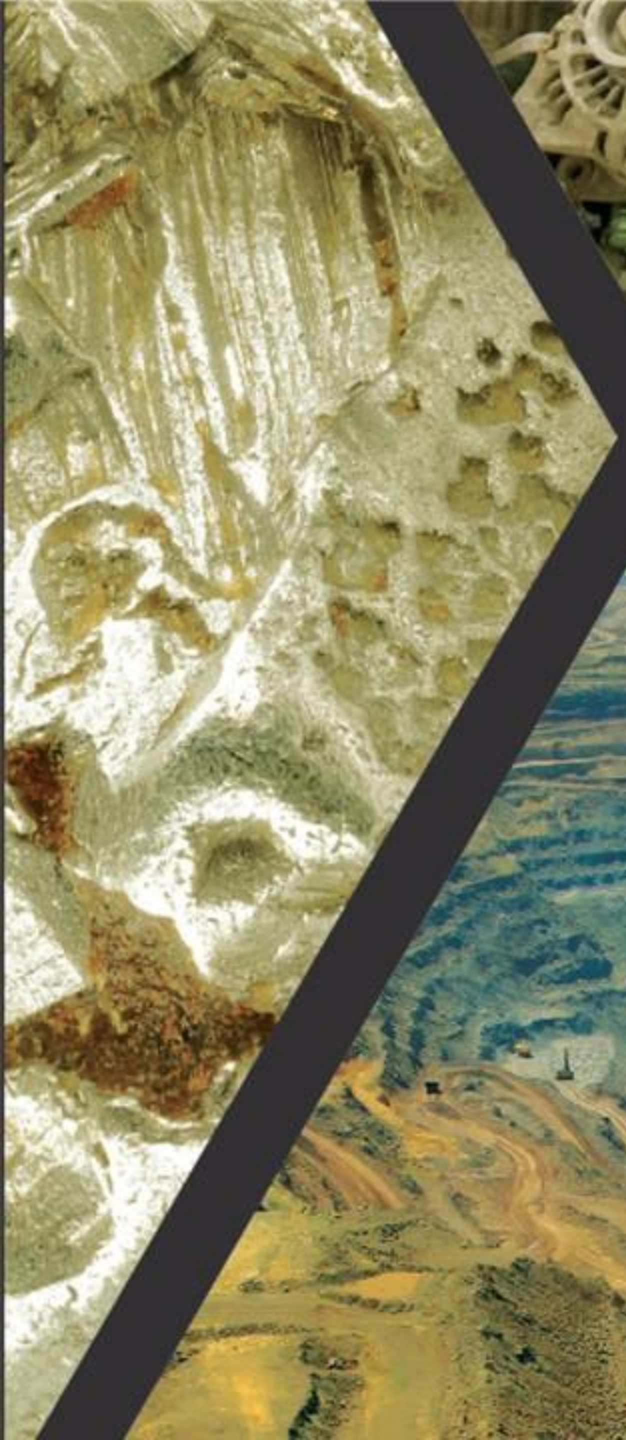


The crucial need to design for recycling to secure metal and CRM supply chains.

METAL RECYCLING EXPO

Introductory Keynote
Frankfurt, Germany, 18-Jun-2026 09:30 – 09:50
Main Expo Hall 3.0

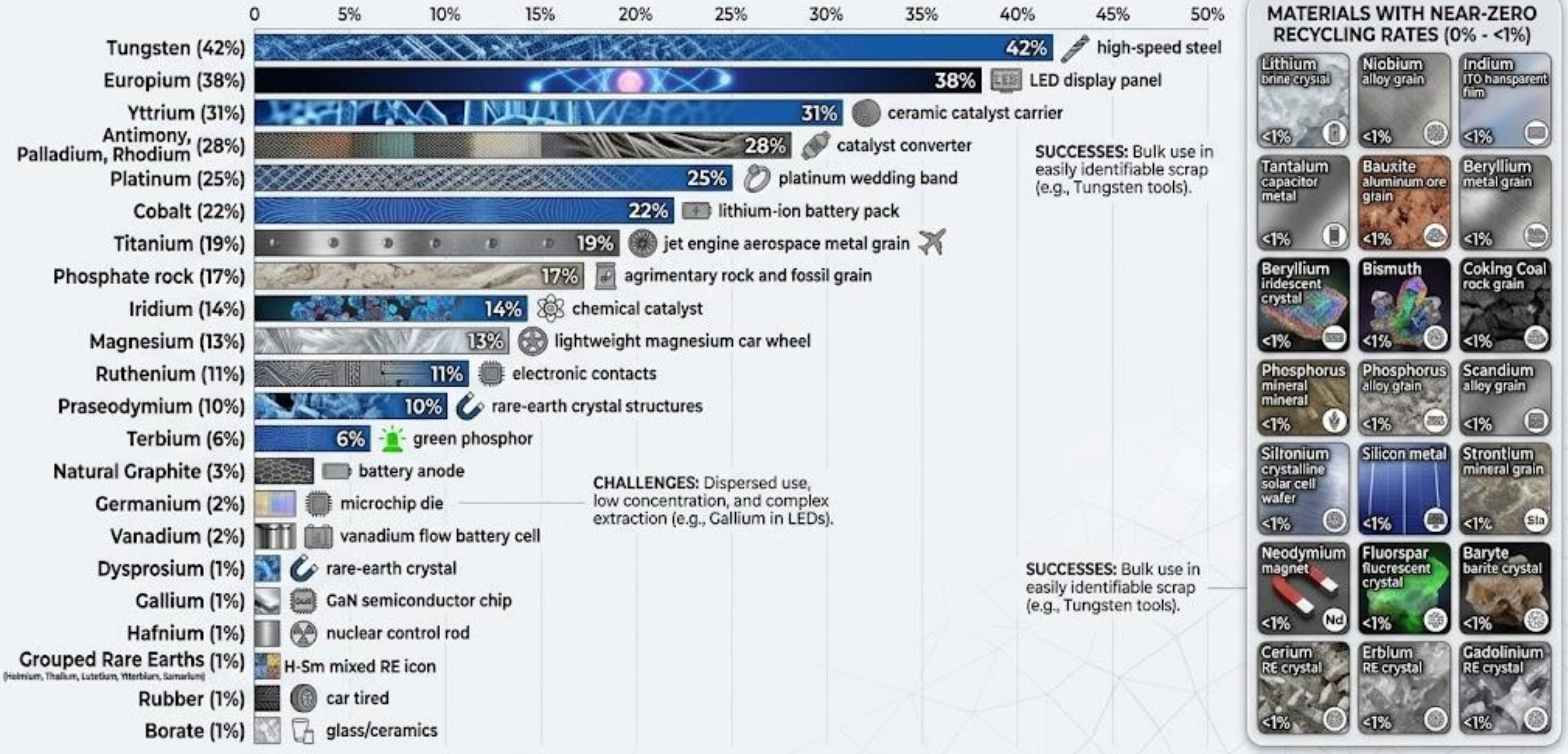
Dr. Gavin D. J. Harper

Critical Materials Research Fellow
Birmingham Business School
College of Social Sciences
University of Birmingham

Affiliated Researcher / Academic Collaborator
Cambridge Industrial Resilience Group
Institute for Manufacturing
University of Cambridge

EU CRITICAL RAW MATERIALS: GLOBAL END-OF-LIFE RECYCLING RATES (EoL-RR)

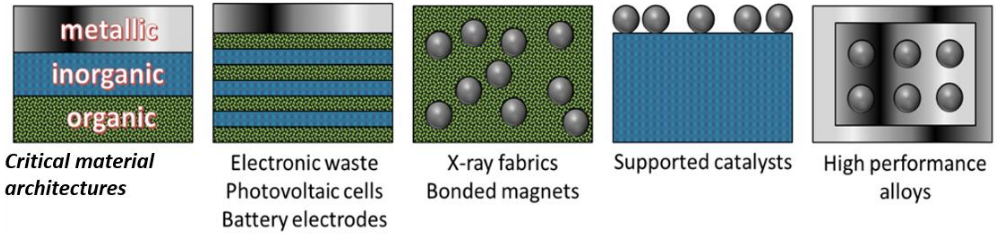
A comprehensive visualization based on European Commission Data



Dr. Gavin D. J. Harper gavin.wales g.d.j.harper@bham.ac.uk

Technology Critical Metals Are Finely Distributed Through Technology Products In A Variety of Ways.

Current physical separation techniques used in recycling often end up mixing materials together in ways that makes them difficult to separate.



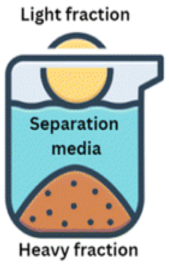
Current recycling processes are not suitable for many TCMs

A toolbox for improved recycling of critical metals and materials in low-carbon technologies

Guillaume Zante [a], Christopher E. Elgar [a], Jennifer M. Hartley [ae], Rudra Mukherjee [b], Jeff Kettle [b], Louise E. Horsfall [c], Allan Walton [de], Gavin D. J. Harper [de] and Andrew P. Abbott [*ae]

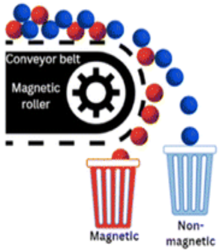
Density separation

- Separates metal from plastics, light metals from heavy metals...
- Wet (shaking table, heavy liquids) or dry (air table)



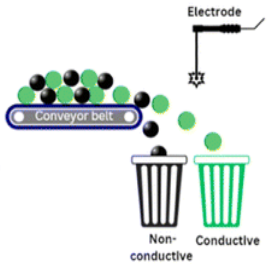
Magnetic separation

- Separates magnetic from non magnetic materials



Electrostatic separation

- Separates conductive from non conductive materials



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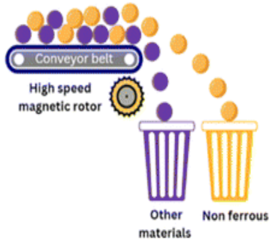
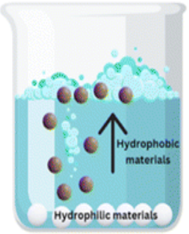
Eddy-current separation

- Separates non-ferrous metals from non conductive materials



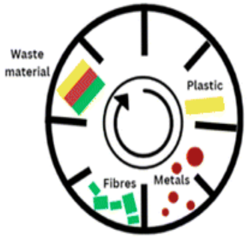
Froth floatation

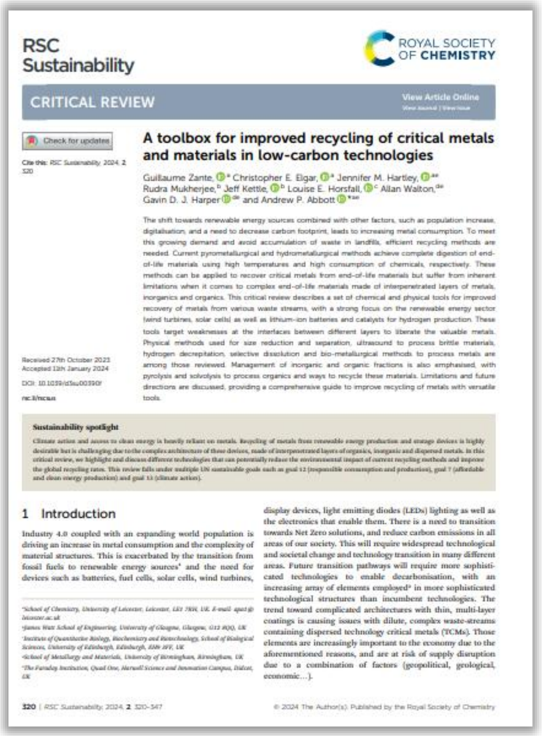
- Separates hydrophobic from hydrophilic materials



Fractionator

- High velocity impacts separates plastics, fibres and metals into fractions of different sizes

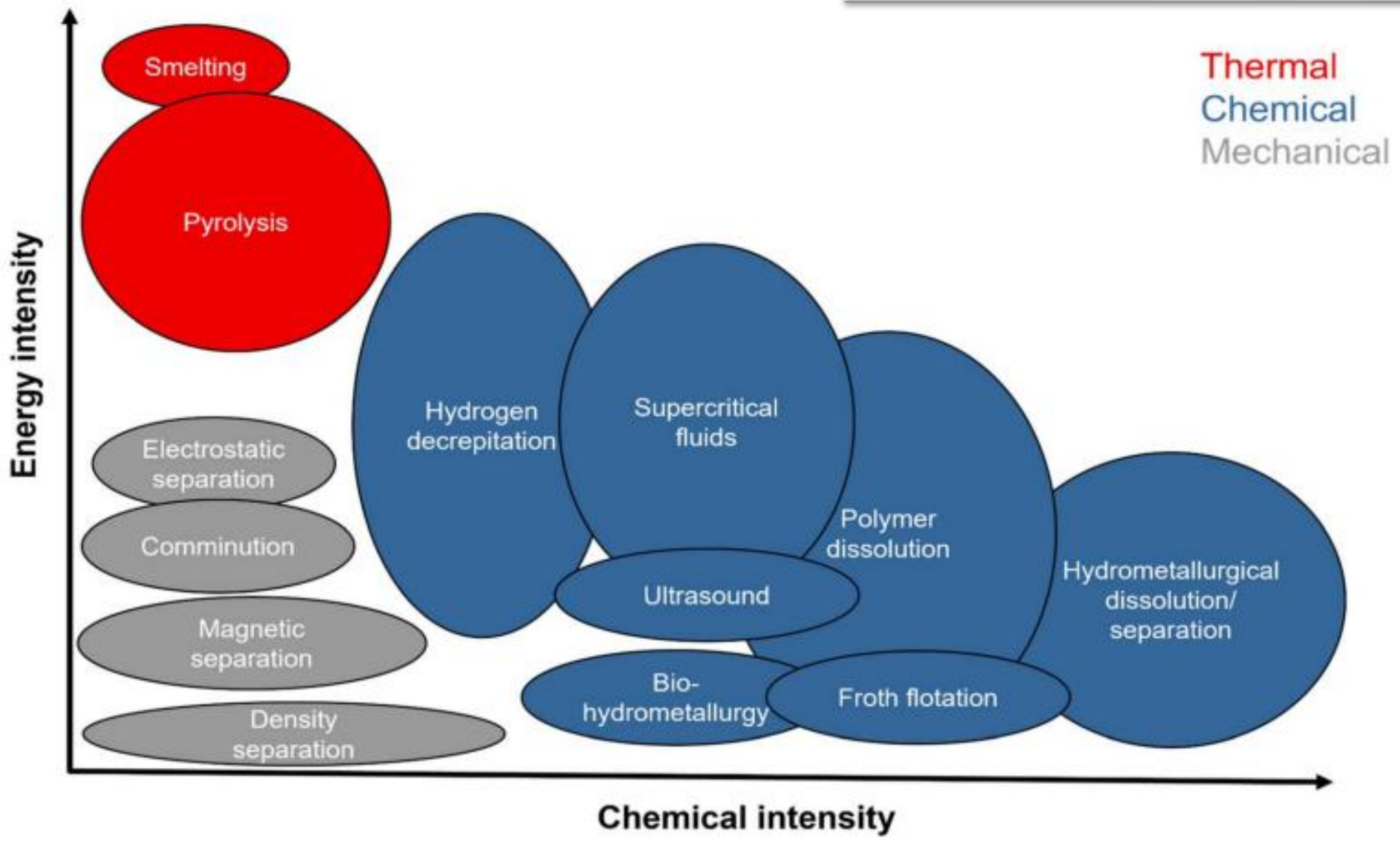



RSC Sustainability
ROYAL SOCIETY OF CHEMISTRY
CRITICAL REVIEW
A toolbox for improved recycling of critical metals and materials in low-carbon technologies
1 Introduction

Assessing the relative energy and chemical intensities of thermal, chemical and mechanical recycling processes.

Design for recycle of devices to ensure efficient recovery of technology critical metals

Molly E. Keal,[a] Sean Scott,[a] Bashayer N. N. Alsulami,[b] Jeff Kettle,[b] Andrew Feeney,[b] Jacqueline S. Edge,[c] Paul A. Anderson,[c] Gavin D. J. Harper,[c] Allan Walton,[c] Guillaume Zante[d] and Andrew P. Abbott*[a]



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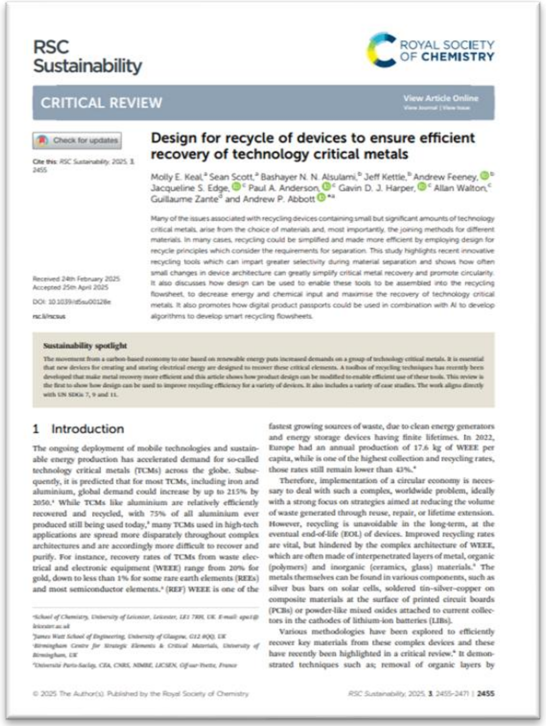
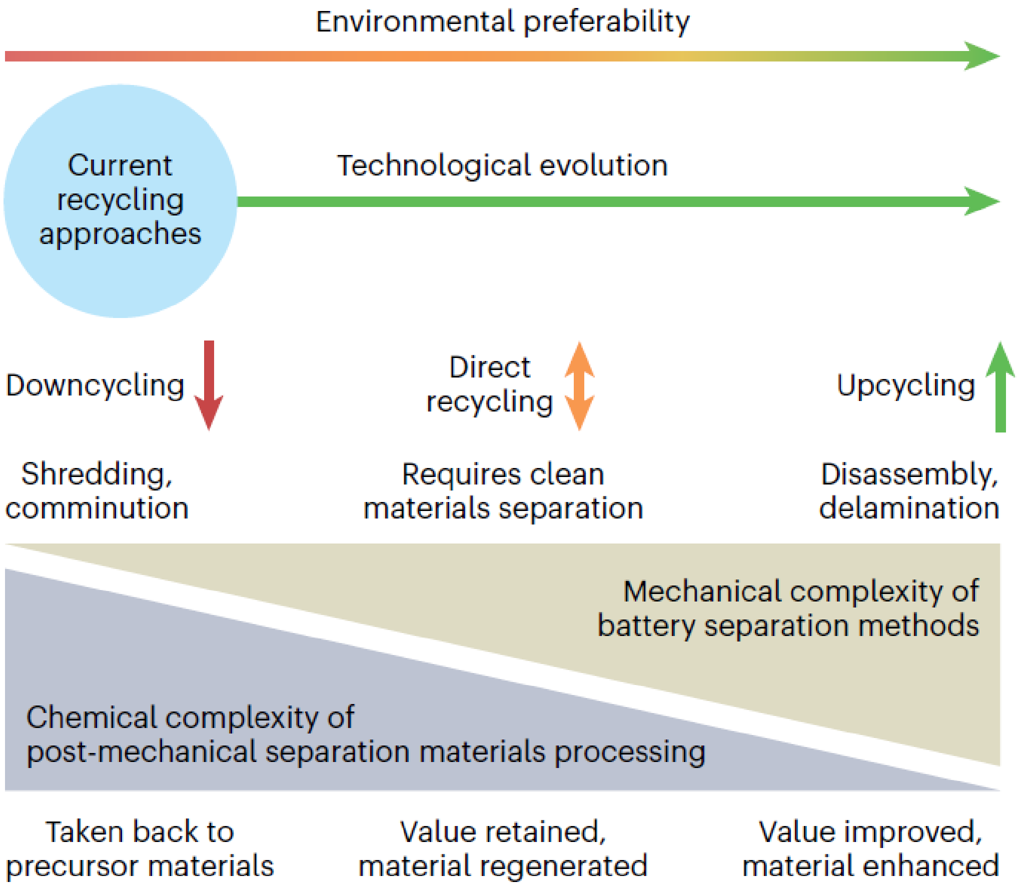


Current recycling techniques downcycle materials; environmentally preferable recycling techniques will preserve and even upcycle the value of the materials.

Harper, G.D.J. Upcycle for enhanced performance. *Nat Sustain* **6**, 725–726 (2023). https://doi.org/10.1038/s41893-023-01090-z



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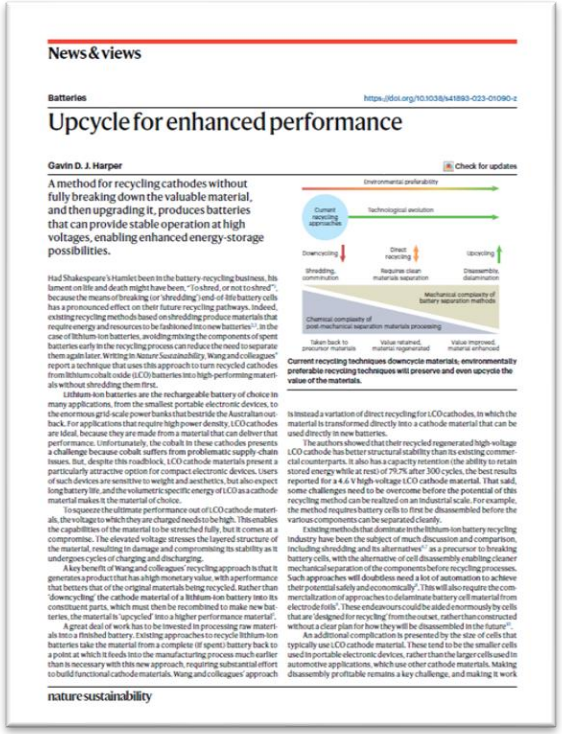

News & views

Batteries

https://doi.org/10.1038/s41893-023-01090-z

Upcycle for enhanced performance

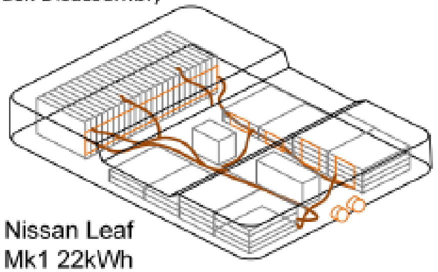
Gavin D. J. Harper

A method for recycling cathodes without fully breaking down the valuable material, and then upgrading it, produces batteries that can provide stable operation at high voltages, enabling enhanced energy-storage possibilities.

nature sustainability

Dr. Gavin D. J. Harper gavin.wales g.d.j.harper@bham.ac.uk

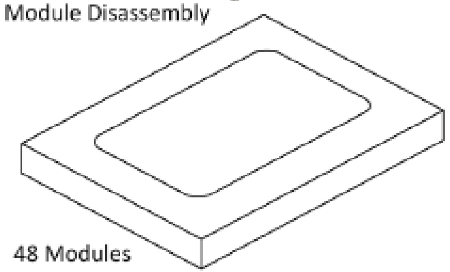
Pack Disassembly



Nissan Leaf
Mk1 22kWh
Battery Pack

- Removal of wiring looms tricky
- Manipulation of connectors (especially where locking tabs fitted)
- High voltages until wiring loom / module links removed
- Lack of data on module condition in many present EV batteries
- Lack of labelling and identifying marks
- Potential fire hazards
- Potential HF off-gassing

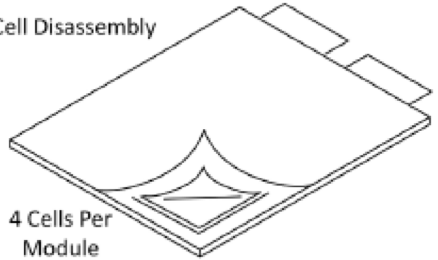
Module Disassembly



48 Modules
Per Pack

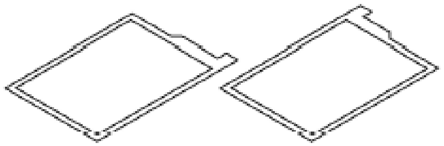
- Sealants may be used in module manufacture (difficult to remove)
- Cells stuck together in modules with adhesives (difficult to separate)
- Components may be soldered together (difficult to separate)
- Module state of charge may not be known

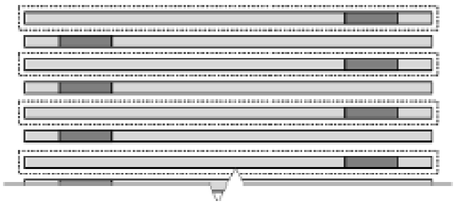
Cell Disassembly



4 Cells Per
Module

- Clean separation of anodes and cathode for direct recycling difficult.
- Very finely powdered materials present risks (nanoparticles)
- Potential for HF compounds formed from electrolyte
- Potential for thermal effects if cells shorted during disassembly
- Chemistries not always known / proprietary
- Additional challenges with cylindrical cells (unwinding spiral)
- Disassembly of stacked structure with encapsulated anodes.





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,*]

A schematic diagram showing the structure of a battery pack, module and cell and the challenges presented at each stage for battery disassembly (Expanded from Harper et.al., 2019).

Resources, Conservation & Recycling


Resources, Conservation & Recycling

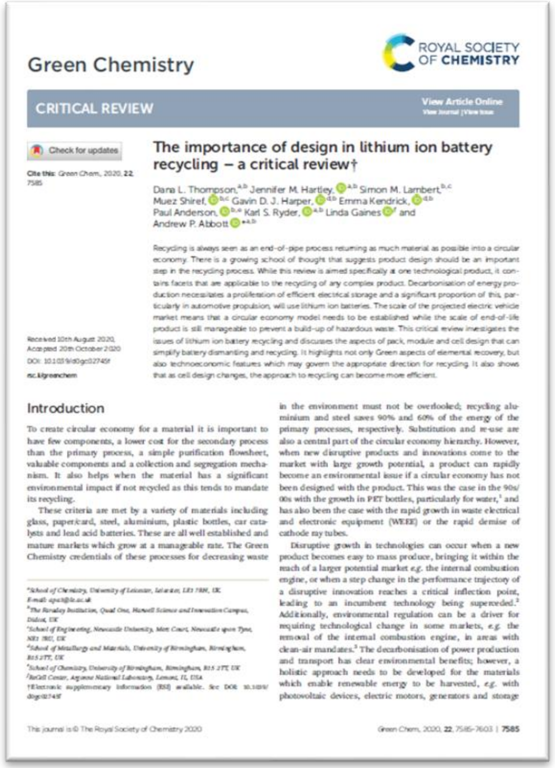
To shred or not to shred: A comparative techno-economic assessment of lithium ion battery hydrometallurgical recycling retaining value and improving circularity in LIB supply chains

(a) Pouch cell tabs ultrasonically welded to copper busbar, (b) module interconnections utilising threaded bolts through solid busbars (c) dismantling
of pack sub-assemblies using standard shop tooling – all Nissan Leaf 1st generation

The importance of design in lithium ion battery recycling – a critical review†

Dana L. Thompson,[a,b] Jennifer M. Hartley,[a,b] Simon M. Lambert,[b,c] Muez Shiref,[b,c] Gavin D. J. Harper,[d,b] Emma Kendrick,[d,b] Paul Anderson,[b,e] Karl S. Ryder,[a,b] Linda Gaines[f] and Andrew P. Abbott *[a,b]

Green Chemistry


Green Chemistry

ROYAL SOCIETY OF CHEMISTRY

CRITICAL REVIEW

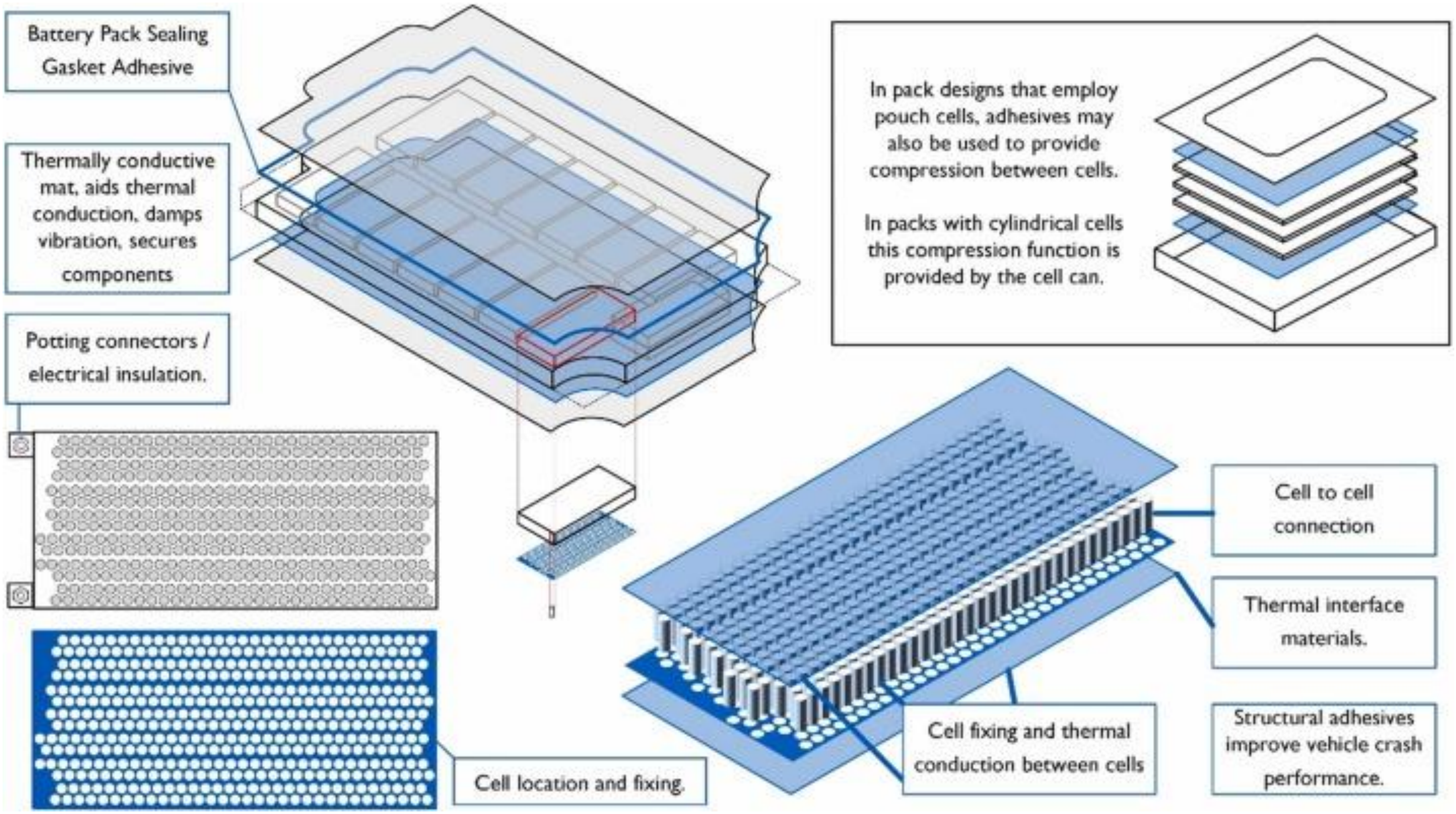
The importance of design in lithium ion battery recycling – a critical review†

Introduction

Examples of where structural adhesives are used within a battery pack using cylindrical cells.

Designing lithium-ion batteries for recycle: The role of adhesives

Sean Scott[a,b], Zayd Islam[a,b], Jack Allen[a,b], Tanongsak Yingnakorn[a,b], Ali Alflakian[b,c], Jamie Hathaway[b,c], Alireza Rastegarpanah[b,c], Gavin D.J. Harper[b,c], Emma Kendrick[b,c], Paul A. Anderson[b,d], Jacqueline Edge[b,e], Laura Lander[b,f], Andrew P. Abbott[a,b,*]




Next Energy

Research article

Designing lithium-ion batteries for recycle: The role of adhesives

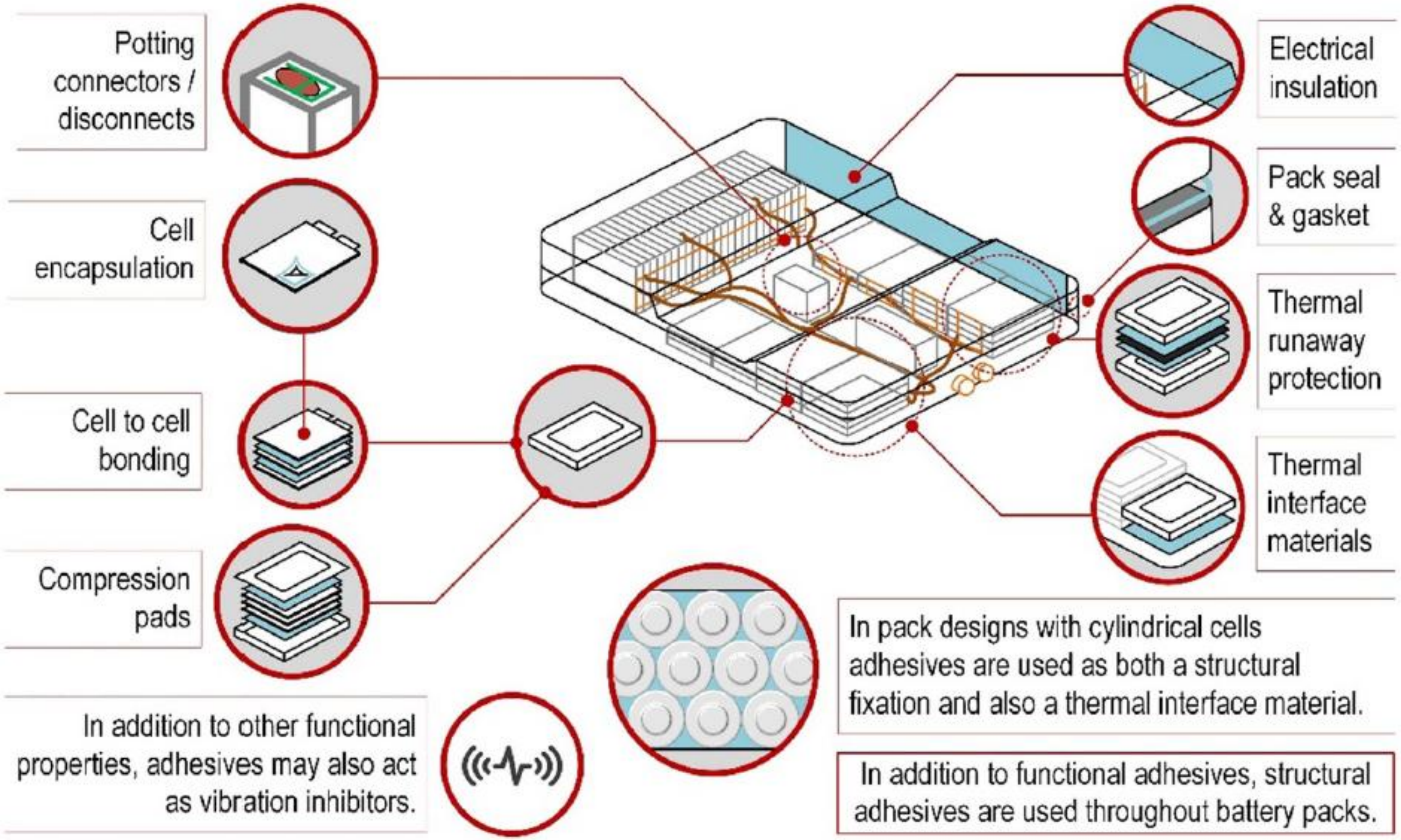
Schematic diagram showing some of the uses of structural adhesives in a typical battery pack

8. Cell disassembly and design for recycling

Andrew P Abbott[1], *Dana Thompson*[1] *and Gavin D J Harper*[2]

[1] School of Chemistry, University of Leicester, Leicester LE1 7RH, United Kingdom

[2] School of Metallurgy and Materials, University of Birmingham, Birmingham B15 2TT, United Kingdom



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Journal of Physics: Energy

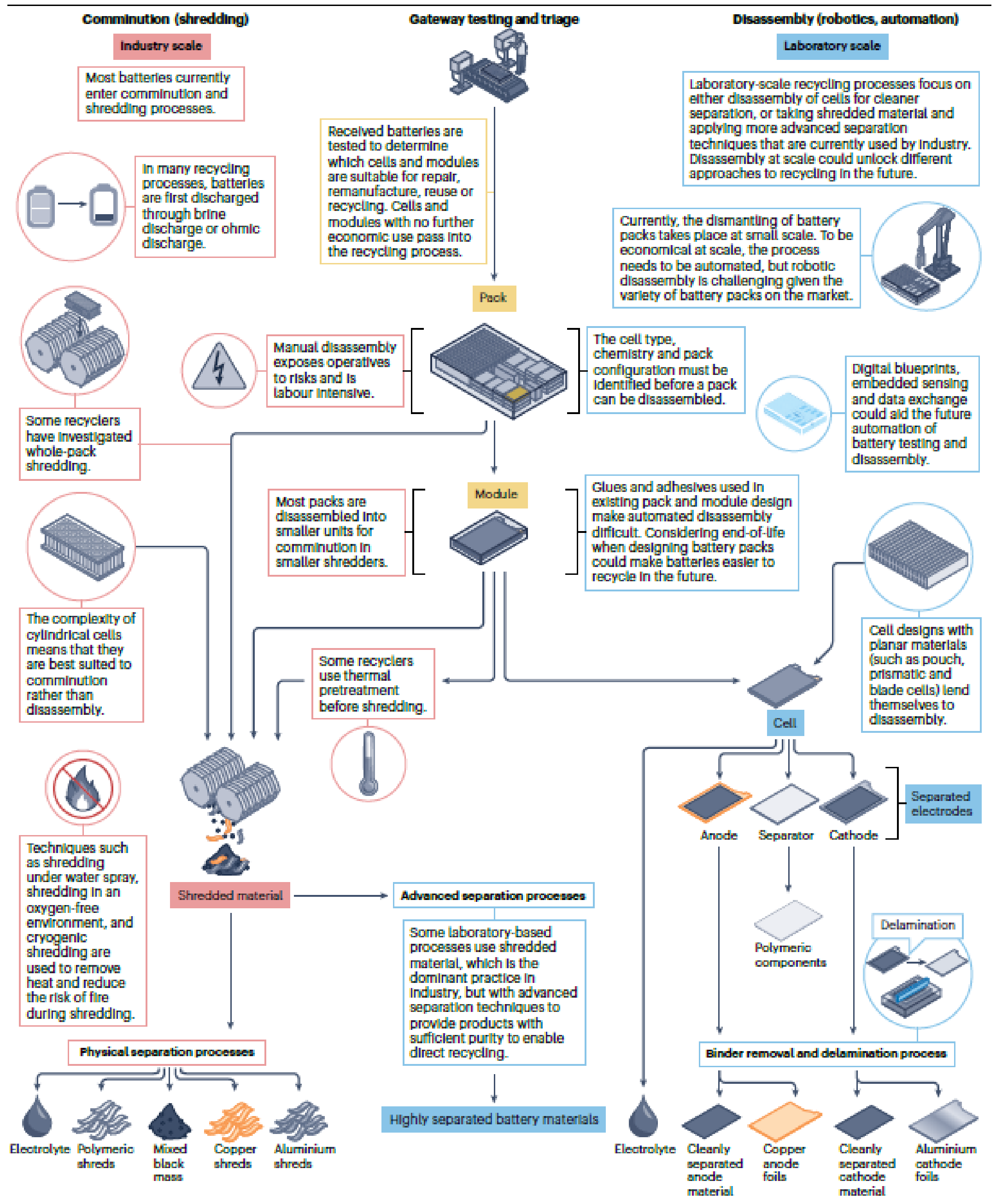
ROADMAP

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

Keywords: recycling, batteries, circular economy, lithium-ion, legislation, sustainability

Abstract

The market dynamics, and their impact on a future circular economy for lithium-ion batteries (LIB), are presented in this roadmap, with safety as an integral consideration throughout the life cycle. At the point of end-of-life (EOL), there is a range of potential options—remanufacturing, reuse and recycling. Diagnostics play a significant role in evaluating the state-of-health and condition of batteries, and improvements to diagnostic techniques are evaluated. At present, manual disassembly dominates EOL disposal, however, given the volumes of future batteries that are to be anticipated, automated approaches to the dismantling of EOL battery packs will be key. The first stage in recycling after the removal of the cells is the initial cell-breaking or opening step.



The evolution of lithium-ion battery recycling

Xiaotu Ma[1,9], Zifei Meng[1,9], Marilena Velonia Bellonia[2], Jeffrey Spangenberger[3], Gavin Harper[4,5], Eric Gratz[6], Elsa Olivetti[7], Renata Arsenault[8] & Yan Wang[1]

Future approaches to Lithium Ion Battery Recycling which recover the maximum amount of material at end of life will require "disassembly" rather than comminution in order to recover the maximum material. A design for recycling approach will aid this.

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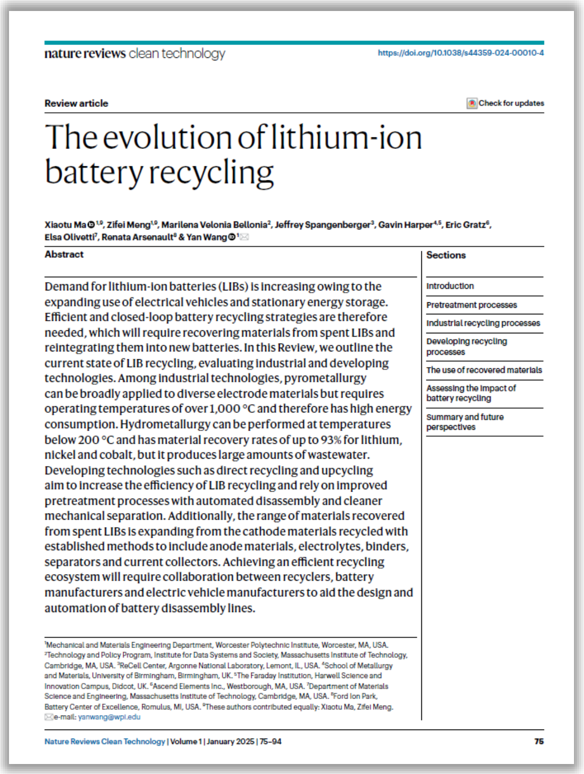

nature reviews clean technology https://doi.org/10.1038/s44359-024-00010-4

Review article Check for updates

The evolution of lithium-ion battery recycling

Xiaotu Ma[1,9], Zifei Meng[1,9], Marilena Velonia Bellonia[2], Jeffrey Spangenberger[3], Gavin Harper[4,5], Eric Gratz[6], Elsa Olivetti[7], Renata Arsenault[8] & Yan Wang[1]

Abstract

Demand for lithium-ion batteries (LIBs) is increasing owing to the expanding use of electrical vehicles and stationary energy storage. Efficient and closed-loop battery recycling strategies are therefore needed, which will require recovering materials from spent LIBs and reintegrating them into new batteries. In this Review, we outline the current state of LIB recycling, evaluating industrial and developing technologies. Among industrial technologies, pyrometallurgy can be broadly applied to diverse electrode materials but requires operating temperatures of over 1,000 °C and therefore has high energy consumption. Hydrometallurgy can be performed at temperatures below 200 °C and has material recovery rates of up to 93% for lithium, nickel and cobalt, but it produces large amounts of wastewater. Developing technologies such as direct recycling and upcycling aim to increase the efficiency of LIB recycling and rely on improved pretreatment processes with automated disassembly and cleaner mechanical separation. Additionally, the range of materials recovered from spent LIBs is expanding from the cathode materials recycled with established methods to include anode materials, electrolytes, binders, separators and current collectors. Achieving an efficient recycling ecosystem will require collaboration between recyclers, battery manufacturers and electric vehicle manufacturers to aid the design and automation of battery disassembly lines.

Sections

[1]Mechanical and Materials Engineering Department, Worcester Polytechnic Institute, Worcester, MA, USA. [2]Technology and Policy Program, Institute for Data Systems and Society, Massachusetts Institute of Technology, Cambridge, MA, USA. [3]ReCell Center, Argonne National Laboratory, Lemont, IL, USA. [4]School of Metallurgy and Materials, University of Birmingham, Birmingham, UK. [5]The Faraday Institution, Harwell Science and Innovation Campus, Didcot, UK. [6]Ascend Elements Inc., Westborough, MA, USA. [7]Department of Materials Science and Engineering, Massachusetts Institute of Technology, Cambridge, MA, USA. [8]Ford Ion Park, Battery Center of Excellence, Romulus, MI, USA. [9]These authors contributed equally: Xiaotu Ma, Zifei Meng. e-mail: yanwang@wpi.edu

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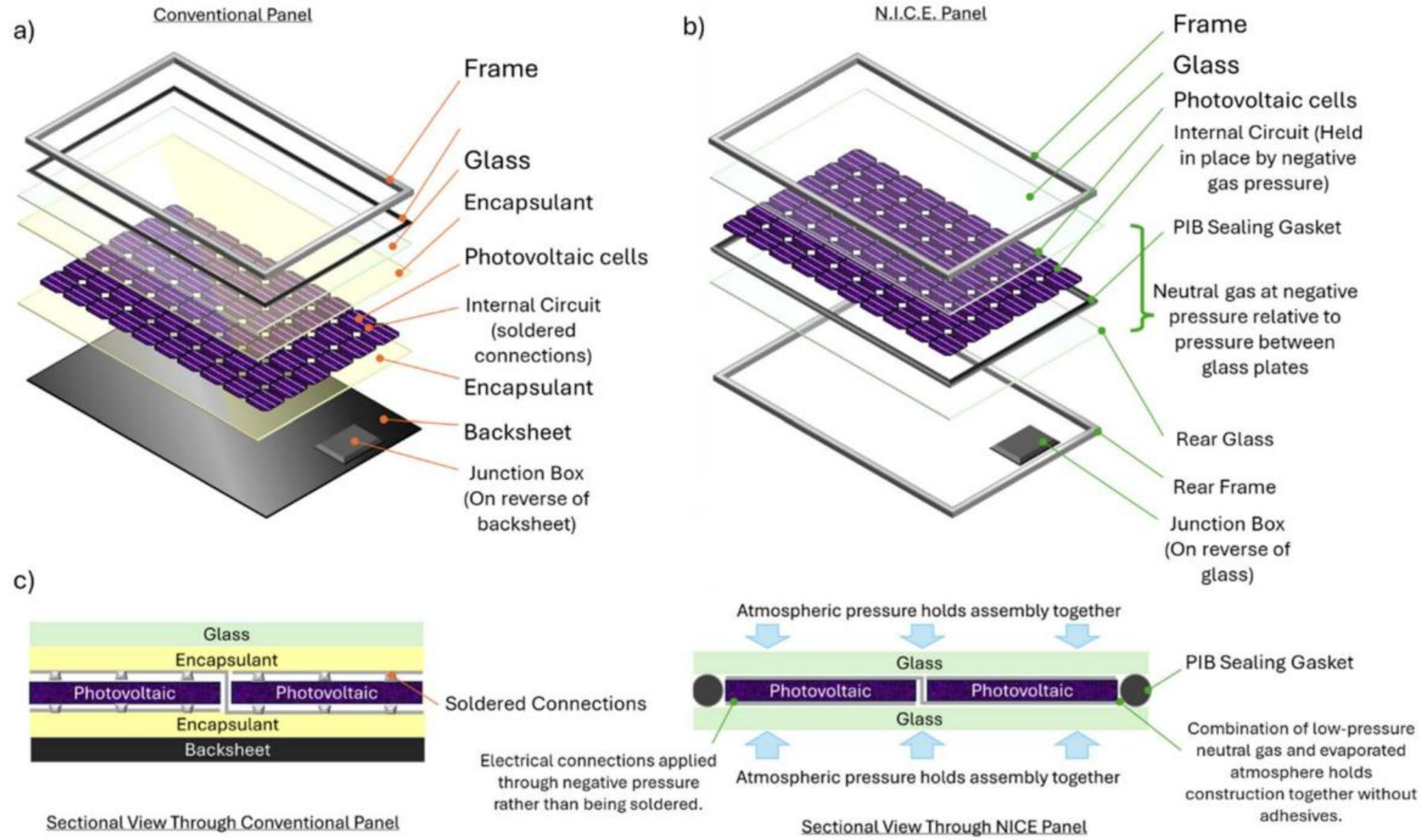
Contrasting a traditional structure of a PV module with polymer encapsulation, to the “NICE” technology module which is designed for easy disassembly at the end of life.

Design for recycle of devices to ensure efficient recovery of technology critical metals

Molly E. Keal,[a] Sean Scott,[a] Bashayer N. N. Alsulami,[b] Jeff Kettle,[b] Andrew Feeney,[b] Jacqueline S. Edge,[c] Paul A. Anderson,[c] Gavin D. J. Harper,[c] Allan Walton,[c] Guillaume Zante[d] and Andrew P. Abbott*[a]



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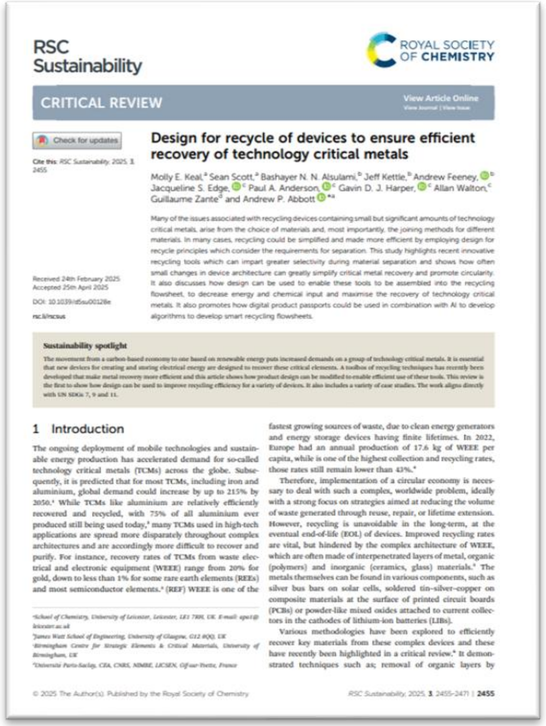

A matrix of fixing methods ranked for 'Ease of Disassembly' on the x-axis and 'Ease of Reassembly' on the y-axis.

Design for recycle of devices to ensure efficient recovery of technology critical metals

Molly E. Keal,[a] Sean Scott,[a] Bashayer N. N. Alsulami,[b] Jeff Kettle,[b] Andrew Feeney,[b] Jacqueline S. Edge,[c] Paul A. Anderson,[c] Gavin D. J. Harper,[c] Allan Walton,[c] Guillaume Zante[d] and Andrew P. Abbott[*a]

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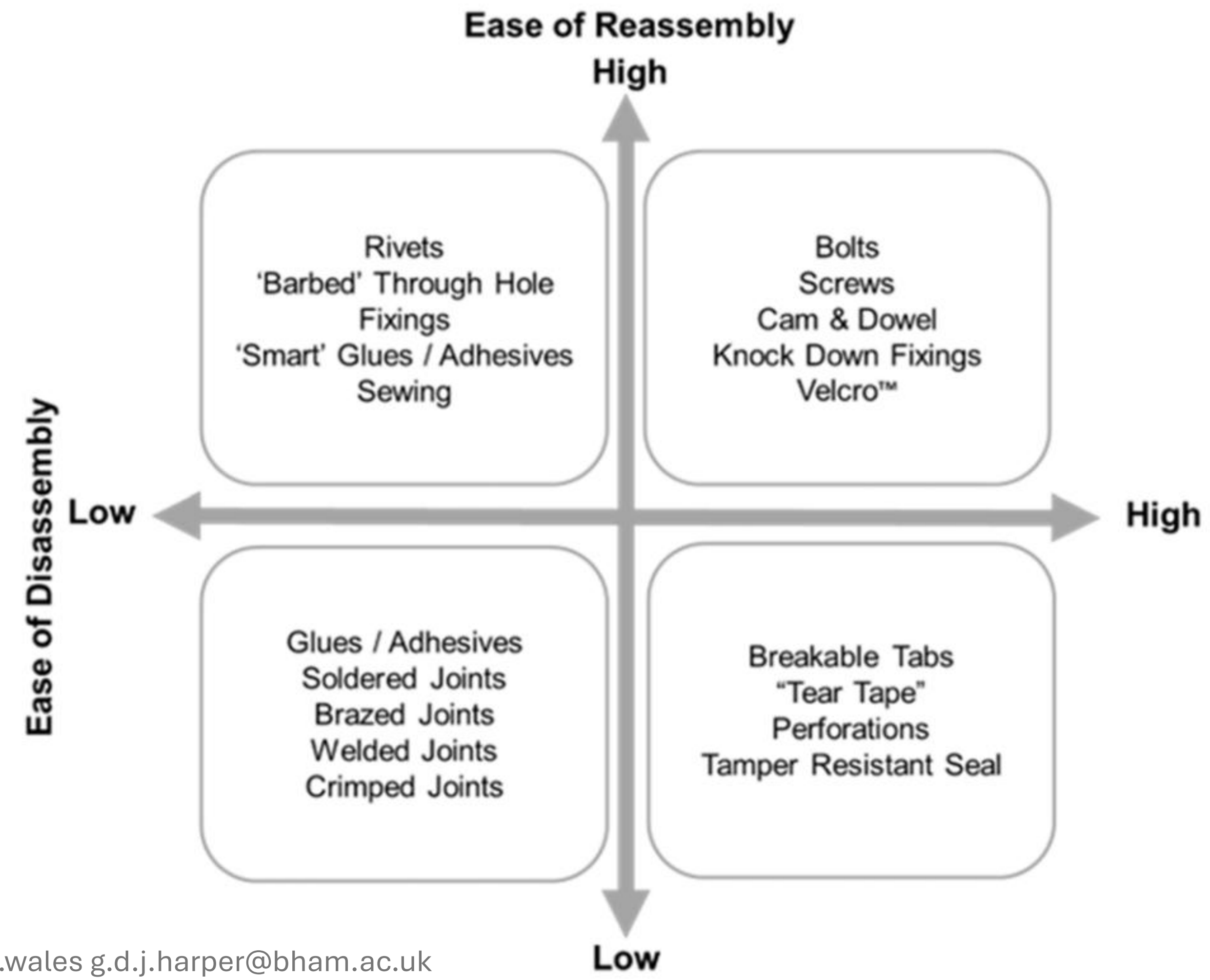

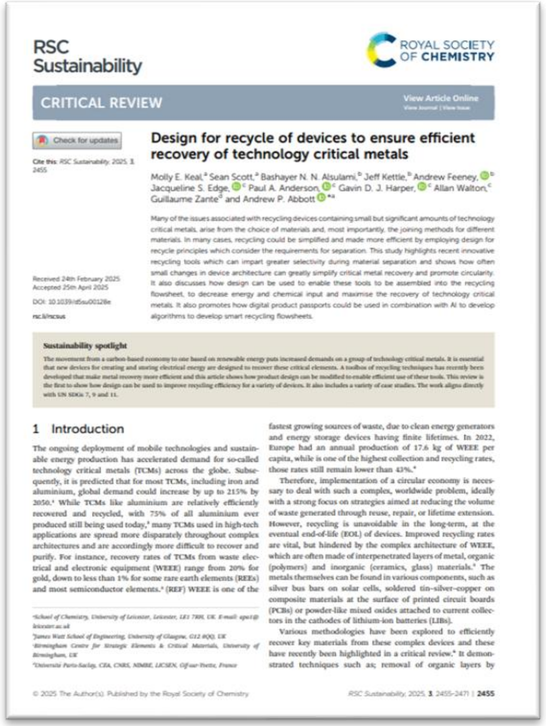

Potential design for recycle tools along with example applications and their respective advantages and disadvantages

Design for recycle of devices to ensure efficient recovery of technology critical metals

Molly E. Keal,[a] Sean Scott,[a] Bashayer N. N. Alsulami,[b] Jeff Kettle,[b] Andrew Feeney,[b] Jacqueline S. Edge,[c] Paul A. Anderson,[c] Gavin D. J. Harper,[c] Allan Walton,[c] Guillaume Zante[d] and Andrew P. Abbott[*a]

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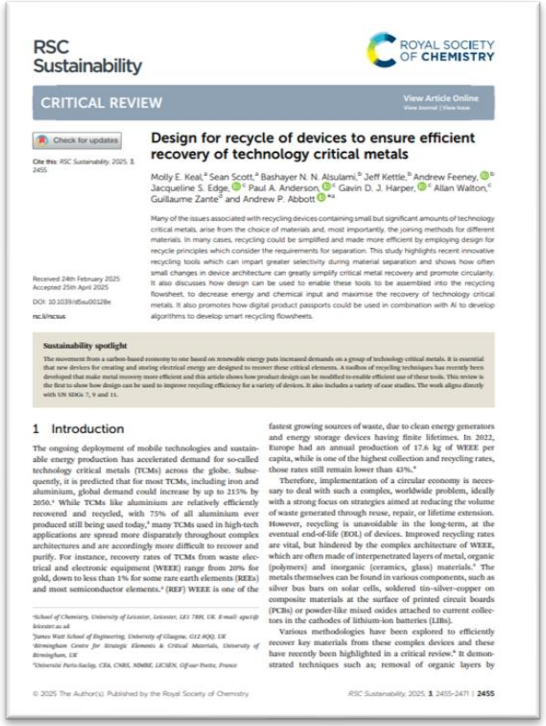
Table 2 Potential design for recycle tools along with example applications and their respective advantages and disadvantages

Tool	Potential application	Advantages	Disadvantages
Etchable substrate under TCMs	Supported PGM catalysts or PCBs	Easier recovery of TCMs	Performance?
Additive manufacturing	Electronic circuitry	Easier assembly	May slow production
Fewer metals in alloys	Aerospace metals	More applications of recycled alloy	Performance?
More easily detachable tech	Speakers in cars or portable electronics, electric motors, replaceable batteries	Pre-concentration of TCMs	Trained disassembly required
Biodegradable composites	Electronic circuitry, wind turbine blades	Reduced EoL waste	Potential degradation in service
Water/solvent dispersible binders	LIBs	Easier to recycle, reduces use of harmful solvents during manufacturing	Need to ensure sufficient stability during use
Design for expected life	All technology	Get the most value out of components during initial use	Critical materials tied up in technology for longer. Can be at odds with design for recycle
Design out TCMs	LIBs, aerospace alloys	Reduces initial costs of manufacturing	Less economic incentive to recycle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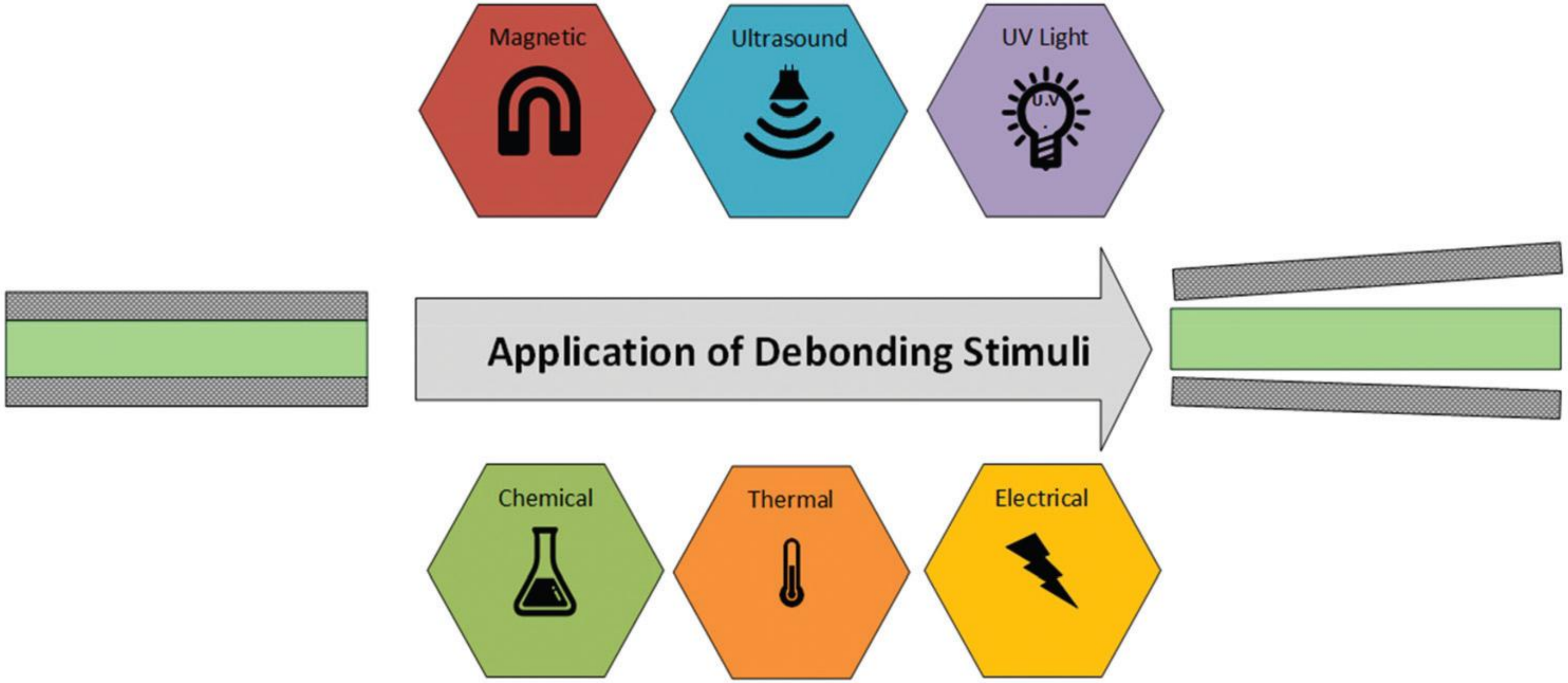
ROYAL SOCIETY OF CHEMISTRY
CRITICAL REVIEW
Design for recycle of devices to ensure efficient recovery of technology critical metals
1 Introduction

Schematic representation of the debonding process using different stimuli.

Debondable adhesives and their use in recycling

Kira R. Mulcahy,[a,b] Alexander F. R. Kilpatrick,[a] Gavin D. J. Harper,[c] Allan Walton[c] and Andrew P. Abbott *[a]

Green Chemistry

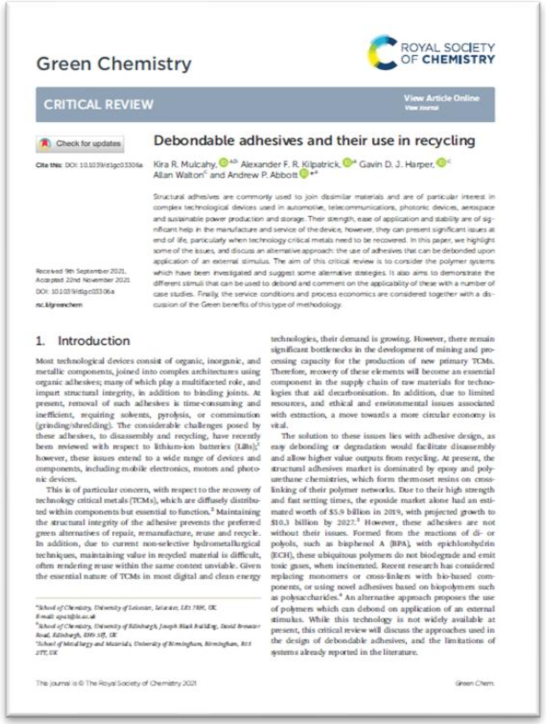


Summary of debonding stimuli, functional groups and applicability

Debondable adhesives and their use in recycling

Kira R. Mulcahy,[a,b] Alexander F. R. Kilpatrick,[a] Gavin D. J. Harper,[c] Allan Walton[c] and Andrew P. Abbott *[a]

Stimulus	UV Light	Thermal	Electrical	Chemical	Magnetic	Ultrasound
Potential uses	Thin transparent materials	Inorganic and metallic components	Bonding metals and conductive substrates	Reactive composite adhesives with stable substrates	Biological/ electronic applications	Better for weak adhesive bonds
Limitations	Opaque additives	Equipment operating at high temp. Non-thermally stable/ conductive substrates. Metals when using microwave radiation	Non-metals Non-conductive substrates (these must be bonded with an intermediate patch)	Needs to not etch the substrate	Magnetic substrates	Needs to be wet recycle process
Notes	Harder with complex geometries	Potentially applicable to most adhesives	Better for thin samples	Diffusion can be slow	Low cost, easy to develop	Surface wetting important



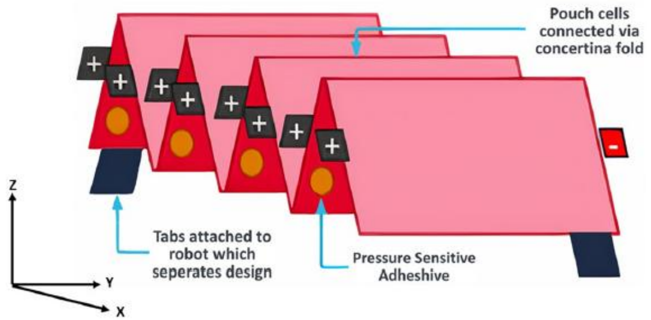
Dr. Gavin D. J. Harper gavin.wales g.d.j.harper@bham.ac.uk

Prototyping batteries in “design for Recycling” configurations.

Designing lithium-ion batteries for recycle: The role of adhesives

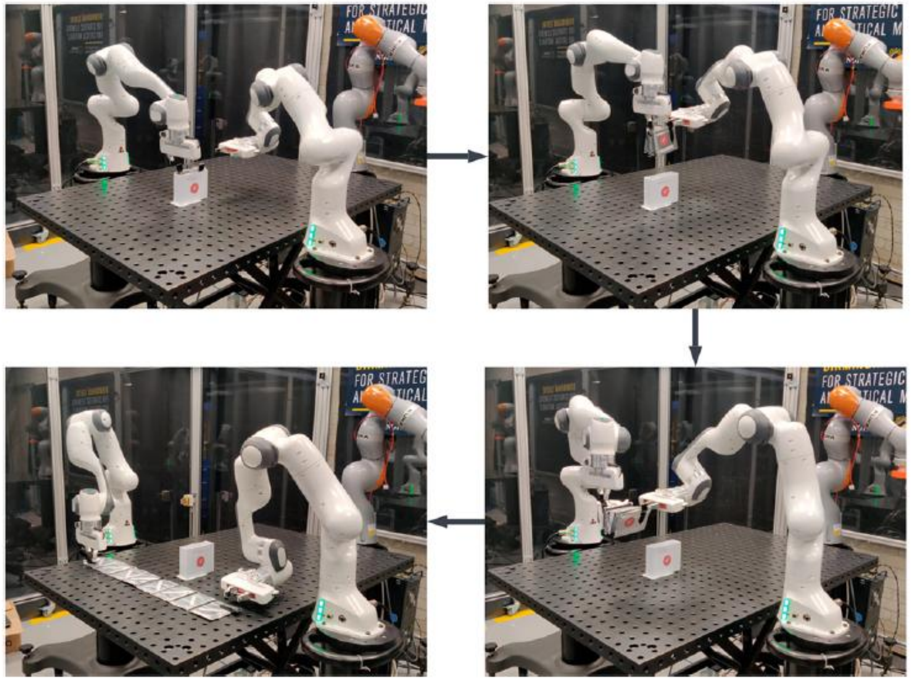
Sean Scott[a,b], Zayd Islam[a,b], Jack Allen[a,b], Tanongsak Yingnakorn[a,b], Ali Alflakian[b,c], Jamie Hathaway[b,c], Alireza Rastegarpanah[b,c], Gavin D.J. Harper[b,c], Emma Kendrick[b,c], Paul A. Anderson[b,d], Jacqueline Edge[b,e], Laura Lander[b,f], Andrew P. Abbott[a,b,*]

a



b

Images showing the stages of robotic module opening when the zigzag cell conformation is used. This process takes place over the course of 15 s.



The proposed zigzag conformation for pouch cells. a) image of the dummy cell used in these experiments and b) the schematic diagram for the conformation
showing placement of the adhesives.


Next Energy

Research article

Designing lithium-ion batteries for recycle: The role of adhesives

1. Introduction

RESCu-M²

TECHNOLOGY ROADMAP

Forward view of the RESCu-M² research programme, Q3 2026 onwards

Dr. Gavin D. J. Harper gavin.wales g.d.j.harper@bham.ac.uk

End-of-life management for wind turbines

Fanran Meng[1] ✉, Jennifer L. Hawkin[1], Lukas Gast[2,3], Stella Job[4], Conchúr M. Ó Brádaigh[1], Jonathan M. Cullen[5], Gary A. Leeke[6], Jon McKechnie[7], Allan K. Poulsen[8], Rachael Rothman[1,9], Anthony J. Ryan[9,10], Iain Todd[1], Allan Walton[11,12], Gavin D. J. Harper[11,12], Zhifeng Yang[13] & Lixiao Zhang[14] ✉

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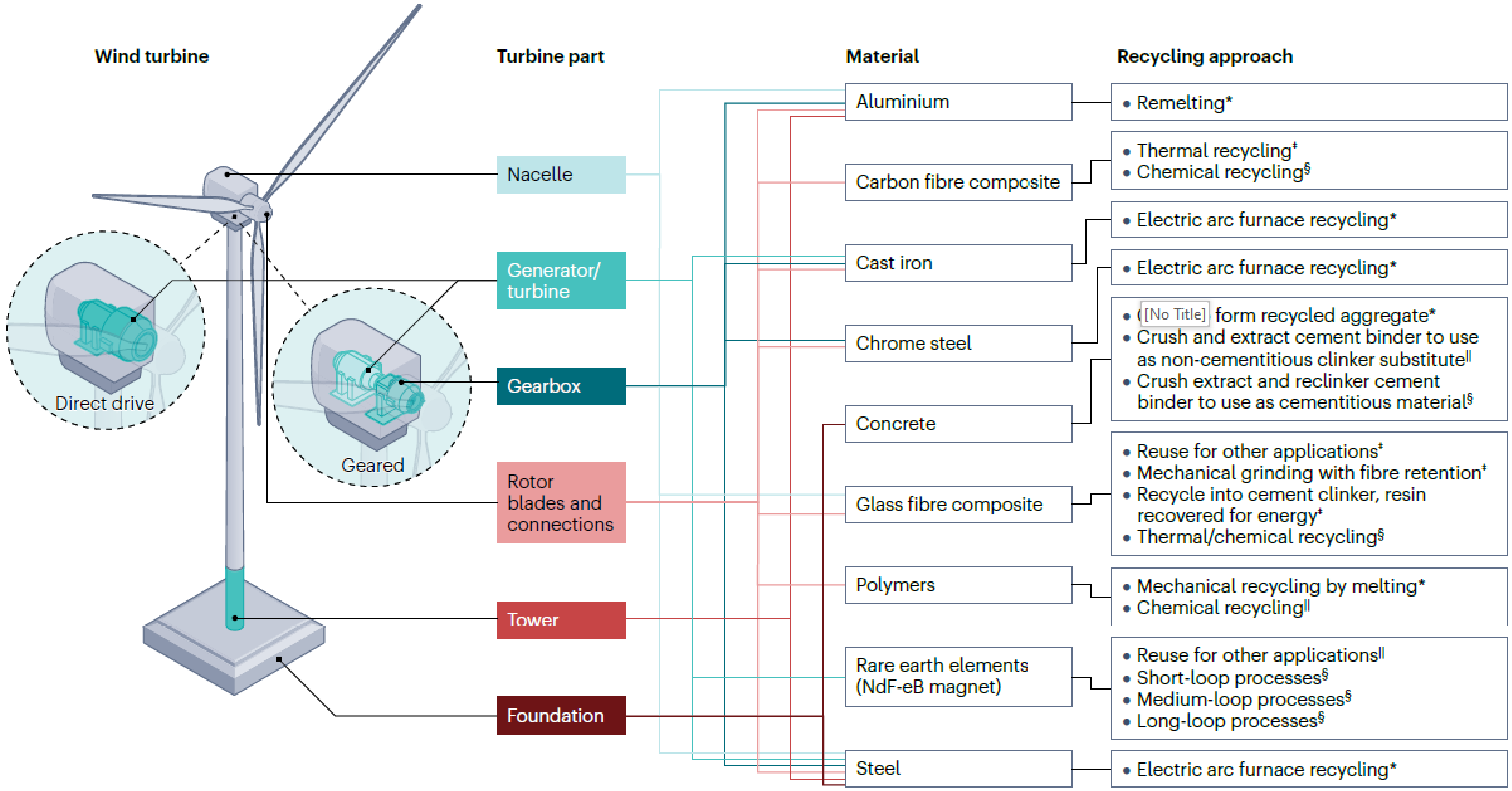

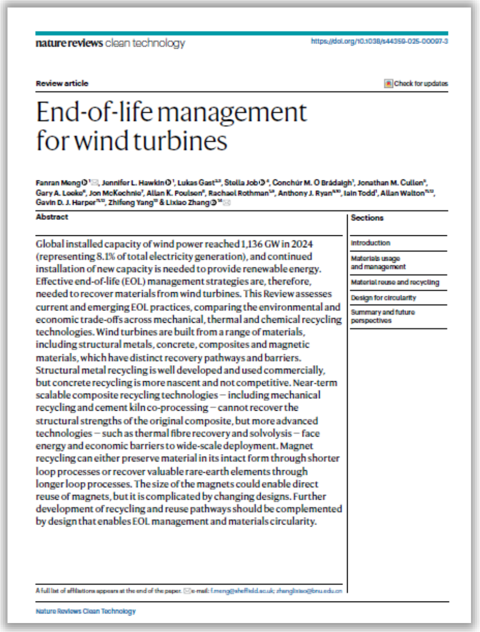

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Review article

End-of-life management for wind turbines

Fanran Meng[1] ✉, Jennifer L. Hawkin[1], Lukas Gast[2,3], Stella Job[4], Conchúr M. Ó Brádaigh[1], Jonathan M. Cullen[5], Gary A. Leeke[6], Jon McKechnie[7], Allan K. Poulsen[8], Rachael Rothman[1,9], Anthony J. Ryan[9,10], Iain Todd[1], Allan Walton[11,12], Gavin D. J. Harper[11,12], Zhifeng Yang[13] & Lixiao Zhang[14] ✉

Abstract

Global installed capacity of wind power reached 1,136 GW in 2024 (representing 8.1% of total electricity generation), and continued installation of new capacity is needed to provide renewable energy. Effective end-of-life (EOL) management strategies are, therefore, needed to recover materials from wind turbines. This Review assesses current and emerging EOL practices, comparing the environmental and economic trade-offs across mechanical, thermal and chemical recycling technologies. Wind turbines are built from a range of materials, including structural metals, concrete, composites and magnetic materials, which have distinct recovery pathways and barriers. Structural metal recycling is well developed and used commercially, but concrete recycling is more nascent and not competitive. Near-term scalable composite recycling technologies – including mechanical recycling and cement kiln co-processing – cannot recover the structural strengths of the original composite, but more advanced technologies – such as thermal fibre recovery and solvolysis – face energy and economic barriers to wide-scale deployment. Magnet recycling can either preserve material in its intact form through shorter loop processes or recover valuable rare-earth elements through longer loop processes. The size of the magnets could enable direct reuse of magnets, but it is complicated by changing designs. Further development of recycling and reuse pathways should be complemented by design that enables EOL management and materials circularity.

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Materials usage and management
Material reuse and recycling
Design for circularity
Summary and future perspectives

A full list of affiliations appears at the end of the paper. ✉e-mail: f.meng@sheffield.ac.uk; zhanglixiao@bnu.edu.cn

Please get in touch:

g.d.j.harper@bham.ac.uk

@gavindjharper

https://www.linkedin.com/in/gavindjharper/

gavin.wales

UNIVERSITY OF BIRMINGHAM
Birmingham Business School

BIRMINGHAM CENTRE
FOR STRATEGIC ELEMENTS
AND CRITICAL MATERIALS

IfM Industrial Resilience Research Group

UNIVERSITY OF CAMBRIDGE