Automotive battery value chains

November 2023

ADVANCED PROPULSION CENTRE UK

Accelerating Progress

This document is aimed at supporting industry, academia and government in the following ways:

Industry

- Identify strategic strengths within the UK for market growth opportunities
- Understand how each company's technology fits in and its contribution to the supply chain
- Identify gaps within the local supply chain and opportunities for foreign direct investment or local scale-up

Academia

- Guide R&D into next-generation technologies to build a strong UK supply chain
- Develop up-skilling and re-skilling programmes to support UK industrial companies train their staff

Government

- Understand where the UK's strengths and gaps lie in the automotive supply chain
- Develop policy, strategy and funding to accelerate scale-up in critical parts of the supply chain
- Support foreign direct investment decisions that complement UK strengths and incentivise local production

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Introduction

Battery cell technology – overview

NMC(A)

Nickel Manganese Cobalt (NMC) is currently the leading battery chemistry for automotive vehicles in the UK and Europe.

Can be used for the widest variety of automotive applications. NMC(A) is a similar high nickel content chemistry. The addition of aluminium (A) increases cycle life.

Relies heavily on the use of critical materials (lithium, cobalt and nickel).

Sodium-ion

Sodium-ion eliminates the use of lithium and cobalt, and potentially nickel.

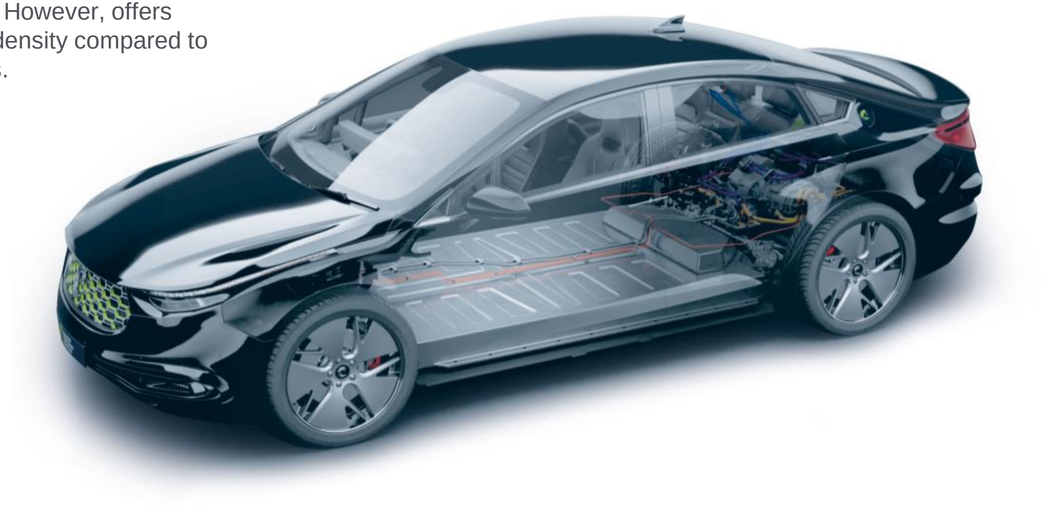
Like lithium-ion batteries there are multiple chemistries some are more likely to be used for automotive or mobility applications than others.

In general sodium-ion chemistries offer a lower energy density compared to lithium-based chemistries. Sodium ion is still in a relatively early development stage compared to lithium ion.

LF(M)P

Lithium Iron Manganese Phosphate LF(M)P offers a potential alternative to NMC for automotive applications, including high-volume cars and vans.

Relies less heavily on the use of critical materials. However, offers reduced energy density compared to NMC chemistries.



Battery value chains – key insights

A broad range of vehicle needs can be supported by a broad range of chemistries giving the automotive industry some strategic decisions to be made.

This insight report provides updated automotive battery value chains for NMC(A), LF(M)P and sodium-ion batteries in the UK, in the 2030 horizon.

NMC(A) and LF(M)P are two types of lithium-ion battery with the highest market share.

Like lithium-ion batteries, sodium-ion batteries come in many different chemistries, each with different properties. It is too early to tell which sodium-ion chemistries will be the most popular and which might gain any automotive market share. This report presents the value chain for two sodium-ion chemistries:

Polyatomic anion-based materials – a possible contender in the micromobility and small urban vehicles space

Prussian blue analogues - unlikely to achieve great penetration in the automotive market but attractive for stationary storage. Also, an interesting study case for the critical materials that are still potentially needed for sodium-ion batteries.

Cell manufacturing and module and pack manufacturing: Cells are often manufactured separately and can be integrated either into modules or directly into packs.

Integrating cells into battery packs

A cell can be integrated into a module with multiple modules making a pack, this is the tried and tested route. The value chains presented in this document describe this complete ‘cell to module to pack’ route.

However, more recently cells are being designed to be directly integrated into a pack or even directly into the chassis.

Cathode chemistry choice impacts cell format options and options for integration into packs.

Image: Tesla Model Y structural battery

Advantages of cell-to-pack / chassis integration

- Reduction in part count >40%
- Reduction in weight >10%
- Increase volume utilisation by 15 to 50% (depending on cell format)
- Use above gains to reduce cell count or use cheaper less energy-dense cells
- All of the above help to reduce costs

Disadvantages of cell-to-pack / chassis integration

- Some trade-offs in mechanical and thermal design
- Design for assembly challenges at the vehicle production line
- Harder to repair, re-use or recycle

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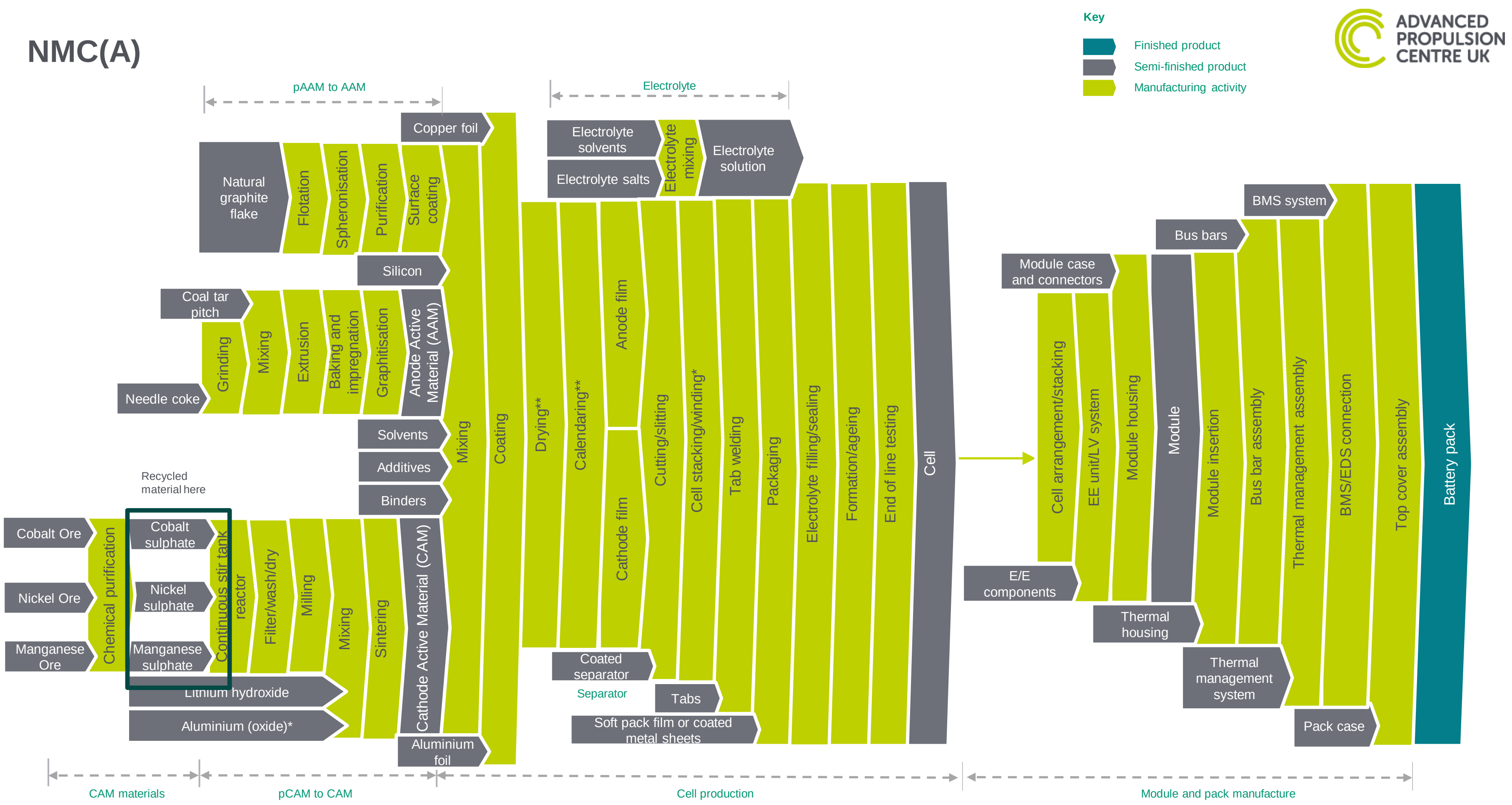
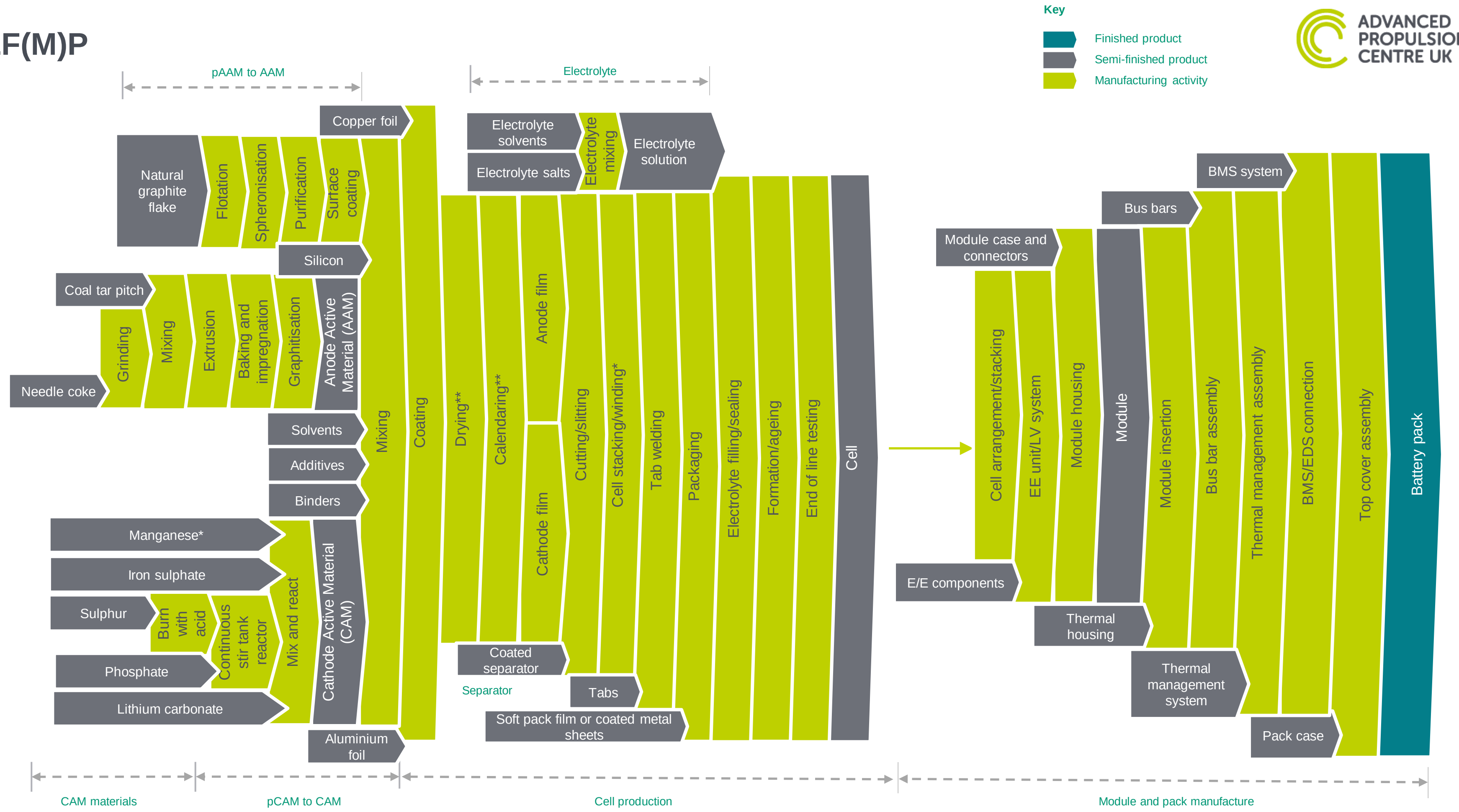
Automotive battery value chains

NMC(A)



*Aluminium can be added to the cathode material as a stabiliser, it is not included in the reaction step but added later. The addition of aluminium could increase cycle life.

LF(M)P

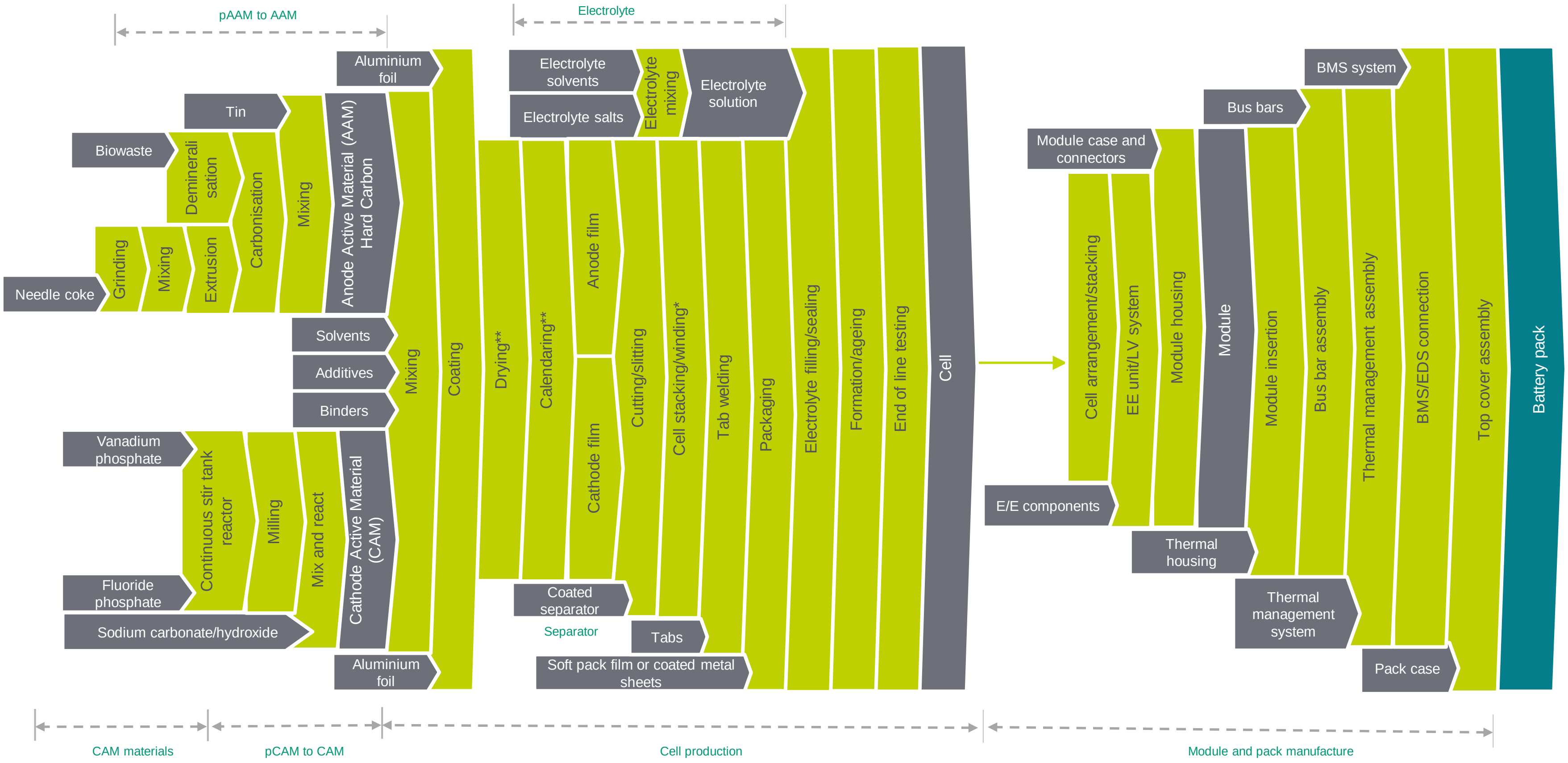


*Manganese can be added to the cathode. Since it is added as part of the reaction it alters the chemistry of the cathode. This changes how the cathode material needs to be handled and processed. LFMP cathodes exhibit higher energy density than LFP cathodes.

Na (Polyatomic anion-based materials)

Key

- Finished product
- Semi-finished product
- Manufacturing activity



There are other possible variations of this developing sodium-based chemistry.

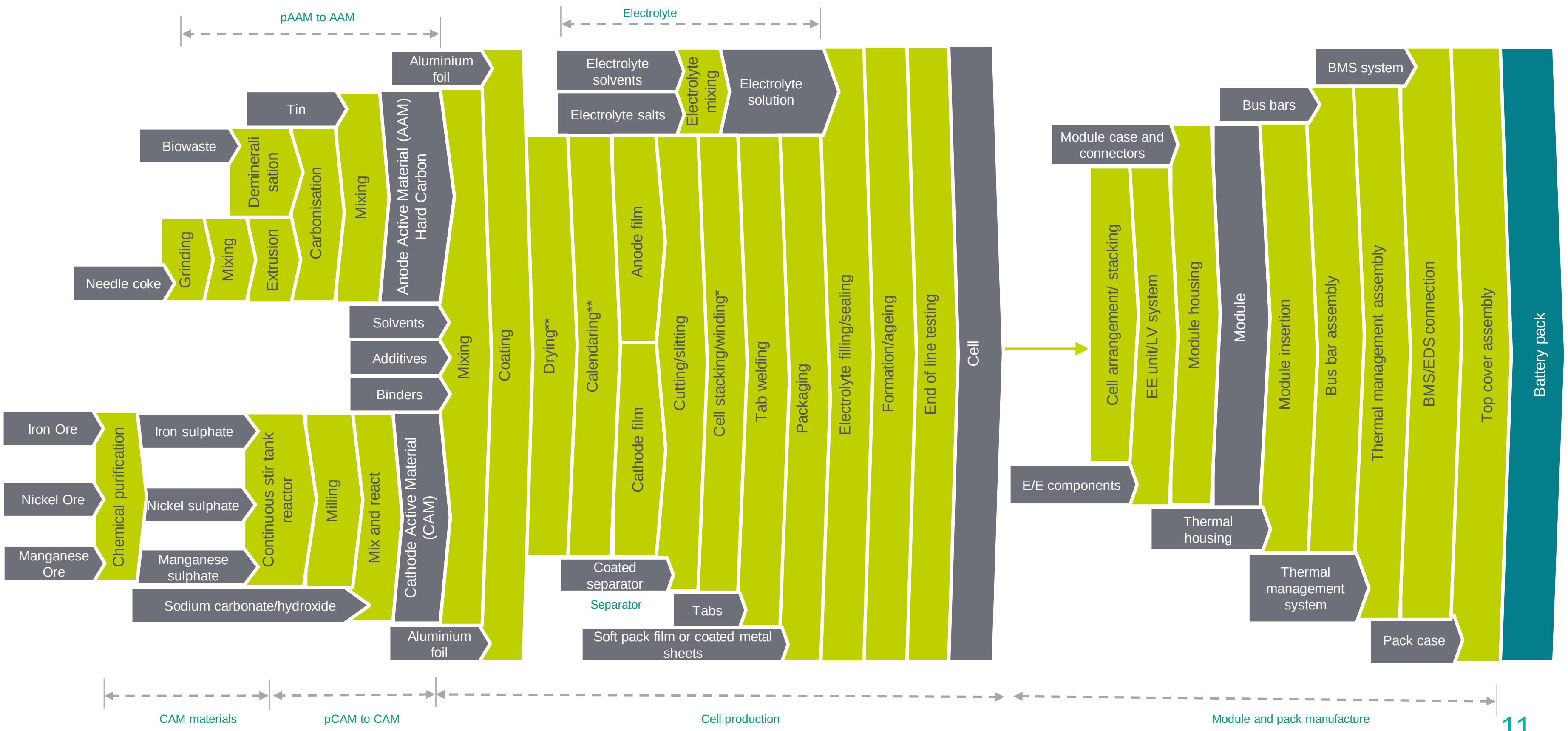
Na (Prussian blue analogues)

Key

Finished product

Semi-finished product

Manufacturing activity



There are other possible variations of this developing sodium-based chemistry.

Primary differences in cell chemistries are in the cathode and anode preparation

Key

- Finished product
- Semi-finished product
- Manufacturing activity

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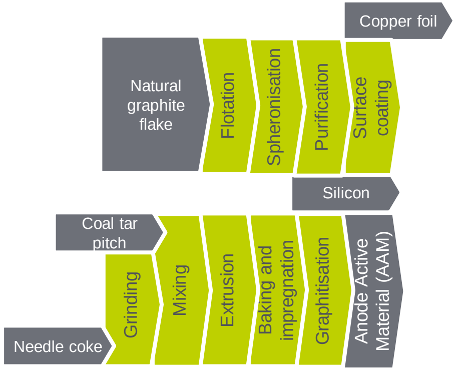
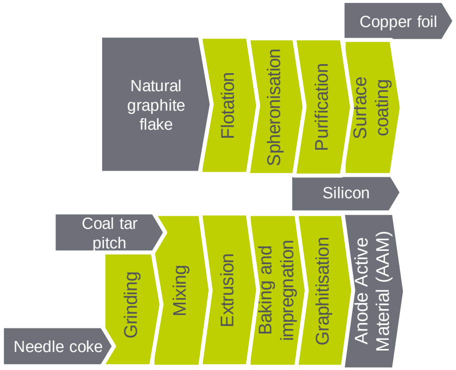
NMC(A)

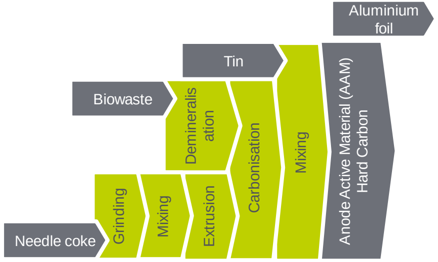
LF(M)P

Na (Prussian blue analogues)

Anode



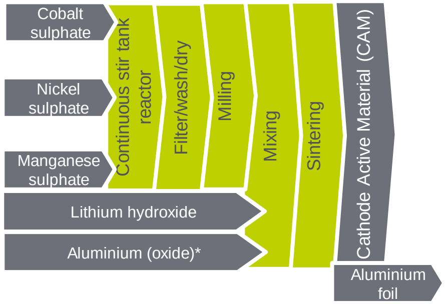


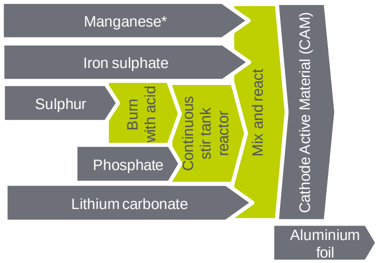


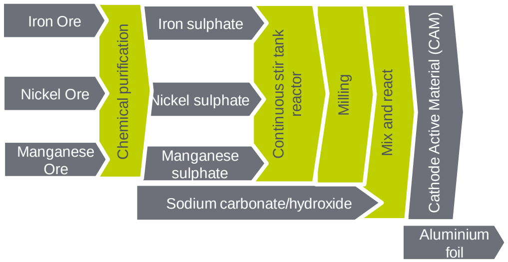
Moving from NMC(A) to LF(M)P the anode is unchanged

Moving from lithium to sodium the anode and anode current collector change as well as the cathode chemistry

Cathode







Example chemistries are shown to illustrate differences.

2030 automotive battery strategy

Complex market dynamic could drive different chemistry strategies across automotive manufacturers

Prioritisation of different market dynamics will differ between OEMs depending on their target market(s).

- Potential demand
- Critical materials supply chain risk
- Material costs
- Battery cell supply chain
- Re-use and recycling
- Automotive performance requirements
- Regulation and trade

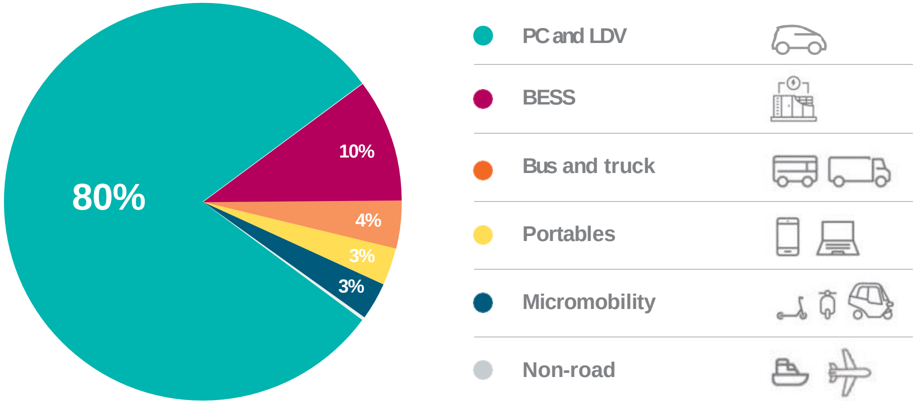
Market dynamics through to 2030: European market potential demand

By 2030, over 80% of battery demand will come from the automotive sector. To access this market requires meeting performance and cost targets.

The lifetime cost and cycle life of sodium-based chemistries compared to lithium-ion chemistries make them well suited to stationary storage, approximately 10% of total battery demand.

However, the incumbent lithium chemistries are likely to meet over three quarters of this stationary storage demand as LF(M)P performs well enough, and is a proven technology, in these applications.

Further demand for low-cost chemistries like sodium-based chemistries could come from two/three-wheeler vehicle markets and urban utility vehicles such as delivery vehicles.



Sources: RhoMotion, WoodMackenzie, BNEF, APC analysis.

Market dynamics through to 2030: critical minerals supply chain risk

OEMs may look to alternative chemistries to reduce reliance on critical minerals, with potentially volatile supply chains.

NMC(A) batteries are currently the leading battery chemistry in Europe and the UK however LF(M)P and sodium-ion offer an opportunity to decouple from risk in certain supply chains.

This needs to be balanced with meeting performance requirements.

While NMC(A) chemistries are the most exposed to supply chain volatility they also offer the highest energy densities.

Sodium-based chemistries can reduce critical mineral use but are unlikely to eliminate the use of critical minerals.

	Lithium use	Nickel use	Cobalt use	Other critical materials
NMC-622	Baseline for comparison	Baseline for comparison	Baseline for comparison	Manganese
NMC-811	Same	Increase	Decrease	Decrease manganese
LF(M)P	Increase	No nickel	No cobalt	Decrease manganese, contains phosphorus
Na (Prussian blue analogues)	No lithium	Decrease	No cobalt	Decrease manganese
Na (Polyatomic anion-based materials)	No lithium	No nickel	No cobalt	No manganese, contains vanadium and phosphorus

This is a non-exhaustive list and represents only three lithium-ion and two emerging sodium-ion chemistries.
SSBs not included in analysis, can use NMC as the cathode to achieve higher energy densities, however they are not expected to achieve significant share in automotive applications prior 2030.
Sources: RhoMotion, WoodMackenzie, BNEF, APC analysis.

Market dynamics through to 2030: material costs

There is significant variability in production costs, and other material costs, depending on cell formats and cell-to-module, cell-to-pack or cell-to-chassis strategies. In addition, lower energy density cells will result in either using more cells to achieve similar vehicle range or a reduction in vehicle range.

This makes direct cost comparisons non-trivial, particularly when trying to compare pack level cost performance.

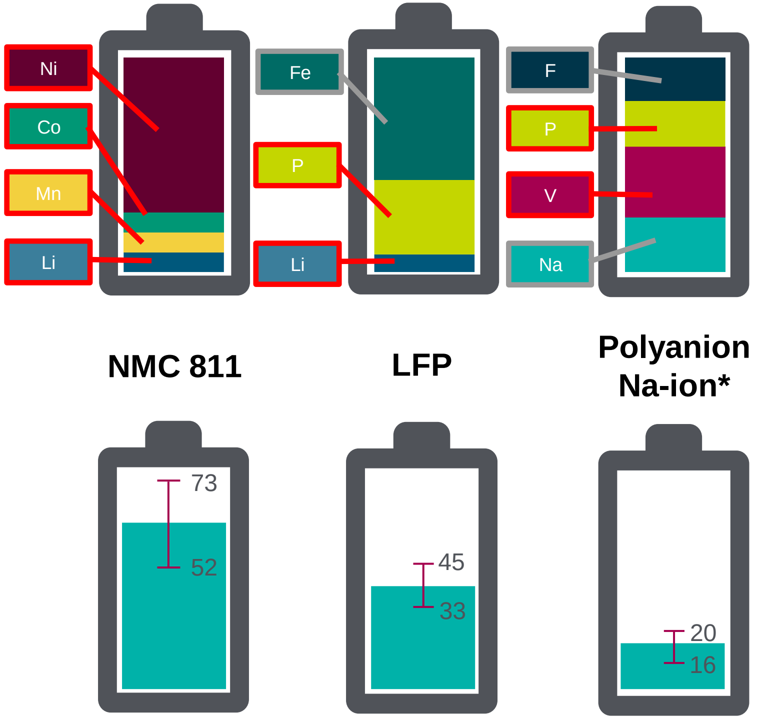
Materials count for a higher percentage of the cost in lithium-ion batteries and are exposed to volatile markets. NMC is sensitive to cobalt and nickel costs while LFP remains sensitive to lithium costs.

Sodium-ion batteries vary in cathode chemistries, each having a different baseline cost. In general, the total material cost is lower per kWh than lithium-based chemistries. Material costs for sodium-ion batteries are expected to be more stable in cost in comparison to lithium-ion batteries.

The cost difference between sodium-ion chemistries and LF(M)P chemistries is potentially very small. Given the potential performance advantage of LF(M)P, cost difference does not make sodium-ion a clear winner.

Approximate cathode material mass content

Materials outlined in red are considered high or increasing criticality as defined by UK Critical Materials Intelligence Centre (CMIC).



Approximate range of cathode material total cost ($/kWh)

- Mass content based on approximate percentages of material. Exact percentages will vary.
- *Pricing shows max. and min. market price for materials from China Jan-22 to Sept-23. Priced per kt and converted to $/kWh based on approx. material weights. Costs are indicative of material difference as lithium-ion materials have well established supply chains while sodium-ion supply chains are emerging and subsidised in China. Material costs also vary over time.

Sources: RhoMotion, WoodMackenzie, BNEF, APC analysis.

Market dynamics through to 2030: European battery cell supply chain

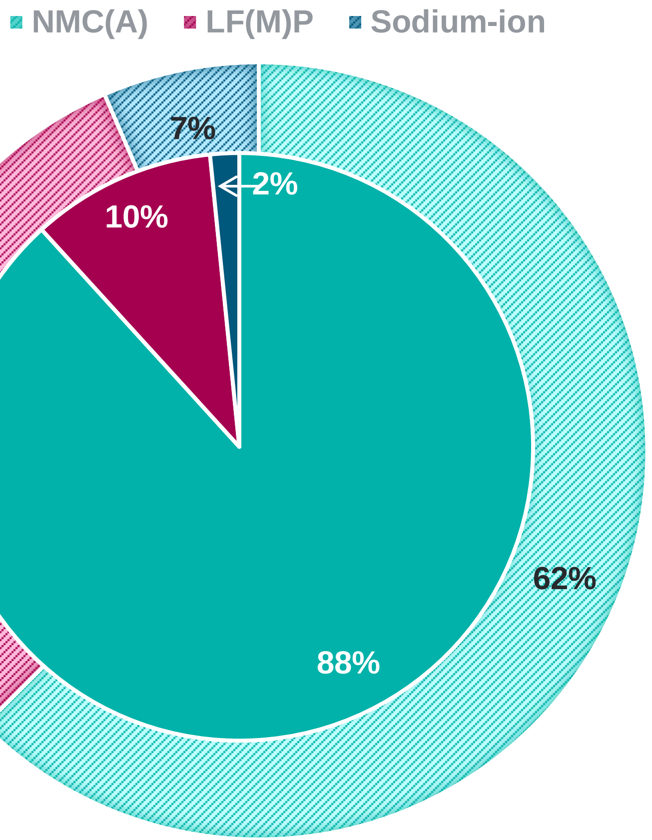
NMC(A) batteries are forecast to dominate cell production in Europe in 2030. An automotive manufacturer looking to diverge from NMC will be looking at a limited local supply chain in this time.

The rules of origin requirements between the UK and Europe place an emphasis on local battery cell supplies.

Whilst only 10% of battery cells made in Europe are expected to be LF(M)P, 30% or more of the vehicles made in Europe are expected to use LFP or LF(M)P by this date. There is an expectation that cheaper chemistries will continue to be imported to support demand. This could mean that in the short term a significant percentage of LFP-based vehicles are not exported from Europe to the UK to avoid incurring tariffs.

LFP production capacity is expected to quickly ramp up to meet demand, however, expected investments beyond a 2030 timeline are not yet confirmed.

If UK-based OEMs wish to take advantage of the benefits of cheaper chemistries like LF(M)P and sodium-based chemistries, there will need to be both clear demand indicators and investment.



Inner chart: Forecast 2030 cell supply
Outer chart: Potential 2030 cell opportunity*

*Cell opportunity forecast based on lithium restricted scenario driving sodium-based battery demand.
Sources: RhoMotion, WoodMackenzie, BNEF, APC analysis.

Market dynamics through to 2030: re-use and recycling

At the vehicle end-of-life, a battery pack can maintain value either for recycling or secondary use. This residual value will be a consideration in choice of battery chemistry.

Recycling of LF(M)P batteries is less economically viable than NMC(A) due to the lack of cobalt and nickel. Sodium-ion batteries are less economically viable than LF(M)P due to the cost difference between lithium and sodium.

However, recycling isn't the only potential revenue from batteries at the end of a vehicle life, with Nissan and JLR already committing to the reuse of batteries for stationary storage.

LF(M)P and sodium-ion batteries are more favourable than NMC(A) for stationary storage applications, where batteries are priced as a function of their age and state of health.

UK automotive manufacturing is export focused, with just 20% of total production sold domestically. Therefore, to minimise regulatory burdens, industry would prefer UK requirements on recycled content to be aligned with international standards.

This creates an added dynamic as the materials in lithium-ion batteries, and particularly NMC(A) batteries, have added value to help meet the European minimum content requirements.

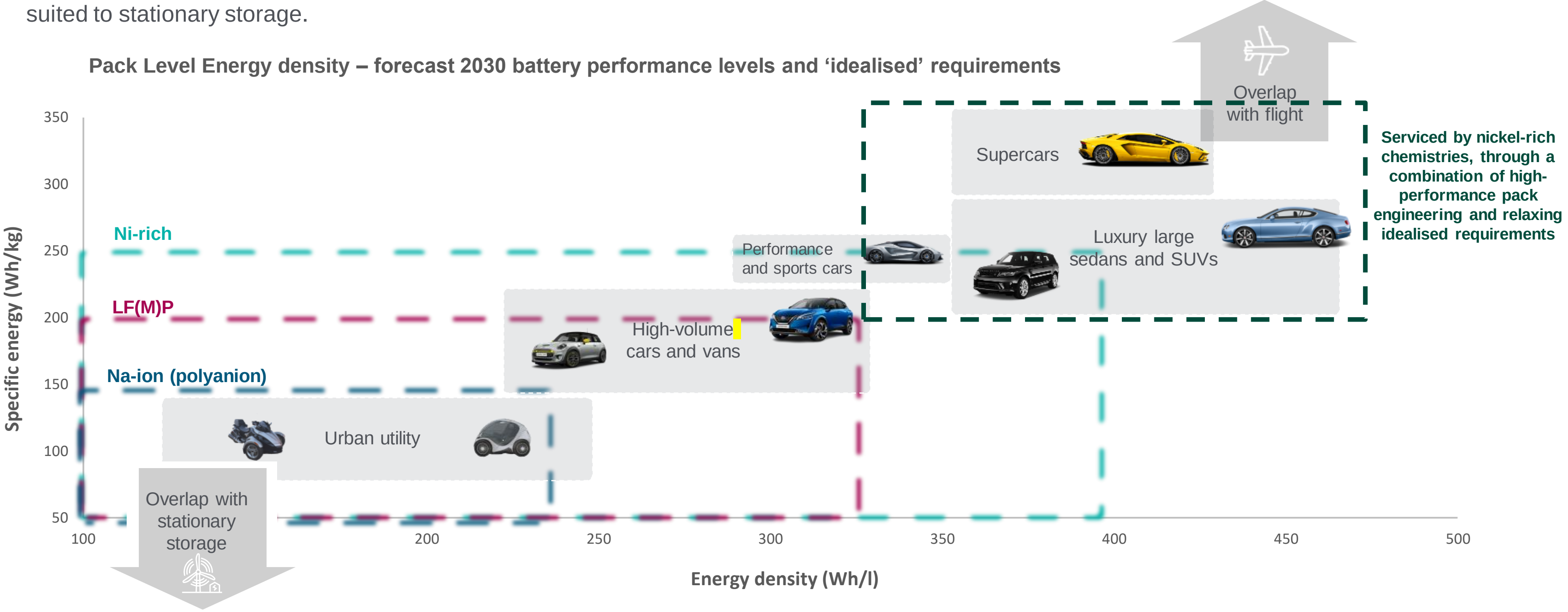
Material	2027 targets (%)	2030 targets (%)	2035 targets (%)
Cobalt	Declare Amount	16	20
Lithium	Declare Amount	6	10
Nickel	Declare Amount	6	12

Sources: RhoMotion, WoodMackenzie, BNEF, APC analysis.

Market dynamics through to 2030: Automotive performance requirements

This chart shows the forecast idealised requirements of the UK automotive industry for battery pack performance. Nickel-rich NMC(A) chemistries are expected to be able to service the majority of the market. LF(M)P is expected to be suitable for a range of high-volume cars and vans. Sodium-based chemistries could technically service micromobility and some urban utility vehicles as well as being suited to stationary storage.

Pack Level Energy density – forecast 2030 battery performance levels and 'idealised' requirements



- Innovation opportunities highlighted in the APC's report Battery Insight Report - 2025 and Beyond need to be developed to increase energy capacity towards the highest idealised requirements.
- Technical risk differs for different chemistries. Sodium-based batteries carry the most technical risk or uncertainty of meeting these performance levels.
- Images are indicative and not intended to convey requirements for particular manufacturers or models.

Market dynamics through to 2030: regulation and trade

The EU Batteries Regulation and UK-EU rules of origin trade agreement have a significant impact on supply chain planning and choice of chemistries.

The EU Batteries Regulation will require both increasing recycled material content and decreasing supply chain carbon footprint: driving localisation of supply.
The trade agreement between the UK and EU includes rules of origin requirements that provide minimum UK-EU originating content requirements to qualify for tariff-free trade, also driving localisation of supply.

2023

- Introduction of EU Batteries Regulation

2024

- Declare carbon footprint
- 50% non-originating allowance for battery cells
- 40% non-originating allowance for battery packs
- 55% non-originating allowance for xEVs

2025

- Recycling efficiency 65%

2026

- Carbon Intensity Labelling
- Battery Passports

2027

- Declare recycled content
- Maximum carbon footprint
- 35% non-originating allowance for battery cells
- 30% non-originating allowance for battery packs
- 45% non-originating allowance for xEVs

2030

- Recycling efficiency 70%
- Minimum recycled content

The UK automotive industry needs to secure a stable NMC(A) supply chain to mitigate against higher costs, and high-volume manufacturers need to invest in LF(M)P

Considering pricing, performance, and supply chain risks UK-based automotive manufacturing is likely to be split between LF(M)P and NMC(A) based battery chemistries for the next decade. Therefore, the UK need to focus scale-up efforts on these chemistries, whilst continuing to invest in R&D for sodium-based chemistries.

Short term	Manufacturing actions	Supply chain actions
LF(M)P	• Encourage UK gigafactorys to produce LF(M)P to ensure flexibility of supply • Low CO_2 cathode production processes that are non-toxic and can accept multiple material inputs	• Secure, European / UK source of phosphates and iron for cathode materials • Secure a steady lithium carbonate supply • Develop viable recycling routes
NMC(A)	• Attract FDI into NMC(A) cathode manufacturing to the UK to fulfil rules of origin requirements for battery cells • Process innovation for methods that enable the removal of NMP from high nickel cathodes	• Secure a long-term supply of low-carbon nickel, cobalt, and manganese sulphates to mitigate raw material price spikes • Encourage precursor Cathode Active Materials (pCAM) refining capability in the UK • Material recovery and reincorporation routes to meet current and future recyclate targets
Sodium-ion	• Manufacturing actions started on global level which require monitoring	• Supply chains developing globally which need monitoring and engagement

Appendix

Glossary and definitions

Lithium ion: Lithium-ion batteries use lithium ions as the charge carrier, there are a wide variety of chemistry options available for the cathode which is primarily responsible for the performance characteristics of the battery.

LFP: Lithium iron phosphate is a relatively low-cost lithium-ion cathode chemistry as it does not contain nickel and cobalt which are costly materials found in other lithium-ion battery chemistries with comparable or better energy density performance.

LF(M)P: LF(M)P, or sometimes written L(M)FP, is made with the addition of manganese to a lithium iron phosphate cathode. The manganese improves energy density.

NMC(A): Despite the lack of a 'L' in the name NMC is a lithium-ion battery cathode chemistry comprising lithium, nickel, manganese, and cobalt. This chemistry has energy density advantages over LFP but has drawbacks in safety, cycle life, and cost. Where energy is the most critical parameter high nickel versions of NMC are used. NMC is one high-nickel cathode chemistry, there are other high-nickel cathode chemistries such as NMCA. NMCA comprises lithium, nickel, manganese, cobalt, and aluminium.

Sodium ion: Sodium-ion batteries use lithium ions as the charge carrier, there are a wide variety of chemistry options available for the cathode which is primarily responsible for the performance characteristics of the battery. In general, sodium-ion batteries are safer and can endure more charge cycles than their lithium-ion counterparts.

Sodium polyanion: This is one promising sodium-ion battery chemistry able to achieve performance that could see application in some transport applications. Particularly where safety and cycle life are primary concerns. The most typical polyanion chemistry comprises of sodium, vanadium phosphate, and fluoride phosphate.

Sodium Prussian blue: This is a variant of a relatively simple and cheap sodium-ion chemistry. Very well suited to stationary storage applications with a low cost and long life. Typically comprising sodium, nickel, manganese, and iron.

SSB: Solid State Batteries. In a solid state battery the liquid electrolyte is replaced with a solid or semi-solid electrolyte. Various cathode chemistries can be supported.

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Glossary and definitions

Ni: Nickel
UK increasing criticality watchlist

Co: Cobalt
UK high criticality material

Mn: Manganese
UK increasing criticality watchlist

Li: Lithium
UK high criticality material

P: Phosphorus
UK increasing criticality watchlist

V: Vanadium
UK high criticality material

Fe: Iron
F: Fluorine
Na: Sodium

H Hydrogen																	He Helium
Li Lithium	Be Beryllium											B Boron	C Carbon	N Nitrogen	O Oxygen	F Fluorine	Ne Neon
Na Sodium	Mg Magnesium											Al Aluminium	Si Silicon	P Phosphorus	S Sulphur	Cl Chlorine	Ar Argon
K Potassium	Ca Calcium	Sc Scandium	Ti Titanium	V Vanadium	Cr Chromium	Mn Manganese	Fe Iron	Co Cobalt	Ni Nickel	Cu Copper	Zn Zinc	Ga Gallium	Ge Germanium	As Arsenic	Se Selenium	Br Bromine	Kr Krypton
Rb Rubidium	Sr Strontium	Y Yttrium	Zr Zirconium	Nb Niobium	Mo Molybdenum	Tc Technetium	Ru Ruthenium	Rh Rhodium	Pd Palladium	Ag Silver	Cd Cadmium	In Indium	Sn Tin	Sb Antimony	Te Tellurium	I Iodine	Xe Xenon
Cs Caesium	Ba Barium	Lanthanide series	Hf Hafnium	Ta Tantalum	W Tungsten	Re Rhenium	Os Osmium	Ir Iridium	Pt Platinum	Au Gold	Hg Mercury	Tl Thallium	Pb Lead	Bi Bismuth	Po Polonium	At Astatine	Rn Radon
Fr Francium	Ra Radium	Actinide series	Rf Rutherfordium	Db Dubnium	Sg Seaborgium	Bh Bohrium	Hs Hassium	Mt Meitnerium	Ds Darmstadtium	Rg Roentgenium	Uub Ununbium	Uut Ununtrium	Uuq Ununquadium	Uup Ununpentium	Uuh Ununhexium	Uus Ununseptium	Uuo Ununoctium

Lanthanide series	La Lanthanum	Ce Cerium	Pr Praseo-dymium	Nd Neodymium	Pm Promethium	Sm Samarium	Eu Europium	Gd Gadolinium	Tb Terbium	Dy Dysprosium	Ho Holmium	Er Erbium	Tm Thulium	Yb Ytterbium	Lu Lutetium
Actinide series	Ac Actinium	Th Thorium	Pa Protactinium	U Uranium	Np Neptunium	Pu Plutonium	Am Americium	Cm Curium	Bk Berkelium	Cf Californium	Es Einsteinium	Fm Fermium	Md Mendelevium	No Nobelium	Lr Lawrencium

Cell manufacturing steps

Mixing: The active materials are mixed with inactive materials just prior to being delivered to the coating machine. This process requires a clean room to ensure low ppm H_2O and no contamination is introduced.

Coating: The anode and cathodes are coated separately in a continuous coating process. The challenges include controlling thickness over time, control across the width of the web, getting the edges right, and controlling foil moisture levels, therefore this process is typically carried out in a clean room.

Drying: After coating, the electrodes are dried. This step is crucial to remove any remaining solvent from the electrode.

Calendaring: After drying, the electrodes are calendared. This process involves passing the electrode through a set of rollers to compress it to a desired thickness. Also, during this stage, the porosity is reduced, leading to an increase in density and adhesion.
The purpose of calendaring is to reduce the porosity of the electrode which improves the particle contact and thus enhances the energy density of the battery.

Cutting: The anode, cathode, and separator sheet are cut/stamped to the desired shape and dimensions. The cut must be clean, defects such as burs will result in local electric stress. Foreign particles can cause shorts. Tool wear in mechanical processes can lead to deformed edges.

Stacking/Winding: In pouch cells and some prismatic cells, anodes, separator sheets, and cathodes are stacked together in a repeated cycle until the required number of layers is reached. For cylindrical cells, the electrodes are wound into a jelly roll configuration. This step requires a clean room environment to ensure the substrates do not contribute contamination to the process.

Packaging: The electrodes are welded together, typically with ultrasonic welding. The electrode-separator-stack is enclosed in a housing.

Electrolyte Filling: After stacking/winding, electrolyte is injected into the cell. This step is particularly sensitive to moisture, and thus requires a specialised ‘dry room’ with extremely low humidity (less than 1%).

Formation/Aging: After electrolyte filling, cells undergo formation where they are charged and discharged for the first time. This step allows for the formation of a solid-electrolyte interface (SEI) and can take up to three weeks to complete. During this process, cells are stored at a controlled temperature which allows the SEI to stabilise.

Testing: Each cell is tested to check performance and safety parameters.

Contact APC for further information

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