold.
Mechanical (i.e. Structures)	**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	**Pack integration and manufacturing** explores novel ways to integrate 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 and End-of-Life for Modules and Packs	**Life cycle** includes the carbon intensity, environmental impact, resource consumption and recyclability of the battery modules and packs. Only by improving all these elements can electric vehicles be a truly sustainable solution.

2020 2025 2030 2035 2040 ...

Cell formats and design

Although the industry is consolidating upon a number of cell formats for volume application, new formats and integration of additional functions will enhance performance in the longer term.

Cell Formats and Design

Electrical Distribution System (including BMS hardware and software)

Thermal (i.e. cooling, heating and thermal materials including thermal propagation)

Mechanical (i.e. Structures)

Pack Integration and Manufacturing

Life Cycle and End-of-Life for Modules and Packs

1

Consolidation of cell formats

As automotive Li-ion cells proliferate, OEMs are likely to gravitate towards certain cell formats, especially for high-volume applications. Three broad cell types are being used: pouch, cylindrical and prismatic.

Pouch cells offer the highest energy density and are relatively lightweight due to their foil casings. Given their uniqueness for EV applications, they require high volumes to be economical. The high energy density can present safety concerns that are heightened by issues with uniformly cooling the pouch. The industry is moving towards the VDA size guidelines, with tabs at either end of the cell.

Cylindrical cells are the most developed and are already highly standardised due to their extensive use in consumer electronics. As a result, they are cost competitive, with the automotive industry gravitating towards the 21700 cell. As they are circular, they do not tesselate well in modules: while this results in lower cell-to-pack ratios, it is easier to put cooling channels between them.

Prismatic cells are a compromise between cylindrical and pouch cells. Packaging density is higher due to their shape, but the volumetric and gravimetric energy density is less than pouch cells. Like pouch cells, they are tailor-made for automotive applications and so require high volumes to be economical, resulting in a price premium. As for pouch cells, OEMs are increasingly adopting the VDA BEV2 and PHEV2 specifications.

2

New cell designs and in-built features

As cell chemistries evolve, new cell formats could be developed to enhance the performance of chemistries. Tesla's announcement of its tabless 4680 cell demonstrates improvements in manufacturing efficiency (by not halting the production line to attach the tabs), energy and power density as well as safety. Other novel concepts like string cells and rolled-ribbon batteries are also being developed but are still in early phases.

However, cell formats are just one element of improved design. Increased functionality is also being sought after by OEMs. In-situ instrumentation and monitoring would provide a step change in health management and BMS development. Optimised designs to improve the thermal performance to the stress across the cell would also increase cell safety and reduce the burden on cooling systems.

2020 2025 2030 2035 2040 ...

Electrical distribution system

BMS software will become more sophisticated, using self-optimisation, AI and real-time monitoring and software updates to improve the performance, health, maintenance and repurposing of batteries.

Roadmap 2020
Electrical Energy Storage | Modules and Pack Roadmap

Cell Formats and Design

Electrical Distribution System
(including BMS hardware and software)

- 1 400V architectures → Widespread adoption of 800V architectures → Novel 1200V architectures
- 2 BMS upgrades using historic data → BMS capable of physics-based SoH and SoC cell tracking → AI enabled BMS using self-updating algorithms, in-situ data
- Telemetry enabled BMS architectures. Off-line updates to vehicle and live monitoring
- Next generation contactors / connectors (e.g. solid state)
- Reducing cost and weight bus bars → Net-shape, multi-material bus bars with enhanced conductivity

Thermal
(i.e. cooling, heating and thermal materials including thermal propagation)

Mechanical
(i.e. Structures)

Pack Integration and Manufacturing

Life Cycle and End-of-Life for Modules and Packs

2020 | 2025 | 2030 | 2035 | 2040 | ...

1

Higher-voltage vehicle architectures

400V architectures have been common for BEVs and will remain for energy-dense, cost-effective applications. The introduction of 800V architectures in the passenger car sector signals a change in strategy. Benefits of higher voltages include thinner lighter cables, smaller, more efficient motors, lower system weight, faster charging and higher power throughput.

800V will initially be adopted in high-performance sectors (e.g. GM's Hummer EV), but this will trickle down to mass-market products. For example, Kia have signalled it will introduce 800V variants for its first dedicated EV platform.

Widespread adoption of 800V and even higher voltages will be spurred by the electrification of HGVs and off-highway equipment, which currently operate at 700–800V. Given the fast-charging requirements and the potential for tethered and catenary vehicles, 1200V could be introduced for these applications.

2

Sophistication of BMS software

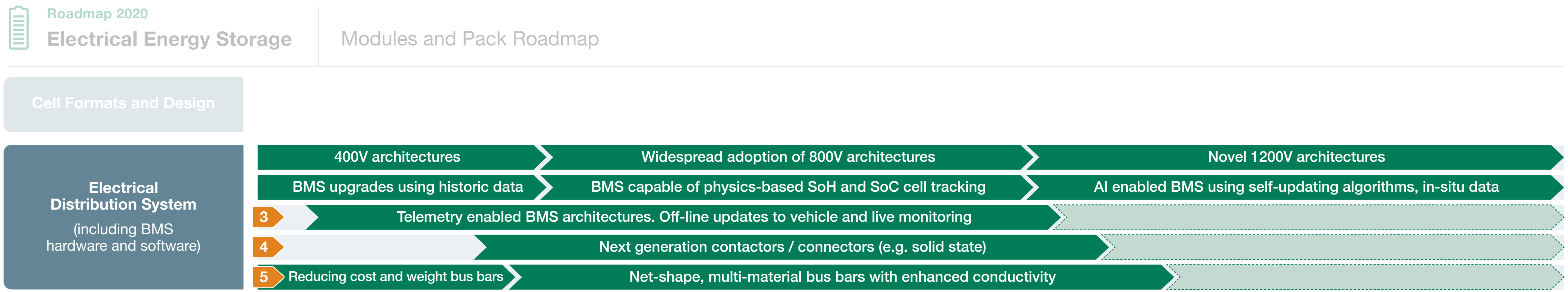
Improvements in existing BMS will lead to better state-of-charge and health information and so to better management of battery life and performance. Near-term innovations in BMS models will be enhanced via accurate real-world performance data that will inform the next model generation.

In the longer term, more sophisticated multi-physics battery models that self-optimise will become more prevalent. AI could enable battery models to self-update and parameterise based on immediate operating conditions (e.g. GPS, vehicle-to-grid, fast charging).

The potential for sensors embedded into cells opens up the opportunity for distributed BMS to monitor and control individual cells. The health of a module is often dictated by the weakest cell. An advanced BMS could isolate one cell or draw power from certain cells based on their health, enabling a degree of self-healing and extension of the life of the cells.

Electrical distribution system

Advances in contactors, connectors and busbars will be needed, particularly to realise the benefits of moving to vehicle architectures with higher voltages.



3

Telemetry enabled BMS

Telemetry offers real-time monitoring and live software updates without vehicle downtime. Over-the-air data transfers help to both modify high-level functionality and adjust BMS parameters as system knowledge increases. Battery operating data can result in early detection of faults and preventive maintenance.

Two-way communications can support big data analysis, improving battery life and performance. As new algorithms develop, they improve battery health and can help schedule battery hardware changes.

A secondary benefit of battery health data is to improve second-life use and uptake. Lack of knowledge about the use history, status and charge condition of a battery can be time consuming and costly for re-purposing the battery. New applications, based on agnostic battery supply chains, are likely to grow with such data.

4

Enhanced contactors and connectors

Contactors and connectors are electrical switching devices, used for turning the high voltage circuit on and off. These are common in EV applications, where a high current carrying capacity is involved. The contacts rapidly open and close in order to be able to handle large loads, however, they can be susceptible to vibration and fatigue issues. To improve quality and reliability of contactors and to enable flexible voltage architectures, new contactor types and concepts are needed.

5

Cost- and space-effective busbars

Low-inductance busbars help distribute power from an EV's battery pack to the electric drive system. Short-term innovations include minimising nickel plating on copper busbars, reducing the amount of expensive nickel powder, which is also used for cathode materials. Introducing aluminium busbars can reduce weight and lower costs, but aluminium may be less suitable for higher-power applications given its poorer thermal conductivity and expansion rates compared to copper. Hybrid copper and aluminium busbars could enable a compromise between cost and performance. More advanced materials such as graphene coating could be used to enhance the conductivity even further.

The unique profiles of batteries, coupled with the high currents, require advanced busbar materials and shapes. Net-shape manufacturing of busbars that minimises joining can reduce complexity. In the longer term, busbars could integrate key power electronics components, including electrolytic capacitors and surface-mount-technology components (e.g. EMI/RFI filters for noise reduction).

Thermal

New recyclable multi-function materials together with active cooling strategies to cope with high-power applications are needed.

Thermal
(i.e. cooling, heating and thermal materials including thermal propagation)

- 1 Active thermal management (integrated, cost effective systems) → Submerged cooling for high volume
- 2 Multi-material cooling plates → New thermal-rejection materials for high power cells and methods for passive cooling
- Reduced energy usage methods for cold climates → Thermal energy storage to maintain battery temperature in cold climates
- Optimisation of existing thermal interface / joining materials → Rationalisation and integration of thermal materials
- Methods for detecting, preventing and suppressing fire propagation / providing containment

2020 | 2025 | 2030 | 2035 | 2040 | ...

1 Active cooling strategies

Forced-air or passive cooling is appropriate for lower C-rated battery packs but is not sufficient for high-power applications or fast charging. The trend for both high-energy and high-power battery packs is to migrate towards water/glycol coolant systems using cooling plates. The most pronounced thermal events are expected to come from rapid charging events >150kW, which waste significant amounts of energy via heat rejection. Pre-cooling the battery, additional cooling pipes and fans or derating charging power to minimise cooling demand are potential strategies.

In the long term, submerged cooling concepts that are used in motorsport applications could transition to the automotive sector. Submerged (or immersion) cooling consists of a dielectric cooling liquid that directly cools the cells and busbars. This can reduce thickness and weight of busbars and uniformly cool the cell. However, the weight and complexity of the cooling loop, combined with the cost of dielectric material, makes this approach more suitable for high-performance vehicles.

2 Enabling passive cooling

Passive cooling is an energy-efficient solution relying on heat sinks, heat spreaders, heat pipes or thermal interface materials to keep batteries at an optimal temperature. Enhanced metal-matrix composite materials can provide enhanced thermal conductivity compared to aluminium and copper cooling plates. As high C-rate battery packs enter the market, new cooling plate materials that can instantly reject heat will be needed. Cooling technologies from the satellite and aerospace sectors could be transferred for high-performance applications but would require manufacturing improvements to be suitable for the automotive sector.

Thermal

Keeping batteries at their optimal temperature will require new materials and methods to more efficiently heat batteries and effectively manage and dissipate heat.

Cell Formats and Design

Electrical Distribution System (including BMS hardware and software)

3

Heating the battery

Batteries operating in cold climates experience significant degradation and are under significant stress through the additional requirements of the HVAC systems, especially for applications like BEV buses. Moreover, energy used to heat the battery pack to the optimal temperature comes from the battery itself, so reducing energy usage from thermal management systems is a priority. Longer term, phase-change materials offer the opportunity to store heat from overusing the battery or other parts of the vehicle and then use it either to heat the battery or for the HVAC system.

4

Rationalising thermal, adhesive and joining materials

Battery modules and packs contain many thermal, adhesive and sealant materials to maintain temperature and structural integrity. Multi-functional materials that can provide adhesive and thermal management properties will be valuable in reducing the amount of wet processes inside the battery pack. These new resins and materials will need to be recyclable to ensure compliance with end-of-life regulations.

Thermal

(i.e. cooling, heating and thermal materials including thermal propagation)

- Active thermal management (integrated, cost effective systems) → Submerged cooling for high volume
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Mechanical (i.e. Structures)

Pack Integration and Manufacturing

Life Cycle and End-of-Life for Modules and Packs

5

Detecting and preventing thermal runaways

Understanding the fire hazards of Li-ion and of other battery chemistries is vital for safe in-vehicle use and for manufacturing, storage and transportation. Thermal runaway leads to pressure increases, gas and particulate emissions, fire or in the worst case explosion. Improved testing and validation, at fast turn-around, allows preventive and suppression strategies to be developed. Further research into new materials and design features that are capable of arresting or diffusing thermal runaways can be of great benefit.

2020 2025 2030 2035 2040 ...

Mechanical

Greater use of polymers and composites together with structural integration can reduce battery pack weight. Work is needed to bring more robust joining techniques into production.

Cell Formats and Design

Electrical Distribution System (including BMS hardware and software)

Thermal (i.e. cooling, heating and thermal materials including thermal propagation)

Mechanical (i.e. Structures)

Pack Integration and Manufacturing

Life Cycle and End-of-Life for Modules and Packs

1

Lightweight battery carriers

Most battery casings and internal support structures are metal. Polymers and composites offer a means to consolidate parts and integrate features. However, polymers require higher volumes to mitigate tooling costs, while composites require process development to achieve higher volume.

In the longer term, batteries are expected to be more readily integrated into the vehicle, for example as primary structural elements.

2

More robust cell joining techniques

Cost reduction is driving the use of alternative and mixed materials within the battery pack, but achieving robust joining of dissimilar materials, at high speed, is essential for performance and durability. New joining techniques need to be developed concurrently with production validation methods to make high-volume manufacturing feasible. Real-time closed-loop production testing can help minimise expensive scrappage costs and eliminate the reliance on end-of-line testing to capture defects.

New electrical connection techniques that reduce takt time, dependency on high precision equipment and the number of failure modes would offer significant benefit to battery QA protocols. Materials used in new joining techniques need to be cognisant of ease-of-disassembly, promoting easier repurposing and energy-efficient end-of-life recycling.

1 Lightweight battery carriers → Lightweight, multi-material pack structures (inc. polymers)

2 High volume cell / module joining techniques → Novel electrical connections

2020 2025 2030 2035 2040 ...

Pack integration and manufacturing

Battery packs and their thermal management will become more integrated into the overall vehicle structure and systems.

Cell Formats and Design

Electrical Distribution System (including BMS hardware and software)

Thermal (i.e. cooling, heating and thermal materials including thermal propagation)

Mechanical (i.e. Structures)

1 Increasing cell-to-pack ratios

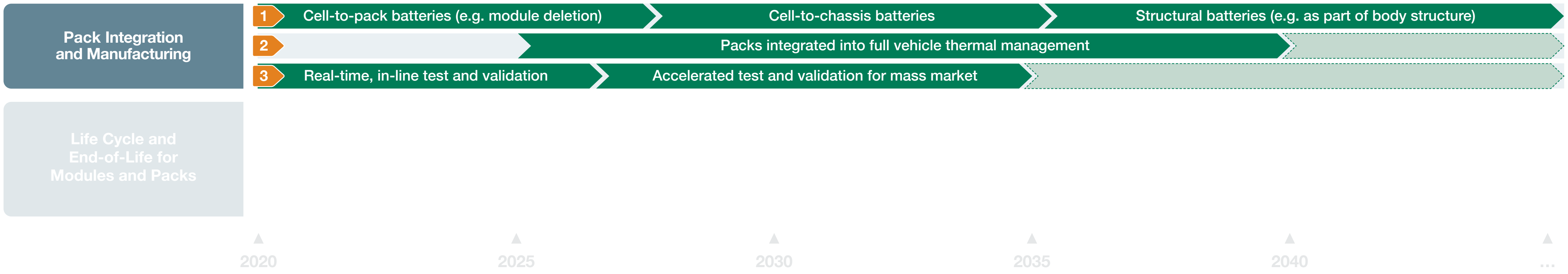
The Blade from BYD achieves a high cell-to-pack ratio through module deletion and removing some housing structures. CATL have gone one step further, announcing cell-to-chassis, whereby the battery becomes part of the chassis. In the longer term, energy storage could be placed throughout the body structure through conductive structures that store power through regenerative braking or photovoltaics placed on the roof or closures.

2 Convergence of thermal management systems

Battery thermal management systems are often separate from motors and power electronics. Once EDUs have been combined to offer weight saving, a single cooling loop would improve efficiency at a vehicle level. The use of phase-change materials could allow heat from semiconductors and electric motors to pre-condition the battery in cold climates.

3 In-situ module and pack validation

In-line cell and module testing can help reduce manufacturing failures and remove end-of-line testing, which can take considerable time. In-line testing also provides the opportunity to test and inspect areas that would otherwise be impossible to test when the battery is fully assembled. Machine tools need to be optimised to test the health of cells and modules and achieve higher speeds with accurate data.



Life cycle

Enhanced traceability and monitoring together with low carbon energy for manufacturing, will be needed to deliver a long-term sustainable solution.

Roadmap 2020
Electrical Energy Storage

Modules and Pack Roadmap

Cell Formats and Design

Electrical Distribution System
(including BMS hardware and software)

Thermal
(i.e. cooling, heating and thermal materials including thermal propagation)

Mechanical
(i.e. Structures)

Pack Integration and Manufacturing

1

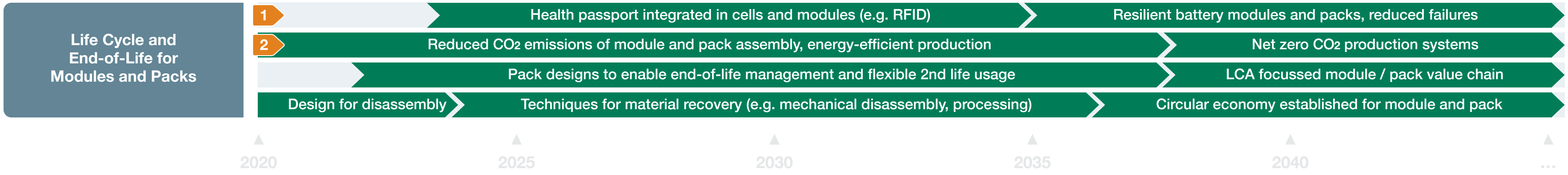
Traceability and monitoring through life

To ensure reliable data, radio-frequency identification (RFID) is one avenue to complement the health data held by the BMS. While there is some level of duplication with the BMS, RFID can hold additional data on production and locality. It also provides a level of redundancy, as data from the BMS can be faulty when recycled.

2

Carbon intensity and environmental impacts

The dual pressure of net-zero CO_2 emissions and vehicles being legislated on a life-cycle basis will require pack and module assemblers to decarbonise their manufacturing processes. While they are low energy users compared to the battery cell supply chain, low-carbon energy sources will be required for energy-intensive processes such as laser welding and other cell-joining and -curing techniques. Pack and module assembly are early candidates to be net-zero compliant.



Life cycle

Approaches are needed to understand when a battery is ready for its second life, and to ensure it is designed to simplify the transition.

Roadmap 2020

Electrical Energy Storage | Modules and Pack Roadmap

- Cell Formats and Design
- Electrical Distribution System (including BMS hardware and software)
- Thermal (i.e. cooling, heating and thermal materials including thermal propagation)
- Mechanical (i.e. Structures)
- Pack Integration and Manufacturing

3

Designing battery packs to enable second life

The demand for battery storage for homes, grid balancing and commercial buildings, coupled with the infancy of battery-recycling processes, makes repurposing EV batteries an attractive option.

Enhanced understanding of battery degradation through improved modelling can notify OEMs on degradation rates over time. This can better inform when a battery could transition from an EV to a second-life application, influencing the design process. Simplifying the mechanical design of battery packs can also enable easy extraction of reusable modules and cells. This reduces refurbishing costs and makes adoption more likely. Finally, standardised, transparent and high-fidelity BMS data that can accurately log voltage, current and battery health as well as collect performance over time will also be needed.

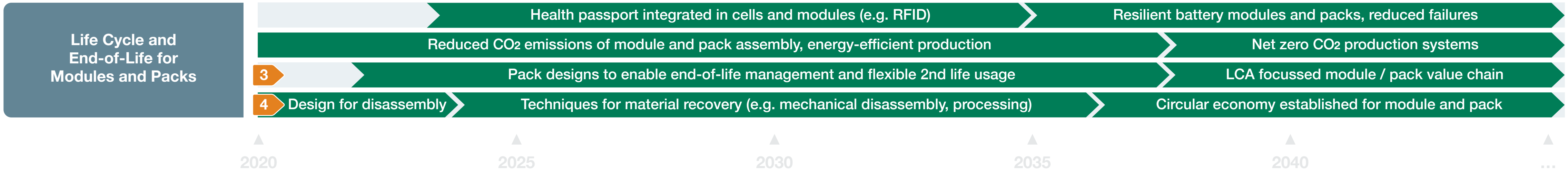
The biggest hurdles for second-life applications for EV batteries are commercial rather than technological. Second-life life cells, which could be 7–10 years old, must compete with new cells which will be cheaper and more more energy dense. However, the move towards LCA legislation may make reusing cells more attractive compared with continuously making new cells.

4

Enabling the extraction of battery cells

Irrespective of whether older EV batteries are successfully commercialised for second-life applications, batteries will eventually need to be recycled. Battery packs are typically designed for their use phase. Sealants, adhesives and mechanical structures are tailored to maximise range, performance and safety. To recycle batteries effectively, the immediate priority is to design battery packs that reduce complexity, remove unrecyclable adhesives and sealants and enable mechanical disassembly of battery packs by simple automated tools (rather than by human labour).

In the short term, most battery housings and closures will be aluminium or steel, which are easily recyclable. However, to reduce weight, polymer and mixed material structures are being explored to extend the range or reduce the battery size, especially in light commercial vehicles and buses, where range is critical. This makes the pack and module structures more difficult to sense, sort and disassemble. As plastics and metals have different and complex recycling routes, tailoring the disassembly processes to account for these variations will add significant costs.



Glossary

Abbreviation	Explanation
Ah	Amp hours. The current (amperage) a battery can provide for one hour.
AI	Artificial Intelligence. Smart machines and algorithms capable of performing tasks that usually require human intelligence.
BMS	Battery Management System. This monitors and manages the health of the battery and measures items such as: voltage, temperature, current, state of health, state of charge and depth of discharge.
CATL	Contemporary Amperex Technology Co., Limited. Chinese company developing and manufacturing Li-ion batteries.
EDU	Electric drive unit. Integrated unit comprising power electronics, transmission and electric motor.
HF	Hydrogen fluoride
HGV	Heavy goods vehicle
HVAC	Heating, ventilation and air conditioning
LCA	Life-cycle assessment. Assessing environmental impacts over all stages of the life-cycle of a product (for instance from raw material extraction, through processing, to manufacture, use and ultimately recycling/disposal).
LTO, LFP, LFMP, NMC, NCA, LMO, eLNO	Examples of various lithium-ion cathode and anode materials used in automotive applications.
Li-S	Lithium sulfur batteries offer higher energy density and reduced cost compared to lithium-ion.
NMP	NMP N-Methyl Pyrrolidone is an expensive solvent material that's needed for the production of battery cells, but it is not contained in the final device. NMP also emits flammable vapours and is highly toxic.
PE, PP, PVDF	Polyethylene, polypropylene and polyvinylidene fluoride are thermoplastic polymers offering useful chemical, thermal and electrical properties.
QA	Quality assurance
SOC	State of charge is the equivalent of a fuel gauge for the battery pack. The units of SOC are commonly expressed as percentage points (0% = empty; 100% = full).
VDA	The Verband der Automobilindustrie e.V. is a German interest group supporting the German automobile industry who have published a series of standards and recommendations for Li-ion battery systems.
VOC	Volatile organic compounds are a variety of chemicals, some of which can have long-term effects on human health.

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This is an industry consensus roadmap facilitated by the APC

Summary of engagements during the 2020 roadmap refresh

Spread of companies that participated in the refresh

109 industry organisations participated in Workshops and Interviews

38 additional industry organisations participated via the Online Survey

Total engagements 147 Industry Organisations

- Tier N (77)
- OEM (29)
- Academia (15)
- Other/Trade (26)

A global view with international participation

Austria	Singapore
Belgium	Sweden
England	Switzerland
Germany	United States
Netherlands	Wales
Scotland	Japan