



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

MET  **L**
RECYCLING
EXPO

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

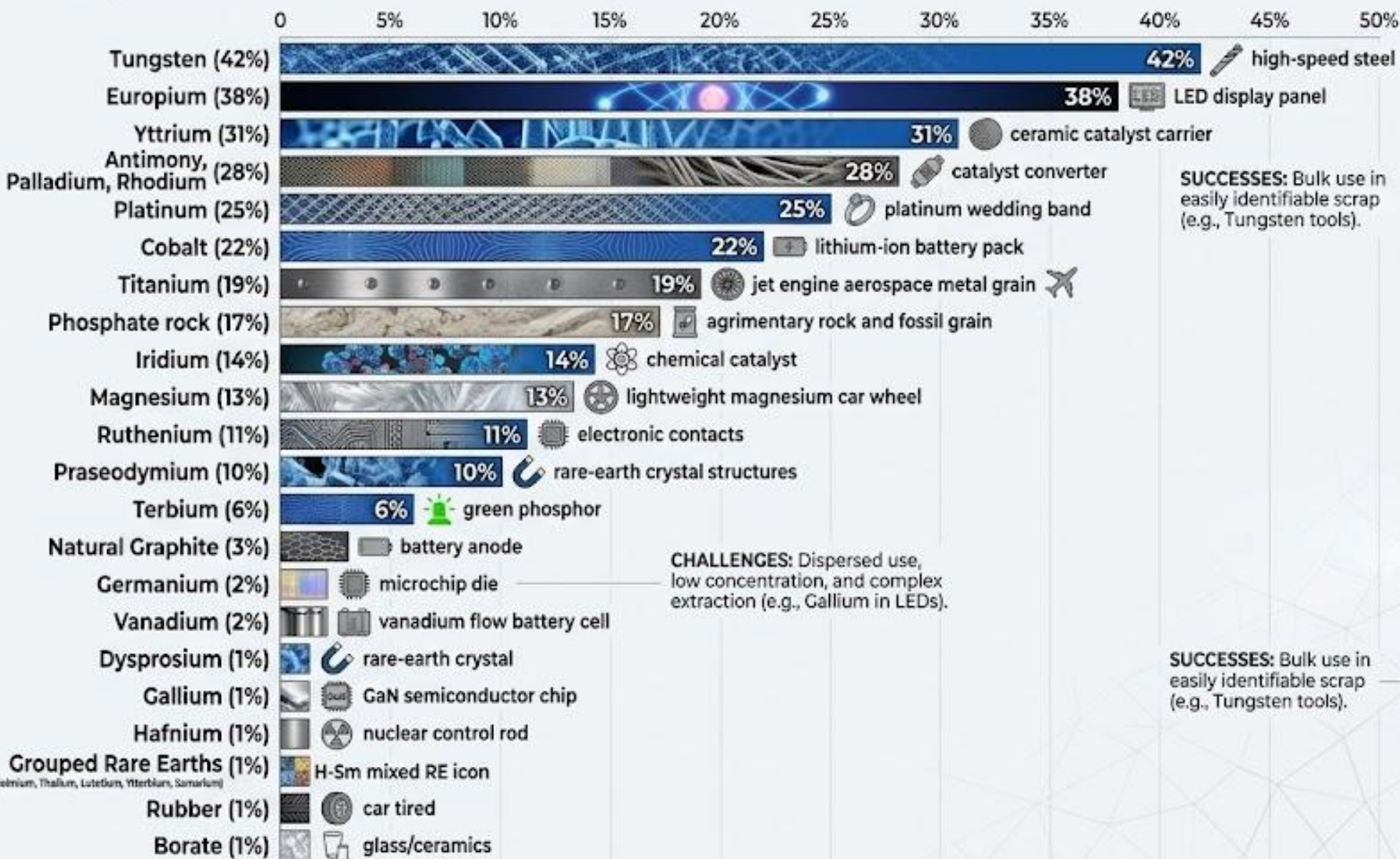
Dr. Gavin D. J. Harper

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



SUCCESSSES: Bulk use in easily identifiable scrap (e.g., Tungsten tools).

CHALLENGES: Dispersed use, low concentration, and complex extraction (e.g., Gallium in LEDs).

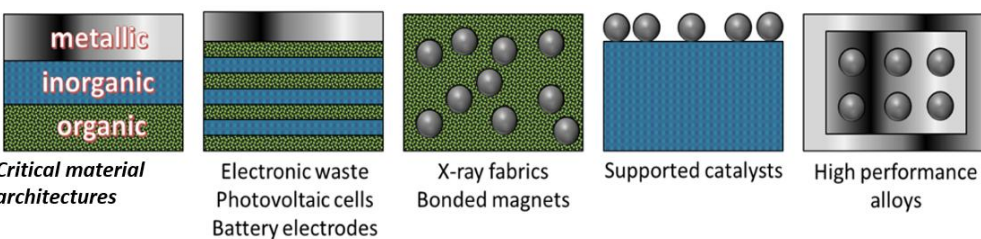
SUCCESSSES: Bulk use in easily identifiable scrap (e.g., Tungsten tools).

MATERIALS WITH NEAR-ZERO RECYCLING RATES (0% - <1%)



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

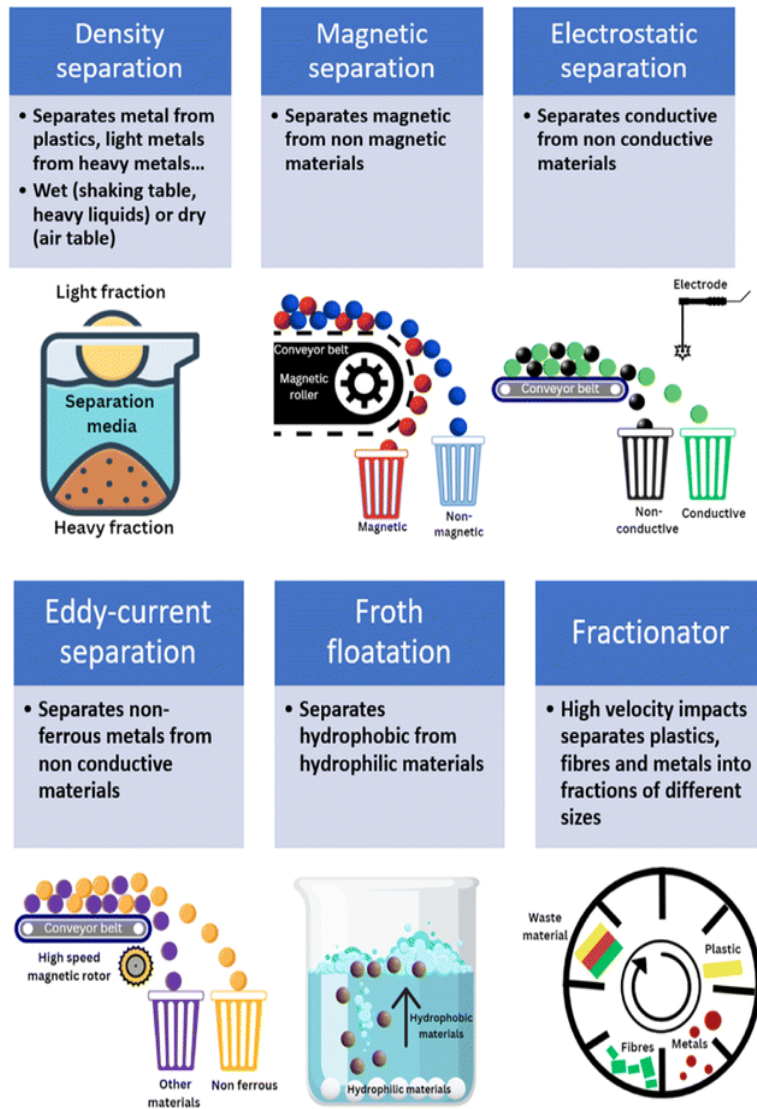
Current physical separation techniques used in recycling often end up mixing materials together in ways that makes them difficult to separate.



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 ^{a,e}, Rudra Mukherjee ^b, Jeff Kettle ^b, Louise E. Horsfall ^c, Allan Walton ^{d,e}, Gavin D. J. Harper ^{d,e} and Andrew P. Abbott ^{d,e}



RSC Sustainability

CRITICAL REVIEW

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

Guillaume Zante, Christopher E. Elgar, Jennifer M. Hartley, Rudra Mukherjee, Jeff Kettle, Louise E. Horsfall, Allan Walton, Gavin D. J. Harper and Andrew P. Abbott

Sustainability spotlight

Climate action and access to clean energy is heavily reliant on metals. Recycling of metals from renewable energy production and storage devices is highly desirable but is challenging due to the complex architecture of these devices, made of interpenetrated layers of organic, inorganic and dispersed metals. In this critical review, we highlight and discuss different technologies that can potentially reduce the environmental impact of current recycling methods and improve the global recycling rates. This review falls under multiple UN sustainable goals such as goal 12 (responsible consumption and production), goal 7 (affordable and clean energy production) and goal 13 (climate action).

1 Introduction

display devices, light emitting diodes (LEDs) lighting as well as the electronics that enable them. There is a need to transition towards Net Zero solutions, and reduce carbon emissions in all areas of our society. This will require widespread technological and societal change and technology transition in many different areas. Future transition pathways will require more sophisticated technologies to enable decarbonisation, with an increasing array of elements employed in more sophisticated technological structures than incumbent technologies. The trend toward complicated architectures with thin, multi-layer coatings is causing issues with dilute, complex waste-streams containing dispersed technology critical metals (TCMs). These elements are increasingly important to the economy due to the aforementioned reasons, and are at risk of supply disruption due to a combination of factors (geopolitical, geological, economic...).

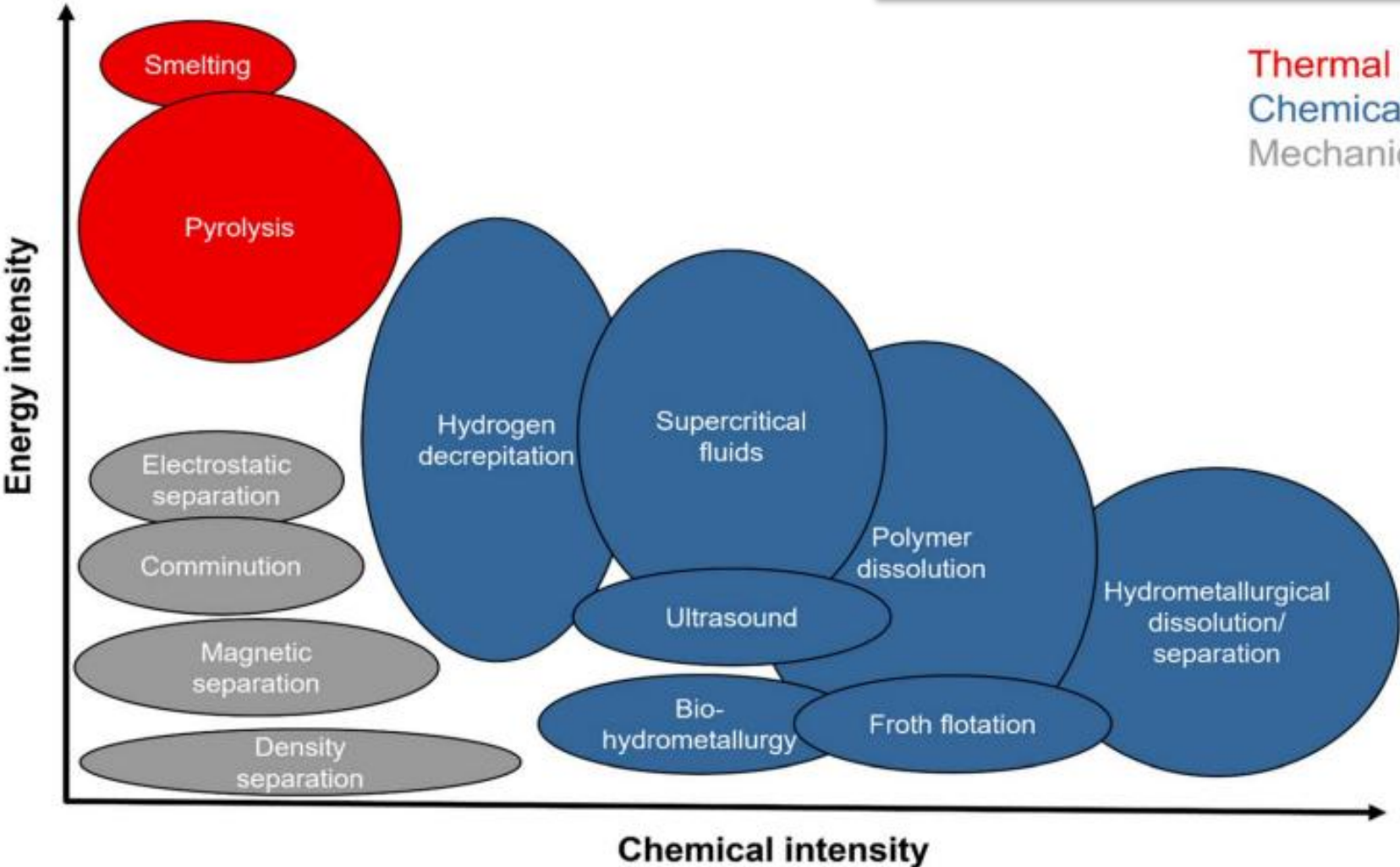
DOI: 10.1039/d3su00090g

© 2024 The Author(s). Published by the Royal Society of Chemistry

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^{b,*a}



RSC Sustainability

RSC Sustainability

CRITICAL REVIEW

Check for updates

Cite this RSC Sustainability 2025, 3, 2455

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^{b,*a}

Many of the issues associated with recycling devices containing small but significant amounts of technology critical metals, arise from the choice of materials and, most importantly, the joining methods for different materials. In many cases, recycling could be simplified and made more efficient by employing design for recycle principles which consider the requirements for separation. This study highlights recent innovative recycling tools which can impart greater selectivity during material separation and shows how often small changes in device architecture can greatly simplify critical metal recovery and promote circularity. It also discusses how design can be used to enable these tools to be assembled into the recycling flowchart, to decrease energy and chemical input and maximise the recovery of technology critical metals. It also promotes how digital product passports could be used in combination with AI to develop algorithms to develop smart recycling flowcharts.

Received 24th February 2025
Accepted 25th April 2025
DOI: 10.1039/d5su00028e
rsc.li/sus

Sustainability spotlight
The movement from a carbon-based economy to one based on renewable energy puts increased demands on a group of technology critical metals. It is essential that new devices for creating and storing chemical energy are designed to recover these critical elements, a number of recycling techniques have recently been developed that make metal recovery more efficient and this article shows how product design can be modified to enable efficient use of these tools. This review is the first to show how design can be used to improve recycling efficiency for a variety of devices. It also includes a variety of case studies. The work aligns directly with UN SDGs 7, 9 and 12.

1 Introduction

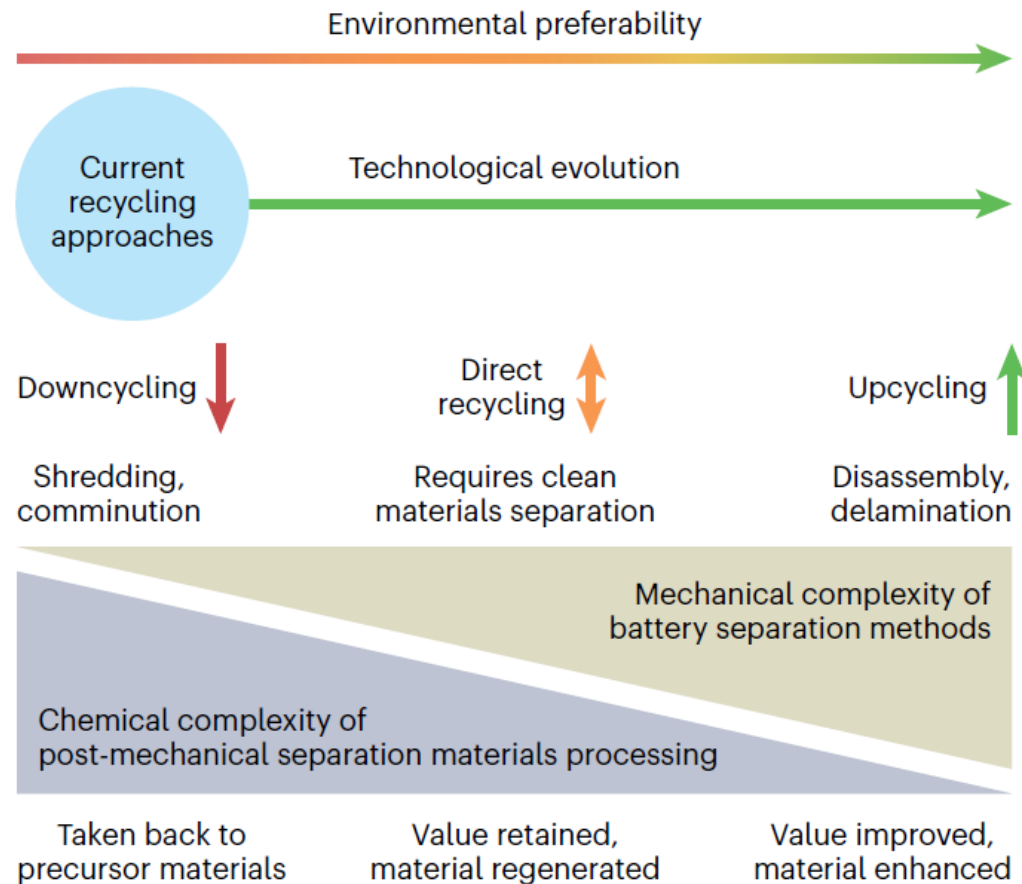
The ongoing deployment of mobile technologies and sustainable energy production has accelerated demand for so-called technology critical metals (TCMs) across the globe. Subsequently, it is predicted that for most TCMs, including iron and aluminium, global demand could increase by up to 215% by 2050.¹ While TCMs like aluminium are relatively efficiently recovered and recycled, with 75% of all aluminium ever produced still being used today,² many TCMs used in high-tech applications are spread more disparately throughout complex architectures and are accordingly more difficult to recover and purify. For instance, recovery rates of TCMs from waste electrical and electronic equipment (WEEE) range from 20% for gold, down to less than 1% for some rare earth elements (REEs) and most semiconductor elements.³ (WEEE is one of the fastest growing sources of waste, due to clean energy generation and energy storage devices having finite lifetimes. In 2022, Europe had an annual production of 17.6 kg of WEEE per capita, while is one of the highest collection and recycling rates, those rates still remain lower than 41%.⁴)

Therefore, implementation of a circular economy is necessary to deal with such a complex, worldwide problem, ideally with a strong focus on strategies aimed at reducing the volume of waste generated through reuse, repair, or lifetime extension. However, recycling is unfeasible in the long-term, at the eventual end-of-life (EOL) of devices. Improved recycling rates are vital, but hindered by the complex architecture of WEEE, which are often made of interpenetrated layers of metal, organic (polymers) and inorganic (ceramics, glass) materials.⁵ The metals themselves can be found in various components, such as silver bus bars on solar cells, soldered tin-lead-copper on composite materials at the surface of printed circuit boards (PCBs) or powder-like mixed oxides attached to current collectors in the cathodes of lithium-ion batteries (LIBs).

Various methodologies have been explored to efficiently recover key materials from these complex devices and these have recently been highlighted in a critical review.⁶ It demonstrated techniques such as: removal of organic layers by

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>



nature sustainability

News & views

Batteries

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

Upcycle for enhanced performance

David D. J. Harper

[Check for updates](#)

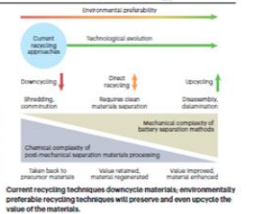
A method for recycling cathodes without fully breaking down the valuable material, and then upgrading it, produces batteries that can provide stable operation at high voltages, enabling enhanced energy-storage possibilities.

Had Shakespeare's Hamlet been the battery-recycling business, his lament on life and death might have been, "To shred, or not to shred", because the means of breaking or shredding 'end of life' battery cells has a pronounced effect on their future recycling pathways. Indeed, existing recycling methods based on shredding produce materials that require energy and resources to be fashioned into new batteries^{1,2}. In the case of lithium-ion batteries, avoiding mixing the components of spent batteries early in the recycling process can reduce the need to separate them again later. Writing in *Nature Sustainability*, Wang and colleagues report a technique that uses this approach to turn recycled cathodes from lithium cobalt oxide (LCO) batteries into high-performing materials without shredding them first.

Lithium-ion batteries are the rechargeable battery of choice in many applications, from the smallest portable electronic device, to the enormous grid-scale power banks that border the Australian outback. For applications that require high power density, LCO cathodes are ideal, because they are made from a material that can deliver that performance. Unfortunately, the cobalt in these cathodes presents a challenge because cobalt suffers from problematic supply-chain issues, but, despite this roadblock, LCO cathode materials present a particularly attractive option for compact electronic devices. Users of such devices are sensitive to weight and aesthetics, but also expect long battery life, and the volumetric specific energy of LCO as a cathode material makes it the material of choice.

To squeeze the ultimate performance out of LCO cathode materials, the voltage to which they are charged needs to be high. This stretches the capabilities of the material to be stretched fully, but it comes at a compromise. The elevated voltage stresses the layered structure of the material, resulting in damage and compromising its stability as it undergoes cycles of charging and discharging.

A key benefit of Wang and colleagues' recycling approach is that it generates a product that has a high material value, with a performance that better than that of the original materials being recycled. Rather than downcycling the cathode material of a lithium-ion battery into its constituent parts, which must then be recombined to make new batteries, the material is upcycled into a higher performance material. A great deal of work has to be invested in processing raw materials into a finished battery. Existing approaches to recycle lithium-ion batteries take the material from a complete set of spent battery back to a point at which it feeds into the manufacturing process much earlier than is necessary with this new approach, requiring substantial effort to build functional cathode materials. Wang and colleagues' approach

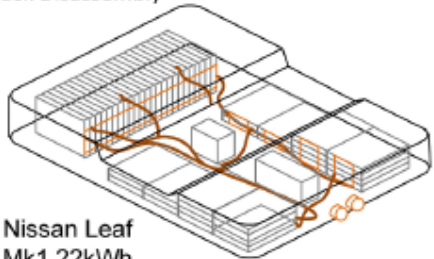


is instead a variation of direct recycling for LCO cathodes, in which the material is transformed directly into a cathode material that can be used directly in new batteries. The authors showed that their recycled regenerated high-voltage LCO cathode has better structural stability than its existing commercial counterparts. It also has a capacity retention (the ability to retain stored energy while at rest) of 79.7% after 300 cycles, the best results reported for a 4.4 V high-voltage LCO cathode material. That said, some challenges need to be overcome before the potential of this recycling method can be realized on an industrial scale. For example, the method requires battery cells to first be disassembled before the various components can be separated and cleaned.

Existing methods that dominate the lithium-ion battery recycling industry have been the subject of much discussion and comparison, including shredding and its alternatives^{3,4} as a precursor to breaking battery cells, with the alternative of cell disassembly enabling cleaner mechanical separation of the components before recycling processes. Such approaches will undoubtedly need a lot of automation to achieve their potential safety and economically. This will also require the commercialization of approaches to decommission battery cell material from electrode foils⁵. These endeavours could be aided enormously by cells that are designed for recycling from the outset, rather than constructed without a clear plan for how they will be dismantled in the future⁶. An additional complication is presented by the size of cells that are typically used in LCO cathode materials. These tend to be the smaller cells used in portable electronic devices, rather than the larger cells used in automotive applications, which have other cathode materials. Making disassembly profitable remains a key challenge, and making it work

nature sustainability

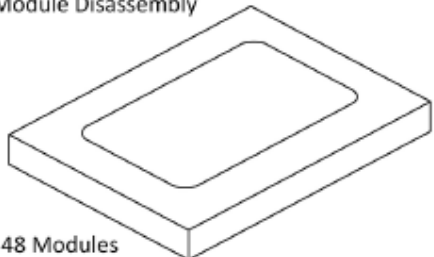
Pack Disassembly



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

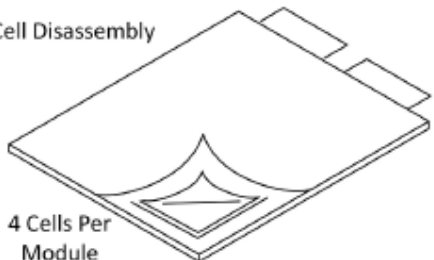
Module Disassembly



48 Modules
Per Pack

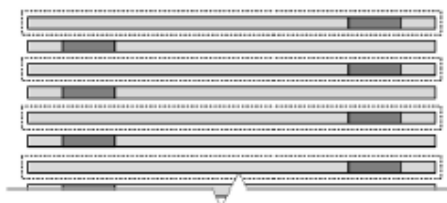
- Sealants may be used in module manufacture (difficult to remove)
- Cells stuck together in modules with adhesives (difficult to separate)
- Components may be soldered together (difficult to separate)
- Module state of charge may not be known

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).



(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^{g,a,b}

Green Chemistry

Green Chemistry

CRITICAL REVIEW

Check for updates

Cite this: Green Chem., 2020, 22, 7585

Received 10th August 2020
Accepted 20th October 2020
DOI: 10.1039/d0gc02249f

Introduction

To create circular economy for a material it is important to have few components, a lower cost for the secondary process than the primary process, a simple purification flowchart, valuable components and a collection and segregation mechanism. It also helps when the material has a significant environmental impact if not recycled as this tends to mandate its recycling.

These criteria are met by a variety of materials including glass, paper and card, steel, aluminium, plastic bottles, car catalysts and lead acid batteries. These are all well established and mature markets which grow at a manageable rate. The Green Chemistry credentials of these processes for decreasing waste

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^{g,a,b}

Recycling is always seen as an end-of-pipe process returning as much material as possible into a circular economy. There is a growing school of thought that suggests product design should be an important step in the recycling process. While this review is aimed specifically at one technological product, it contains factors that are applicable to the recycling of any complex product. Decarbonisation of energy production necessitates a proliferation of efficient electrical storage and a significant proportion of this, particularly in automotive propulsion, will use lithium ion batteries. The scale of the projected electric vehicle market means that a circular economy model needs to be established while the scale of end-of-life product is still manageable to prevent a build-up of hazardous waste. This critical review investigates the issues of lithium ion battery recycling and discusses the aspects of pack, module and cell design that can simplify battery dismantling and recycling. It highlights not only Green aspects of elemental recovery, but also techno-economic features which may govern the appropriate direction for recycling. It also shows that as cell design changes, the approach to recycling can become more efficient.

In the environment must not be overlooked; recycling aluminium and steel saves 96% and 60% of the energy of the primary processes, respectively. Substitution and reuse are also a central part of the circular economy hierarchy. However, when new disruptive products and innovations come to the market with large growth potential, a product can rapidly become an environmental issue if a circular economy has not been designed with the product. This was the case in the 1960s with the growth in PET bottles, particularly for water,¹ and has also been the case with the rapid growth in waste electrical and electronic equipment (WEEE) or the rapid demise of cathode ray tubes.

Disruptive growth in technologies can occur when a new product becomes easy to mass produce, bringing it within the reach of a larger potential market e.g. the internal combustion engine, or when a step change in the performance trajectory of a disruptive innovation reaches a critical inflection point, leading to an incumbent technology being superseded.² Additionally, environmental regulation can be a driver for requiring technological change in some markets, e.g. the removal of the internal combustion engine, in areas with clean-air mandates.³ The decarbonisation of power production and transport has clear environmental benefits; however, a holistic approach needs to be developed for the materials which enable renewable energy to be harvested, e.g. with photovoltaic devices, electric motors, generators and storage

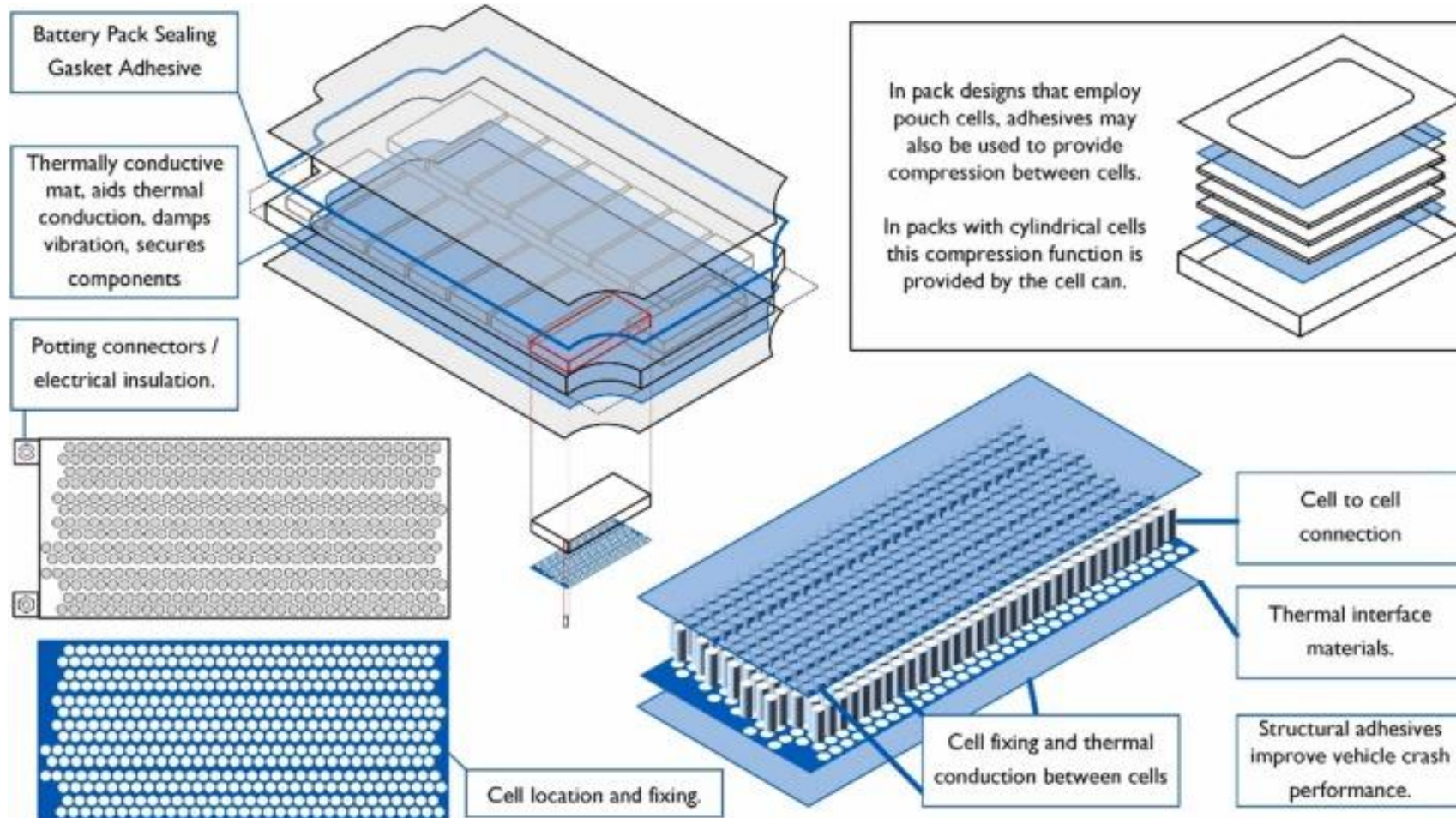
The journal is © The Royal Society of Chemistry 2020

Green Chem., 2020, 22, 7585–7603 | 7585

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,*}



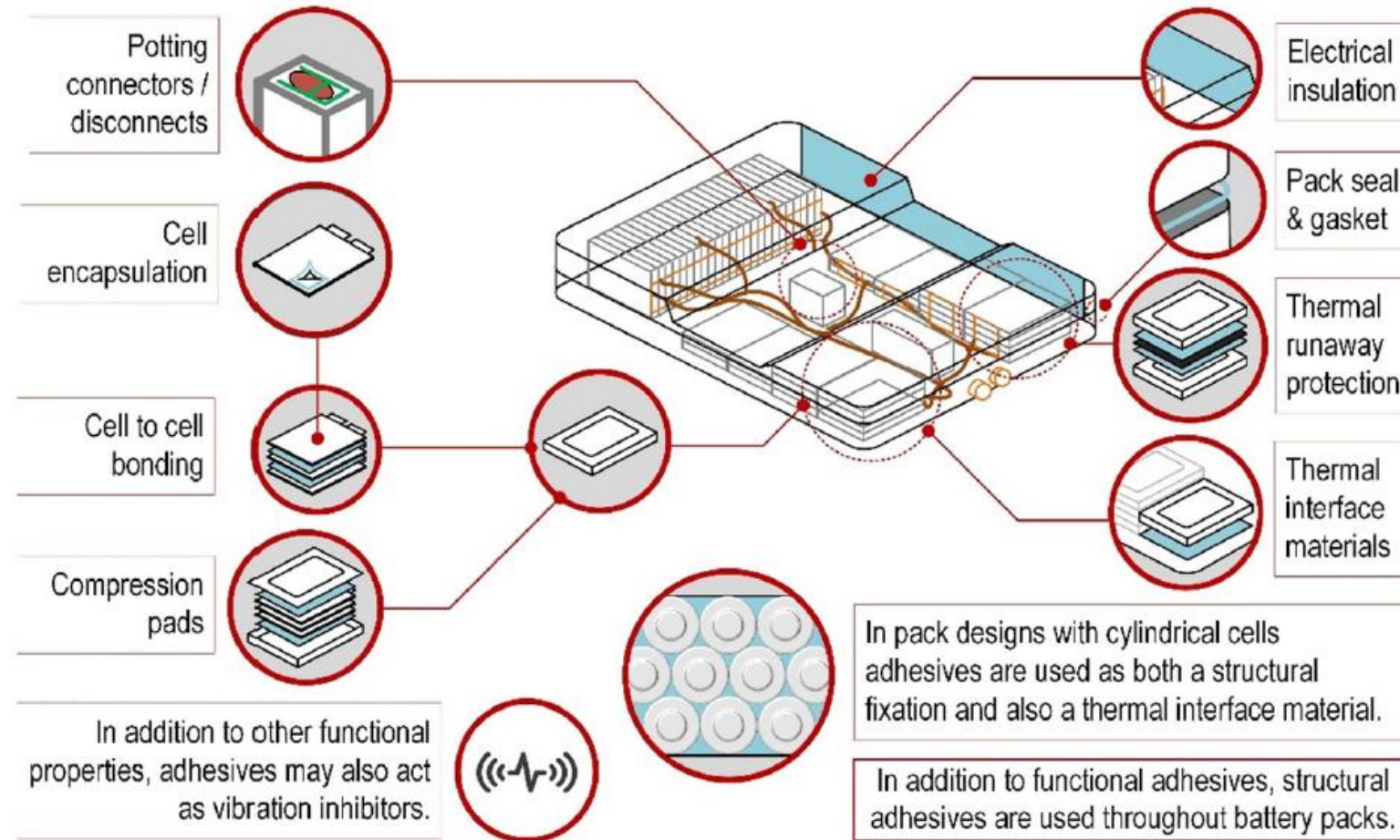
Schematic diagram showing some of the uses of structural adhesives in a typical battery pack

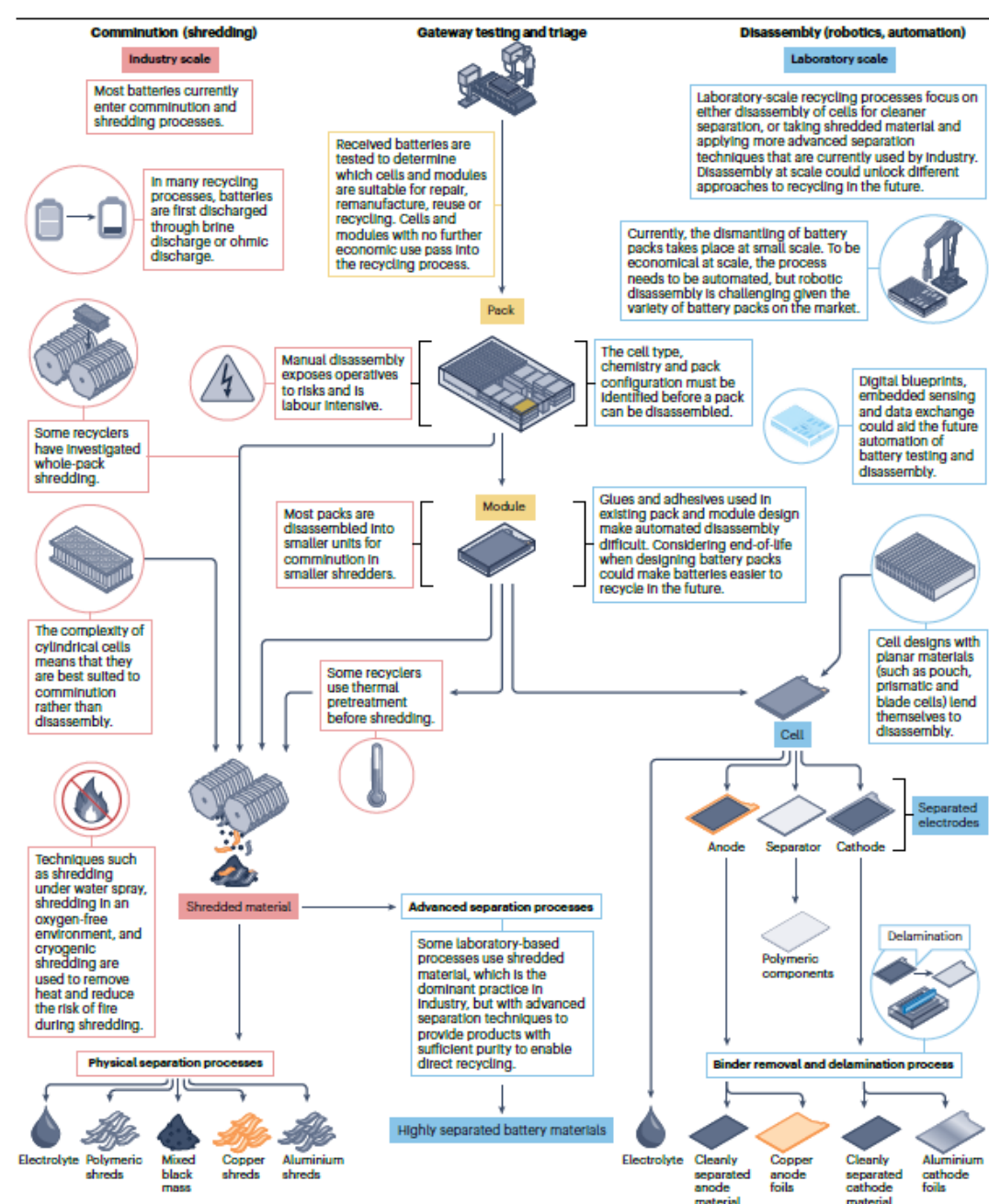
8. Cell disassembly and design for recycling

Andrew P Abbott¹, Dana Thompson¹ and Gavin D J Harper²

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





The evolution of lithium-ion battery recycling

Xiaotu Ma^{1,9}, Zifei Meng^{1,9}, Marilena Velonia Bellonia², Jeffrey Spangenberg³, Gavin Harper^{4,5}, Eric Gratz⁶, Elsa Olivetti⁷, Renata Arsenault⁸ & Yan Wang^{1,9}✉

nature reviews clean technology

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.

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 Bellonia², Jeffrey Spangenberg³, Gavin Harper^{4,5}, Eric Gratz⁶, Elsa Olivetti⁷, Renata Arsenault⁸ & Yan Wang^{1,9}✉

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

Introduction
Pretreatment processes
Industrial recycling processes
Developing recycling processes
The use of recovered materials
Assessing the impact of battery recycling
Summary and future perspectives

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

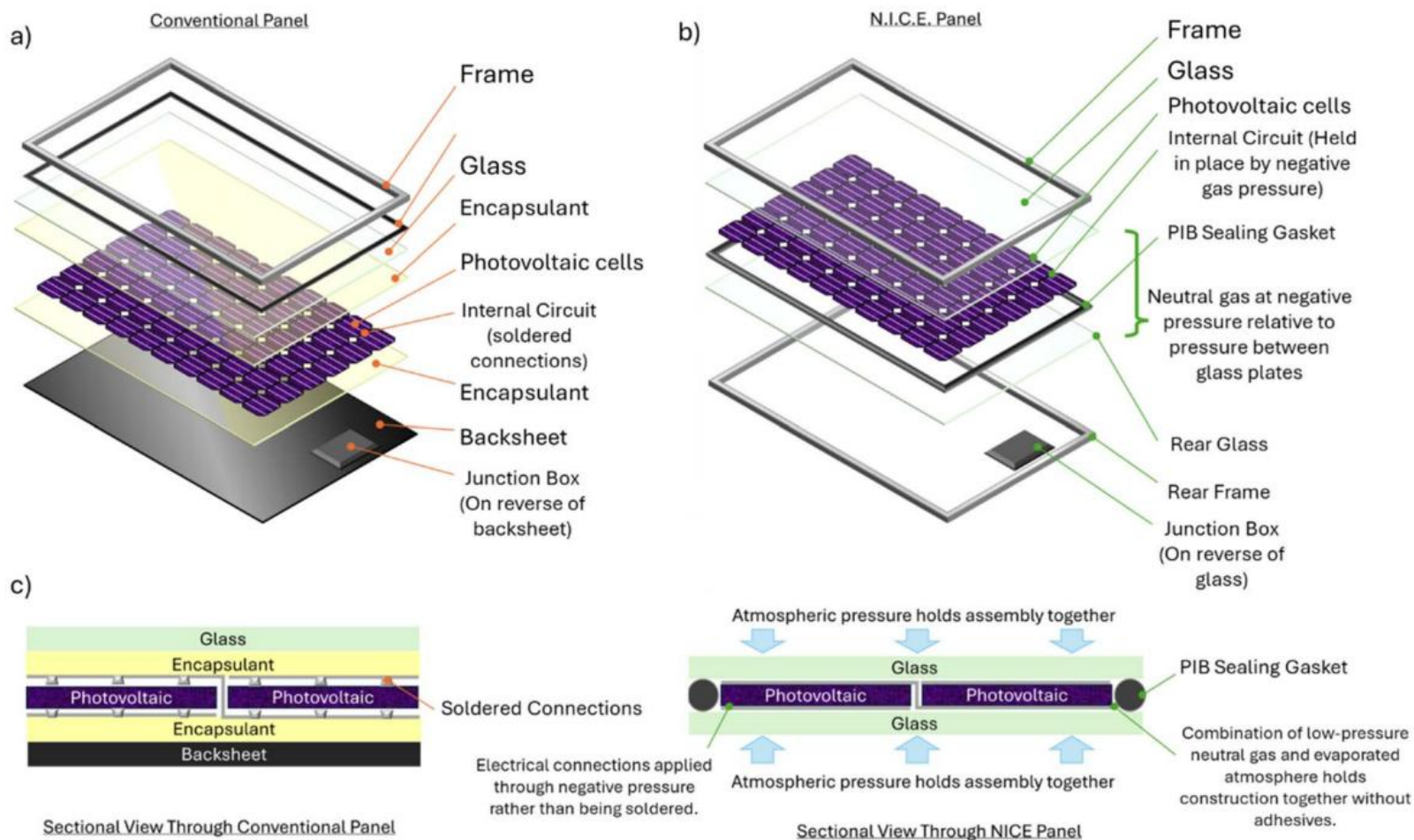
Nature Reviews Clean Technology | Volume 1 | January 2025 | 75–94

75

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^{b,*a}



RSC
Sustainability

RSC
Sustainability

CRITICAL REVIEW

Check for updates

Cite this RSC Sustainability 2025, 3, 2455

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^{b,*a}

Many of the issues associated with recycling devices containing small but significant amounts of technology critical metals, arise from the choice of materials and, most importantly, the joining methods for different materials. In many cases, recycling could be simplified and made more efficient by employing design for recycle principles which consider the requirements for separation. This study highlights recent innovative recycling tools which can impart greater selectivity during material separation and shows how often small changes in device architecture can greatly simplify critical metal recovery and promote circularity. It also discusses how design can be used to enable these tools to be assembled into the recycling flowchart, to decrease energy and chemical input and maximise the recovery of technology critical metals. It also promotes how digital product passports could be used in combination with AI to develop algorithms to develop smart recycling flowcharts.

Sustainability spotlight

The movement from a carbon-based economy to one based on renewable energy puts increased demands on a group of technology critical metals. It is essential that new devices for creating and storing electrical energy are designed to recover these critical elements. A number of recycling techniques have recently been developed that make metal recovery more efficient and this article shows how product design can be modified to make efficient use of these tools. This review is the first to show how design can be used to improve recycling efficiency for a variety of devices. It also includes a variety of case studies. The work aligns directly with UN SDGs 7, 9, and 12.

1 Introduction

The ongoing deployment of mobile technologies and sustainable energy production has accelerated demand for so-called technology critical metals (TCMs) across the globe. Subsequently, it is predicted that for most TCMs, including iron and aluminium, global demand could increase by up to 215% by 2050.¹ While TCMs like aluminium are relatively efficiently recovered and recycled, with 75% of all aluminium ever produced still being used today,² many TCMs used in high-tech applications are spread more disparately throughout complex architectures and are accordingly more difficult to recover and purify. For instance, recovery rates of TCMs from waste electrical and electronic equipment (WEEE) range from 20% for gold, down to less than 1% for some rare earth elements (REEs) and most semiconductor elements.³ (WEE) WEEE is one of the

fastest growing sources of waste, due to clean energy generators and energy storage devices having finite lifetimes. In 2022, Europe had an annual production of 17.6 kg of WEEE per capita, which is one of the highest collection and recycling rates, those rates still remain lower than 41%.⁴

Therefore, implementation of a circular economy is necessary to deal with such a complex, worldwide problem, ideally with a strong focus on strategies aimed at reducing the volume of waste generated through reuse, repair, or lifetime extension. However, recycling is unfeasible in the long term, at the eventual end-of-life (EOL) of devices. Improved recycling rates are vital, but hindered by the complex architecture of WEEE, which are often made of heterogeneous layers of metal, organic (polymers) and inorganic (ceramics, glass) materials.⁵ The metals themselves can be found in various components, such as silver bus bars on solar cells, soldered tin-silver-copper on composite materials at the surface of printed circuit boards (PCBs) or powder-like mixed oxides attached to current collectors in the cathodes of lithium-ion batteries (LIBs).

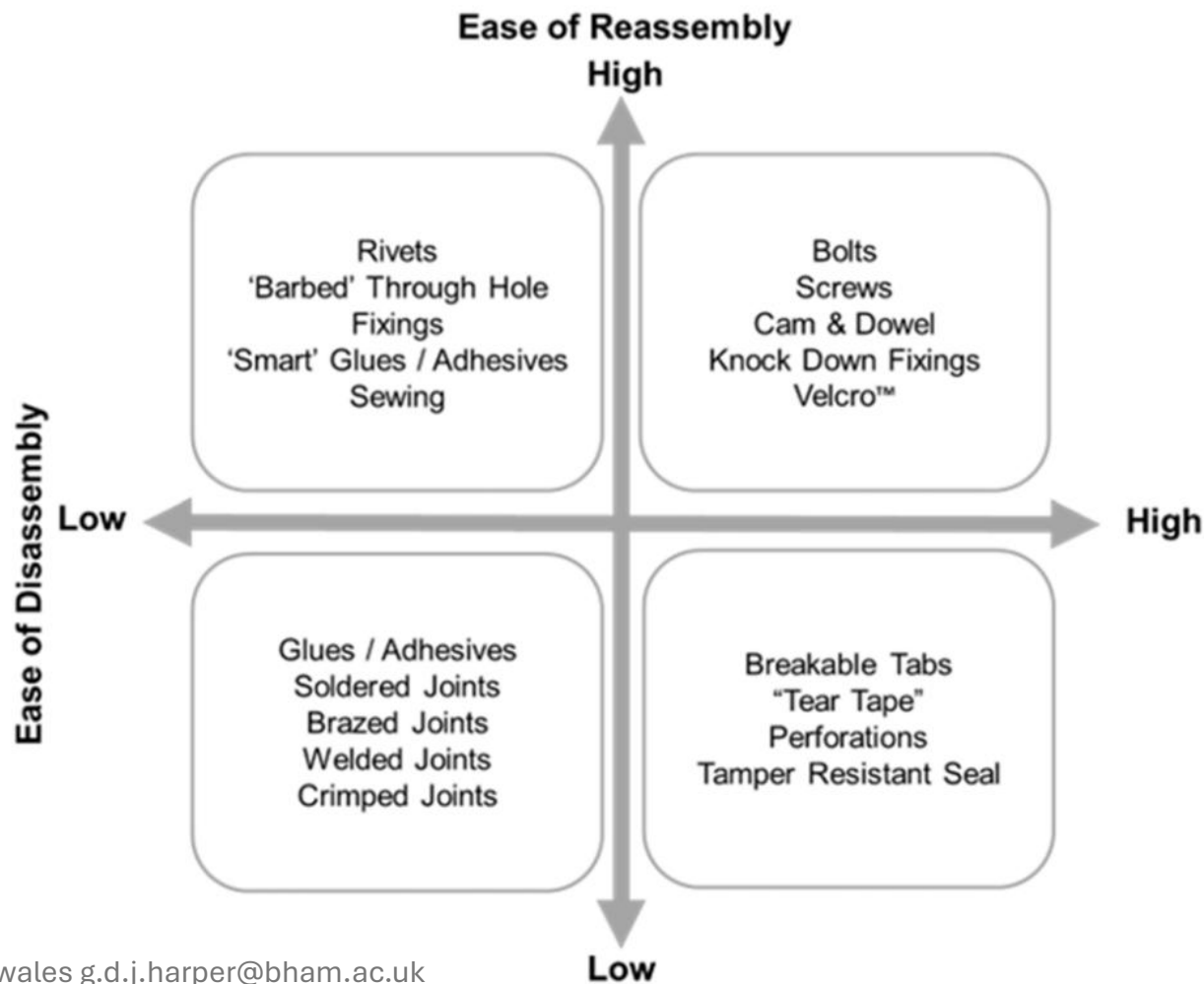
Various methodologies have been explored to efficiently recover key materials from these complex devices and these have recently been highlighted in a critical review.⁶ It demonstrated techniques such as: removal of organic layers by

^a School of Chemistry, University of Birmingham, Edgbaston, 151 7RH, UK. E-mail: g.p.abbott@bham.ac.uk
^b School of Engineering, University of Glasgow, G12 8QQ, UK
^c Birmingham Centre for Strategic Elements & Critical Materials, University of Birmingham, UK
^d University of Luxembourg, 151, rue de Luxembourg, L-1511, Luxembourg, Luxembourg

© 2025 The Author(s). Published by the Royal Society of Chemistry

RSC Sustainability, 2025, 3, 2455–2471 | 2455

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^{b,*a}

RSC Sustainability

RSC Sustainability

CRITICAL REVIEW

Check for updates
Cite this RSC Sustainability 2025, 3, 2455

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^{b,*a}

Many of the issues associated with recycling devices containing small but significant amounts of technology critical metals, arise from the choice of materials and, most importantly, the joining methods for different materials. In many cases, recycling could be simplified and made more efficient by employing design for recycle principles which consider the requirements for separation. This study highlights recent innovative recycling tools which can impart greater selectivity during material separation and shows how often small changes in device architecture can greatly simplify critical metal recovery and promote circularity. It also discusses how design can be used to enable these tools to be assembled into the recycling flowchart, to decrease energy and chemical input and maximise the recovery of technology critical metals. It also promotes how digital product passports could be used in combination with AI to develop algorithms to develop smart recycling flowcharts.

Received 24th February 2025
Accepted 25th April 2025
DOI: 10.1039/d5su00028e
rsc/sustainability

Sustainability spotlight

The movement from a carbon-based economy to one based on renewable energy puts increased demands on a group of technology critical metals. It is essential that new devices for creating and storing electrical energy are designed to recover these critical elements. A number of recycling techniques have recently been developed that make metal recovery more efficient and this article shows how product design can be modified to make efficient use of these tools. This review is the first to show how design can be used to improve recycling efficiency for a variety of devices. It also includes a variety of case studies. The work aligns directly with UN SDGs 7, 9 and 12.

1 Introduction

The ongoing deployment of mobile technologies and sustainable energy production has accelerated demand for so-called technology critical metals (TCMs) across the globe. Subsequently, it is predicted that for most TCMs, including iron and aluminium, global demand could increase by up to 215% by 2050.¹ While TCMs like aluminium are relatively efficiently recovered and recycled, with 75% of all aluminium ever produced still being used today,² many TCMs used in high-tech applications are spread more disparately throughout complex architectures and are accordingly more difficult to recover and purify. For instance, recovery rates of TCMs from waste electrical and electronic equipment (WEEE) range from 20% for gold, down to less than 1% for some rare earth elements (REEs) and most semiconductor elements.³ (WEE) WEEE is one of the

fastest growing sources of waste, due to clean energy generators and energy storage devices having finite lifetimes. In 2022, Europe⁴ had an annual production of 17.6 kg of WEEE per capita, which is one of the highest collection and recycling rates, those rates still remain lower than 41%.

Therefore, implementation of a circular economy is necessary to deal with such a complex, worldwide problem, ideally with a strong focus on strategies aimed at reducing the volume of waste generated through reuse, repair, or lifetime extension. However, recycling is unfeasible in the long-term, at the eventual end-of-life (EOL) of devices. Improved recycling rates are vital, but hindered by the complex architecture of WEEE, which are often made of interpenetrated layers of metal, organic (polymers) and inorganic (ceramics, glass) materials.⁵ The metals themselves can be found in various components, such as silver bus bars on solar cells, soldered tin-lead-copper on composite materials at the surface of printed circuit boards (PCBs) or powder-like mixed oxides attached to current collectors in the cathodes of lithium-ion batteries (LIBs).

Various methodologies have been explored to efficiently recover key materials from these complex devices and these have recently been highlighted in a critical review.⁶ It demonstrated techniques such as: removal of organic layers by

^aSchool of Chemistry, University of Leicester, Leicester, LE1 7RH, UK. E-mail: ap.abbott@le.ac.uk
^bJames Watt School of Engineering, University of Glasgow, G12 8QQ, UK
^cStirlingham Centre for Storage Elements & Critical Materials, University of Birmingham, UK
^dUniversity of Portsmouth, PO1 1AB, UK. E-mail: g.d.j.harper@bham.ac.uk

© 2025 The Author(s). Published by the Royal Society of Chemistry

RSC Sustainability, 2025, 3, 2455–2471 | 2455

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

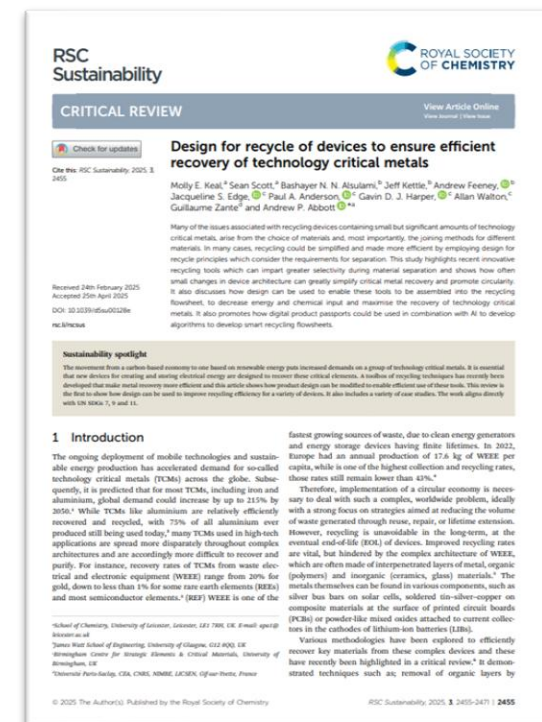
Design for recycle of devices to ensure efficient recovery of technology critical metals

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



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

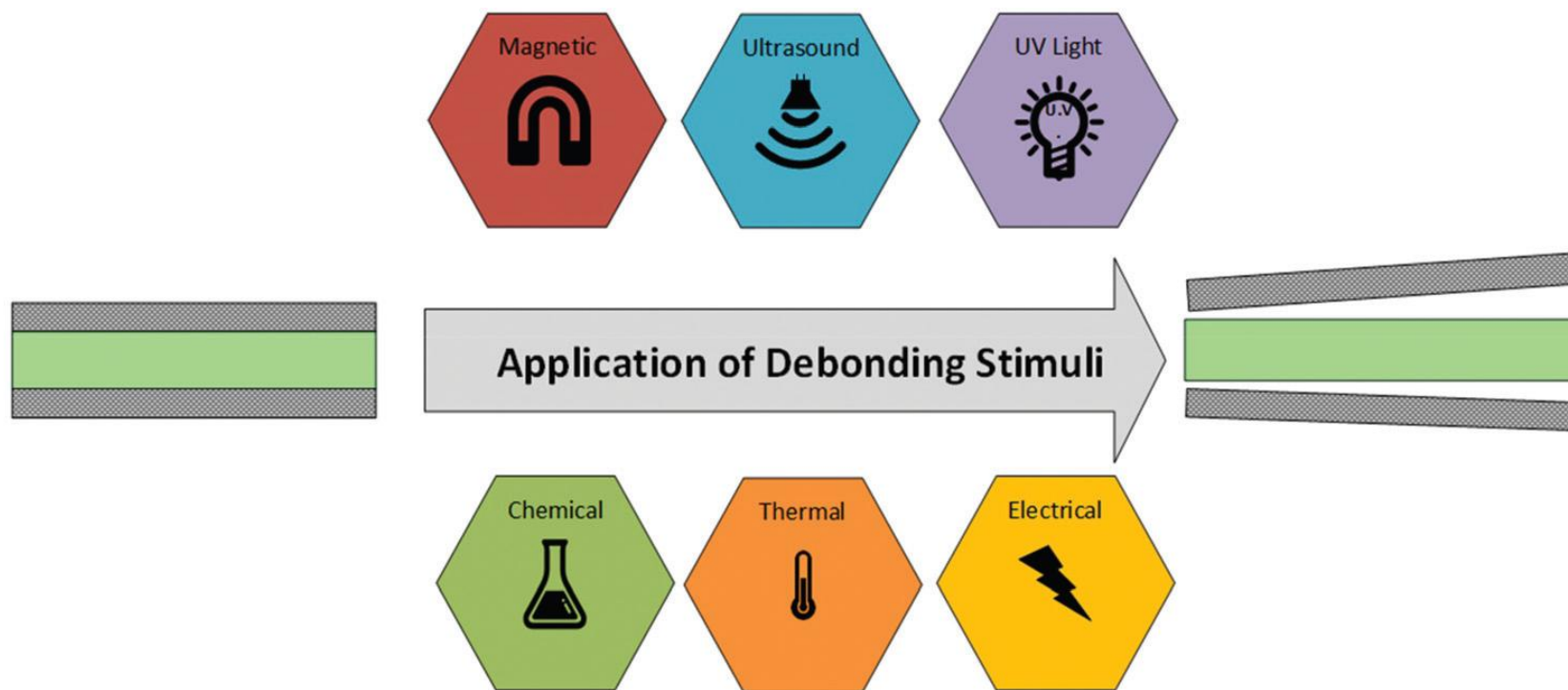
Tool	Potential application	Advantages	Disadvantages
Etchable substrate under TCMs	Supported PGM catalysts or PCBs	Easier recovery of TCMs	Performance?
Additive manufacturing	Electronic circuitry	Easier assembly	May slow production
Fewer metals in alloys	Aerospace metals	More applications of recycled 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



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

Green Chemistry

CRITICAL REVIEW

Check for updates

Cite this: DOI: 10.1039/c5gc00001a

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}

Received 10 September 2015
Accepted 21st November 2015
DOI: 10.1039/c5gc00001a
rsc.li/greenchem

1. Introduction

Most technological devices consist of organic, inorganic, and metallic components, joined into complex architectures using organic adhesives; many of which play a multifaceted role, and impart structural integrity. In addition to binding joints. At present, removal of such adhesives is time-consuming and inefficient, requiring solvents, pyrolysis, or comminution (grinding/blending). The considerable challenges posed by these adhesives, to disassembly and recycling, have recently been reviewed with respect to lithium-ion batteries (LIBs); however, these issues extend to a wide range of devices and components, including mobile electronics, motor and photo-aid devices.

This is of particular concern, with respect to the recovery of technology critical metals (TCMs), which are diffusely distributed within components but essential to function.¹ Maintaining the structural integrity of the adhesive prevents the preferred green alternatives of repair, remanufacture, reuse and recycle. In addition, due to current non-selective hydrometallurgical techniques, maintaining value in recycled material is difficult, often rendering reuse within the same content unviable. Given the essential nature of TCMs in most digital and clean energy

technologies, their demand is growing. However, there remain significant bottlenecks in the development of mining and processing capacity for the production of new primary TCMs. Therefore, recovery of these elements will become an essential component in the supply chain of new materials for technologies that aid decarbonisation. In addition, due to limited resources, and ethical and environmental issues associated with extraction, a move towards a more circular economy is vital.

The solution to these issues lies with adhesive design, as easy debonding or degradation would facilitate disassembly and allow higher value outputs from recycling. At present, the structural adhesives market is dominated by epoxy and polyurethane chemistries, which form their strength on cross-linking of their polymer networks. Due to their high strength and fast setting times, the epoxy market alone had an estimated worth of \$5.9 billion in 2015, with projected growth to \$10.3 billion by 2022.² However, these adhesives are not without their issues. Formed from the reactions of di- or polyols, such as bisphenol A (BPA), with epichlorohydrin (ECH), these ubiquitous polymers do not biodegrade and emit toxic gases, when incinerated. Recent research has considered replacing monomers or cross-linkers with bio-based components, or using novel adhesives based on biopolymers such as polyurethanes.³ An alternative approach proposes the use of polymers which can debond on application of an external stimulus. While this technology is not widely available at present, this critical review will discuss the approaches used in the design of debondable adhesives, and the limitations of systems already reported in the literature.

^aSchool of Chemistry, University of Edinburgh, Edinburgh, LE1 7UH, UK
E-mail: ap.abbott@ed.ac.uk
^bSchool of Chemistry, University of Birmingham, Joseph Black Building, Edgbaston Road, Birmingham, B15 2TT, UK
^cSchool of Metallurgy and Materials, University of Birmingham, Birmingham, B15 2TT, UK

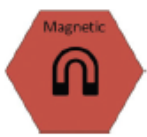
This journal is © The Royal Society of Chemistry 2015

Green Chem.

Summary of debonding stimuli, functional groups and applicability

Debondable adhesives and their use in recycling

Kira R. Mulcahy,^{id a,b} Alexander F. R. Kilpatrick,^{id a} Gavin D. J. Harper,^{id c} Allan Walton^c and Andrew P. Abbott^{id *a}

Stimulus						
Potential uses	Thin transparent materials	Inorganic and metallic components	Bonding metals and conductive substrates	Reactive composite adhesives with stable substrates Needs to not etch the substrate	Biological/electronic applications Magnetic substrates	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 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



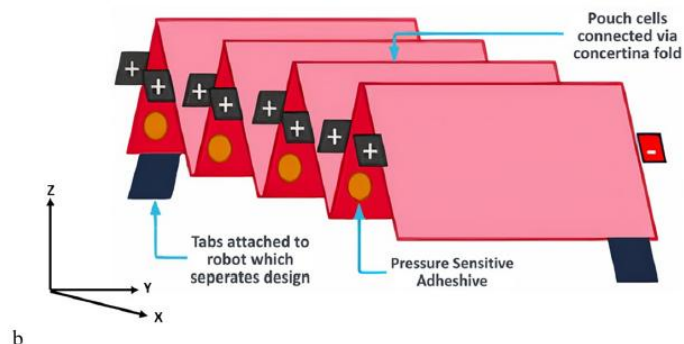
Prototyping batteries in “design for Recycling” configurations.

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

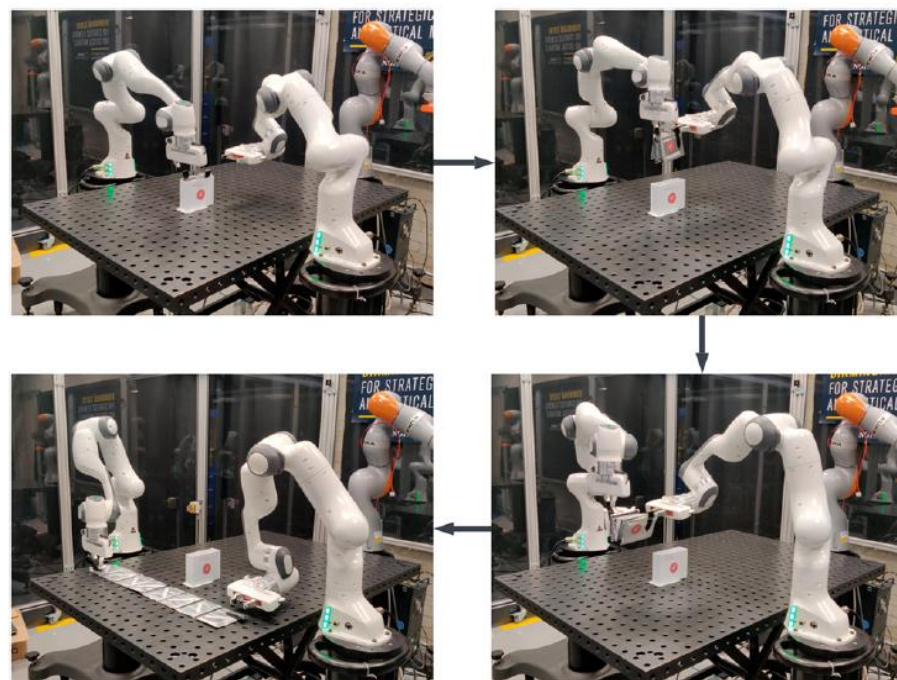
Sean Scott^{a,b}, Zayd Islam^{a,b}, Jack Allen^{a,b}, Tanongsak Yingnakorn^{a,b}, Ali Alflakian^{b,c}, Jamie Hathaway^{b,c}, Alireza Rastegarpanah^{b,c}, Gavin D.J. Harper^{b,c}, Emma Kendrick^{b,c}, Paul A. Anderson^{b,d}, Jacqueline Edge^{b,e}, Laura Lander^{b,f}, Andrew P. Abbott^{a,b,*}



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.

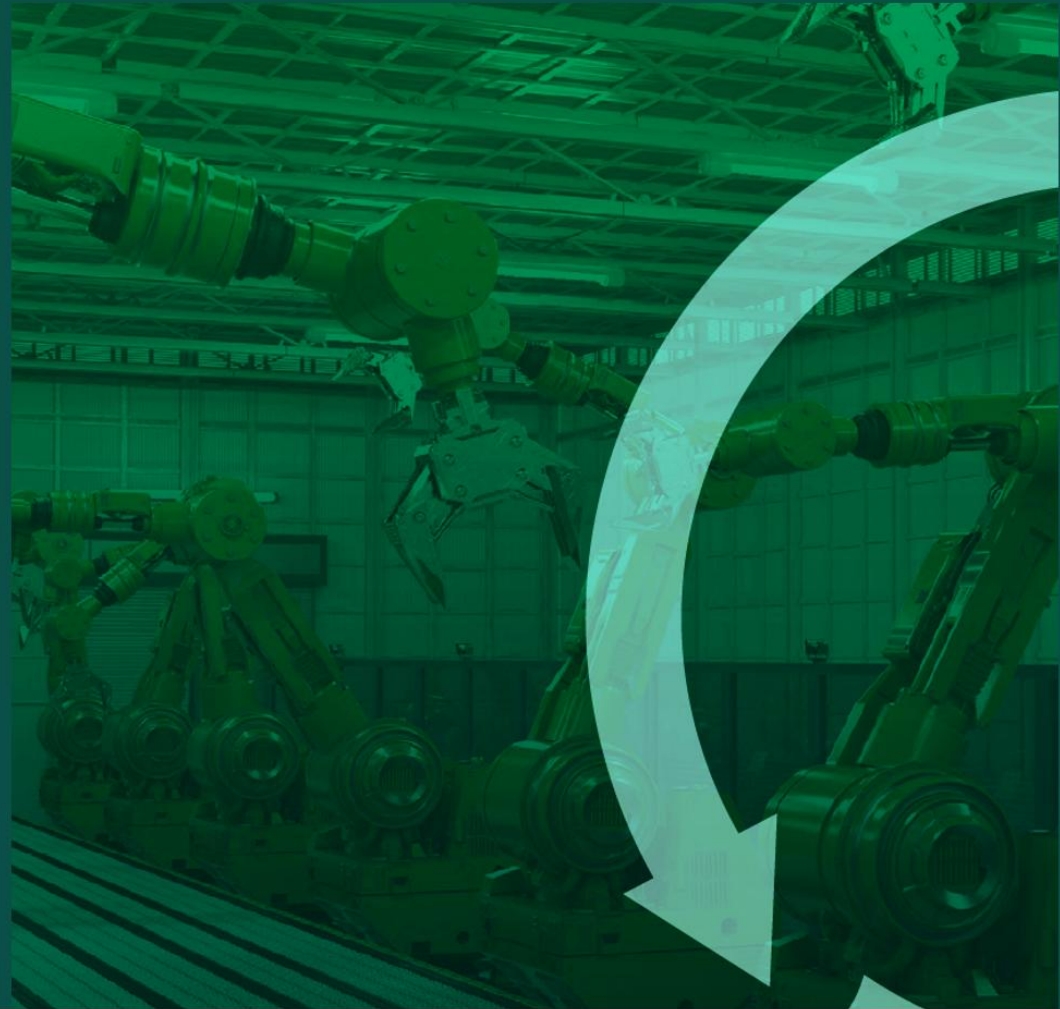




RESCU-M²

TECHNOLOGY **ROADMAP**

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



UNIVERSITY OF
BIRMINGHAM


**University
of Brighton**


Loughborough
University


University of
Strathclyde


The
University
Of
Sheffield.


LEEDS

mtc  where
progress
happens

 Durham
University

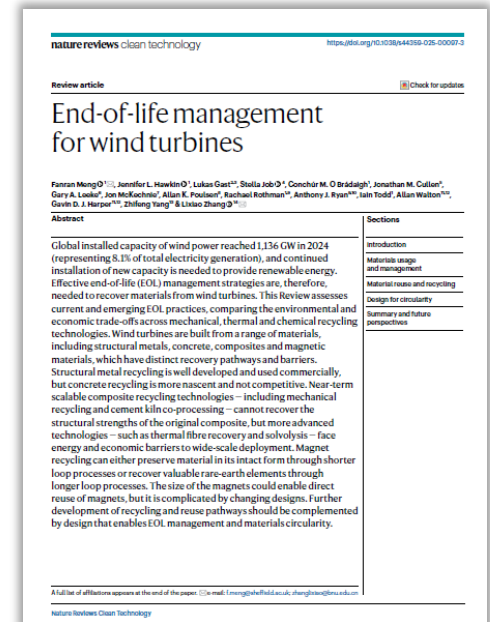
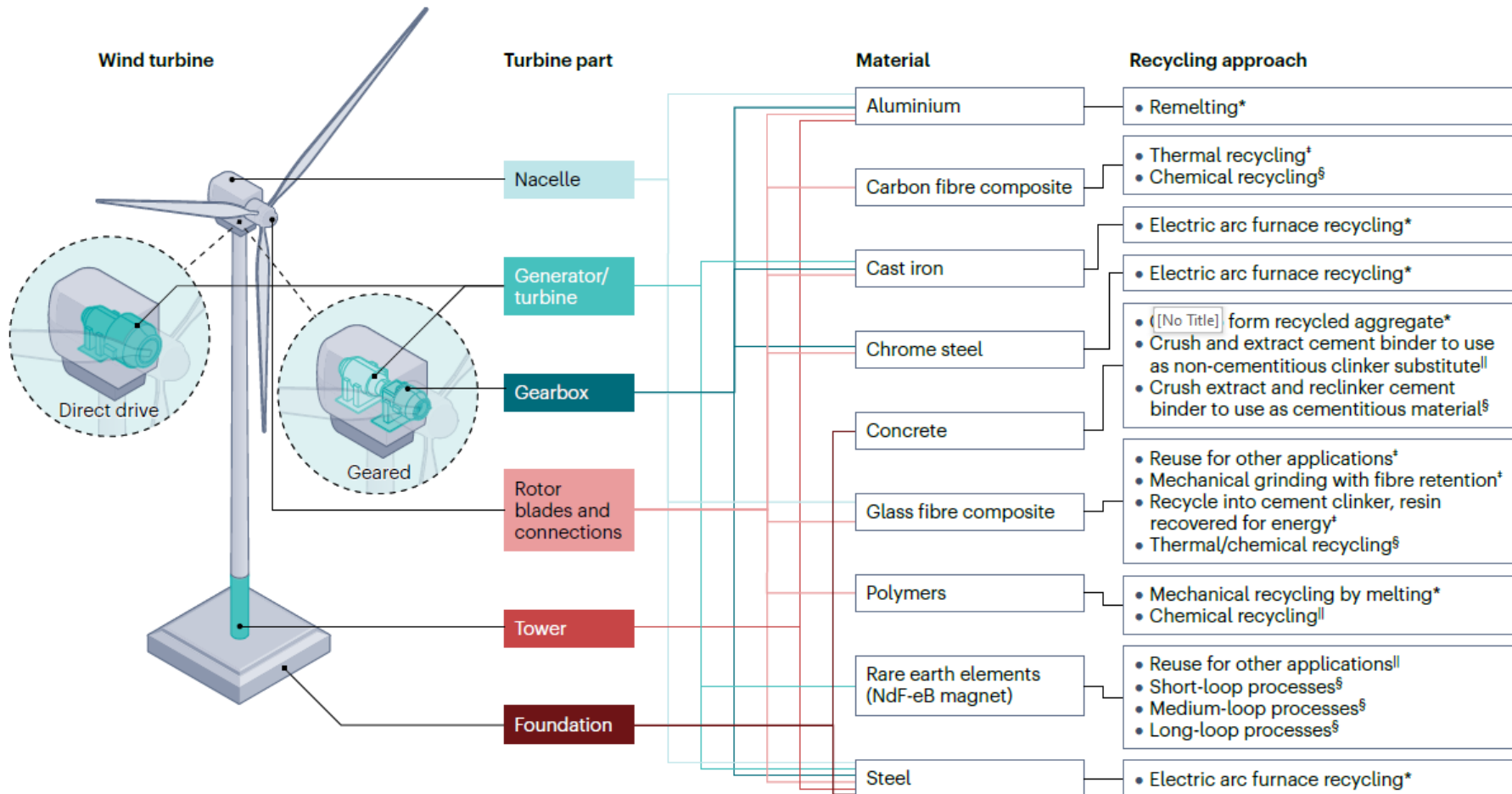
 **UKRI**

Engineering and
Physical Sciences
Research Council

End-of-life management for wind turbines

Fanran Meng¹✉, Jennifer L. Hawkin¹, Lukas Gast^{2,3}, Stella Job⁴, Conchúr M. Ó Brádaigh¹, Jonathan M. Cullen⁵, Gary A. Leeke⁶, Jon McKechnie⁷, Allan K. Poulsen⁸, Rachael Rothman^{1,9}, Anthony J. Ryan^{9,10}, Iain Todd¹, Allan Walton^{11,12}, Gavin D. J. Harper^{11,12}, Zhifeng Yang¹³ & Lixiao Zhang¹⁴✉

nature reviews clean technology



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