TEAM DEFENCE INFORMATION

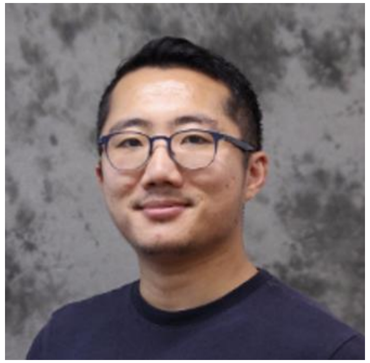
Critical Raw Materials for Defence Online Snack

Fewer Mines more Megawatts: Strengthening the UK Battery Supply Chain

UNIVERSITY OF LEICESTER | Centre for Sustainable Materials Processing

BIRMINGHAM CENTRE FOR STRATEGIC ELEMENTS AND CRITICAL MATERIALS

🎤 **Dr Jake Yang**



- UK's battery recycling landscape
- Long-loop vs short-loop recycling

🎤 **Prof Andy Abbott**

- Timeline for establishing a circular economy for lithium-ion batteries

🎤 **Dr Gavin Harper**

- Technology Road mapping Future Lithium-Ion Battery Recycling

Driving sustainable Defence supply chains through collaboration.

Format:
- Three 10-minute expert presentations
- 30-minute interactive panel Q&A
- Audience questions encouraged

THE FARADAY INSTITUTION ReLiB
REUSE & RECYCLING OF LITHIUM ION BATTERIES

Reuse & Recycling of Lithium-Ion Batteries

The ReLiB Project

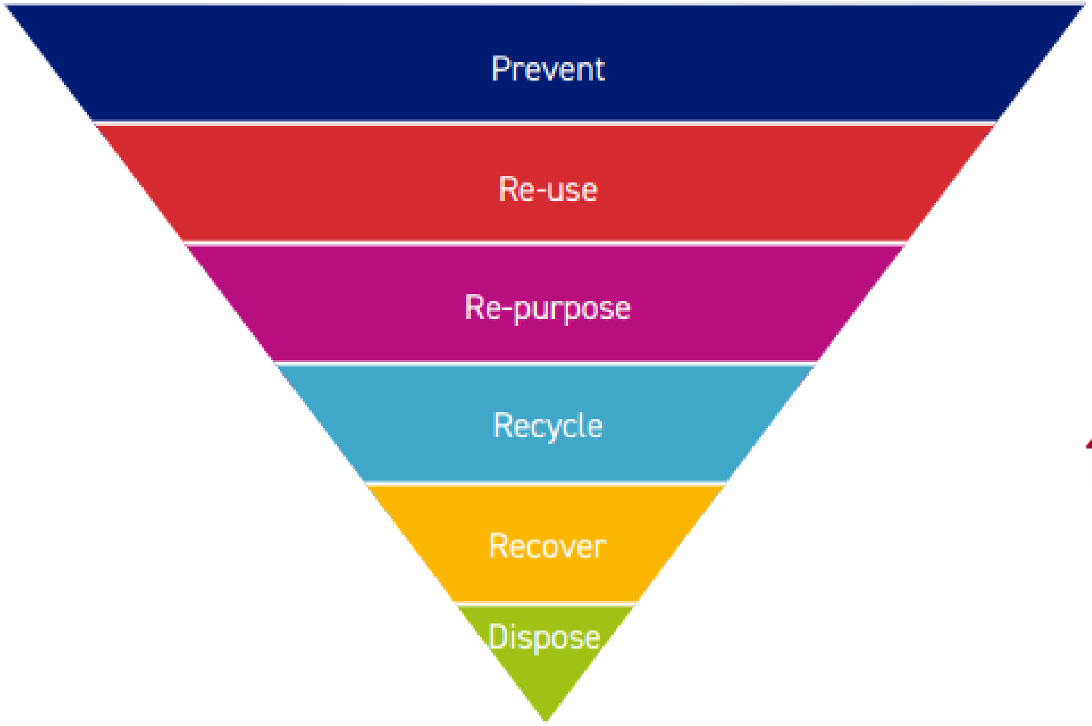
What is ReLiB?

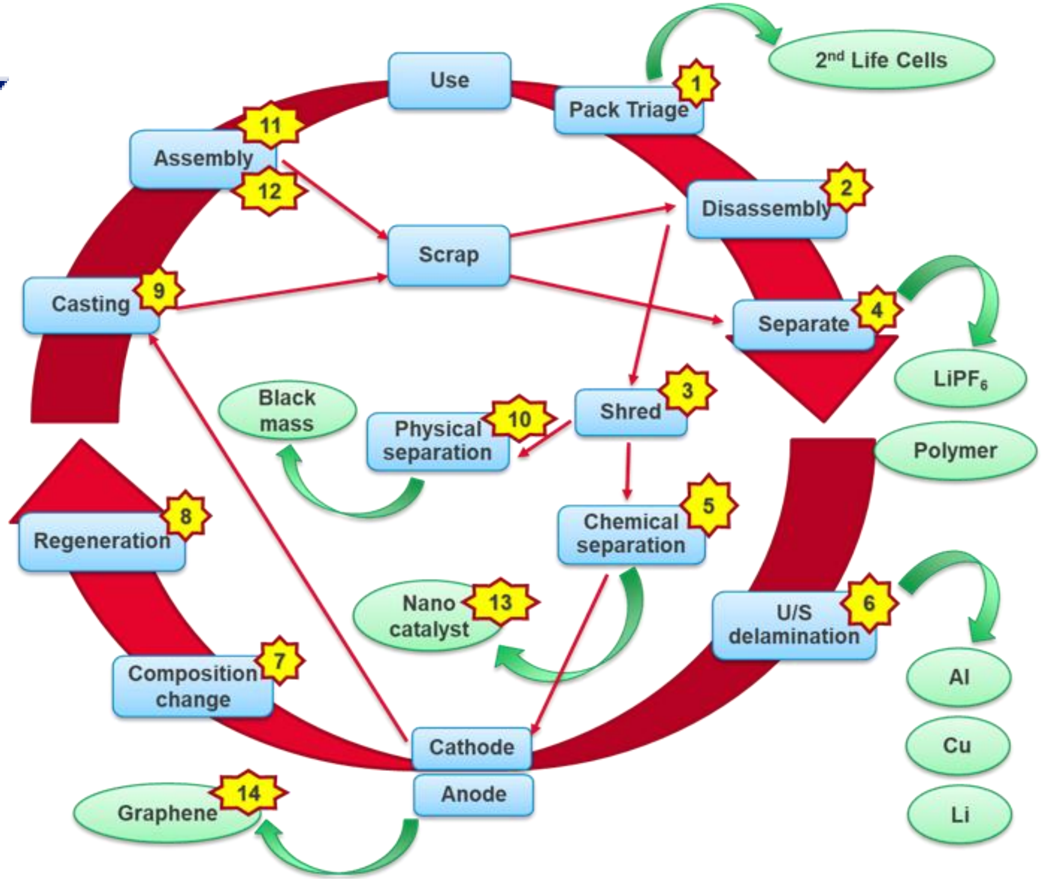
ReLiB is a £18m basic research project led by University of Birmingham, that aims to provide technological solutions, and thought leadership, to the challenges of re-using and comprehensively recycling lithium-ion batteries of different chemistry systems. Our UK academic collaborators are The University of Edinburgh, Newcastle University, University of Leicester, University of Oxford, Imperial College London & University College London.

ReLiB research areas

Here are some of the aspects that ReLiB has been working on

Waste management hierarchy (Faraday Insight 9, Sept. 2020)



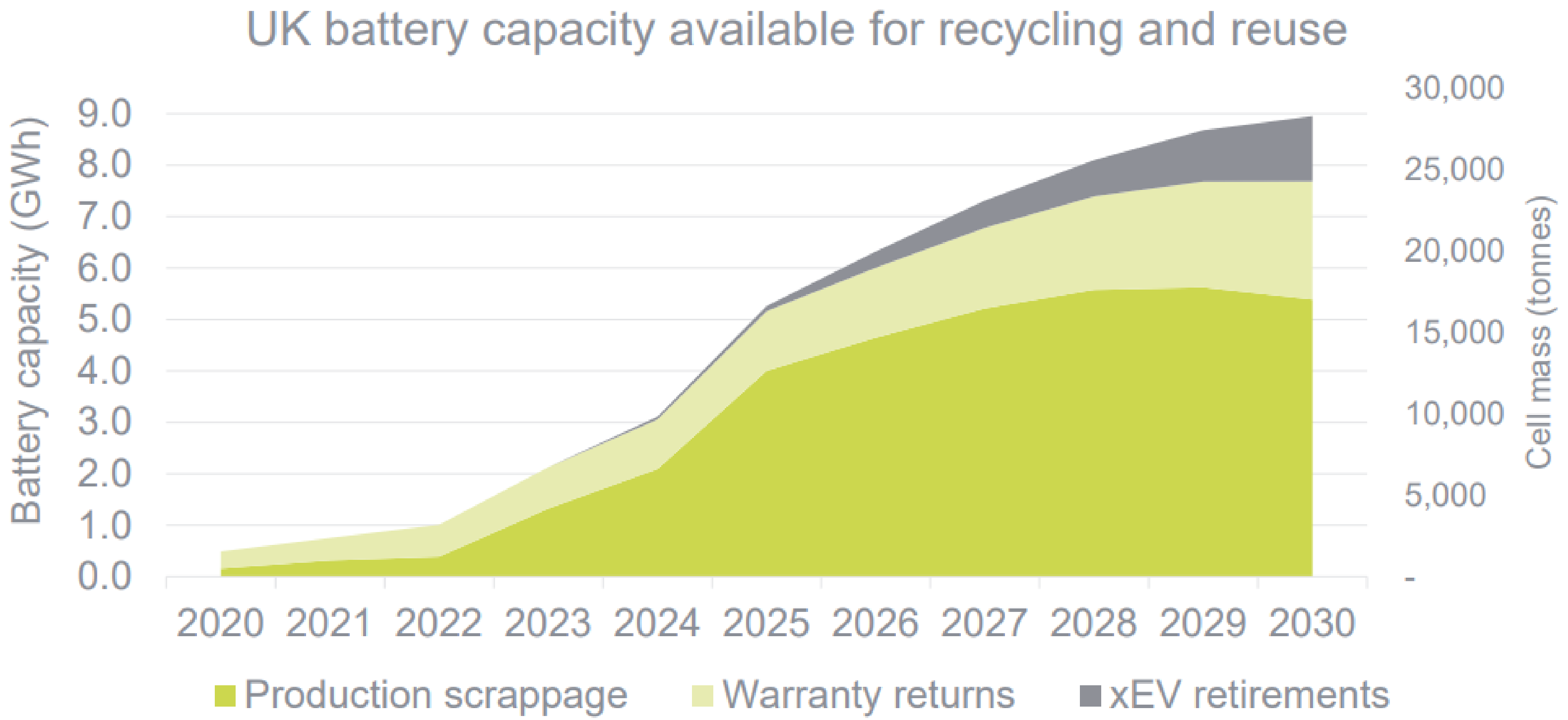


Collaborators:

University of Birmingham, University of Leicester, University of Oxford, University of Newcastle, University of Edinburgh, Imperial College, UCL

Nature, 2019, 575, 75–86 (ca. 3000 citations)

The UK recycling landscape is growing but...

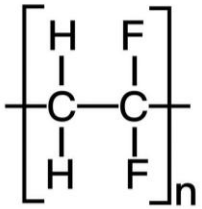


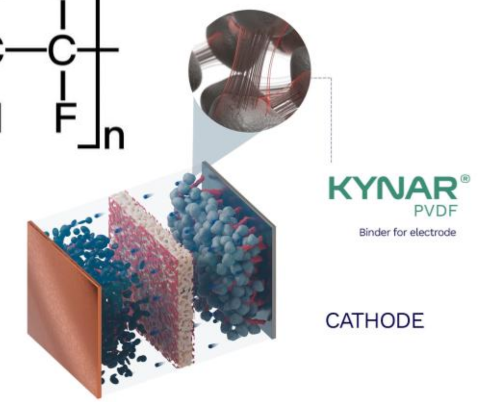
- No large-scale capacity for battery recycling in the UK
- 30,000 tonnes of batteries to be processed
- *Ca*. 3 tonnes per hour (assume 5 recyclers)
- Permit and hazard
- Large barrier for SME and entrepreneurs for entry

Barriers to recycling of LIB at industrial scale

- Batteries are difficult to open
- **Irreversible glues are used** to hold cells together
- Modules can take 2h to manually disassemble*
- PVDF binders ("forever chemical") are a nightmare to remove

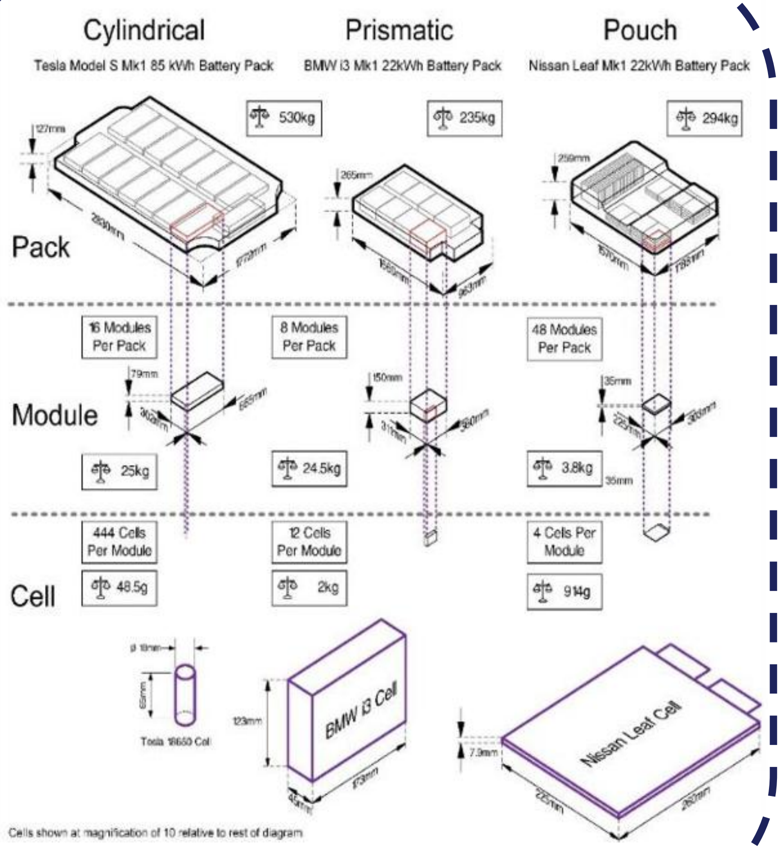
PVDF





Tesla Model S composed of 4416 cells held together with strong adhesive

https://www.youtube.com/watch?v=4JiDZVO9NdM



Main LiB recycling challenges

**Applied Energy*, 2023, 331, 120437
Green Chem., 2020, **22**, 7585-7603

What is short-loop LiB recycling?

Long-loop recycling (industrial standard)

pyrometallurgy & hydro-metallurgy

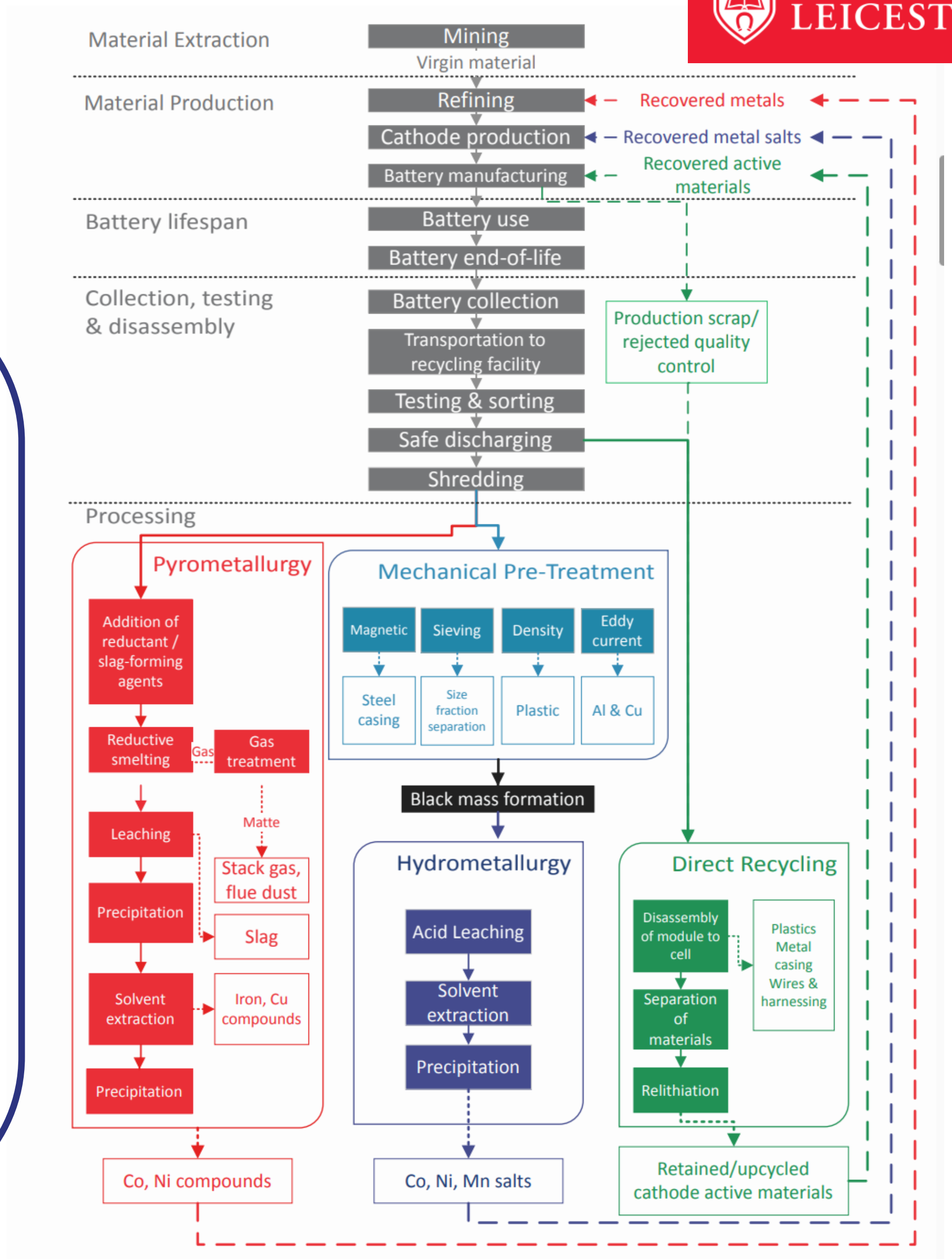
- Higher operation costs (£££)
- Higher carbon emissions
- Recovers low-cost battery precursor materials
- Low sensitivity to mixed battery streams

Short-loop/direct recycling (PoC)

- Lower operation costs (£)
- Lower carbon emissions
- Recovers high-cost battery-ready materials
- Highly sensitive to battery chemistry

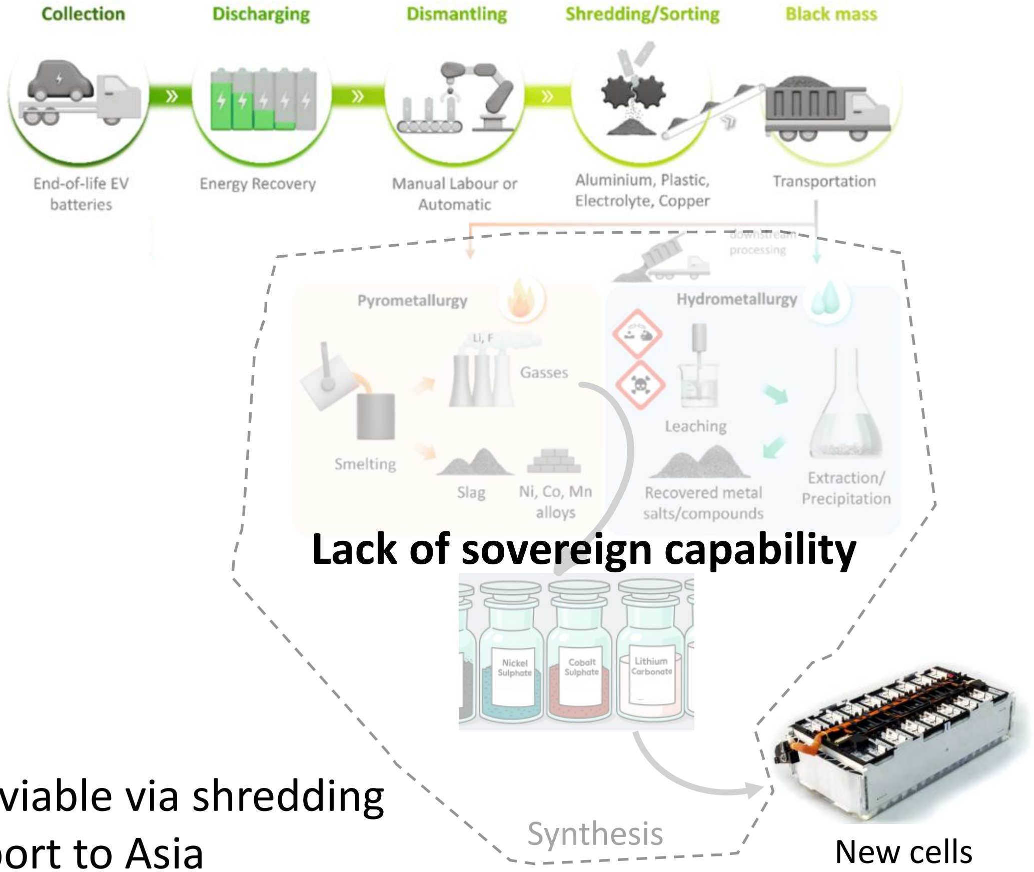
Technical flowsheet

UNIVERSITY OF LEICESTER



Source: Jonathan Leong, Business Intelligence Manager, Faraday Institution, **Faraday Insights - Issue 20**

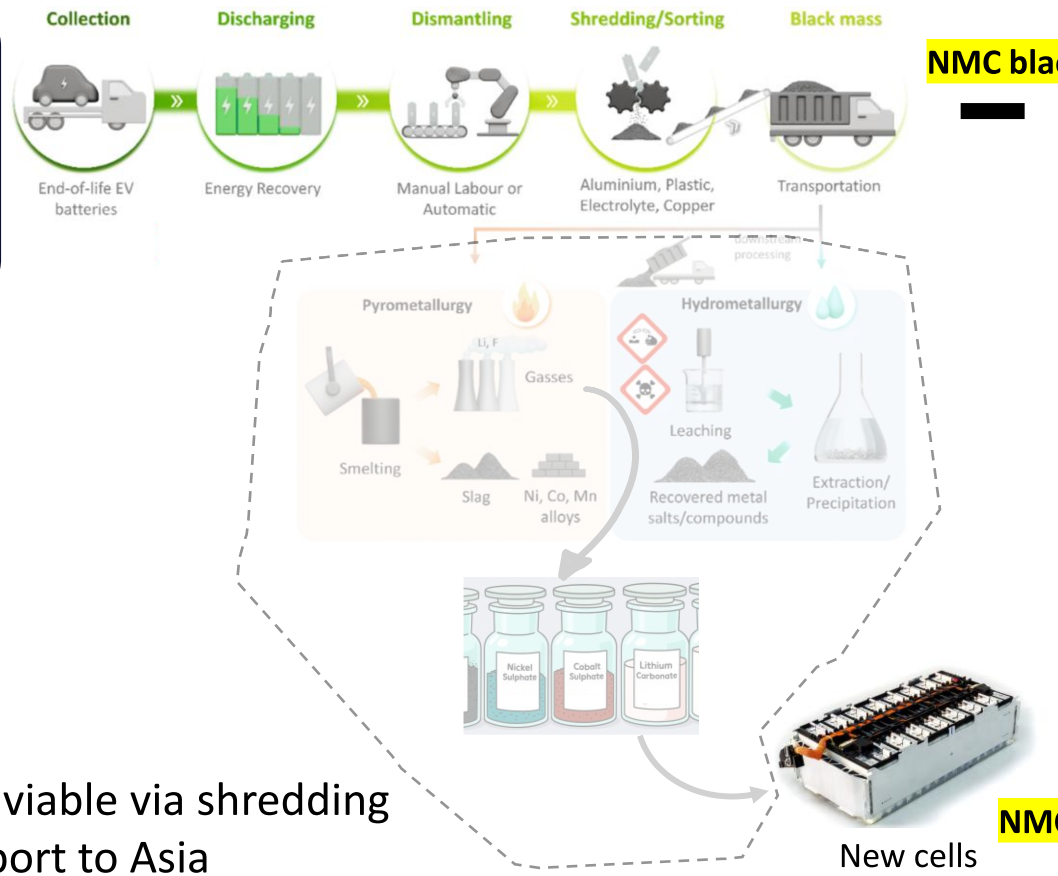
UK LIB recycling landscape (simplified)



New cells

- Recycling only viable via shredding
- Black mass export to Asia

UK LIB recycling landscape (simplified)



NMC black mass £5-10 / kg

Direct recycling(?)

NMC CAM £40-120 / kg

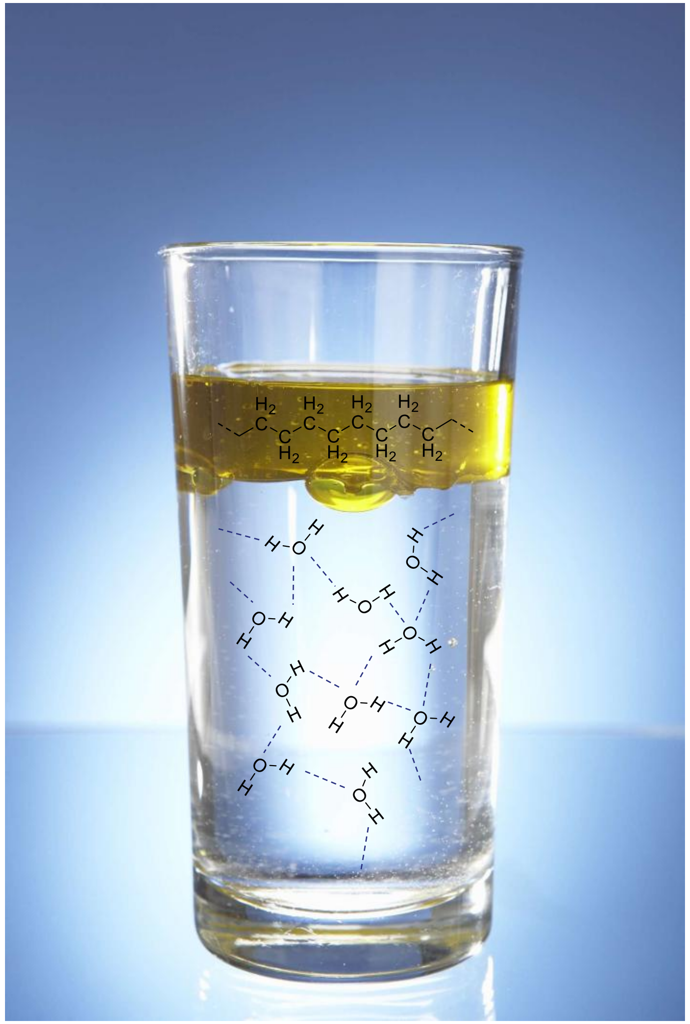
- Recycling only viable via shredding
- Black mass export to Asia

- *High profitability by retaining battery crystalline structures*

Direct recycling strategy

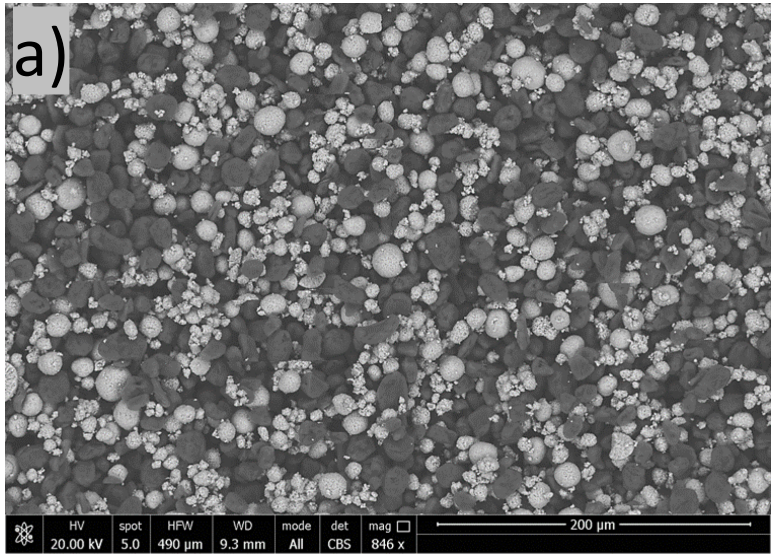
Black Mass Purification:
(Top Secret Ingredient)

- 1% vegetable oil in water (no surfactants)
- Ultrasound-generation of o/w nanoemulsion
- *Patent-pending technology*

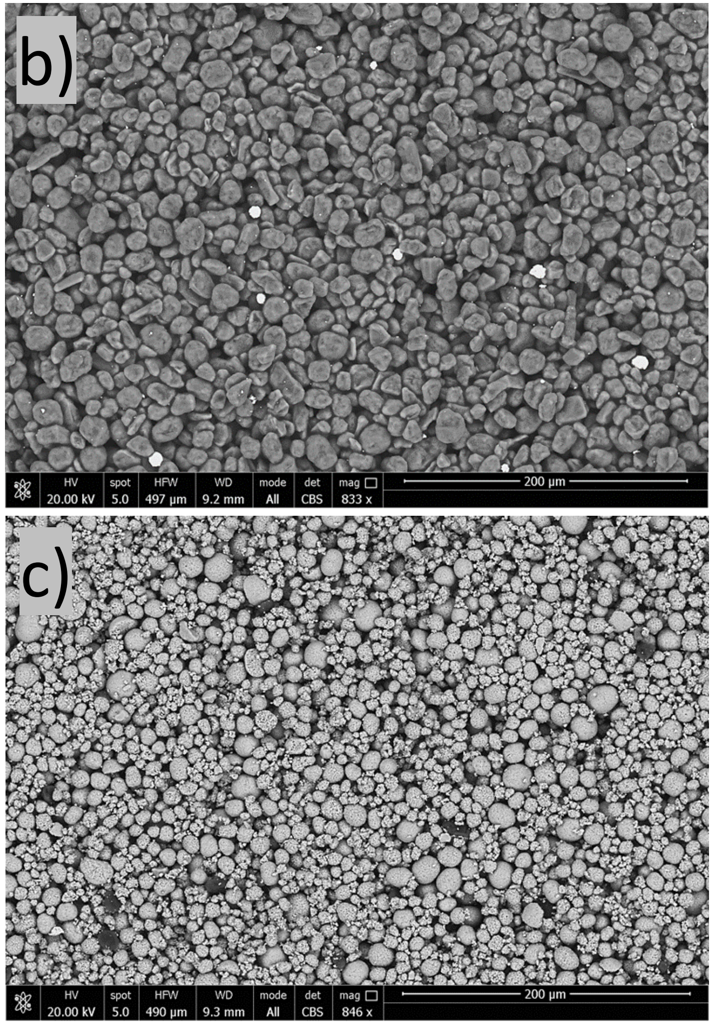


RSC Sustainability, 2025, **3**, 1516-1523

Purifying Lithium-ion battery black mass



o/w nanoemulsion



(a) graphite/NMC622 prestine blend before separation; (b) graphite after separation; (c) NMC622 after separation.

- *Near-instant black mass purification*
- *Patent-pending technology*

RSC Sustainability, 2025, **3**, 1516-1523

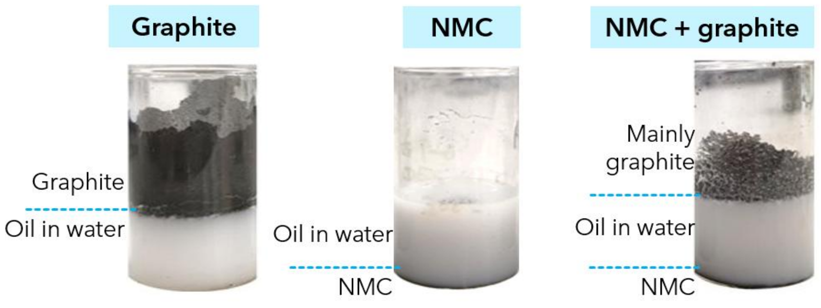
Technoeconomic Analysis

	Energy input MWh/t	Energy Cost £/t	Chemical input £/t	Total Costs £	Component, Yield / kg/ t, yield %	Value /£/t	Total value / £/t	profit £/ t
Long-loop recycling Hydrometallurgical	5.78	1502	610*	2112	Cu 20kg 98%	100	2383	£270
					Al 30 kg 98%	20		
					Li_2CO_3 6kg 80%	9		
					115 kg of LNO recovered as $NiSO_4$	1285		
					69 kg of LMO recovered as $MnSO_4$	11		
					46 kg of LCO recovered as $CoSO_4$	869		
					Graphite 228 kg 95%	89		
Short-loop recycling Thermal (Induction) + o/w emulsion + Regeneration	1.99	517	864	1381	Cu 20kg 98%	100	9225	>£6,000
					Al 98%	20		
					No lithium	0		
					Graphite 228 kg 95%	89		
					NMC 225 kg 98%	9016		

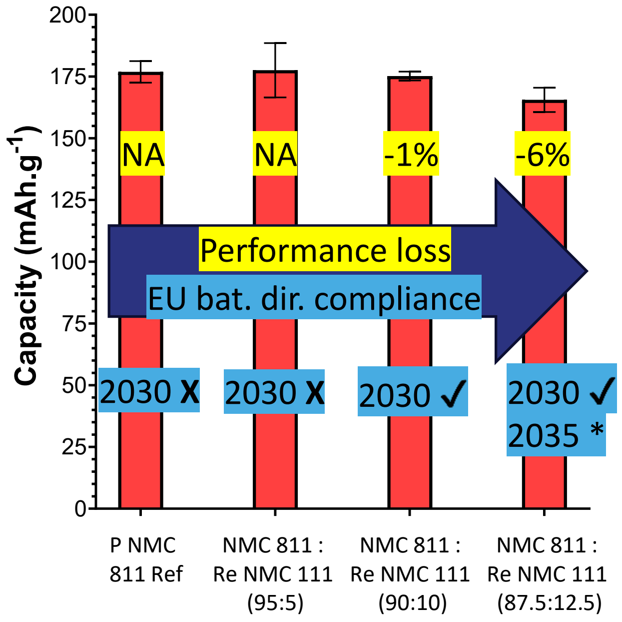
Just started: UKRI Proof-of-concept grant (1 year, TRL: 3,4 → 5,6)

EU Bat. Directive Compliant cells?

Nanoemulsion of vegetable oil in water rapidly purifies lithium metal oxide (hydrophilic) from graphite (hydrophobic).



Recovered NMC111 mixed with NMC 811 to form cells that are EU Battery Directive compliant



Data taken from lithium half-cells: NMC vs. lithium metal disc; LP57 electrolyte; 10^{th} cycle at 0.1C; 4.2 V – 3.0 V voltage range; P = pristine and Re = recovered. * EU battery compliant for lithium & cobalt contents, but not for nickel

Unpublished work

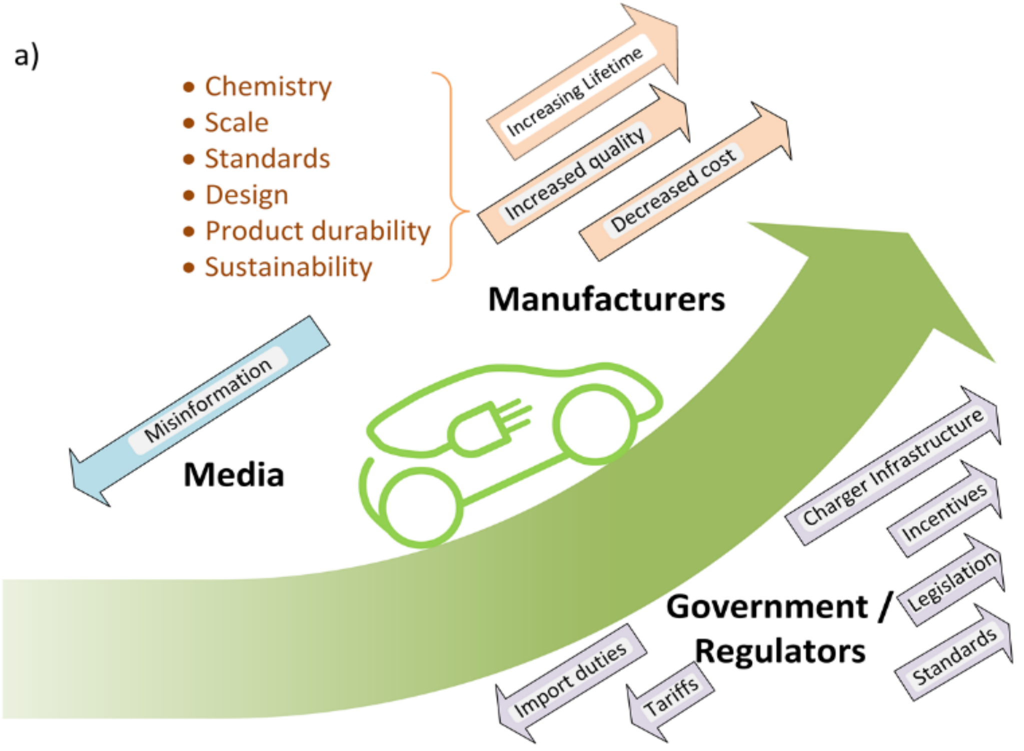
Kick starting the LIB market

Requirements:

A standard high-quality product

A charging infrastructure

Price parity with current technology



[LIB review](https://doi.org/10.1038/s41586-019-1682-5)
https://doi.org/10.1038/s41586-019-1682-5

Product costs

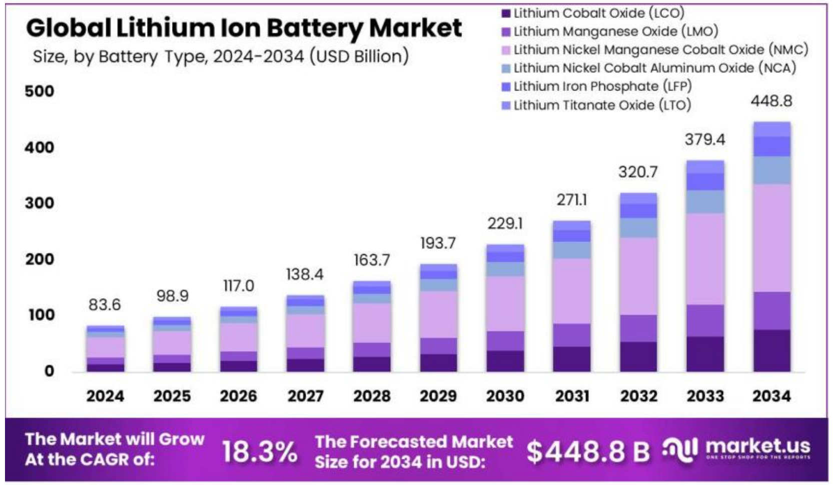
Price parity between ICE and EVs was obtained in 2025

In the UK EVs are 12% to 19% more expensive than ICEs

Total Cost of Ownership (TCO) is already about £6 less per 100 miles for new EVs

Strong market for used EVs with lifetimes already > 15 yrs

New gigafactories and more sustainable battery chemistries will ensure that prices will continue to decrease



Achieving circularity

Requires a dialog between manufacturers, recyclers and legislators

Lead acid batteries are the most efficiently recycled product on the market (>99%)

LIBs are more complex – designed for performance and safety

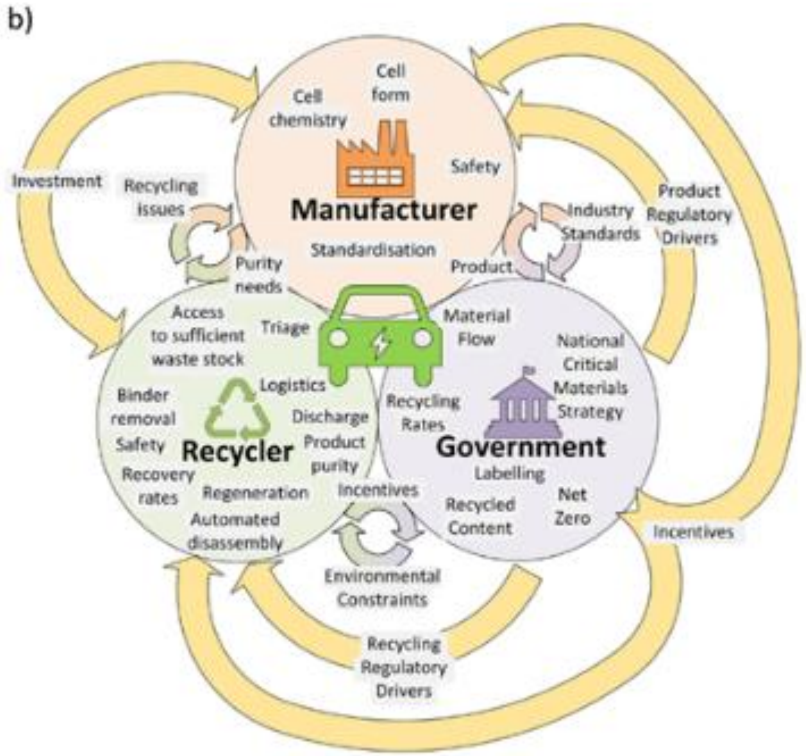
Currently a disconnect between recyclers and manufacturers

Challenges with product costs and performance

No real market for recycled material in the EU

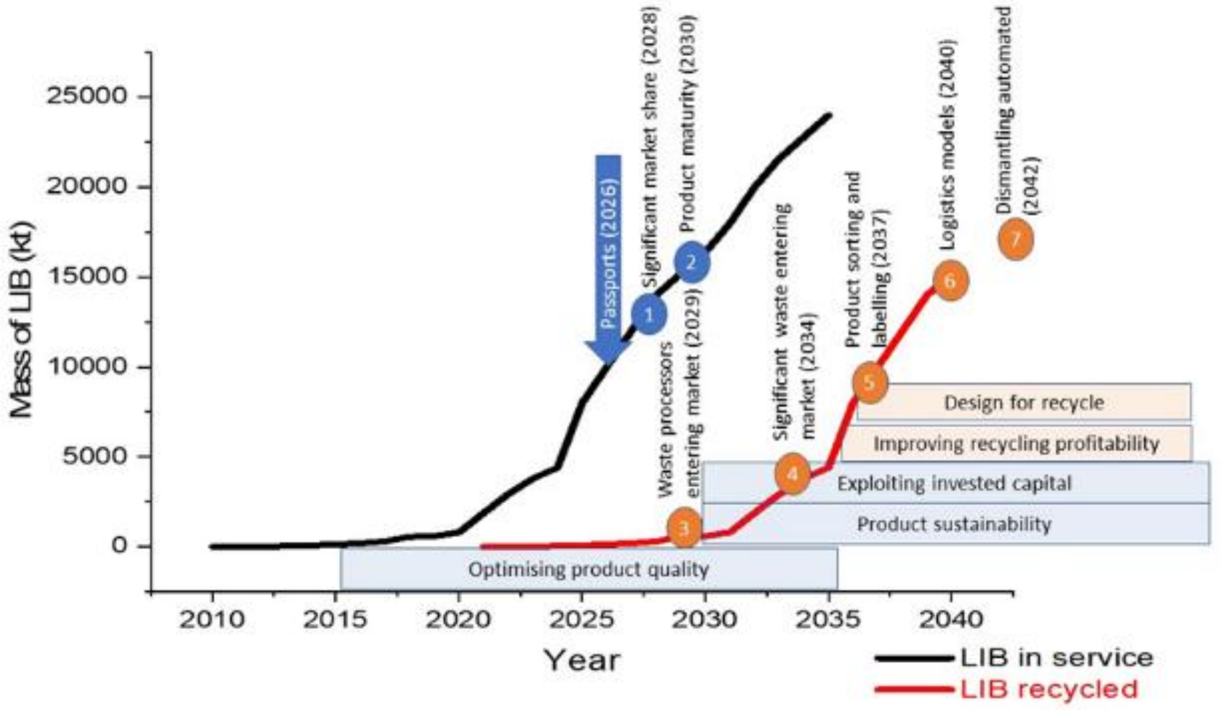
Key unknown

What is a permissible level of performance in recycled material?



[Timeline paper](https://doi.org/10.1039/D5EB00144G)
https://doi.org/10.1039/D5EB00144G

Timeline to Circularity

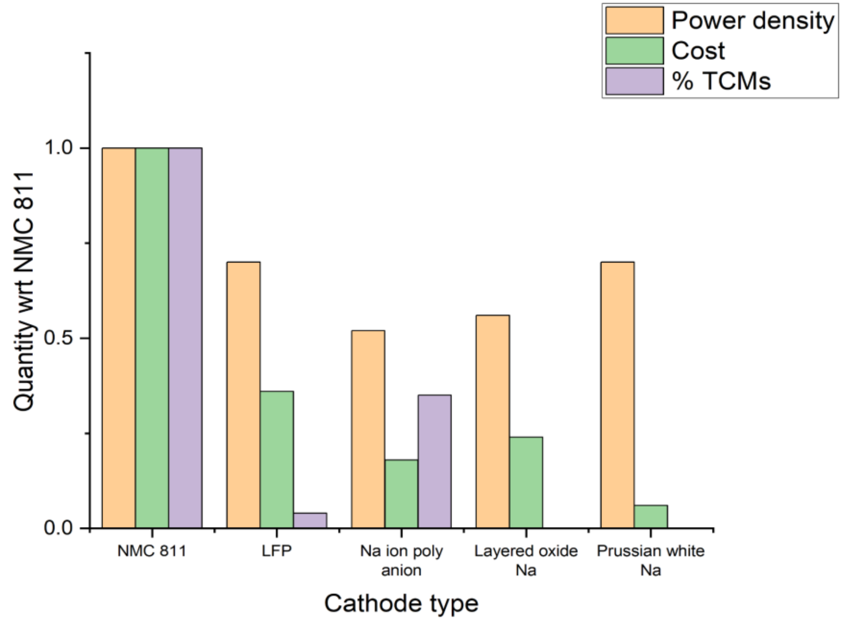


EV market trajectory towards a circular economy. Timeframes for each process (boxes) and milestones (numbers) are estimates based on the length of research and time taken for product-to-market, and of expected recycling equipment and EV battery lifetimes.

[Timeline paper](https://doi.org/10.1039/D5EB00144G)
https://doi.org/10.1039/D5EB00144G

Factors affecting timeline

- Fluctuations in market size
- Ensuring product quality and its effects on longevity
- Product sustainability
- Exploiting invested capital
- Waste handlers and significant waste entering the market
- Automation of disassembly
- Improvements in recycling efficiency



TEA of pack disassembly
https://doi.org/10.1016/j.apenergy.2022.120437

Design for recycle

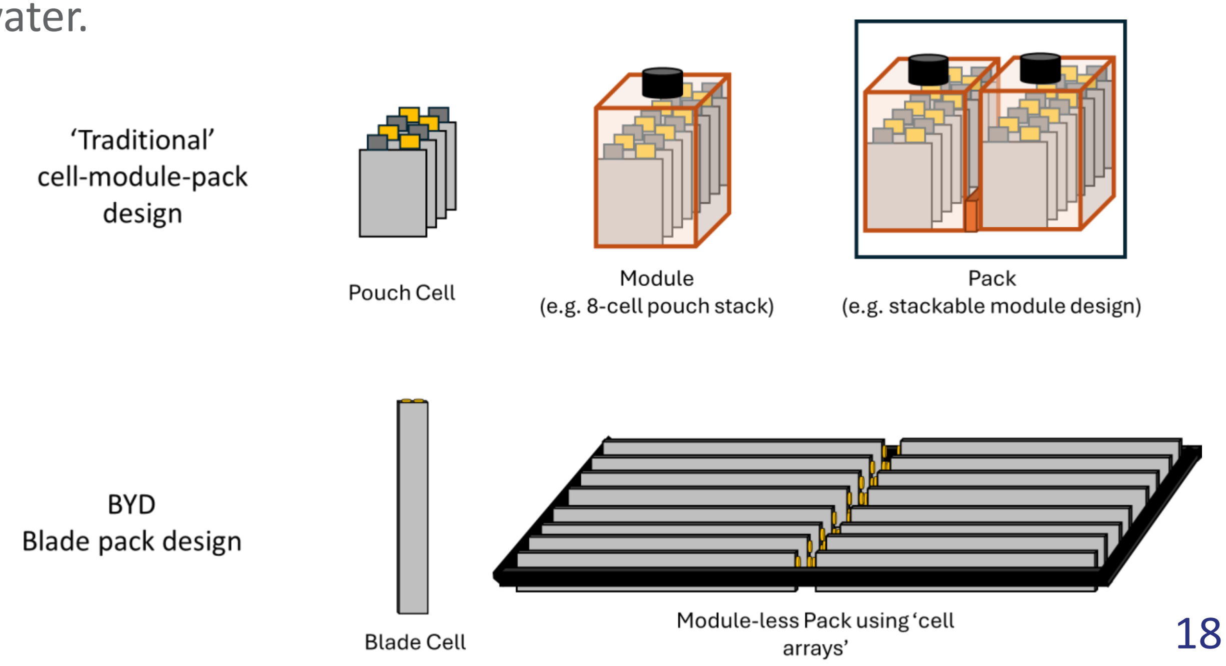
- Fewer but larger cells
- Minimal use of thermoset adhesives
- Fewer fixing types
- Cells that are more easily opened
- Cells that can be rejuvenated by flushing out the old electrolyte and replacing with new
- Electrode binders that can be fully dispersed using water.
- Debondable adhesives

https://doi.org/10.1039/D1GC03306A

- Design for recycle

https://doi.org/10.1039/D0GC02745F

https://doi.org/10.1016/j.nxener.2023.100023



Legislation

Needs to be robust but flexible in a fast-changing market

Probable that EU Battery Directive will not be applicable due to insufficient scrap material on the market

Region	Regulation
	Li recovery rate 90%, Ni, Co, Mn, Cu, Al and REE 98%. Energy consumption for 1t Li_2CO_3 < 18 MWh. Fluorine recovery > 99.5%
	Li recovery rate 80%, Ni, Co and Cu 95% 2031 – New cells must contain 16% Co, 6% Li and 6% Ni from recycled sources 2036 – New cells must contain 26% Co, 12% Li and 16% Ni from recycled sources 2027 – Digital Battery Passport required
	No EPR regulations for WEEE or EV batteries. 9 states have some battery recycling regulations
	EVs are not differentiated from other vehicles. All demand recycling rates are >95%. The buyer pays a fee to cover EOL processing at the point of sale.

Table 1: International regulations for EV waste handling

Conclusions

1. Many countries saw an increase in EV sales during the late 2010s and these vehicles will come to end of life in the period 2030-2035. While some countries have a recycling infrastructure in place, many do not but the timeline gives an indication of when these changes are required.

2. The volumes of EVs currently coming to market will require a different infrastructure for handling in 2035-2040, e.g., pack labelling and standard pack architecture. OEMs need to think about the change in handling protocols brought about by the increased volume. Economies of scale will only be achieved with automated disassembly.

3. Significant differences in the legislation governing waste in different producer and consumer nations may lead to confusion about recycling responsibility.

4. Some of the targets in battery directives are unachievable due to the flows of markets and the immaturity of recycling markets.

5. Forums must be established to bring together pack designers and recyclers to look for quick wins in disassembly. Design for recycle needs to be more overtly discussed.

6. All stakeholders can affect the trajectory of product adoption, and only by working together can policy targets be met. National and regional policy changes can rapidly affect adoption and influence consumer confidence.

Recycling LIB roadmap
https://doi.org/10.1088/2515-7655/acaa57

Technology Road-mapping Future Lithium Ion Battery Recycling

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Birmingham Business School

UNIVERSITY OF BIRMINGHAM

BIRMINGHAM CENTRE FOR STRATEGIC ELEMENTS AND CRITICAL MATERIALS

THE FARADAY INSTITUTION ReLiB

REUSE & RECYCLING OF LITHIUM ION BATTERIES

Team Defence 27.01.2026

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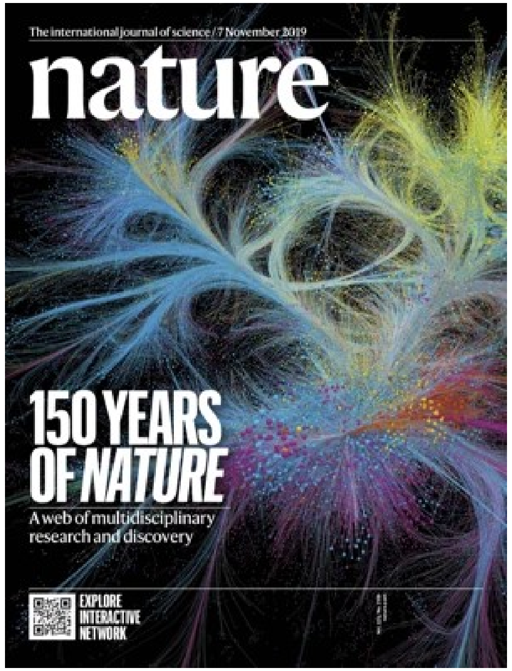
Review | Published: 06 November 2019

Recycling lithium-ion batteries from electric vehicles

Gavin Harper ✉, Roberto Sommerville, Emma Kendrick, Laura Driscoll, Peter Slater, Rustam Stolkin, Allan Walton, Paul Christensen, Oliver Heidrich, Simon Lambert, Andrew Abbott, Karl Ryder, Linda Gaines & Paul Anderson ✉

Nature **575**, 75–86 (2019) | Cite this article



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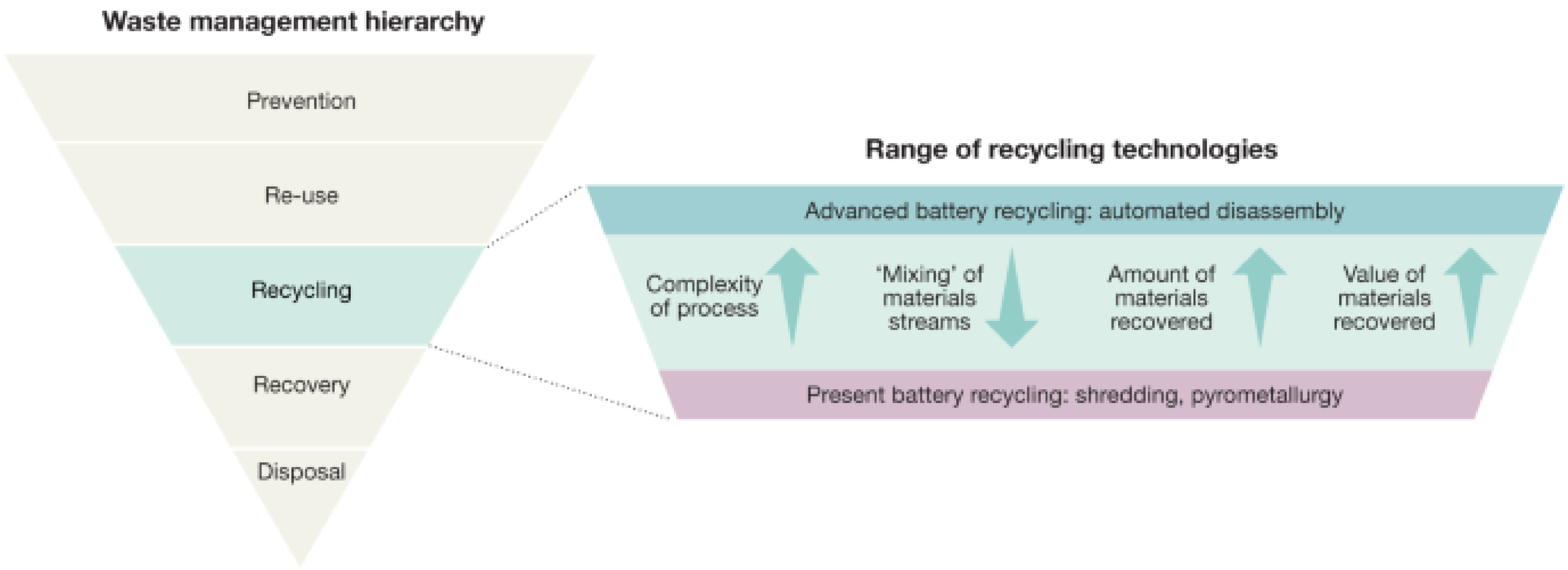

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JPhys Energy:

Roadmap for a Sustainable Circular Economy of Lithium Ion Batteries

JPhys Energy™

From the publisher of the *Journal of Physics* series

Roadmap for a sustainable circular economy in lithium-ion and future battery technologies

AVAILABLE OPEN ACCESS IN JPHYS ENERGY

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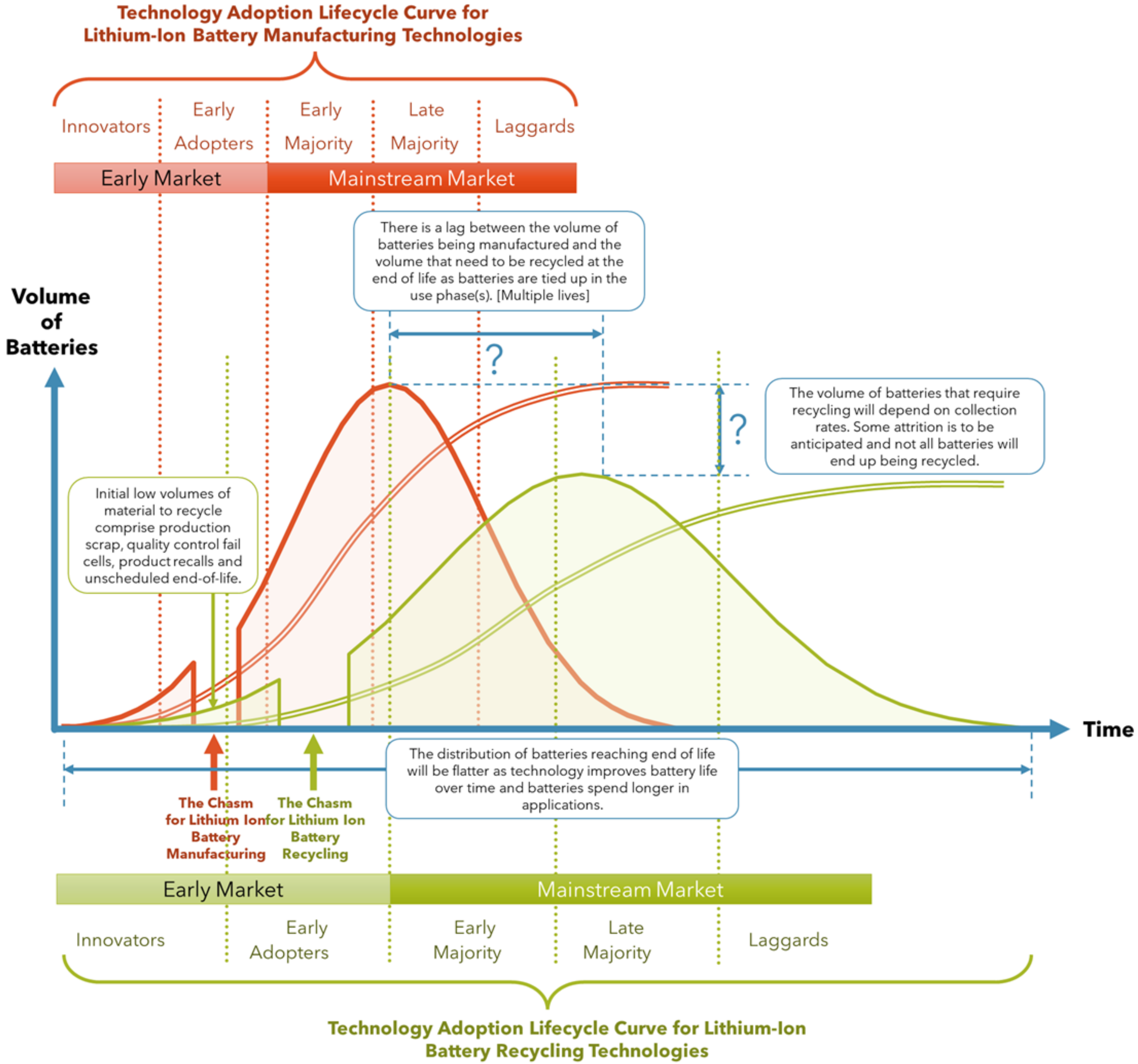
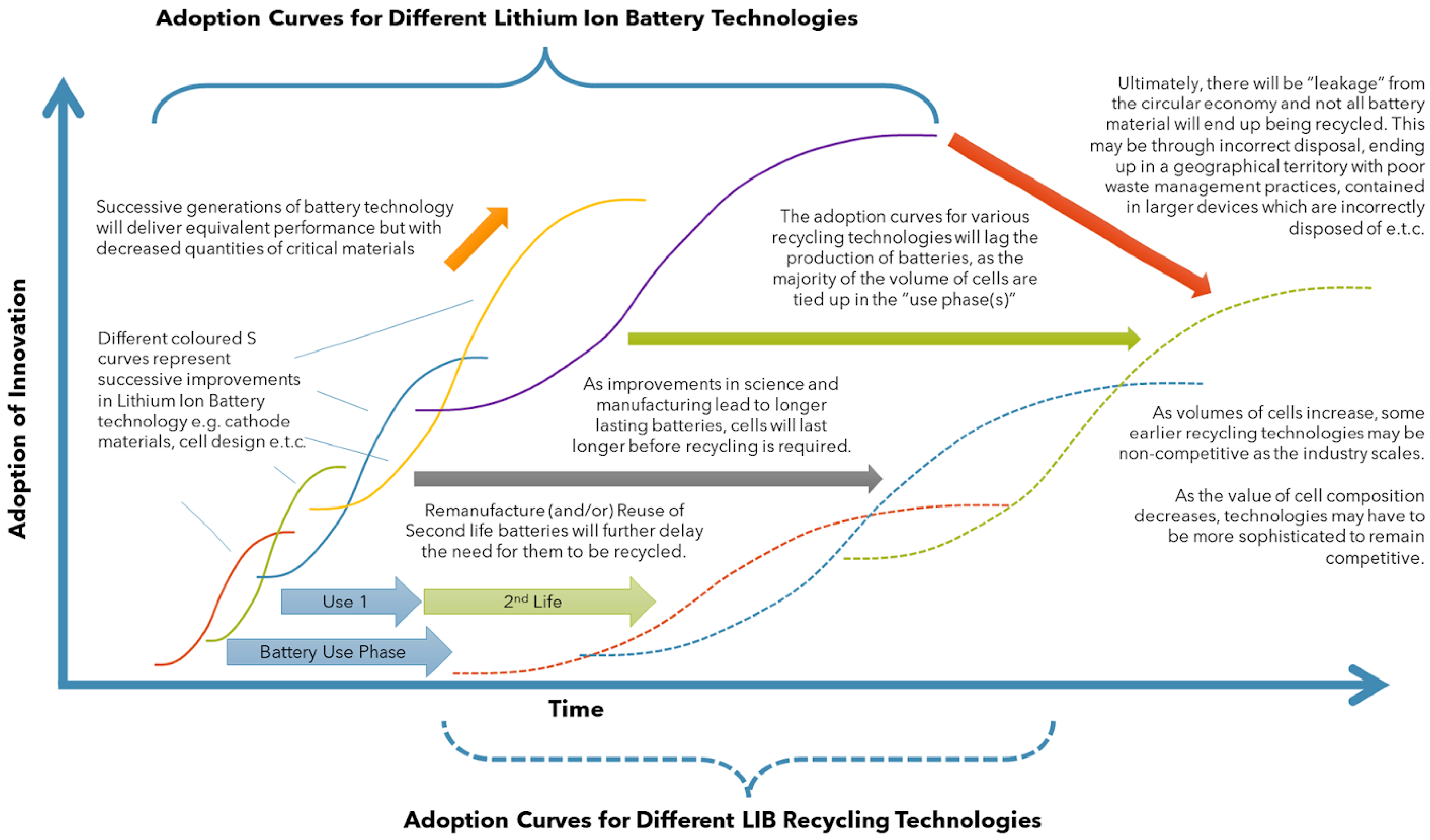
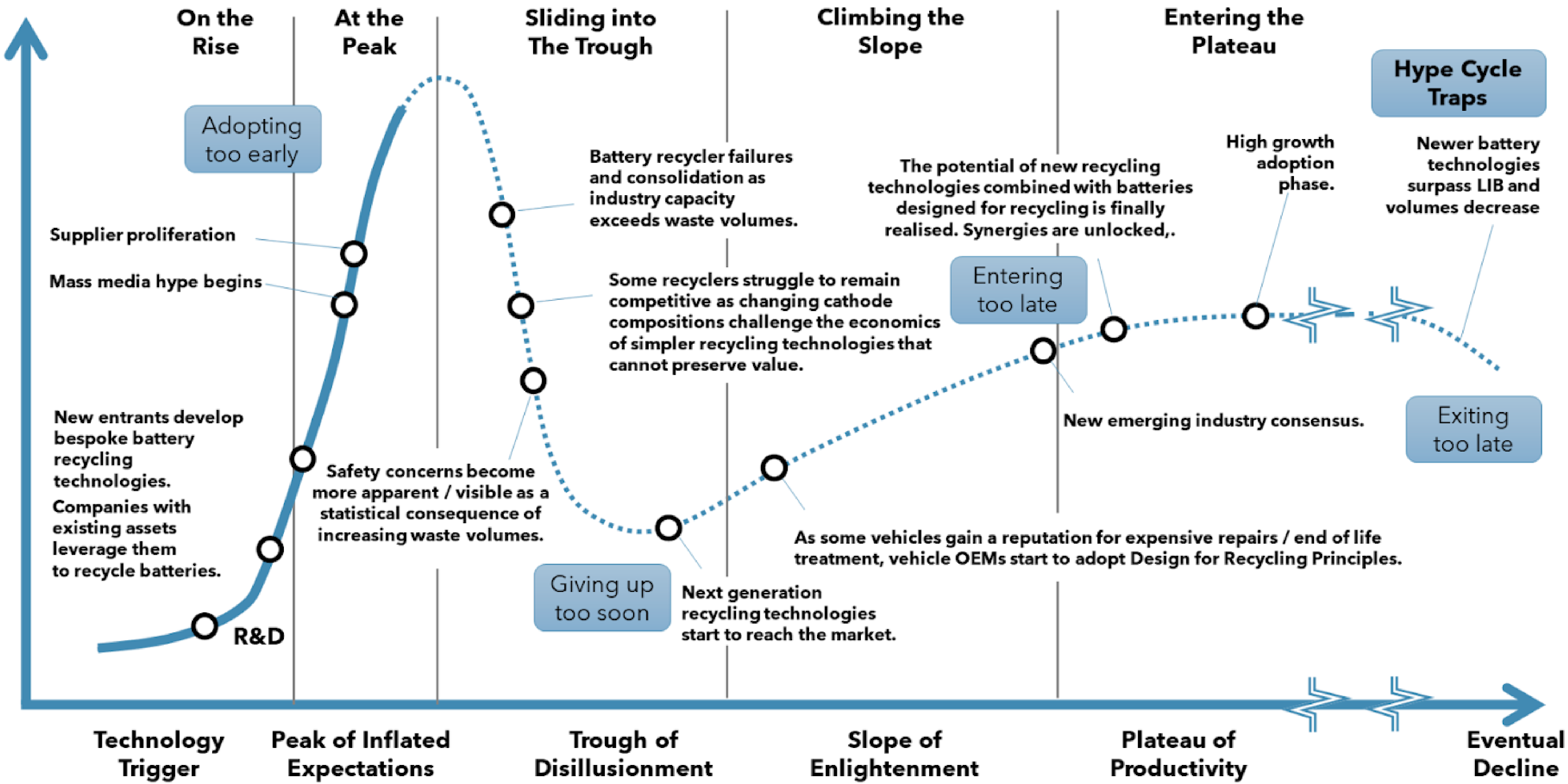
Gavin D J Harper, Emma Kendrick, Paul A Anderson, Wojciech Mrozik, Paul Christensen, Simon Lambert, David Greenwood, Prodip K Das, Mohamed Ahmeid, Zoran Milojevic, Wenjia Du, Dan J L Brett, Paul R Shearing, Alireza Rastegarpanah, Rustam Stolkin, Roberto Sommerville, Anton Zorin, Jessica L Durham, Andrew P Abbott, Dana Thompson, Nigel D Browning, B Layla Mehdi, Mounib Bahri, Felipe Schanider-Tontini, D Nicholls, Christin Stallmeister, Bernd Friedrich, Marcus Sommerfeld, Laura L Driscoll, Abbey Jarvis, Emily C Giles, Peter R Slater, Virginia Echavarri-Bravo, Giovanni Maddalena, Louise E Horsfall, Linda Gaines, Qiang Dai, Shiva J Jethwa, Albert L Lipson, Gary A Leeke, Thomas Cowell, Joseph Gresle Farthing, Greta Mariani, Amy Smith, Zubera Iqbal, Rabeeh Golmohammadzadeh, Luke Sweeney, Vannessa Goodship, Zheng Li, Jacqueline Edge, Laura Lander, Viet Tien Nguyen, Robert J R Elliot, Oliver Heidrich, Margaret Slattery, Daniel Reed, Jyoti Ahuja, Aleksandra Cavoski, Robert Lee, Elizabeth Driscoll, Jen Baker, Peter Littlewood, Iain Styles, Sampriti Mahanty and Frank Boons

27 chapters from 65 leading researchers



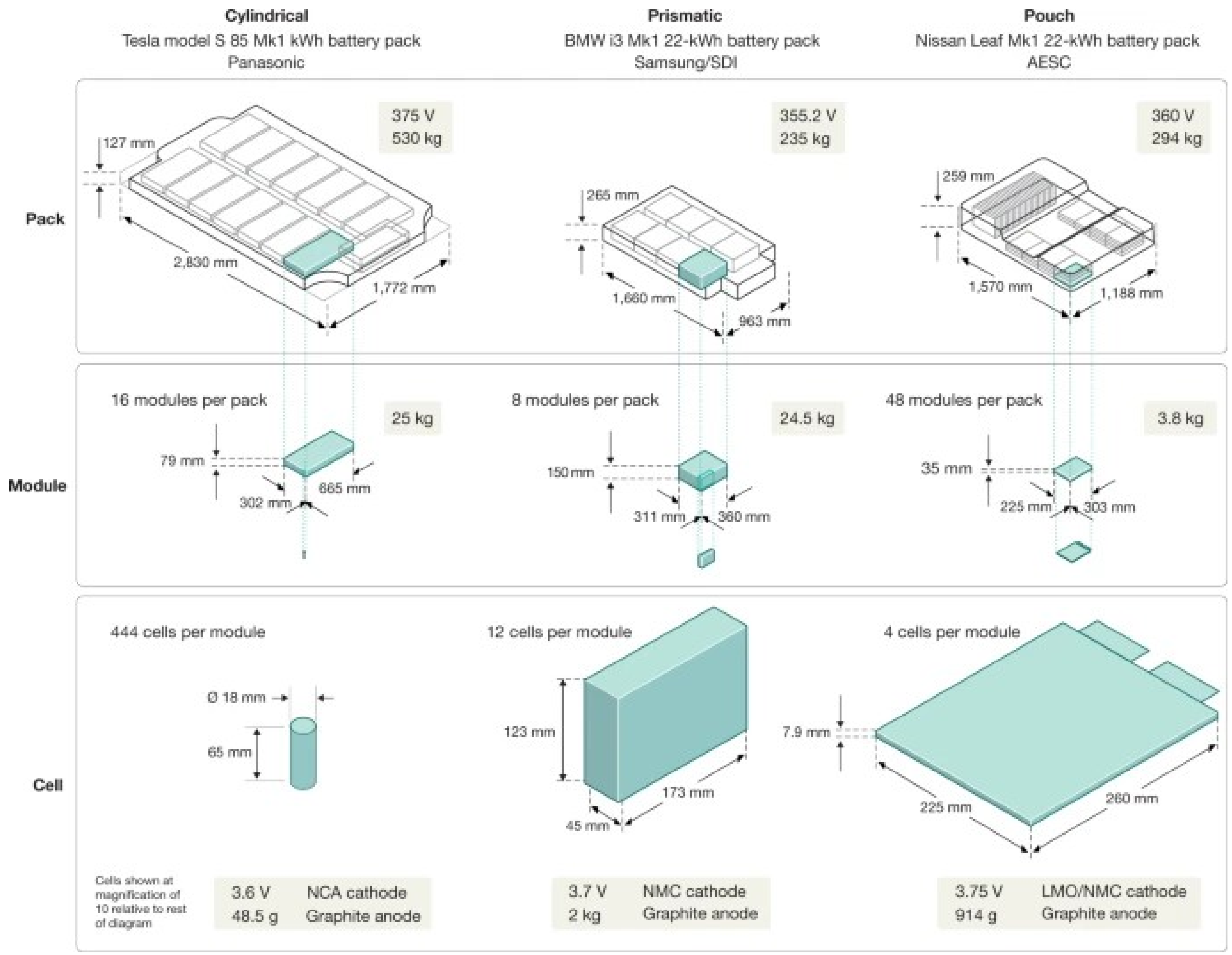
Technology Adoption Lifecycle Curve for Lithium-Ion Battery Manufacturing Technologies
Innovators
Early Adopters
Early Majority
Late Majority
Laggards
Early Market
Mainstream Market
There is a lag between the volume of batteries being manufactured and the volume that need to be recycled at the end of life as batteries are tied up in the use phase(s). [Multiple lives]
Volume of Batteries
?
The volume of batteries that require recycling will depend on collection rates. Some attrition is to be anticipated and not all batteries will end up being recycled.
Initial low volumes of material to recycle comprise production scrap, quality control fail cells, product recalls and unscheduled end-of-life.
Time
The distribution of batteries reaching end of life will be flatter as technology improves battery life over time and batteries spend longer in applications.
The Chasm for Lithium Ion Battery Manufacturing
The Chasm for Lithium Ion Battery Recycling
Early Market
Mainstream Market
Innovators
Early Adopters
Early Majority
Late Majority
Laggards
Technology Adoption Lifecycle Curve for Lithium-Ion Battery Recycling Technologies


Adoption Curves for Different Lithium Ion Battery Technologies
Adoption of Innovation
Successive generations of battery technology will deliver equivalent performance but with decreased quantities of critical materials
Different coloured S curves represent successive improvements in Lithium Ion Battery technology e.g. cathode materials, cell design e.t.c.
Use 1
2nd Life
Battery Use Phase
Remanufacture (and/or) Reuse of Second life batteries will further delay the need for them to be recycled.
As improvements in science and manufacturing lead to longer lasting batteries, cells will last longer before recycling is required.
The adoption curves for various recycling technologies will lag the production of batteries, as the majority of the volume of cells are tied up in the "use phase(s)"
Ultimately, there will be "leakage" from the circular economy and not all battery material will end up being recycled. This may be through incorrect disposal, ending up in a geographical territory with poor waste management practices, contained in larger devices which are incorrectly disposed of e.t.c.
As volumes of cells increase, some earlier recycling technologies may be non-competitive as the industry scales.
As the value of cell composition decreases, technologies may have to be more sophisticated to remain competitive.
Time
Adoption Curves for Different LIB Recycling Technologies



On the Rise
At the Peak
Sliding into The Trough
Climbing the Slope
Entering the Plateau
Hype Cycle Traps
Adopting too early
Supplier proliferation
Mass media hype begins
New entrants develop bespoke battery recycling technologies.
Companies with existing assets leverage them to recycle batteries.
R&D
Battery recycler failures and consolidation as industry capacity exceeds waste volumes.
Some recyclers struggle to remain competitive as changing cathode compositions challenge the economics of simpler recycling technologies that cannot preserve value.
Safety concerns become more apparent / visible as a statistical consequence of increasing waste volumes.
Giving up too soon
Next generation recycling technologies start to reach the market.
As some vehicles gain a reputation for expensive repairs / end of life treatment, vehicle OEMs start to adopt Design for Recycling Principles.
The potential of new recycling technologies combined with batteries designed for recycling is finally realised. Synergies are unlocked,.
Entering too late
New emerging industry consensus.
High growth adoption phase.
Newer battery technologies surpass LIB and volumes decrease
Exiting too late
Technology Trigger
Peak of Inflated Expectations
Trough of Disillusionment
Slope of Enlightenment
Plateau of Productivity
Eventual Decline

COMPLEXITY AND VARIATION IN ELECTRIC VEHICLE PACK DESIGN



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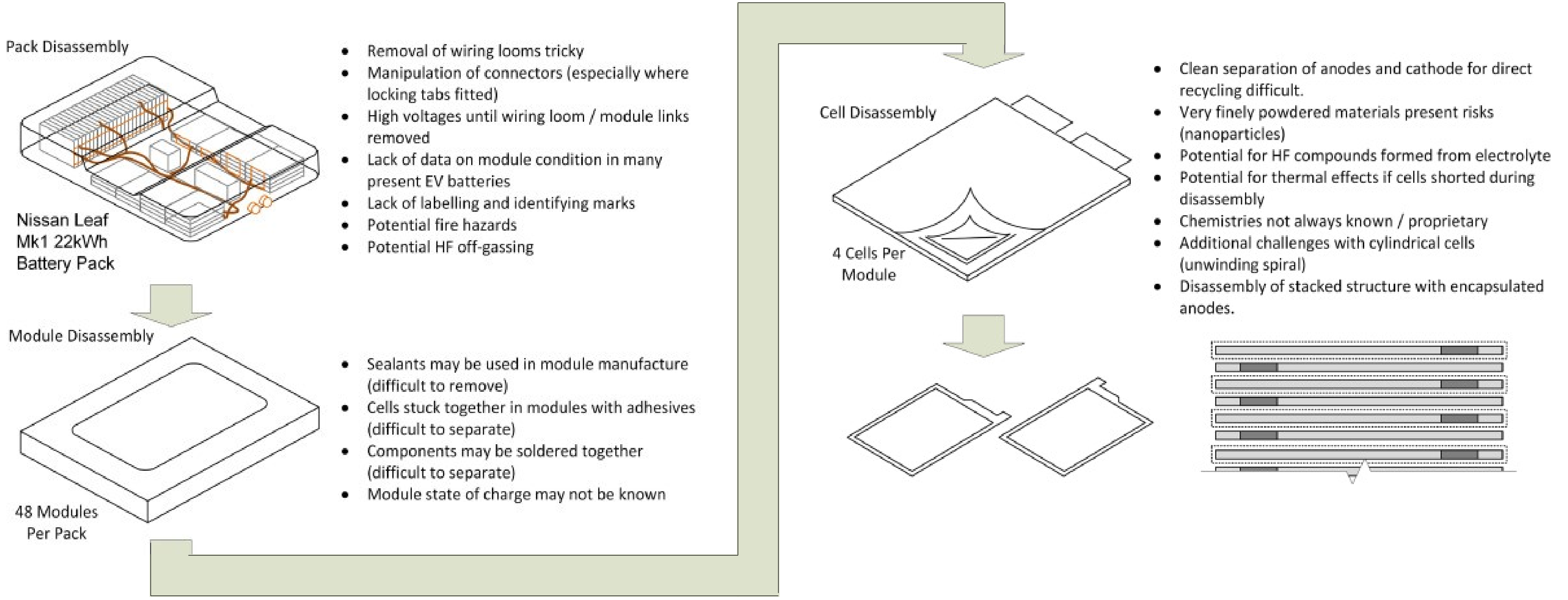


Resources, Conservation & Recycling 175 (2021) 105741

Contents lists available at ScienceDirect

Resources, Conservation & Recycling

journal homepage: www.elsevier.com/locate/resconrec

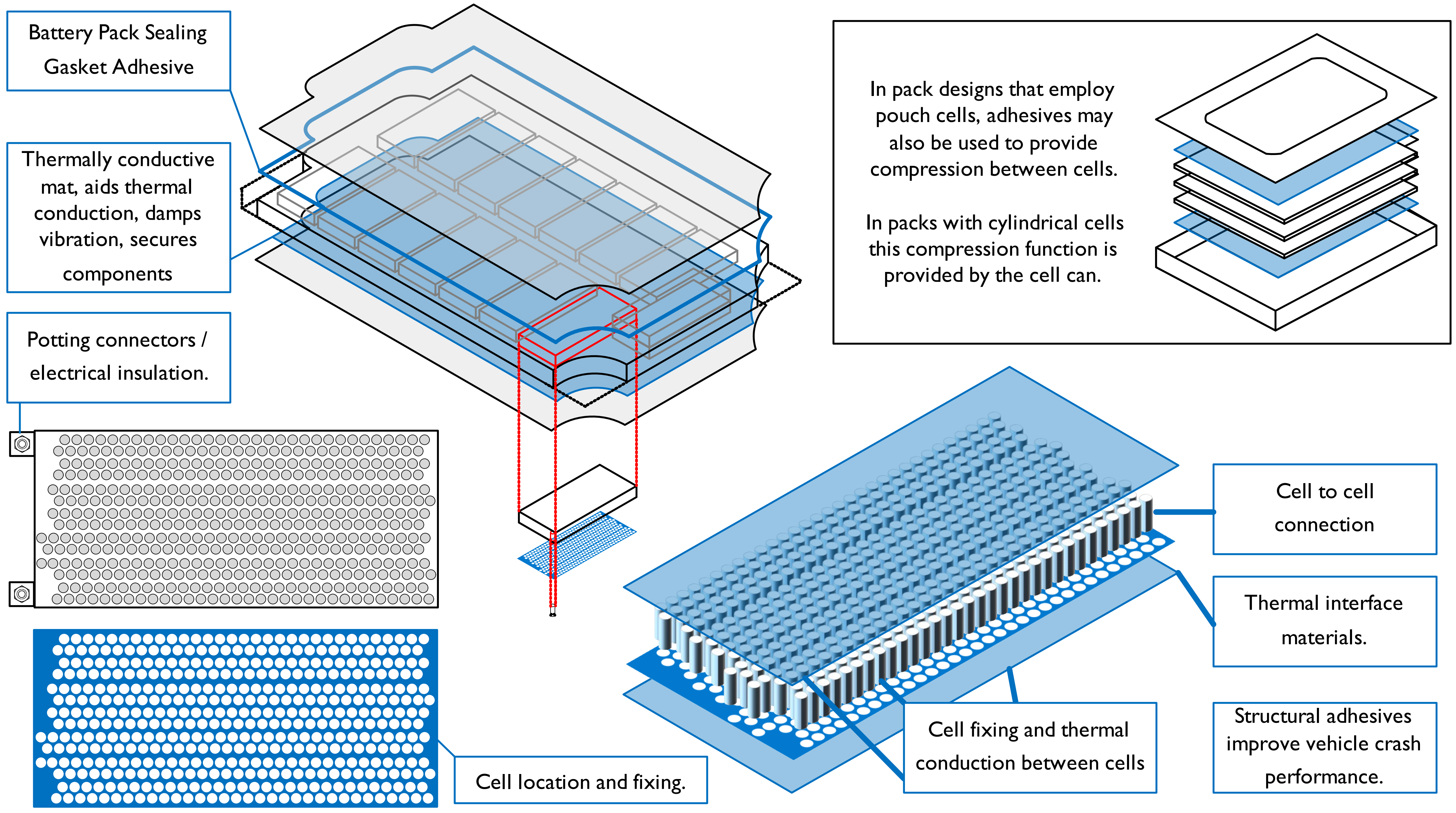
ELSEVIER

Full length article

To shred or not to shred: A comparative techno-economic assessment of lithium ion battery hydrometallurgical recycling retaining value and improving circularity in LIB supply chains

Dana Thompson [a,b], Charlotte Hyde [a], Jennifer M. Hartley [a,b], Andrew P. Abbott [a,b], Paul A. Anderson [b,c], Gavin D.J. Harper [b,d,*]

COMPLEXITY IN EV PACK DISASSEMBLY


Battery Pack Sealing Gasket Adhesive
Thermally conductive mat, aids thermal conduction, damps vibration, secures components
Potting connectors / electrical insulation.
In pack designs that employ pouch cells, adhesives may also be used to provide compression between cells.
In packs with cylindrical cells this compression function is provided by the cell can.
Cell to cell connection
Thermal interface materials.
Structural adhesives improve vehicle crash performance.
Cell fixing and thermal conduction between cells
Cell location and fixing.

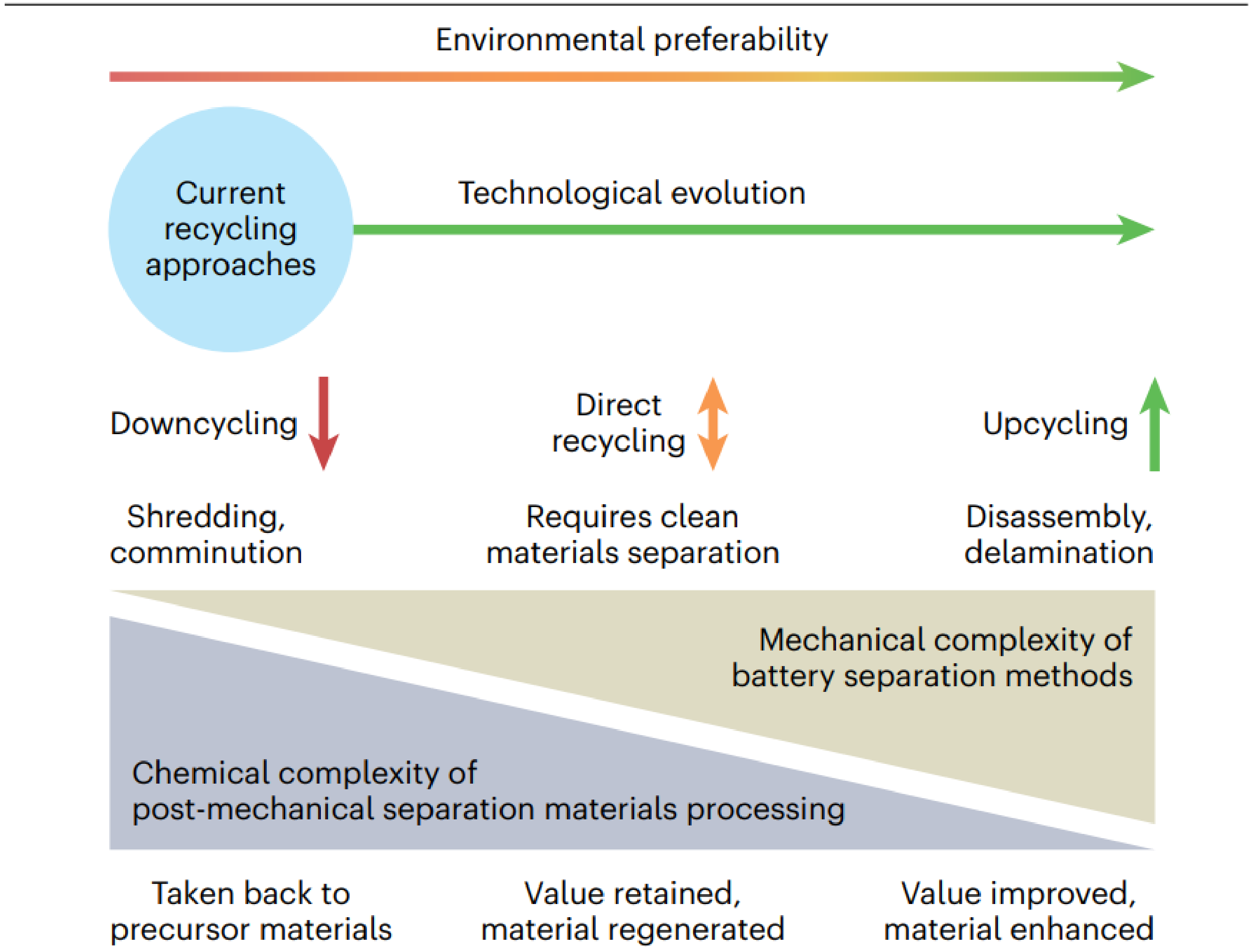
News & views

nature sustainability

Batteries

Upcycle for enhanced performance

Gavin D. J. Harper



Current recycling techniques downcycle materials; environmentally preferable recycling techniques will preserve and even upcycle the value of the materials.

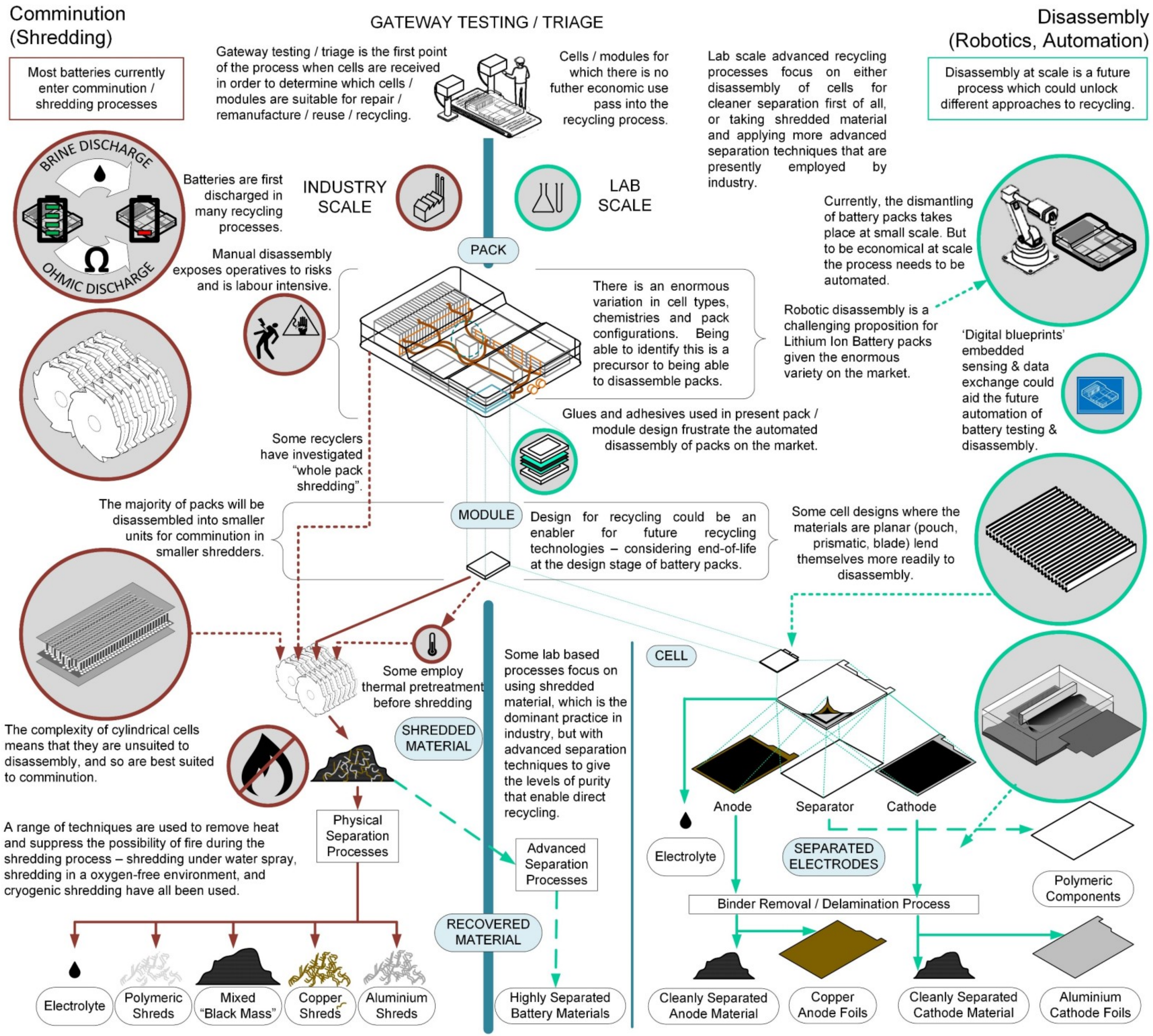
nature reviews
clean technology

Review Article | Published: 15 January 2025

The evolution of lithium-ion battery recycling

Xiaotu Ma, Zifei Meng, Marilena Velonia Bellonia, Jeffrey Spangenberger, Gavin Harper, Eric Gratz, Elsa Olivetti, Renata Arsenault & Yan Wang ✉

Nature Reviews Clean Technology **1**, 75–94 (2025) | Cite this article



ReLIB technology pipeline

RECYCLING 1.0	RECYCLING 2.0	RECYCLING 3.0	RECYCLING 4.0
1 Pyrometallurgy	2 Current & developing hydrometallurgical techniques	3 Recycling aided by cell disassembly on current cells	4 Redesign of cells and design for recycling aiding improved recycling processes
recovery <50%	recovery 60–80%?	>90% recovery	99%+ recovery
established technology	generic materials separation & purification processes	bespoke materials separation & purification processes	necessary to adopt ‘design for recycle’ principles now

Recycling 3.0: cell disassembly coupled with bespoke separation processes based on short loop/direct recycling and upcycling maintains value in recovered materials streams

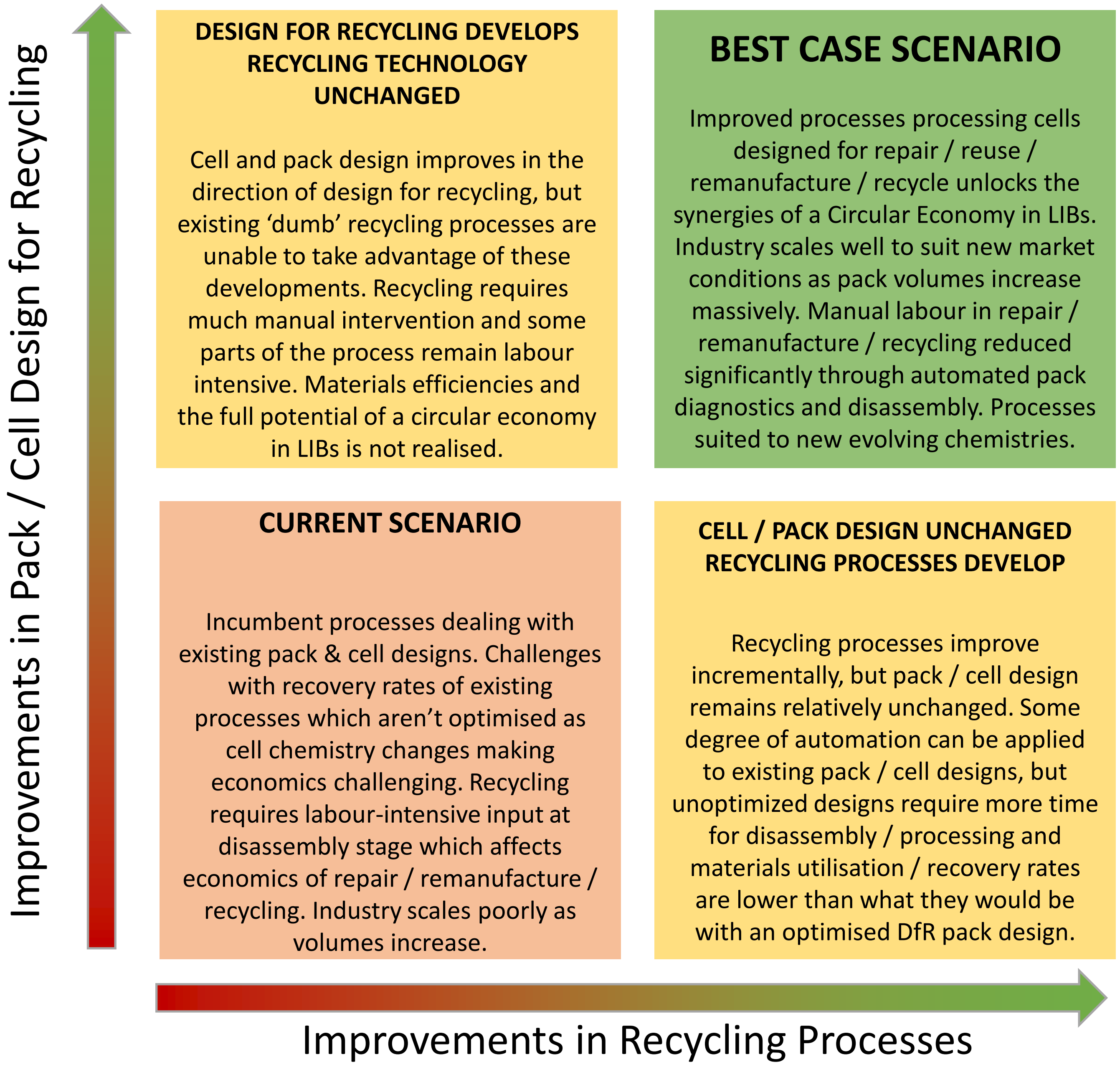
- brings lower value materials into play

Recycling 4.0: maintains recovery rates will require ***both adoption of ‘design for recycle’* and *commitment to zero-waste recycling***

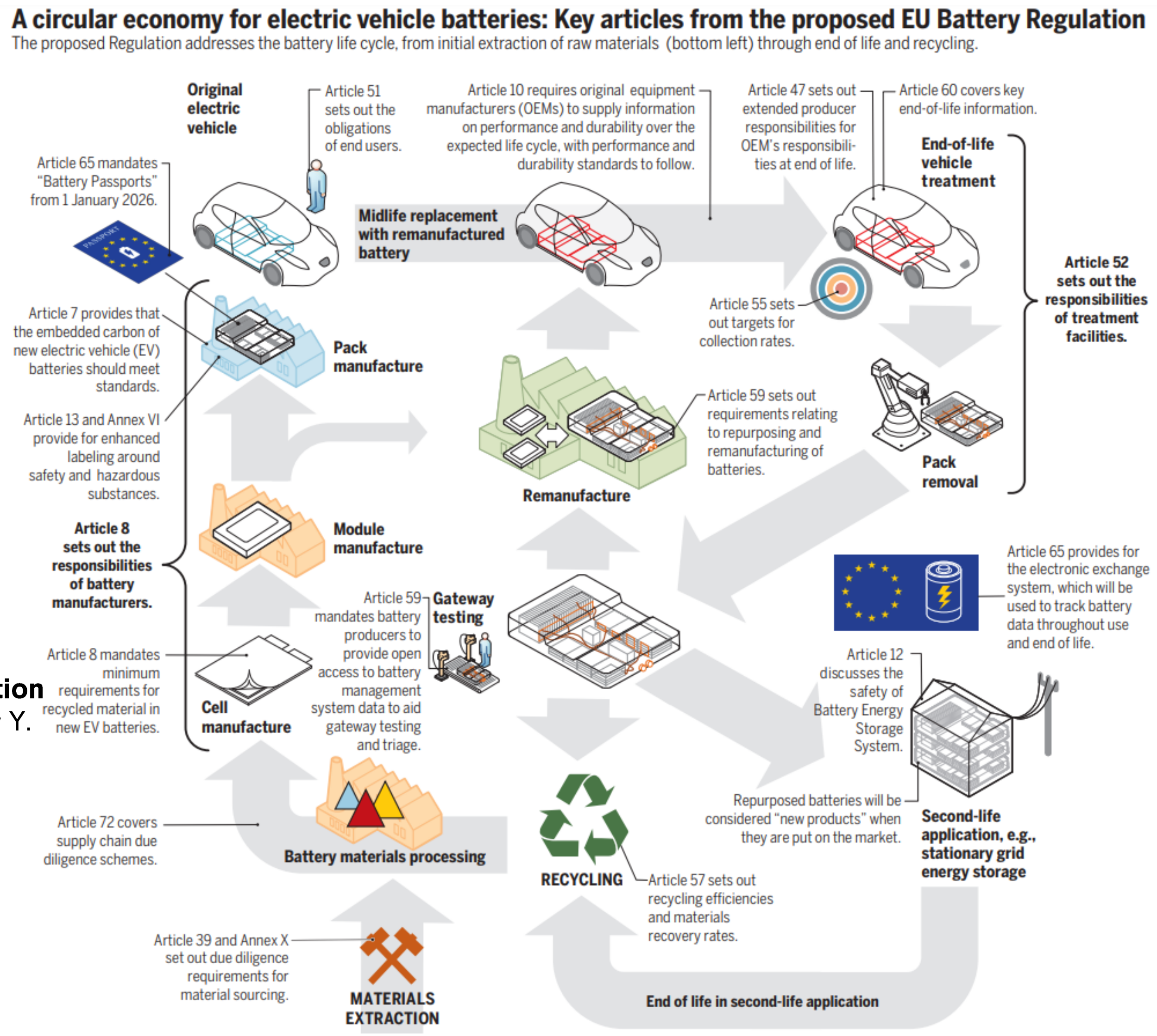
- materials recovery from waste streams from waste processing—biorecovery?

****pack wt%***

Unlocking the potential of a circular economy of battery technology critical metals requires the development of recycling processes and design for recycling in tandem.



Regulating EV Battery Recycling



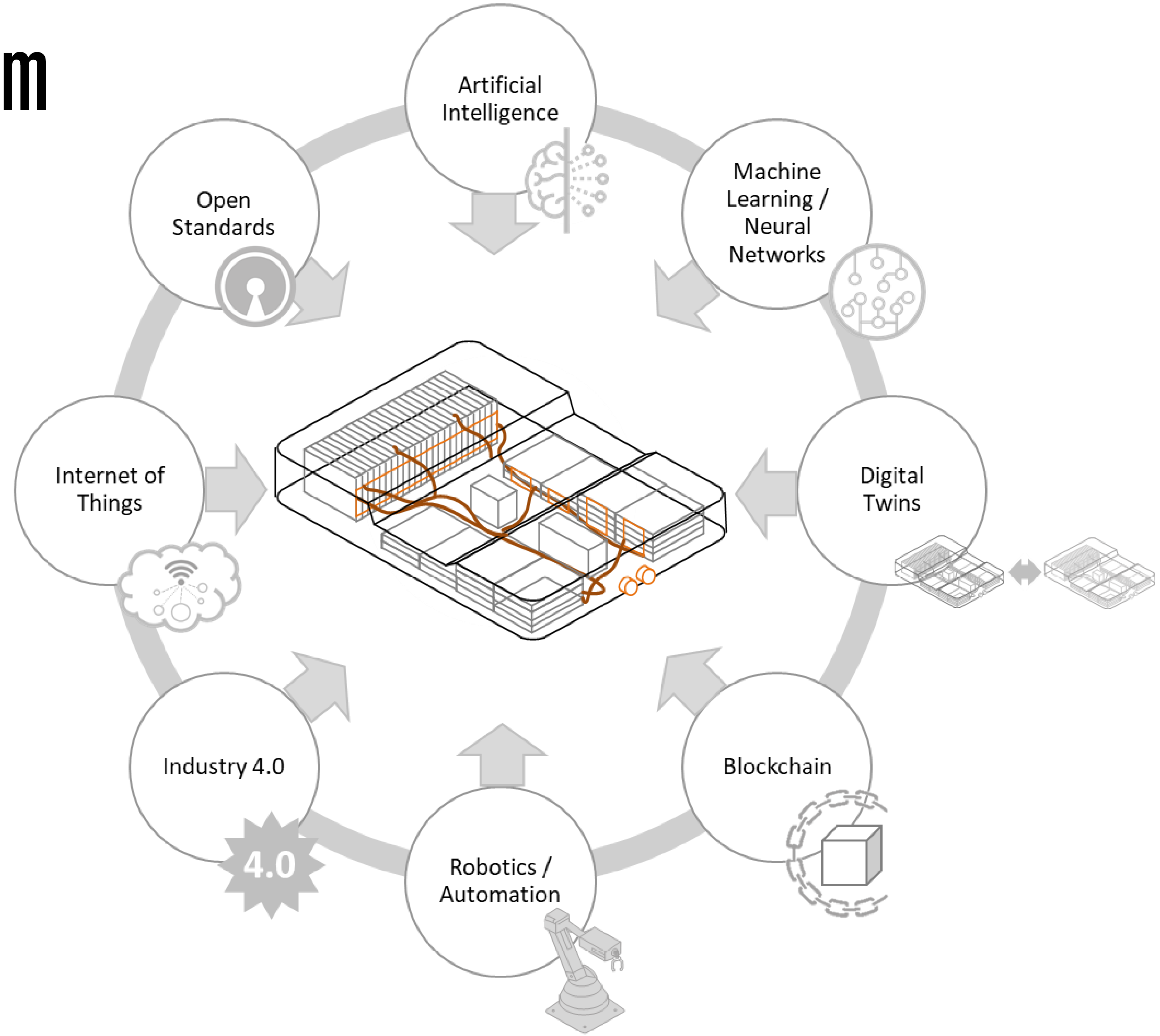
THE FARADAY INSTITUTION

ReLiB
REUSE & RECYCLING OF LITHIUM ION BATTERIES

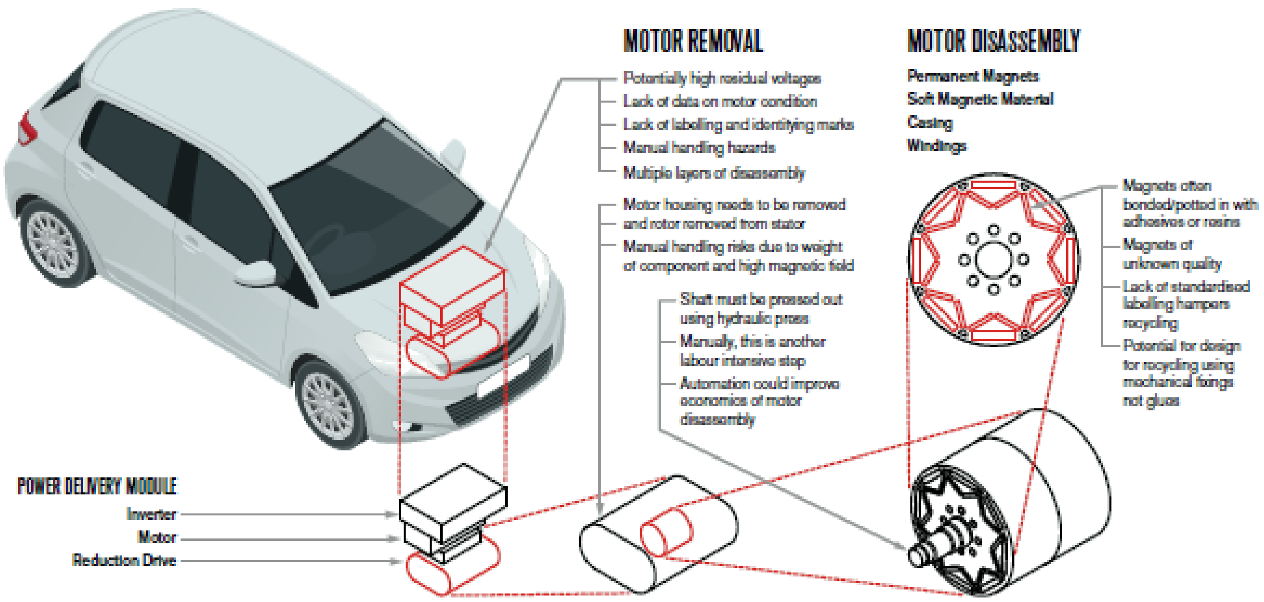
Global implications of the EU battery regulation
Hans Eric Melin, Mohammad Ali Rajaeifar, Anthony Y. Ku, Alissa Kendall, Gavin Harper & Oliver Heidrich
SCIENCE ▪ 23 Jul 2021 ▪ Vol 373, Issue 6553
pp. 384-387 ▪ DOI: 10.1126/science.abh1416

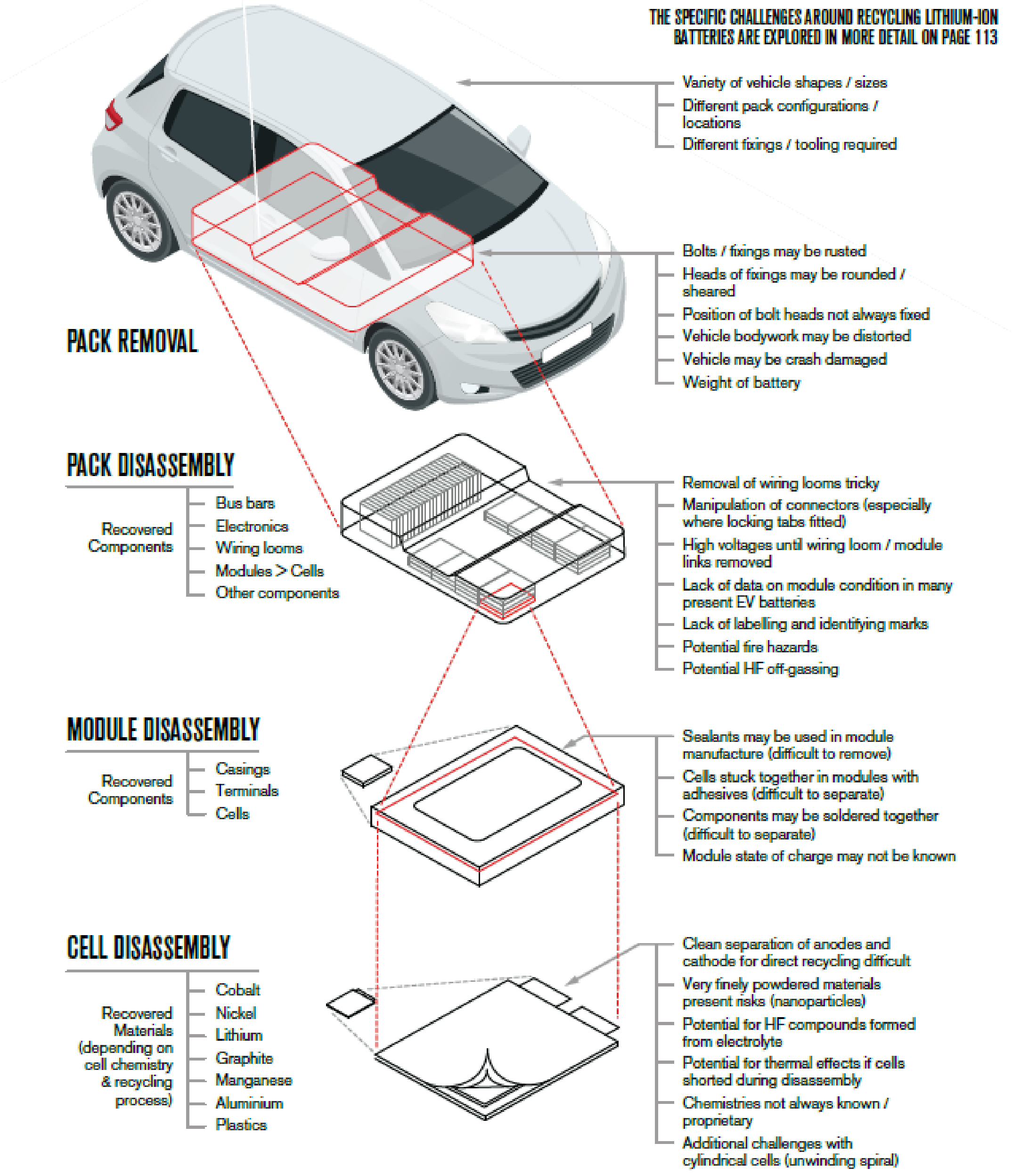
Science

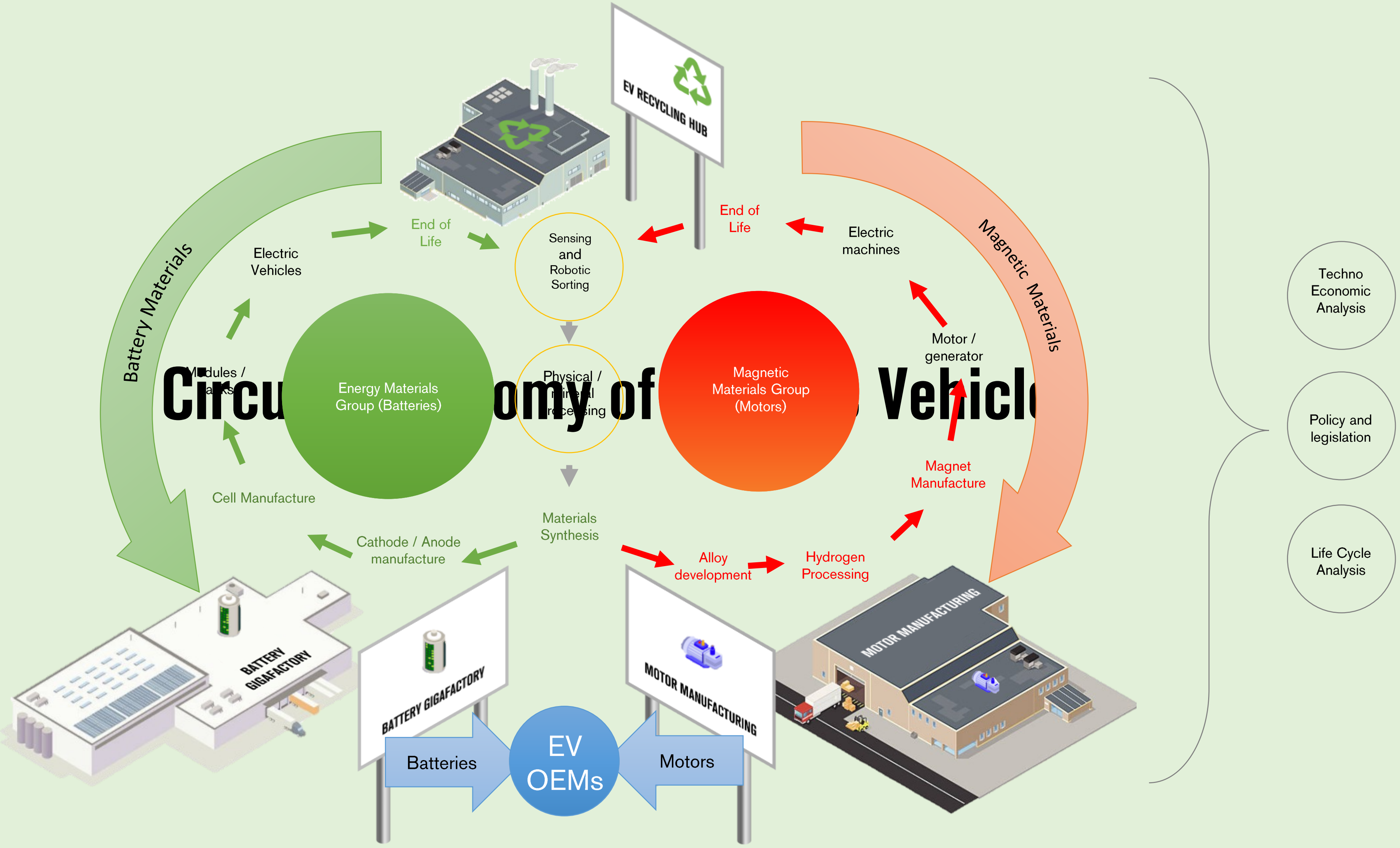
Digitalisation of Lithium Ion Battery Recycling



Synergy between the automated disassembly of Lithium Ion Batteries and Electric Vehicle Motors







EV RECYCLING HUB
Battery Materials
Magnetic Materials
End of Life
Electric Vehicles
Sensing and Robotic Sorting
End of Life
Electric machines
Energy Materials Group (Batteries)
Magnetic Materials Group (Motors)
Motor / generator
Magnet Manufacture
Cell Manufacture
Materials Synthesis
Cathode / Anode manufacture
Alloy development
Hydrogen Processing
BATTERY GIGAFACTORY
BATTERY GIGAFACTORY
MOTOR MANUFACTURING
MOTOR MANUFACTURING
Batteries
EV OEMs
Motors
Techno Economic Analysis
Policy and legislation
Life Cycle Analysis

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