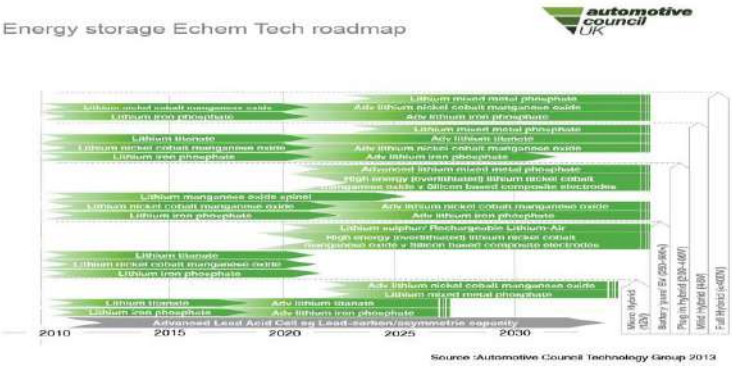
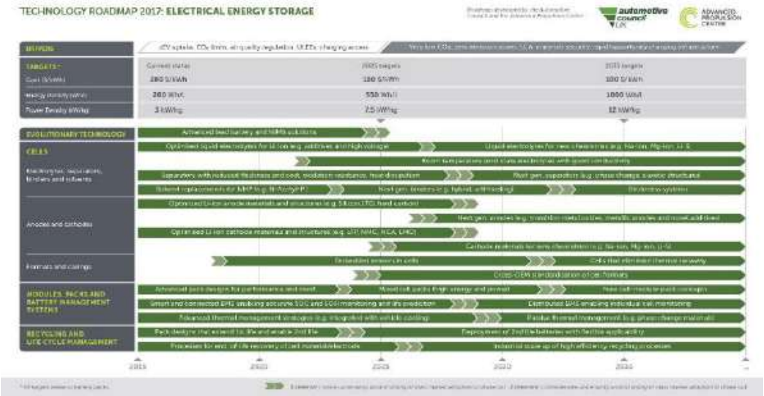
# Electrical Energy Storage Roadmap

Updated by the Advanced Propulsion Centre in collaboration with and on behalf of the Automotive Council

# Executive summary – *Electrical Energy Storage*




- **The 2013 roadmap largely focused on progressing cathode chemistries**, predicting a shift in early 2020s to more advanced (mainly lithium-based) chemistries.

- **2017 roadmap has applied a wider battery system perspective** and considers manufacturing and life cycle challenges.

- **2017 roadmap has been built using a targets-based approach,** informed by consensus amongst a wide range of industry and academic experts. Key targets are cost, energy and power density.

- **Roadmap shows that 2025 targets can be met using evolution of current technology**, but limited room for improvement beyond then.

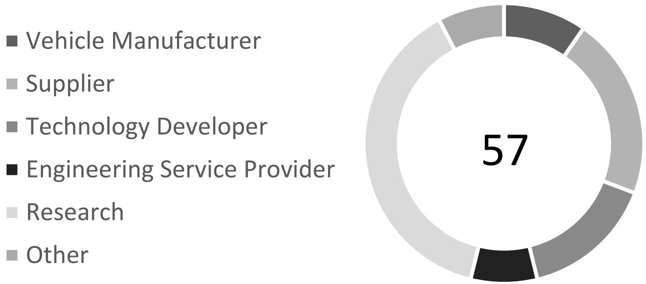
- **Innovation is needed at cell, module and pack level** in order to step from the currently dominant lithium ion technology towards much higher performance lithium and non-lithium approaches post 2025, including novel cell and pack formats.

- A key risk is the **current absence of a sustainable high volume solution for end of life batteries.**

# **Update process:** *The Electrical Energy Storage Roadmap was updated via a structured consensus-building process involving 57 experts*

- A public workshop was held at the Advanced Propulsion Centre hub on the 10th January 2017
- The process was co-ordinated by the Advanced Propulsion Centre on behalf of Automotive Council
- The Advanced Propulsion Centre Electrical Energy Storage Spoke, supported by an expert Steering Group, helped to shape the roadmap before and after the workshop

**Electrical Energy Storage Steering Group and Workshop Attendees**




**Pre-Event Email** — **1 day workshop with 52 attendees** — **Post-Event Email**

| Pre-event Common Assumptions Briefing | Collective Briefing Process | Breakout Sessions | Post-Event Debrief |
|---|---|---|---|

## **Technical targets:** *Mass market adoption of ultra low emission vehicles drives challenging cost and performance targets for future automotive battery systems*

### Drivers of change

- $CO_2$ and air quality objectives challenge the universal application of ICE powertrains
- **Electrification** features in product plans of almost every OEM across all sectors
- On board electrical energy storage features in **all xEV formats** and is vital to BEV and PHEV in particular
- Despite progress, existing electrical energy storage solutions do not fare well against fuels for **energy density or cost**, impeding application in mass markets
- Characteristics such as **lifetime and recyclability** require improvement to meet mainstream automotive demands
- In response to these challenges, **ambitious long term targets** have been set to drive innovation; these targets cannot be attained using traditional lithium ion technologies.
- **Cost, power and energy density targets should be read independently from one another**, different OEMs will prioritise different targets based on their product requirement

| Pack Targets | Energy-led[1] | Power-led[1] | 2017 | 2025 | 2035 |
|---|---|---|---|---|---|
| Cost ($/kWh)[2] | x | | 280 | 150 | 100 |
| Energy Density (Wh/l) | x | | 280 | 550 | 1000 |
| Power Density (kW/kg) | | x | 3 | 7.5 | 12 |
| Pack Life (Years) | x | x | 8 | 10 | 15 |
| Recyclability (%) | x | x | 10 -> 50 | 75 | 95 |
| **Cell Targets** | **Energy-led[1]** | **Power-led[1]** | **2017** | **2025** | **2035** |
| Cost ($/kWh)[2] | x | | 130 | 80 | 50 |
| Energy Density (Wh/l) | x | | 750 | 1000 | 1400 |
| Energy Density (Wh/kg) | x | | 250 | 350 | 500 |
| Operating Temperature range (°C)[3] | x | x | -20 -> 60 | -30 -> 70 | -40 -> 80 |

1 – Energy-led applications typified by BEV, power-led by PHEV or bus
2 – Cost targets relate to EV passenger car volume production
3 - Temperature range: bottom end is limit of charge acceptance, top end where de-rating required

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# **Technology categories:** *Parallel innovations in cells, modules, packs and 2nd life will be required to reach long term targets that existing battery technology cannot reach*

**DRIVERS**

- xEV uptake, $CO_2$ limits, air quality regulation, ULEZs, charging access
- Very low CO2, zero emission zones, LCA, materials security, rapid/opportunity charging infrastructure

| TARGETS* | Current status | 2025 targets | 2035 targets |
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**EVOLUTIONARY TECHNOLOGY**

Commercially available battery technology that may evolve to better suit hybrid applications

**CELLS**

Electrolytes, separators, binders and solvents

Chemistry and electrode structure is key to performance and cost improvements.

Anodes and cathodes

Formats and casings

Thermal management and pack design are dictated by physical form

**MODULES, PACKS AND BATTERY MANAGEMENT SYSTEMS**

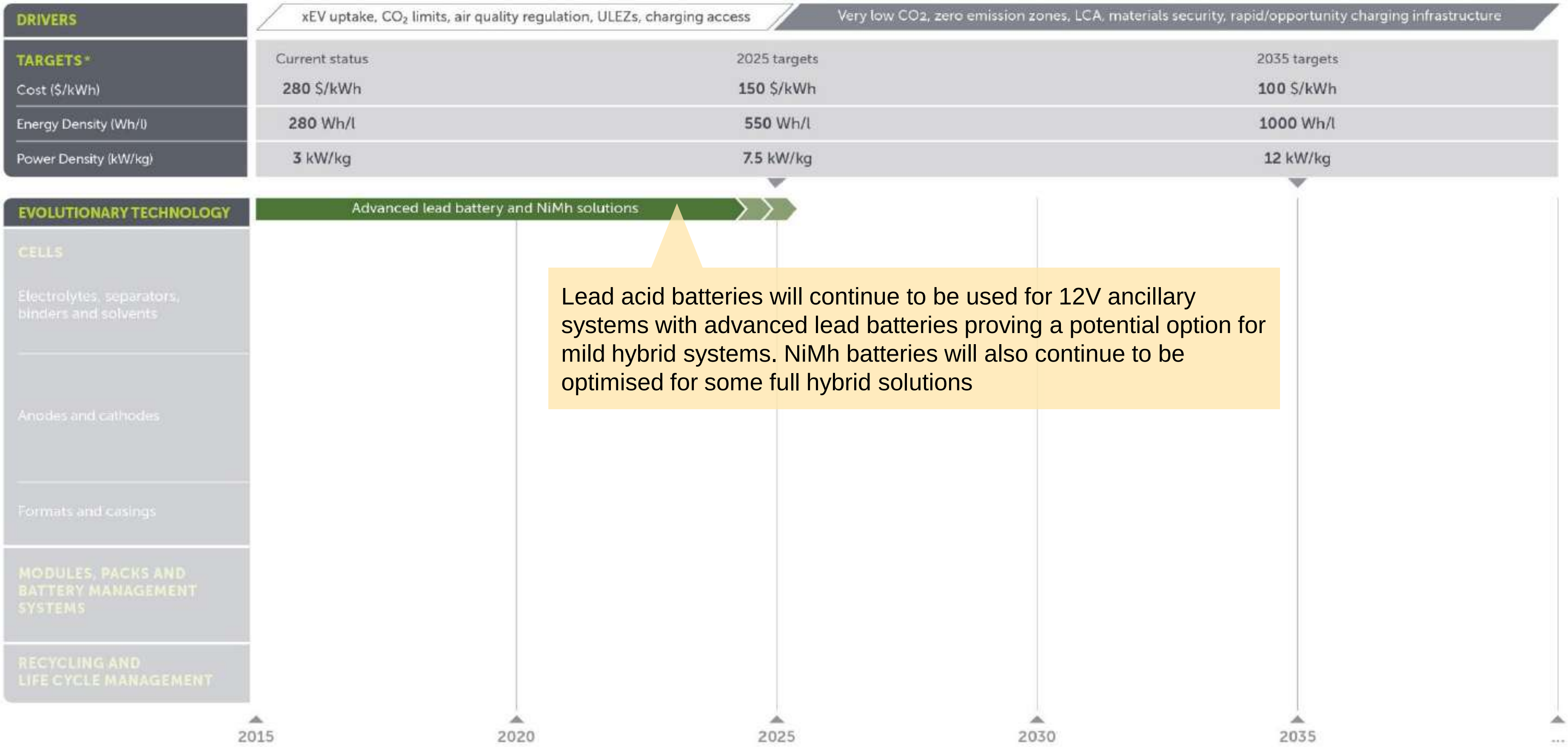
OEM choice is based on performance and cost at a pack level

**RECYCLING AND LIFE CYCLE MANAGEMENT**

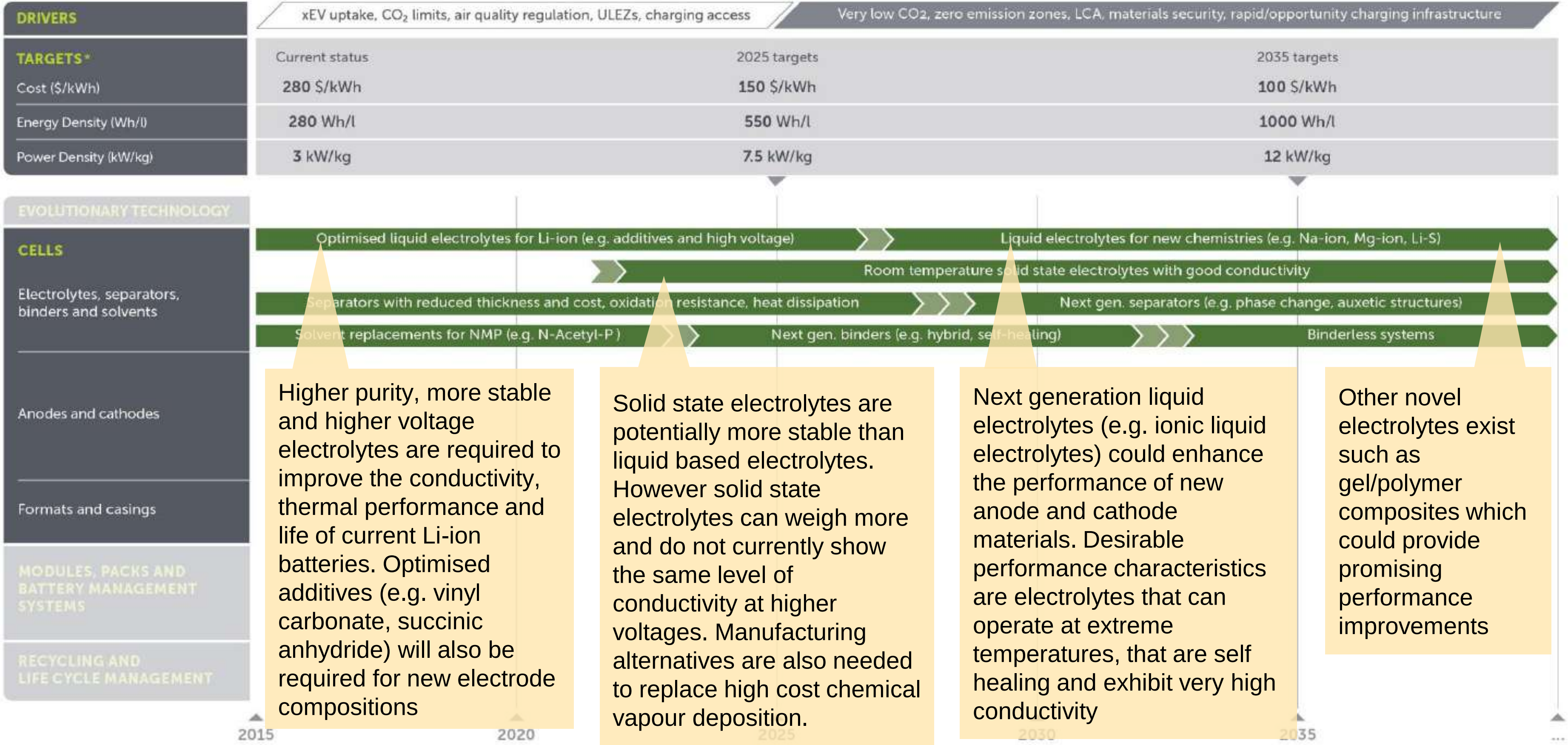
Total cost to OEM includes managing batteries after 1st life usage to avoid unintended consequences in the future.

2015 2020 2025 2030 2035 ...

## **Evolutionary technology:** *Existing battery technology such as advanced lead acid and nickel metal hydride will continue to evolve for lower cost and lower voltage applications*



# **Cells:** *Advancements in electrolytes will be needed to improve existing lithium ion chemistries with new electrolyte concepts required for next generation chemistries*



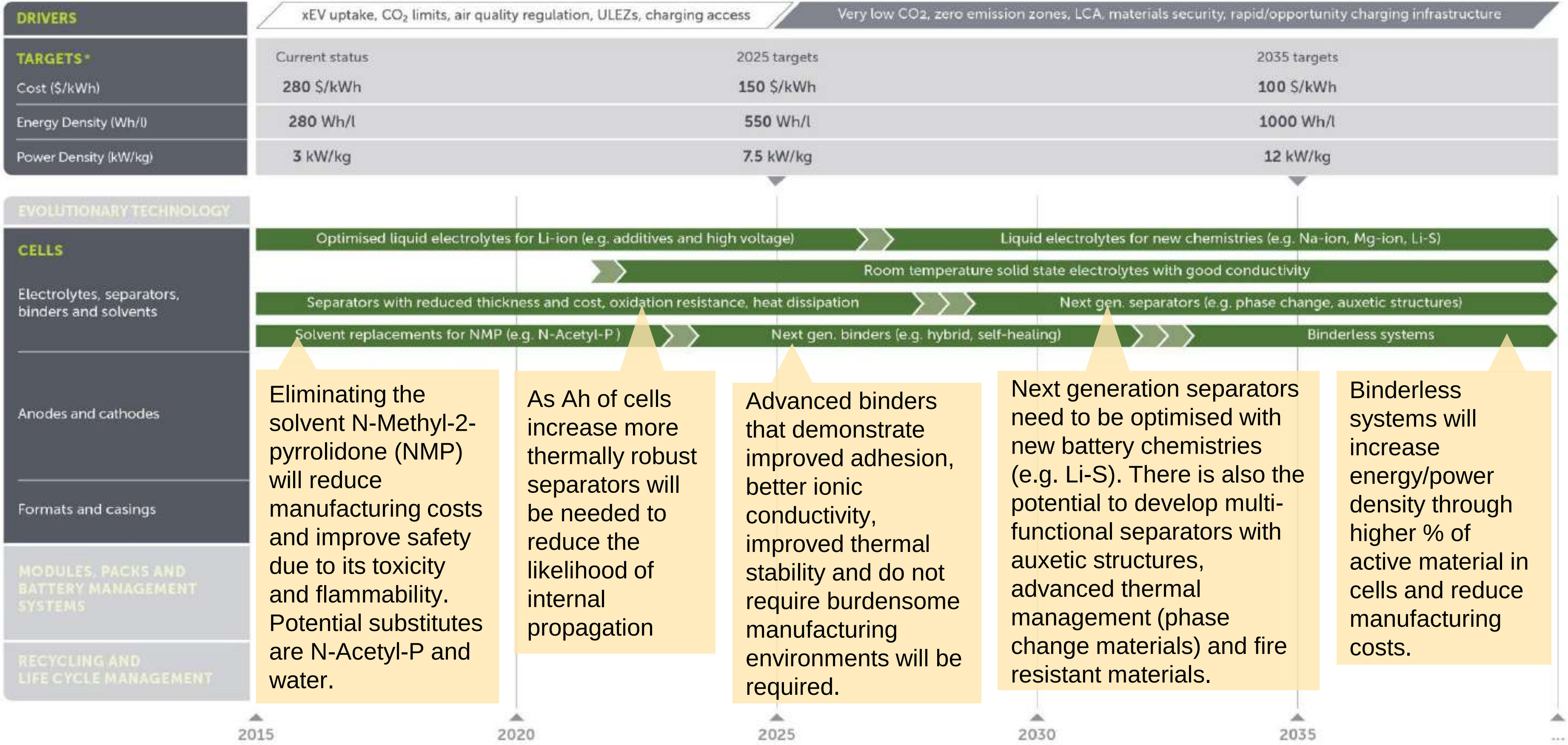

Higher purity, more stable and higher voltage electrolytes are required to improve the conductivity, thermal performance and life of current Li-ion batteries. Optimised additives (e.g. vinyl carbonate, succinic anhydride) will also be required for new electrode compositions

Solid state electrolytes are potentially more stable than liquid based electrolytes. However solid state electrolytes can weigh more and do not currently show the same level of conductivity at higher voltages. Manufacturing alternatives are also needed to replace high cost chemical vapour deposition.

Next generation liquid electrolytes (e.g. ionic liquid electrolytes) could enhance the performance of new anode and cathode materials. Desirable performance characteristics are electrolytes that can operate at extreme temperatures, that are self healing and exhibit very high conductivity

Other novel electrolytes exist such as gel/polymer composites which could provide promising performance improvements

# **Cells:** *Separators, binders & solvents need to evolve to support lithium ion, leading to bigger steps into new chemistries*




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.

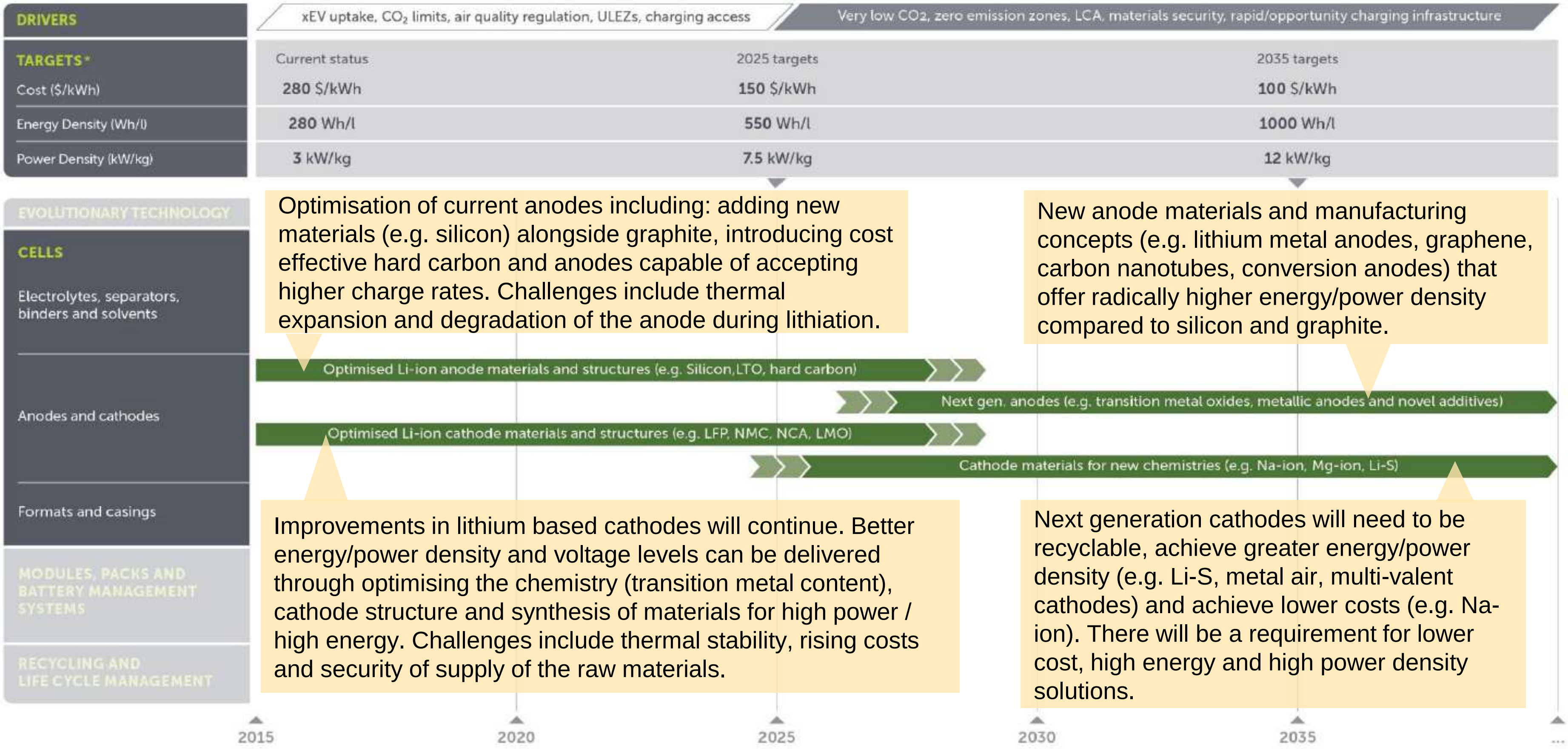
As Ah of cells increase more thermally robust separators will be needed to reduce the likelihood of internal propagation

Advanced binders that demonstrate improved adhesion, better ionic conductivity, improved thermal stability and do not require burdensome manufacturing environments will be required.

Next generation separators need to be optimised with new battery chemistries (e.g. Li-S). There is also the potential to develop multi-functional separators with auxetic structures, advanced thermal management (phase change materials) and fire resistant materials.

Binderless systems will increase energy/power density through higher % of active material in cells and reduce manufacturing costs.

# **Cells:** *Anode & cathode materials and structure improvements are fundamental to the development of lithium ion and new chemistries*



## **Cells:** *Cell formats and casings impact performance and thermal stability and need to evolve to support existing and new chemistries*

| | | | |
|---|---|---|---|
| DRIVERS | xEV uptake, $CO_2$ limits, air quality regulation, ULEZs, charging access | Very low CO2, zero emission zones, LCA, materials security, rapid/opportunity charging infrastructure | |
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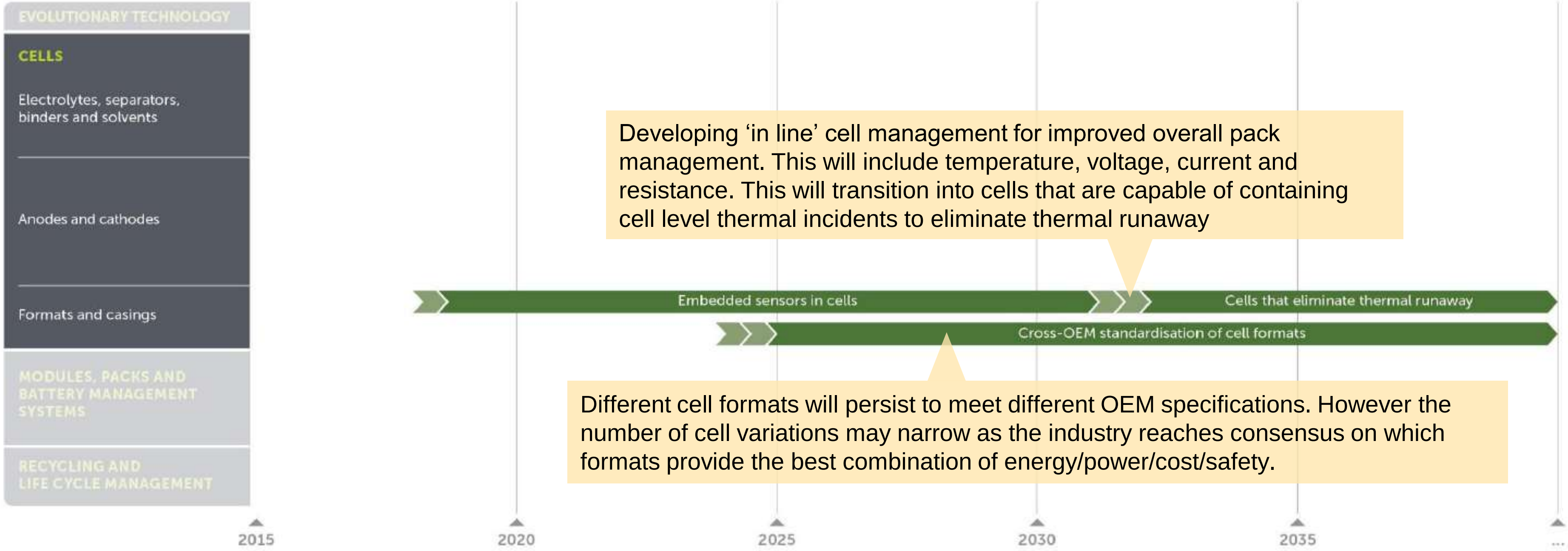


Developing ‘in line’ cell management for improved overall pack management. This will include temperature, voltage, current and resistance. This will transition into cells that are capable of containing cell level thermal incidents to eliminate thermal runaway

Different cell formats will persist to meet different OEM specifications. However the number of cell variations may narrow as the industry reaches consensus on which formats provide the best combination of energy/power/cost/safety.

## **Packs, modules and battery management systems:** *Packs can integrate all of the developments in cells, modules and battery management systems to deliver higher power/energy, safety and efficiency*

**DRIVERS**

xEV uptake, $CO_2$ limits, air quality regulation, ULEZs, charging access

Very low $CO_2$, zero emission zones, LCA, materials security, rapid/opportunity charging infrastructure

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EVOLUTIONARY TECHNOLOGY

CELLS

Electrolytes, separators, binders and solvents

Anodes and cathodes

Formats and casings

As volumes increase, there will be the need for cost-effective solutions for existing platforms and new platforms that will be developed to cater for the inclusion of battery packs. Improving pack densities will also be critical in the short term.

Packs will need to be developed with higher power charging, for hybrid battery/lithium ion supercaps and the potential for mixed cell types. This requires more complex BMS systems to manage power/energy requirement and cooling.

New cell-module-pack concepts could emerge in order to reduce weight and volume in a safe system with more robust interconnects. Pack densities of >65% will be desirable to reduce mass overheads and increase energy/power density.

Novel cooling methods could potentially be employed such as using phase change materials to store the heat

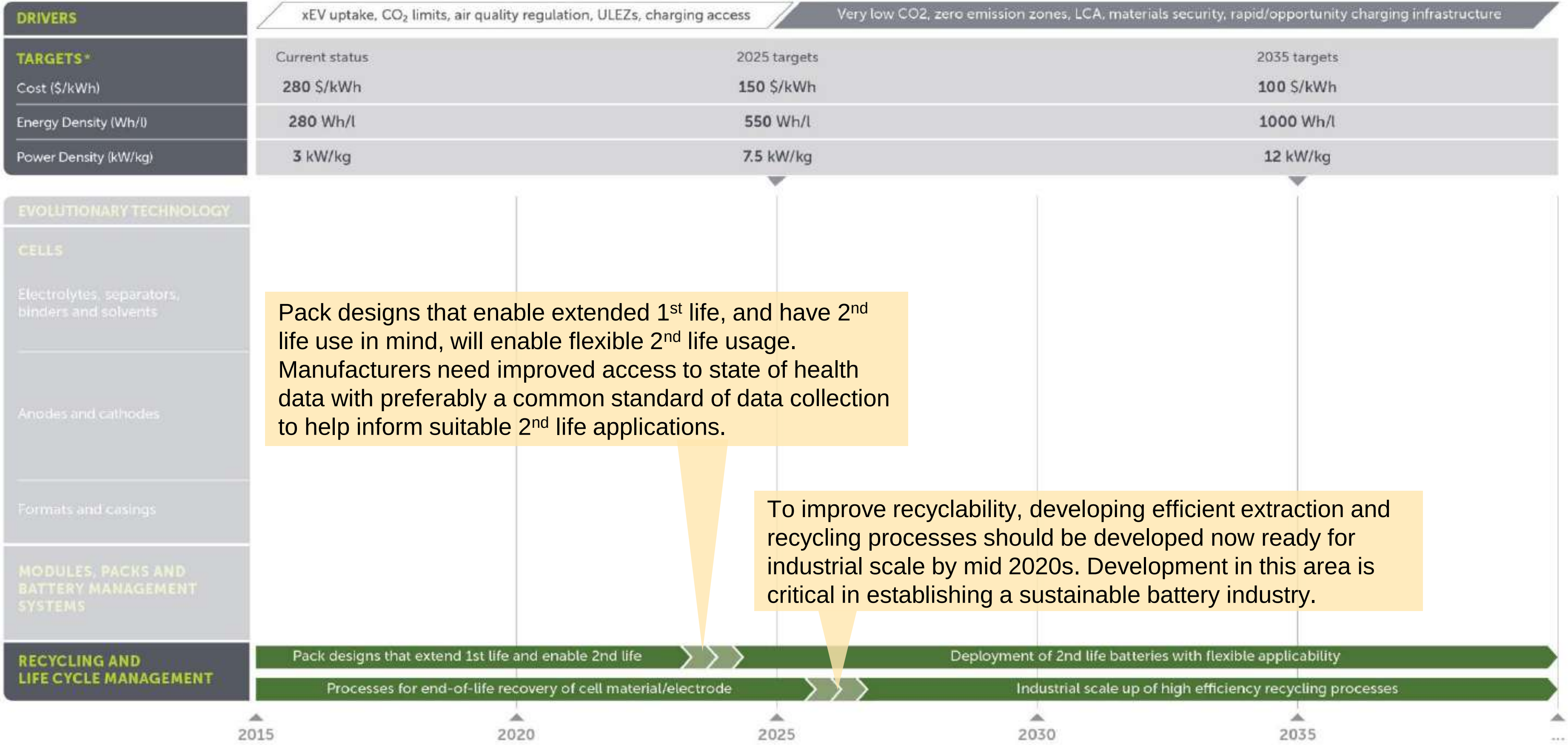
**MODULES, PACKS AND BATTERY MANAGEMENT SYSTEMS**

- Advanced pack designs for performance and manf. → Mixed cell packs (high energy and power) → New cell-module-pack concepts
- Smart and connected BMS enabling accurate SOC and SOH monitoring and life prediction → Distributed BMS enabling individual cell monitoring
- Advanced thermal management strategies (e.g. integrated with vehicle cooling) → Passive thermal management (e.g. phase change materials)

Thermal management of a battery is critical to maintain performance, stop degradation and prevent thermal runaway. Challenges relate not only to temperature management of packs but the temperature differentiation between cells.

Improvements in existing BMS will provide better state of charge & health info to better manage battery life and performance. BMS's will evolve from sensing to prediction of performance enabled by to distributed BMS's to carry out cell level monitoring to maximise use of active material

# **Recycling and life cycle management:** *Battery packs need to be designed with 2nd life and end-of-life in view with recycling processes requiring industrial scale up*




Pack designs that enable extended 1st life, and have 2nd life use in mind, will enable flexible 2nd life usage. Manufacturers need improved access to state of health data with preferably a common standard of data collection to help inform suitable 2nd life applications.

To improve recyclability, developing efficient extraction and recycling processes should be developed now ready for industrial scale by mid 2020s. Development in this area is critical in establishing a sustainable battery industry.

# TECHNOLOGY ROADMAP 2017: **ELECTRICAL ENERGY STORAGE**

*Roadmap developed by the Automotive Council and the Advanced Propulsion Centre*

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## DRIVERS

- xEV uptake, $CO_2$ limits, air quality regulation, ULEZs, charging access
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## TARGETS *

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## EVOLUTIONARY TECHNOLOGY

- Advanced lead battery and NiMh solutions

## CELLS

### Electrolytes, separators, binders and solvents

- Optimised liquid electrolytes for Li-ion (e.g. additives and high voltage) → Liquid electrolytes for new chemistries (e.g. Na-ion, Mg-ion, Li-S)
- Room temperature solid state electrolytes with good conductivity
- Separators with reduced thickness and cost, oxidation resistance, heat dissipation → Next gen. separators (e.g. phase change, auxetic structures)
- Solvent replacements for NMP (e.g. N-Acetyl-P ) → Next gen. binders (e.g. hybrid, self-healing) → Binderless systems

### Anodes and cathodes

- Optimised Li-ion anode materials and structures (e.g. Silicon,LTO, hard carbon)
- Next gen. anodes (e.g. transition metal oxides, metallic anodes and novel additives)
- Optimised Li-ion cathode materials and structures (e.g. LFP, NMC, NCA, LMO)
- Cathode materials for new chemistries (e.g. Na-ion, Mg-ion, Li-S)

### Formats and casings

- Embedded sensors in cells → Cells that eliminate thermal runaway
- Cross-OEM standardisation of cell formats

## MODULES, PACKS AND BATTERY MANAGEMENT SYSTEMS

- Advanced pack designs for performance and manf. → Mixed cell packs (high energy and power) → New cell-module-pack concepts
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- Advanced thermal management strategies (e.g. integrated with vehicle cooling) → Passive thermal management (e.g. phase change materials)

## RECYCLING AND LIFE CYCLE MANAGEMENT

- Pack designs that extend 1st life and enable 2nd life → Deployment of 2nd life batteries with flexible applicability
- Processes for end-of-life recovery of cell material/electrode → Industrial scale up of high efficiency recycling processes

2015 | 2020 | 2025 | 2030 | 2035 | ...

** All targets relate to battery packs.*

***1 chevron** = some uncertainty around timing of mass market adoption or phase out **2 chevrons** = considerable uncertainty around timing of mass market adoption or phase out*

## **Glossary:** *Explanation of acronyms and terms not described in the roadmap due to space constraints*

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- **BMS (Battery management system) –** *A BMS 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.*
- **LCA (Life cycle analysis)** – *Identifying the total environmental impact of a given product.*
- **LTO, LFP, NMC, NCA, LMO –** *These are all examples of common lithium ion chemistries used in automotive applications. LTO is an example of a high power chemistry whereas the remaining four are typically used in applications requiring higher energy density.*
- **NiMh (Nickel metal hydride) –** *Nickel metal hydride is a battery technology used in early hybrid vehicles such as the Toyota Prius and Honda Insight*
- **NMP (N-Methyl Pyrrolidone) –** *NMP 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.*
- **SOC (State of charge) –** *State of charge (SOC) 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).*
- **SOH (State of health) –** *State of health (SOH) is an indication of how healthy a battery pack, module or cell is compared to its ideal conditions. SOH does not correspond to a particular physical quality as there is no consensus in the automotive industry on how SOH should be determined. However designers of a battery management system may use any of the following parameters highlighted in the BMS bullet point.*
- **V2X (Vehicle-to-X)** – *Vehicle-to-X refers to an intelligent transport system where all vehicles and infrastructure systems are interconnected with each other.*

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