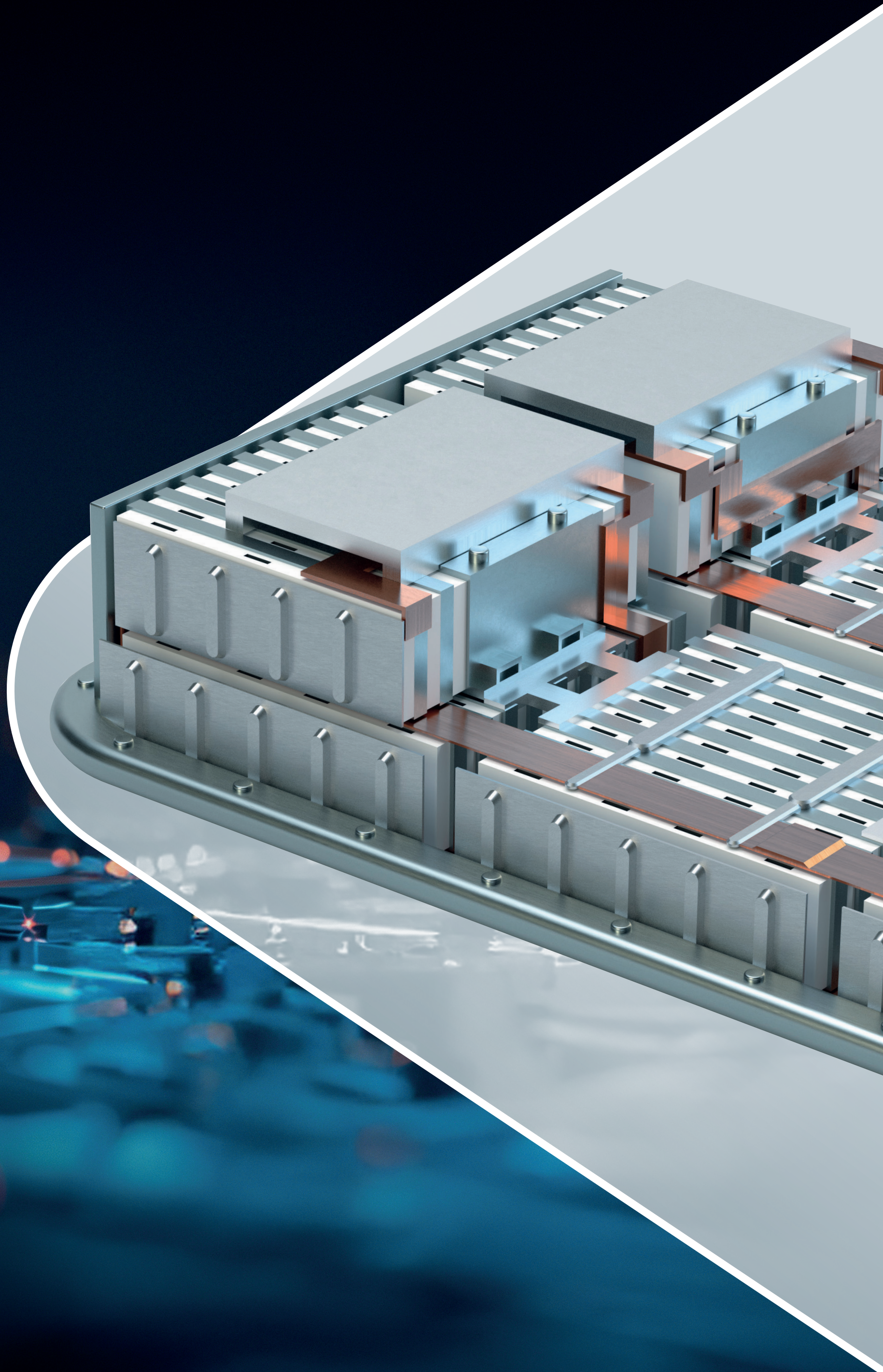
Electric Energy Storage

Technology Roadmap

2024



automotive council UK

ADVANCED PROPULSION CENTRE UK

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

Information correct at time of publication

The 2024 technology roadmaps provide a view of technology adoption in the automotive industry. These roadmaps help academia, industry and policy-makers understand where research and development (R&D) efforts are likely to be focussed, highlight key milestones in technology adoption, and through the supporting documents explore challenges and opportunities.

The documents available for each roadmap are as follows:

The executive roadmap

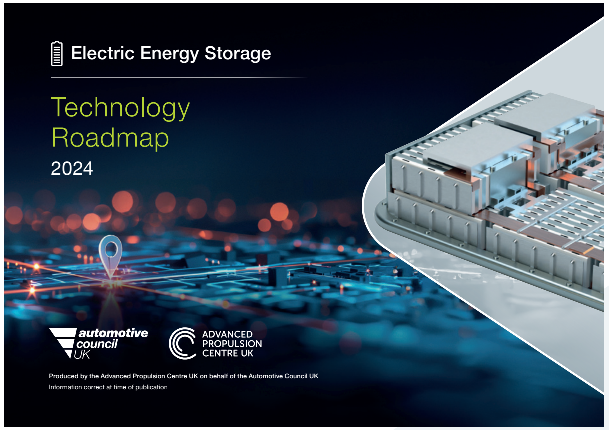
The executive roadmap provides a high-level view of forecast mass adoption of technology within the automotive industry. Mass adoption requires technology, supply-chain, manufacturing and market readiness and in some instances, regulatory readiness.

The narrative report

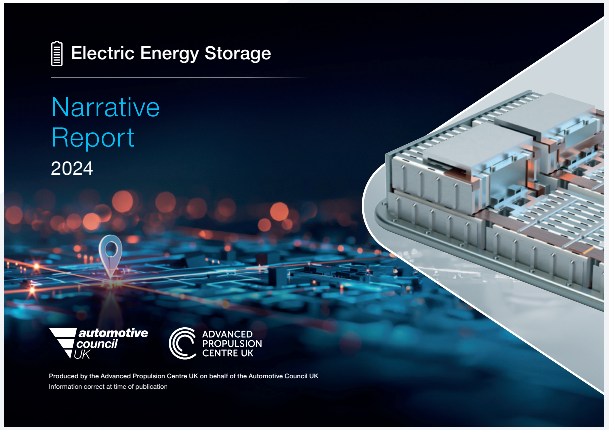
The narrative report supports the executive roadmap by providing the context behind the technologies on the roadmap. The narrative considers regulatory and market drivers alongside the work required to develop individual technologies and their supply chain.

The innovation opportunities report

The innovation opportunities report is intended to take a deeper dive in to the R&D steps required to enable technologies on the roadmap.



Technology roadmap

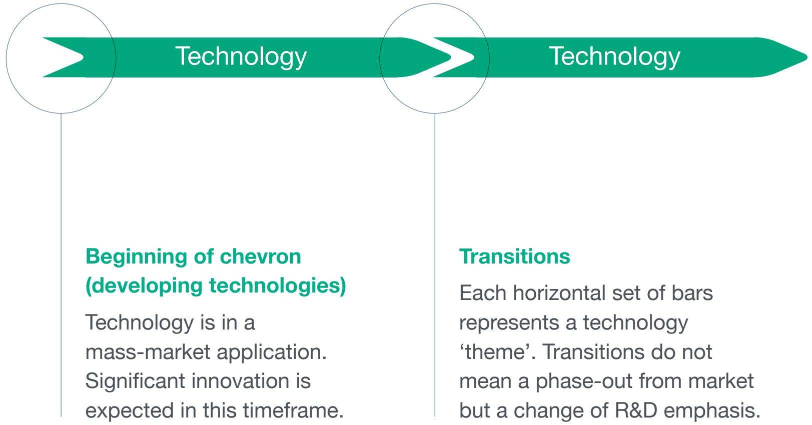


Narrative report

Introduction to the technology roadmap

This technology roadmap represents a snapshot-in-time view of the global automotive industry propulsion technology forecast for mass-market adoption.

- Chevrons with text describing a technology indicate when a technology is expected to reach mass-market adoption in the automotive industry.
- Technology adoption will vary from region to region, this is recognised and discussed in the narrative report that accompanies this executive roadmap.
- Technology adoption varies within different sectors of the automotive industry and, where appropriate, this is indicated on the roadmap and discussed in the accompanying narrative report.
- Some technologies may be feasible before appearing on the roadmap, many technologies that do not appear until later are technically feasible now. However, the roadmap considers not just technology maturity but also market, supply chain and regulatory impacts. These are discussed in the accompanying narrative report.
- Some chevrons appear to start on the 2025 line, this is considered as equivalent to a technology being available now.



Beginning of chevron (developing technologies)

Technology is in a mass-market application. Significant innovation is expected in this timeframe.

Transitions

Each horizontal set of bars represents a technology 'theme'. Transitions do not mean a phase-out from market but a change of R&D emphasis.

Technology indicators for energy-focused, cost-sensitive applications

Technology indicators that industry is likely to achieve in a mass-market competitive environment.

		NIB			LF(M)P			NMC(A)		
		2025	2030	2040	2025	2030	2040	2025	2030	2040
Cell materials roadmap balanced indicators	Cell (Wh/kg)	120-160	140-180	150-200	100-160	150-250	150-250	200-300	250-350	300-500
	Cell (Wh/l)	200-300	200-350	300-400	300-400	300-550	400-650	500-750	600-950	800-1300

		NIB			LF(M)P			NMC(A)		
		2025	2030	2040	2025	2030	2040	2025	2030	2040
Modules and pack roadmap balanced indicators	Charge acceptance continuous C-rate (C)	2.5	3.5	3.5	2.5	3.5	>4	2.5	3.5	>4
	Pack (Wh/kg)	80-150	90-160	100-180	60-140	90-200	100-220	120-200	160-300	200-420
	Pack (Wh/l)	80-200	80-250	120-300	120-260	120-360	160-450	200-500	250-600	350-850

NIB

Sodium-ion batteries use sodium-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.

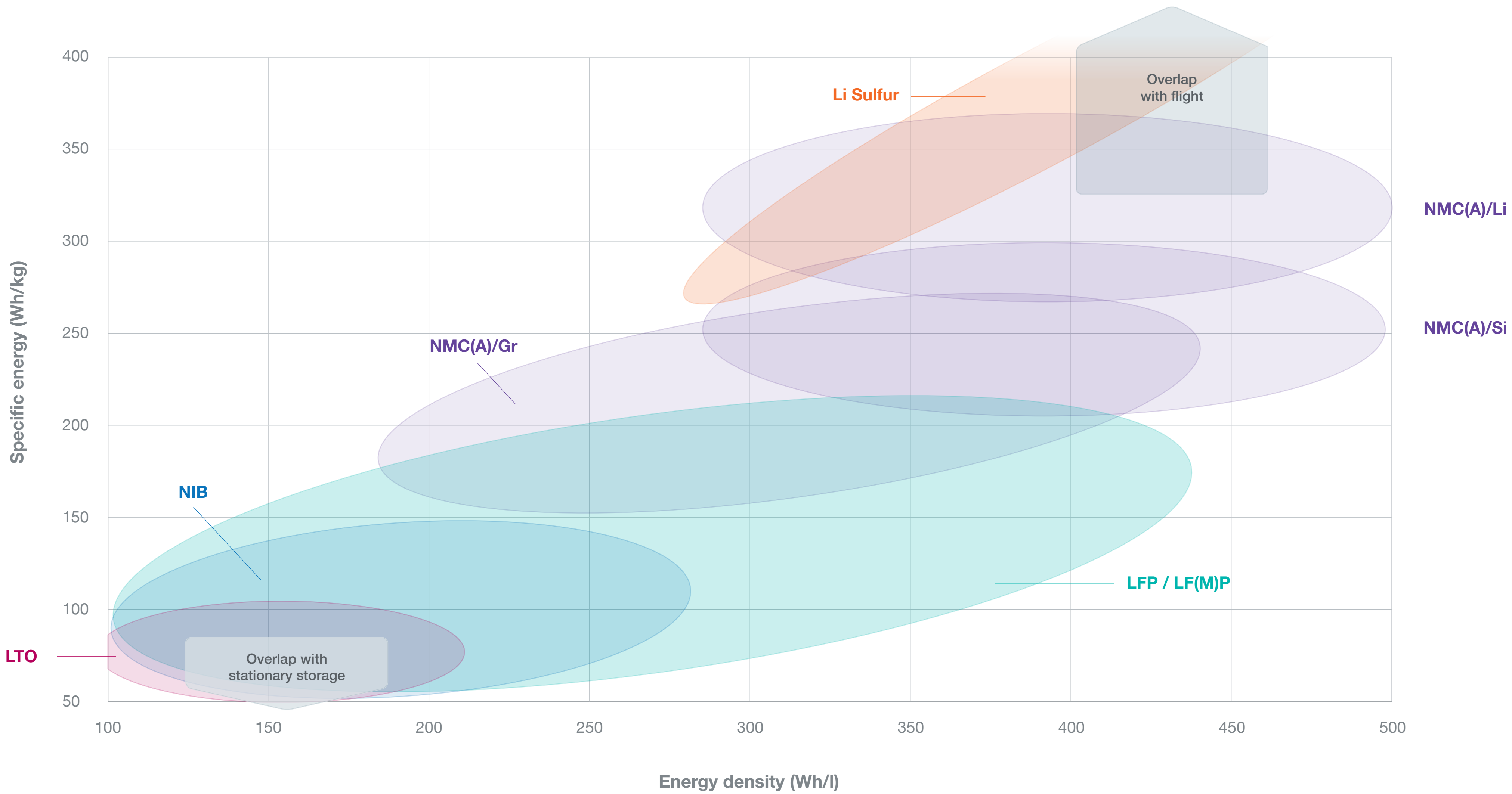
LF(M)P

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 an ‘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 LF(M)P but has drawbacks in safety, cycle life and cost. Where energy is the most critical parameter, high nickel versions of NMC are used. There are other high-nickel cathode chemistries such as NMCA. NMCA comprises lithium, nickel, manganese, cobalt and aluminium.

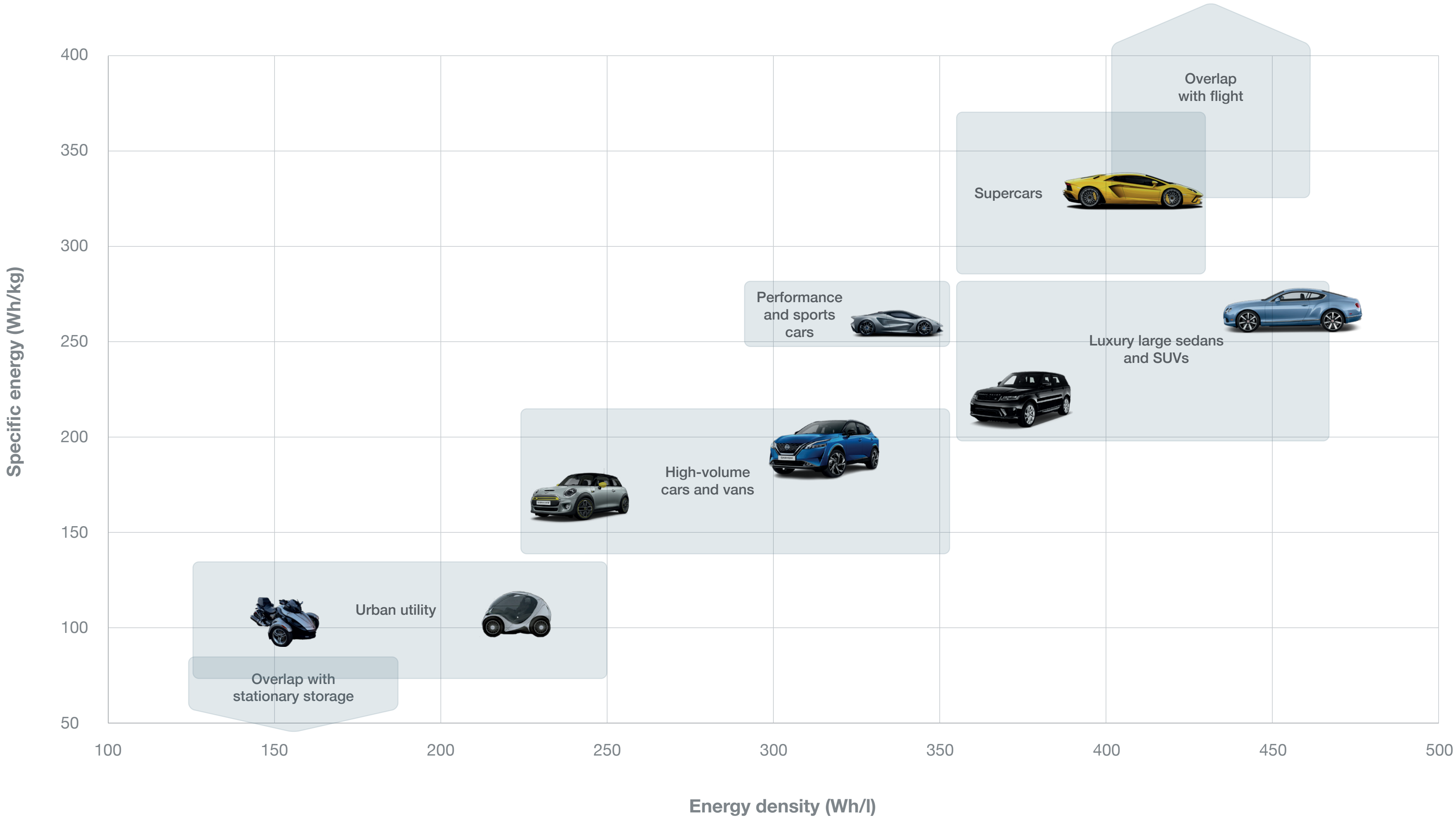
2035-2040 forecast battery pack performance



Gr Graphite dominant anode **Si** Silicon dominant anode **Li** Lithium metal anode

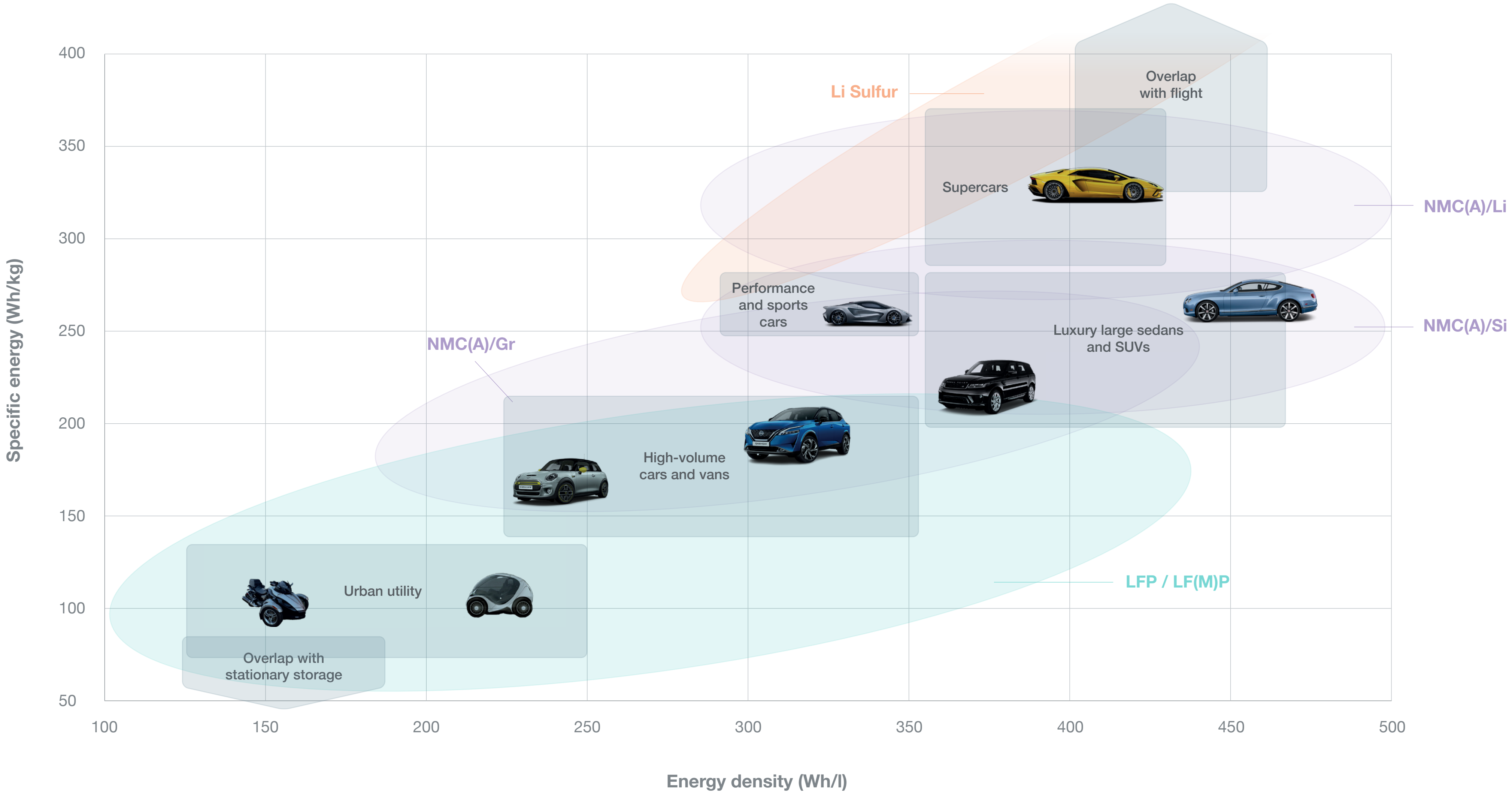
LTO and NIB may have lower energy density than other cathode chemistries but they offer high cycle life and high c-rates. This makes them highly suitable for applications that require rapid power delivery and longer lifetimes, for example off-highway / NRMM and stationary storage.

2035 Automotive industry ‘ideal’ requirements



Gr Graphite dominant anode **Si** Silicon dominant anode **Li** Lithium metal anode

2035-2040 pack level performance compared to 'idealised' requirements

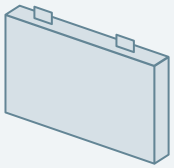


Gr Graphite dominant anode **Si** Silicon dominant anode **Li** Lithium metal anode

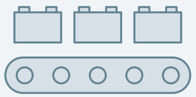
Two electrical energy storage roadmaps

Cells and manufacturing roadmap

See page 9



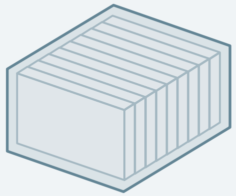
Cells



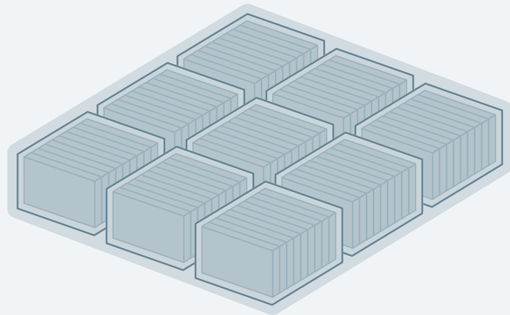
Manufacturing

Modules and packs roadmap

See page 15



Modules



Packs

Cells and manufacturing roadmap

	2025	2030	2035	2040
Electrodes - Anodes - Cathodes	Click to expand (page 10)			
Other active materials - Electrolyte materials - Separators - Current collectors	Click to expand (page 11)			
Solvents, binders and additives	Click to expand (page 12)			
Manufacturing and processing	Click to expand (page 13)			
Life cycle - Life cycle impact - Material recovery	Click to expand (page 14)			

Technology is in a mass market application. Significant innovation is expected in this timeframe.
Transitions do not mean a phase-out from market but a change of R&D emphasis.
Fluid timings: these technologies have less consensus on when they will occur on the timeline, and may be implemented earlier or later than they appear. They may be adopted in niche vehicle applications.

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.

Cells and manufacturing roadmap

Compress all

Technology is in a mass market application. Significant innovation is expected in this timeframe.
Transitions do not mean a phase-out from market but a change of R&D emphasis.
Fluid timings: these technologies have less consensus on when they will occur on the timeline, and may be implemented earlier or later than they appear. They may be adopted in niche vehicle applications.

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.

Cells and manufacturing roadmap

2025 | 2030 | 2035 | 2040

▸ **Electrodes** — Click to expand (page 10)

Other active materials

Electrolyte materials

- Higher voltage liquid electrolytes
- Liquid electrolytes for new chemistries, e.g. Li-S, metal-air
- Reduced toxicity electrolytes, e.g. non-fluoro containing
- Hybrid and semi-solid state batteries with high ionic conductivity, e.g. gel polymer and 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 and fire suppression
- Enhanced separator functionality, e.g. phase change
- Separator materials with enhanced ion conductivity, e.g. ceramic oxide coatings
- Bio-derived separator materials reducing environmental impact
- Self-healing separator materials

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
- 3D structured electrodes for increased surface area, e.g. electrochemical, plasma or laser treatment
- Hybrid current collectors, e.g. metal alloys, metal coated polymers

▸ **Solvents, binders and additives** — Click to expand (page 12)

▸ **Manufacturing and processing** — Click to expand (page 13)

▸ **Life cycle** — Click to expand (page 14)

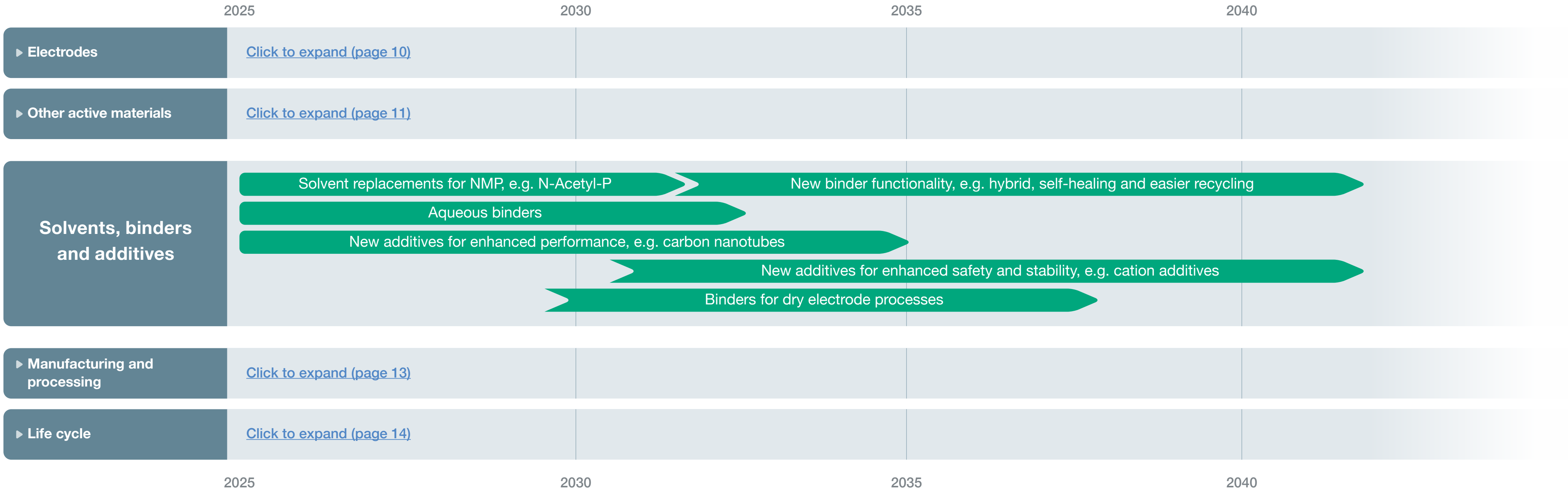
2025 | 2030 | 2035 | 2040

Compress all

Technology is in a mass market application. Significant innovation is expected in this timeframe.
Transitions do not mean a phase-out from market but a change of R&D emphasis.
Fluid timings: these technologies have less consensus on when they will occur on the timeline, and may be implemented earlier or later than they appear. They may be adopted in niche vehicle applications.

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.

Cells and manufacturing roadmap

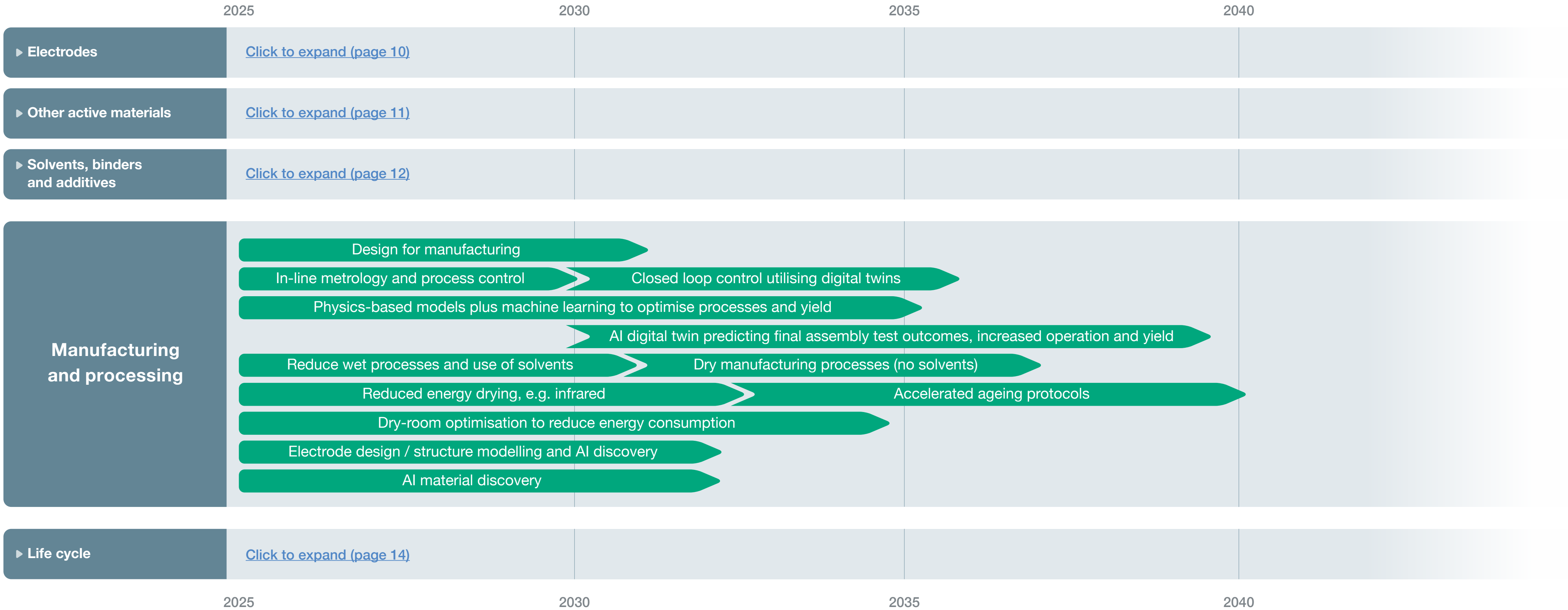


Compress all

Technology is in a mass market application. Significant innovation is expected in this timeframe.
Transitions do not mean a phase-out from market but a change of R&D emphasis.
Fluid timings: these technologies have less consensus on when they will occur on the timeline, and may be implemented earlier or later than they appear. They may be adopted in niche vehicle applications.

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.

Cells and manufacturing roadmap



Compress all

Technology is in a mass market application. Significant innovation is expected in this timeframe.
Transitions do not mean a phase-out from market but a change of R&D emphasis.
Fluid timings: these technologies have less consensus on when they will occur on the timeline, and may be implemented earlier or later than they appear. They may be adopted in niche vehicle applications.

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.

Cells and manufacturing roadmap

2025 | 2030 | 2035 | 2040

- Electrodes — Click to expand (page 10)
- Other active materials — Click to expand (page 11)
- Solvents, binders and additives — Click to expand (page 12)
- Manufacturing and processing — Click to expand (page 13)

Life cycle

Life cycle impact

- Reduce cell material wastage / increased yield
- Longer life cycle cells
- Reduced CO_2 in manufacturing processes, e.g. electrodes, dry processes and electrolyte refilling -> lower energy footprint
- Improved formation and ageing procedures -> lower energy footprint
- Net zero CO_2-eq production systems
- LCA-focussed value chain
- Circular economy established for all cell materials
- Safer, more sustainable and lower energy cell-material substitutions
- Adoption of more abundant / less critical materials

Material recovery

- Design for recycling
- Cell-material reconditioning and reuse, e.g. electrode regeneration or remanufacturing defect material
- Pilot cell-material recycling
- High-volume and high-efficiency cell-material recovery

2025 | 2030 | 2035 | 2040

Compress all

Technology is in a mass market application. Significant innovation is expected in this timeframe.
Transitions do not mean a phase-out from market but a change of R&D emphasis.
Fluid timings: these technologies have less consensus on when they will occur on the timeline, and may be implemented earlier or later than they appear. They may be adopted in niche vehicle applications.

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.

Modules and packs roadmap

	2025	2030	2035	2040
Cell format and design	Click to expand (page 16)			
Module and pack innovations - Electrical distribution system - Thermal - Mechanical - Pack integration and manufacturing	Click to expand (page 17) (and page 18)			
Life cycle - Life cycle impact - Material recovery	Click to expand (page 19)			
	2025	2030	2035	2040

Technology is in a mass market application. Significant innovation is expected in this timeframe.
Transitions do not mean a phase-out from market but a change of R&D emphasis.
Fluid timings: these technologies have less consensus on when they will occur on the timeline, and may be implemented earlier or later than they appear. They may be adopted in niche vehicle applications.

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.

Modules and packs roadmap

	2025	2030	2035	2040

Cell format and design

- Cell formats to optimise packaging, economics and safety
- New cell formats and features, e.g. tabless 46xx, U-cell, bipolar, thermal flow and improved joining
- Smart cells with built-in sensors

Module and pack innovations

Click to expand (page 17) (and page 18)

Life cycle

Click to expand (page 19)

	2025	2030	2035	2040

Compress all

Technology is in a mass market application. Significant innovation is expected in this timeframe.
Transitions do not mean a phase-out from market but a change of R&D emphasis.
Fluid timings: these technologies have less consensus on when they will occur on the timeline, and may be implemented earlier or later than they appear. They may be adopted in niche vehicle applications.

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.

Modules and packs roadmap

2025 | 2030 | 2035 | 2040

▸ Cell format and design — Click to expand (page 16)

Module and pack innovations

Electrical distribution system (including BMS hardware and software)

- Widespread adoption of 800 V architectures → Novel 1200 V architectures
- BMS upgrades using machine learning on historic data
- BMS capable of physics-based SoH and SoC cell tracking → AI enabled BMS using self-updating algorithms and in-situ data
- Telemetry-enabled BMS architectures; offline updates to vehicle → On-line monitoring with multiple small sensors – predicting SoH
- Wireless BMS → Individual cell balancing / control
- V2H / V2L → V2X
- Swappable battery support
- Wireless / catenary charging for mass-transit systems
- Reducing cost and weight bus bars → Net-shape, multi-material bus bars with enhanced conductivity
- Use of battery to supply all power, e.g. 12/48 V
- Next-generation contactors / connectors, e.g. solid-state

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

- Submerged cooling for high performance
- Active thermal management (integrated and cost-effective systems)
- Multi-material cooling plates → New thermal-rejection materials for high-power cells and new methods for passive cooling
- Phase change materials (PCMs) for cooling
- Reduced energy usage methods for cold climates
- Optimisation of existing thermal interface / joining materials → Rationalisation and integration of thermal management with other vehicle systems
- Methods for detecting, preventing and suppressing fire propagation / providing containment
- Methods for detecting and tolerating thermal events before runaway

▸ Module and packs innovations — Click to expand (page 17) (and page 18)

▸ Life cycle — Click to expand (page 19)

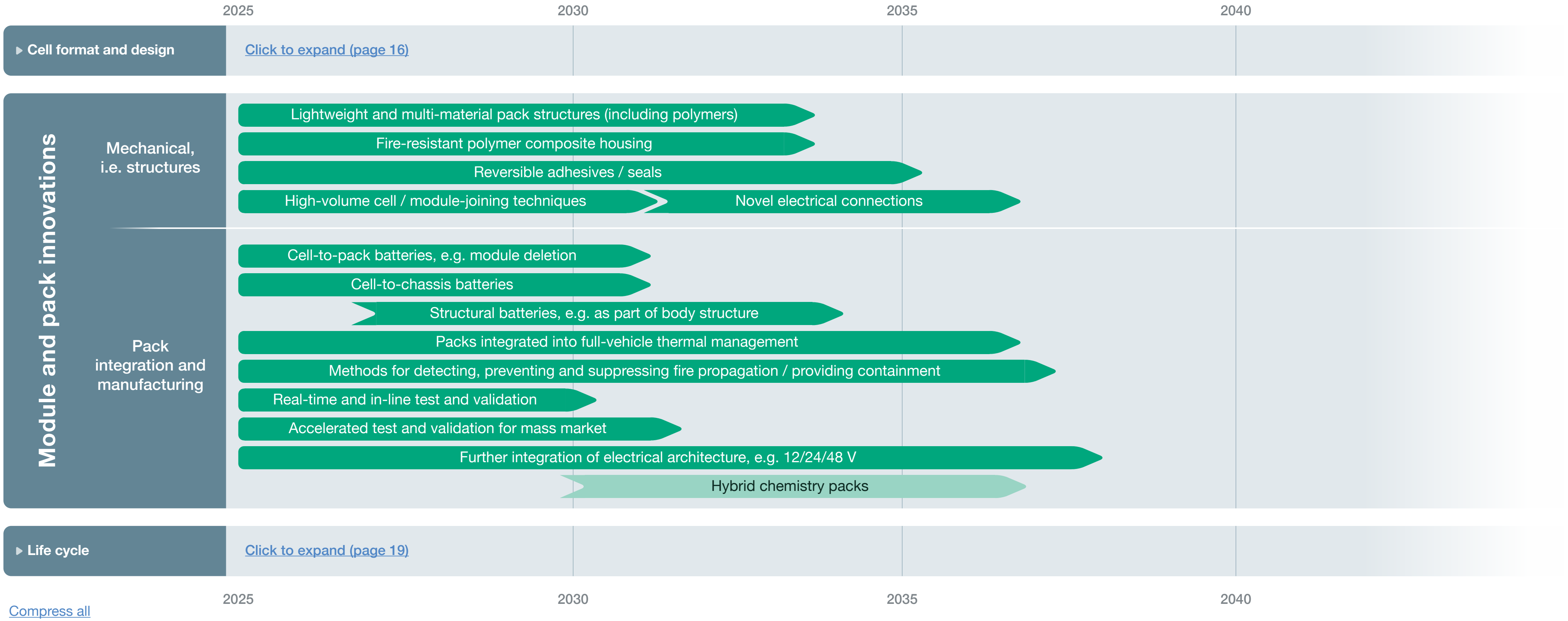
2025 | 2030 | 2035 | 2040

Compress all

- Technology is in a mass market application. Significant innovation is expected in this timeframe.
- Transitions do not mean a phase-out from market but a change of R&D emphasis.
- Fluid timings: these technologies have less consensus on when they will occur on the timeline, and may be implemented earlier or later than they appear. They may be adopted in niche vehicle applications.

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.

Modules and packs roadmap

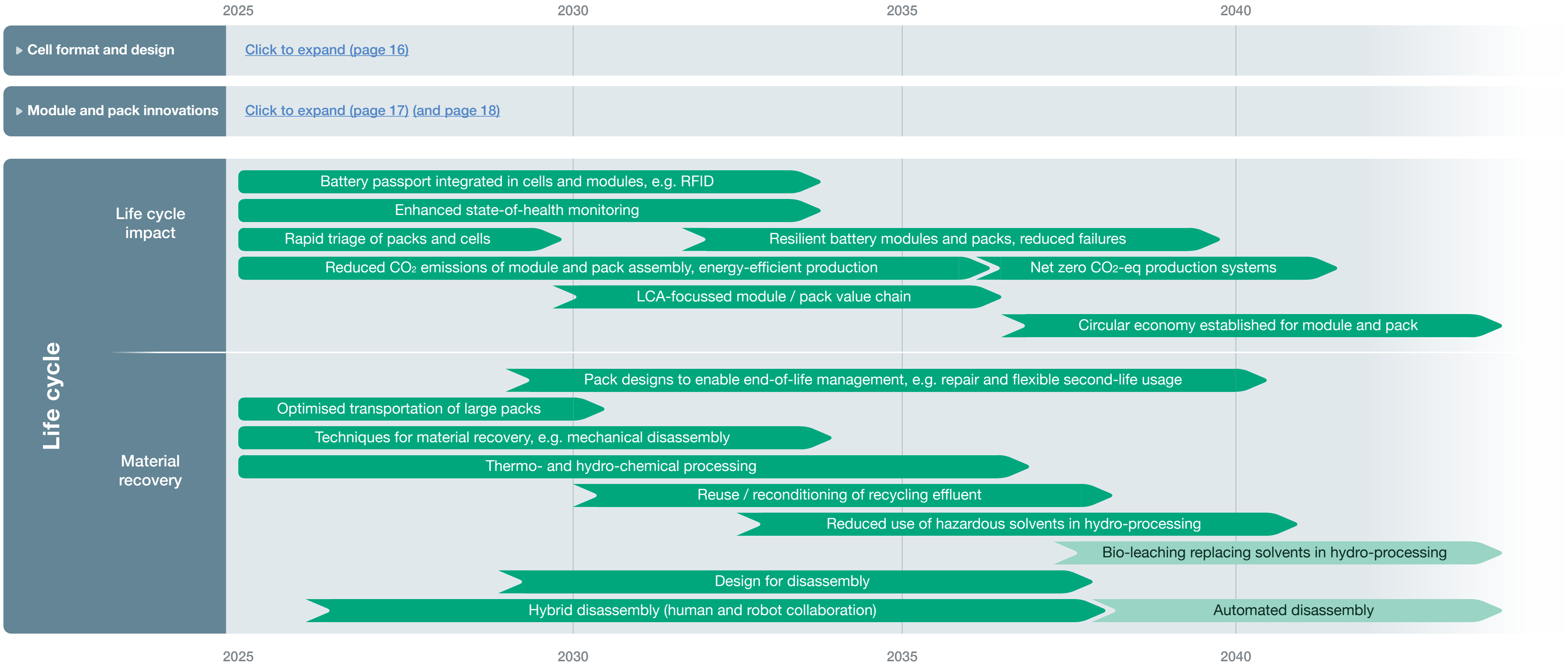


Compress all

Technology is in a mass market application. Significant innovation is expected in this timeframe.
Transitions do not mean a phase-out from market but a change of R&D emphasis.
Fluid timings: these technologies have less consensus on when they will occur on the timeline, and may be implemented earlier or later than they appear. They may be adopted in niche vehicle applications.

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.

Modules and packs roadmap



Compress all

Technology is in a mass market application. Significant innovation is expected in this timeframe.
Transitions do not mean a phase-out from market but a change of R&D emphasis.
Fluid timings: these technologies have less consensus on when they will occur on the timeline, and may be implemented earlier or later than they appear. They may be adopted in niche vehicle applications.

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.

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

System-Level Roadmaps

Mobility of People

Mobility of Goods

Technology Roadmaps

Electric Machines

Power Electronics

Electrical Energy Storage

Lightweight Vehicle and Powertrain Structures

Internal Combustion Engines

Hydrogen Fuel Cell System and Storage

Find all the roadmaps at

www.apcuk.co.uk/technology-roadmaps

automotive council UK

ADVANCED PROPULSION CENTRE UK

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

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

V01 09/24