ROYAL SOCIETY OF CHEMISTRY

Decarbonisation: materials and circularity challenges for clean technologies

The role of Critical Raw Materials in reaching net-zero emissions

August 2021

Contents

1 Introduction

This report, a summary of discussions from an expert roundtable held by the Environment, Sustainability and Energy Division of the Royal Society of Chemistry, explores the role of Critical Raw Materials (CRMs) in some of the technologies that will be crucial for reaching a decarbonised, net zero emissions future. It considers the innovations needed in batteries, electric vehicles and wind power, and the pivotal role that the chemical sciences has to play in achieving them. The opportunities for the sustainable and circular design, manufacture, use and end-of-life of each of these technologies is also examined.

In line with the UK Government's planned expansion of low carbon energy supplies, UK electricity production is set to be zero carbon by 2035, along with a suspension of the sale of new petrol and diesel cars and vans by 2040.[1] Delivering this transition will require billions of pounds of investment in clean energy infrastructure and new low carbon technologies, such as wind turbines, solar panels, energy storage capacity, and electric vehicles. Significant amounts of CRMs – as well as technology metals and critical materials more broadly – will also be needed to build them, such as the lithium in the battery of an electric vehicle or the neodymium in the permanent magnets of a wind turbine generator.

In 2019, the UK generated approximately 1.6 metric tons (Mt) of electronic waste,[2] containing 379,000 kg of CRMs worth £148 million a year.[3] In the same year, 59% of electronic waste was recycled in Northern Europe. However, due to a lack of recycling infrastructure, the dissipation of waste in pre-processing recycling operations, and losses in pyrometallurgical recovery processes which sacrifice CRMs in favour of higher value materials, the majority of the CRMs contained within waste is lost.[2]

The CRMs locked in mobile phones and personal electronics, for example, are explored in the Royal Society of Chemistry's Elements in Danger campaign.[4] Waste electronics are typically exported to other countries instead of being fed back into the UK's manufacturing base, with many end-of-life products containing metals and minerals in higher concentrations than primary resources.[5] This represents a missed opportunity for the UK economy.[6]

Ahead of the UN Climate Change Conference (COP26) in Glasgow, Scotland, the Royal Society of Chemistry is working to draw on the experiences and perspectives of the chemical sciences community to help inform its engagement with policymakers, the research community, and the public.[7] During an expert roundtable organised by the Royal Society of Chemistry's Environment, Sustainability and Energy Division held in March 2021, experts from academia, industry, and policy were asked to consider the use of CRMs in technologies such as electric vehicles, energy storage, and wind power. They specifically considered the scientific and technological challenges in the sustainable use of CRMs, as well as the changes to structures and connections needed across the value chain to achieve sustainable CRM use.

2 Summary of discussion

Participants highlighted that manufacturers, policymakers, end users and scientists working in research and development (R&D) should carefully consider how CRMs are sourced, used and retained within a circular economy, especially at end-of-life. This approach is key for ensuring that these technologies can be deployed at the levels at which they are needed, as part of a decarbonised future. Four key factors were identified:

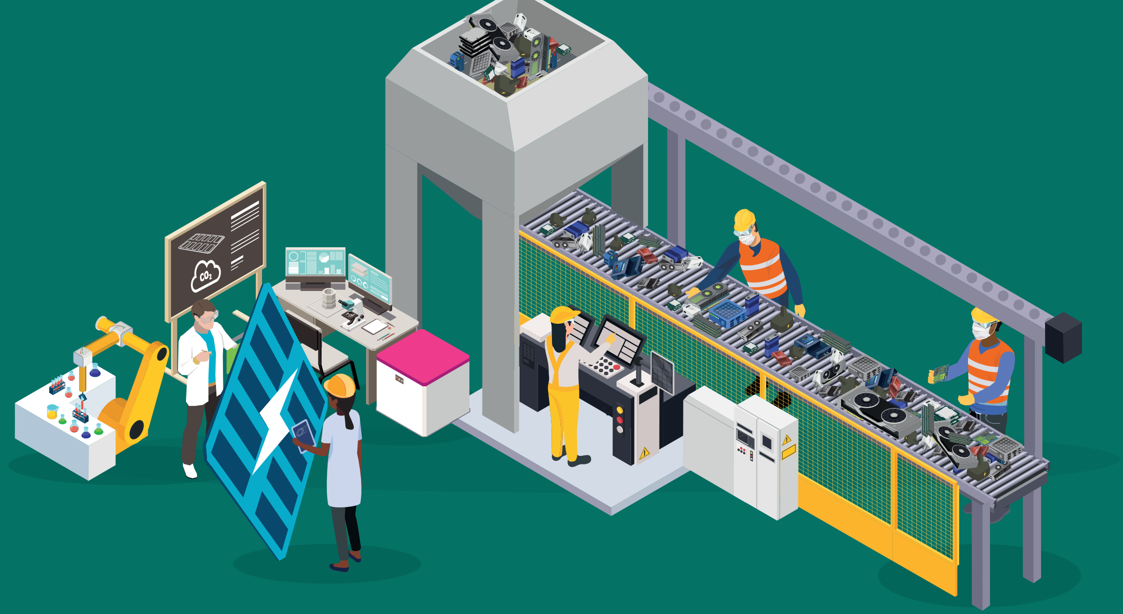
A transition from a linear to a circular economy is fundamental for a sustainable future for batteries, electric vehicles and wind power:

- Under a linear system, technologies at their end-of-life are not sufficiently utilised, creating waste and representing a loss to the UK's manufacturing industry.
- Technologies should be designed to minimise their full lifecycle impact and cost.
- More accurate metrics should be developed to track technologies and their component materials throughout their lifetimes, monitored by material tracking databases.
- The standardisation of manufacturing protocols and consistent labelling of components in these technologies should be developed to enable their circular use, such as the composition and construction of batteries.

Collaboration is critical, between industry partners and between industry and academia:

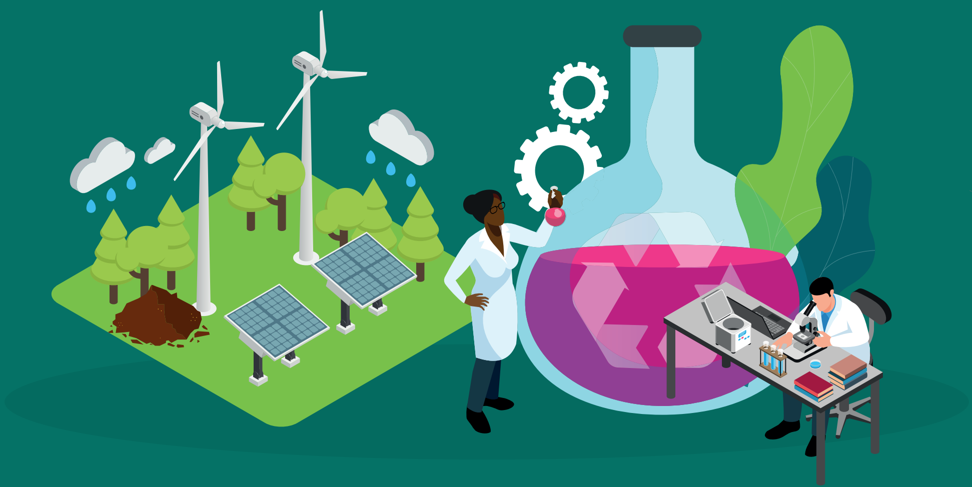
- There are specific technical challenges that could benefit from collaboration between chemists, engineers and designers, and which can promote circularity.
- Collaborations need to be implemented and supported at a variety of scales, such as local partnerships, national funding programmes, and broader initiatives that enable careers in the circular economy.
- Solutions that promote the recovery and circular use of CRMs need to be integrated and shared across sectors and supply chains. Private sector innovation should be supported by academic and government partners.

The chemical sciences are contributing solutions for the more sustainable use of CRMs in low carbon technologies:



- This includes innovation for more sustainable pyro- and hydrometallurgy, novel CRM separation techniques, and the targeted recovery of CRMs from waste.
- Chemists – at universities and in partnership with industry – are applying advancements in CRM recovery to areas of technological importance, such as electric vehicle battery end-of-life processing.
- Chemists working at the earliest stages of discovery in the area of CRM use and recovery are considering product design and construction when developing their research. This includes the role of design in enabling effective recovery of CRMs and CRM-bearing components.

Remaining challenges need innovative solutions from the chemical sciences:



- More tailored recovery techniques are needed to avoid the unintentional loss of CRMs during end-of-life technology processing, such as more advanced smelting approaches. Safe and economically viable recovery techniques should be promoted.
- Innovative chemical solutions are needed to enable circular design, such as the safe disassembly of batteries and the reuse of their valuable components.
- Sustainable recovery practices need further development to reduce their environmental and emissions impact, by minimising their solvent and energy requirements, for example. Interdisciplinary approaches are critical, such as collaboration between engineers and chemists to understand how to best chemically and physically recover CRMs.

3 The importance of CRMs and their recovery

Critical Raw Materials are those raw materials that are economically and strategically important for the economy but have a high risk associated with their supply. They have, for example, a significant economic importance for key sectors (such as consumer electronics, environmental technologies, automotive, aerospace, defence, health and steel), a high supply risk due to a very high import dependence or there is a lack of viable substitutes.[8] An increasing penetration of electronics in consumer and industrial markets, the deployment of technology for climate change mitigation, and the adoption of technologies to support Industry 4.0 are all contributing to an increase in demand for critical metals.[9]

The EU, for example, monitors a list of CRMs as part of its Raw Materials Initiative which is updated every three years.[10] The 2020 list contains 30 materials, with bauxite, lithium, titanium and strontium added in this iteration and helium removed (while it remains a concern in terms of supply concentration, helium is deemed to have declined in economic importance). Criticality is, of course, subjective to the context in which it is being discussed. For this reason, it is important to also consider elements and materials that are not on this list, such as broader technology metals or critical materials.

CRMs such as cobalt, lithium and rare earth elements (such as neodymium, dysprosium and praseodymium) are vital commodities in the rapid development and adoption of digital devices and low carbon technologies, and as supply chains adapt to their scarcity and global availability, their use must be carefully considered.[11] For example, global demand for lithium is forecast to grow by over 20% a year in the next decade,[12] and global demand for cobalt, also required for lithium-ion batteries, is predicted to approximately double by 2030.[13] Demand for other materials associated with electric vehicles, such as magnesium for lightweight alloys, is also projected to increase.[14] A recent report from the University of Birmingham – *Securing Technology-Critical Metals for Britain* – discusses this in detail.[15]

A range of metallurgical and chemical solutions exist to recover CRMs from waste, and their suitability varies across waste streams. Current approaches rely on pyrometallurgy (melting sources of metals at high temperatures) and hydrometallurgy (the use of aqueous solutions to leach metals, typically with strong acids or oxidising agents).[16] In situations where non-aqueous solvents are required, conventional processes employ solvents that are fossil fuel-based, toxic, and not environmentally benign.

Solutions such as battery electrolytes, which are both hazardous and contain valuable lithium salts, are also often lost in recovery processes. Furthermore, the mixed nature of waste feedstocks often requires complicated, selective chemistries during chemical recovery steps. By considering the wider recycling process (such as physical separation steps that promote disassembly rather than simple shredding), less complicated, more efficient, and lower impact chemistries can often be employed later in the process.[17] More tailored and integrated solutions are needed to achieve a more sustainable and circular approach to CRM recovery.

Linear approaches to manufacturing and consumption remain prevalent, with materials used and technologies often designed without end-of-life disassembly or reuse in mind.[18] With an increased adoption of technologies that require CRMs, the recovery and reuse of these technologies and the materials used in their construction needs to be made standard practice. This can be achieved by designing technologies with circularity in mind. Examples of this include:

- the use of modular components that enable end-of-life material separation
- the use of materials that reduce reliance on raw materials, promote extended product lifetimes, and enable disassembly, reuse, or recycling
- the localisation of manufacturing to point of consumption and recycling (therefore reducing transport, improving lifecycle impacts, and favouring the economics of business with the provision of domestic secondary raw materials).

4 Low carbon technology focus

In this section, we look in more depth at the challenges and opportunities faced by the sustainable and circular use of CRMs in the context of three key low carbon technologies, namely batteries, electric vehicles and wind power.

CRMs are also found in other low carbon technologies, such as solar panels, low energy lighting and a variety of electronic products, but these are not discussed in this report.

4.1 Batteries

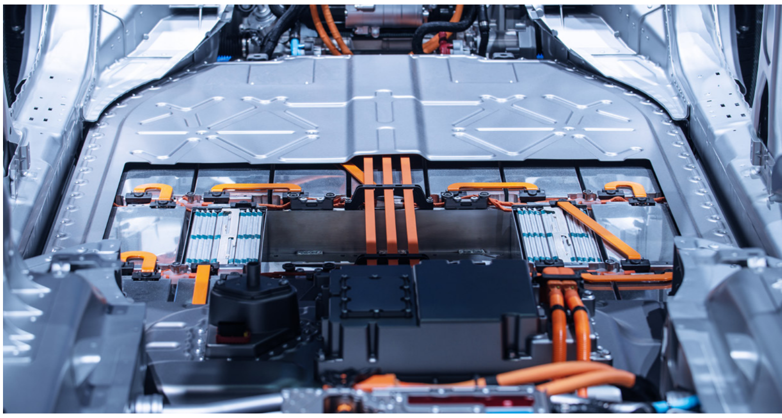
Scientific and technological challenges

While the UK Government's phasing out of the sale of new petrol and diesel cars from 2030 is crucial for the reduction of greenhouse gas emissions, it will also lead to a significantly greater number of electric vehicle batteries in production, operation, and end-of-life processing.[19]

With a typical lifetime of eight to ten years and a mass of 300 kg to 600 kg if used in an electric vehicle,[20] batteries have the potential to become a significant waste stream. While these batteries can be used for storage capacity in static applications for up to 20 years post-vehicle use, the valuable materials contained within them can also be recovered, therefore avoiding the extraction of new minerals through mining. Roundtable participants highlighted the importance of these batteries being designed with circularity in mind so that they can be appropriately managed at end-of-life.[17] In addition to electric vehicle batteries, they also discussed batteries for other applications.

Knowing where materials are in the supply chain and in waste streams can support efforts to extract CRMs from products and wastes, therefore ensuring that they are not lost from the economy. For example, it is not only battery supply chains that use elements such as cobalt and nickel, but also the supply chains of products such as semiconductors or corrosion-resistant alloys.[21] The benefits of this recovery could be substantial, with one tonne of lithium requiring the processing of 250 tonnes of ore or 750 tonnes of brine, in comparison to just 28 tonnes of end-of-life batteries.[22] Participants noted that:

- **Legislators should make it clear who is responsible for handling batteries at end-of-life, as battery ownership and recycling responsibility can vary**. For example, a battery or electric vehicle manufacturer can be made responsible for recycling, therefore incentivising more circular design. This strategy is used in China.[23]



The US has recently introduced a bill that considers guidelines of this nature,[24] and proposed updates to EU battery legislation recommend a similar approach.[25] While extended producer responsibility (EPR) compliance schemes are already in place under existing EU and UK law, roundtable participants suggested that these should focus on individual producer responsibility (IPR). This could require producers to pay the cost of end-of-life processing of their own products as opposed to paying into schemes that manage this responsibility collectively for members. Legislators should, however, be mindful of the unintended consequences of regulation and not inadvertently impede or slow the transition to zero carbon mobility.[26]

- **The use of secondary raw materials (recycled waste material injected back into the economy[27]) should be incentivised across the entire battery manufacturing value chain, not just in isolated areas**. In addition, consumers should know how to return products and be incentivised to do so - this should be the case for both individual battery packs and waste electrical and electronic equipment (WEEE) that contain batteries.
- **Battery design should be based on how energy is actually used and by taking into consideration how they are repurposed after their first use**. For example, batteries with greater capacities are under continuous development but are not needed for all applications. This battery development may require a range of different battery chemistries and technological innovations, such as intelligent storage or grid distribution. Participants highlighted the repurposing of electric vehicle batteries to stationary energy storage as a key opportunity.

- **Alternatives to standard batteries, such as lithium cobalt oxide ($LiCoO_2$) batteries, have a key role to play**. Lithium iron phosphate ($LiFePO_4$) batteries – originally de-prioritised for electric vehicles due to their relatively low energy density – are being used by some car manufacturers, such as the Chinese company BYD and US company Tesla, as they do not require the costly and scarce elements of cobalt and nickel.[28,29]

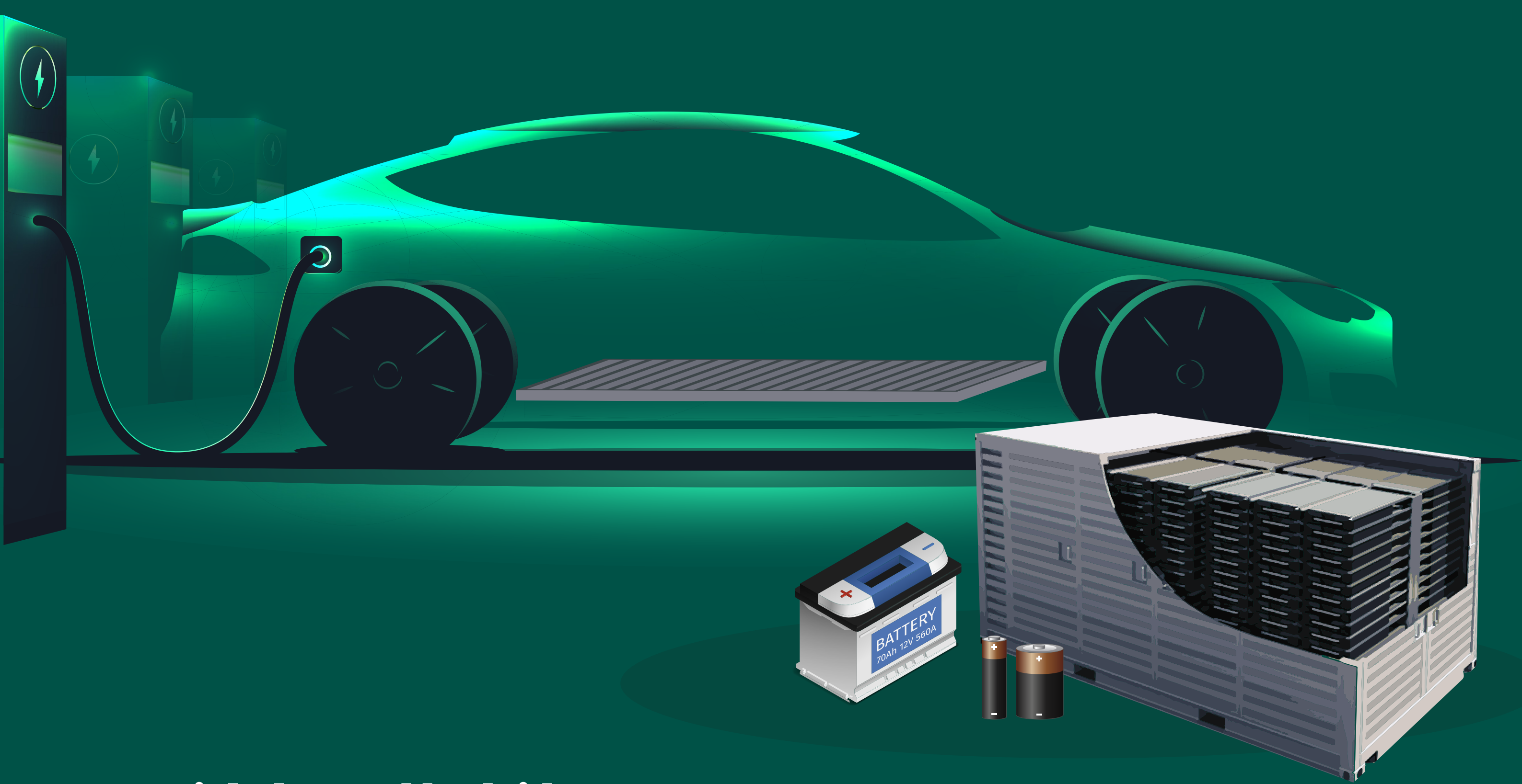
Despite their longer lifetimes, there is a risk that these cells will be less attractive for commercial end-of-life recovery due to the lower value of their constituents. This will mean that recycling will have to effectively valorise all battery components as the high value cathode metals, which have been primary targets of lithium-ion recycling to date, are absent. Circular economy strategies to regenerate added-value raw materials from recycling to feed domestic battery manufacturing may offer an opportunity to increase the cost benefit of recycling. Pyrometallurgical processes that sacrifice other valuable battery components – such as electrolytes, graphite and polymeric battery parts – in favour of high yielding cathode metals should be avoided in the future.

- **Safer battery formulations and technological improvements in how batteries are managed at end-of-life could be impactful.** Due to their advantageous high energy density and the presence of highly reactive lithium metal, lithium-ion batteries possess a propensity to catch fire, representing a significant challenge to the waste industry.
- **Despite their importance, few battery recycling plants are based in the UK**, increasing the cost and environmental impact of their participation in the UK's circular economy.

Exporting secondary reserves of vital materials to economic competitors is not ideal as these material supplies are needed to feed the UK's own manufacturing base. UK-based original equipment manufacturers pay between £3 and £8 per kg to recycle end-of-life lithium-ion batteries that are exported abroad for material recovery, while the material must later be repurchased.[30]

The safe disassembly of batteries is challenging, both in terms of human and environmental harm. Roundtable participants highlighted a number of technical challenges, such as:

- **The separation of components for recycling**. Battery disassembly is complex and one of the largest barriers to recycling. More considered design, such as separable battery components, can make it easier to reclaim high value materials, and structures to promote the recovery of lesser value resources may require explicit policy intervention and funding support.
- **The disassembly of batteries when their contents are unknown**. Batteries need to be labelled consistently to identify their contents and chemistries, as proposed by updates to EU battery legislation, so that substances of concern, such as mercury and cadmium, can be monitored. Furthermore, the use of the same connectives, adhesives, and corrosion protection coatings across the industry would help to mitigate this challenge. Labelling batteries to identify their specific chemistry can also help end-of-life processors to sort and recycle them in a cost-effective way. It can also provide important information to those repurposing batteries for second life applications.



Nickel-metal hydride

13	Al	Aluminium
25	Mn	Manganese
27	Co	Cobalt
28	Ni	Nickel
57	La	Lanthanum
58	Ce	Cerium
59	Pr	Praseodymium
60	Nd	Neodymium

Lead acid

50	Sn	Tin
82	Pb	Lead

Alkaline

25	Mn	Manganese
30	Zn	Zinc

Redox flow

3	Li	Lithium
22	Ti	Titanium
23	V	Vanadium
26	Fe	Iron

Lithium-sulfur

3	Li	Lithium
6	C	Carbon
16	S	Sulfur

Lithium-ion

3	Li	Lithium
6	C	Carbon
25	Mn	Manganese
26	Fe	Iron
27	Co	Cobalt
28	Ni	Nickel
39	Y	Yttrium

Figure 1: Elements commonly found in different types of batteries[31,32,33]

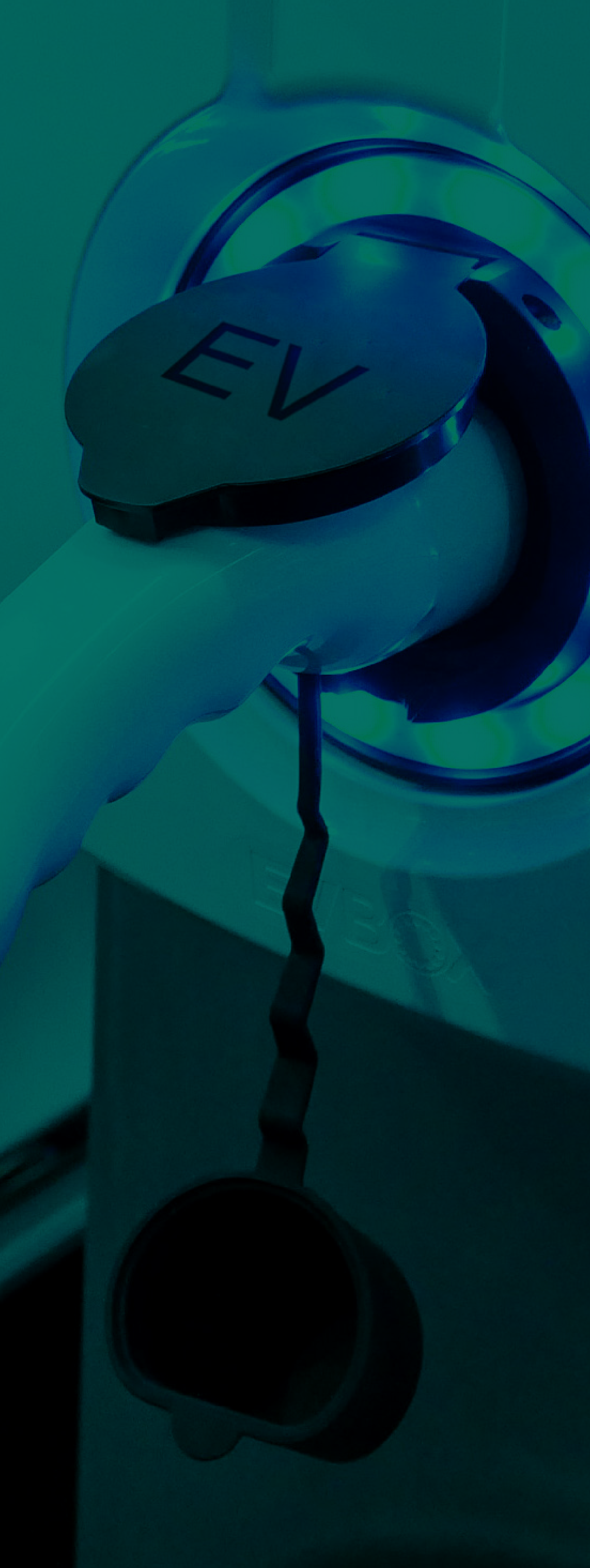
There are many classes of battery that utilise differing chemistries and elements in their construction, with further variation by manufacturer. The following lists are not exhaustive but demonstrate a battery's reliance on elements that may be scarce or used in high volume.

Specific examples and opportunities

Participants highlighted the following examples of best practice and future opportunities:

- **Hydrometallurgical recycling of batteries** typically involves steps such as acid–base leaching, solvent extraction, precipitation, ion exchange, and electrolysis.[34] Separation techniques that can reclaim materials with high purity and efficiency are sought.
- **Lithium-ion battery electrolytes can be extracted with liquid and supercritical carbon dioxide or other solvents to help to render batteries safer for further processing**.[35] Electrolytes are also valuable and can be recovered for further recycling. The Lithorec II programme explored this approach.[36]
- **Deep Eutectic Solvents (DESs) can offer a more environmentally friendly form of solvatometallurgical processing** in comparison to traditional methods which are energy-intensive and generate hazardous waste.[37] They offer unique solubilities that can be used to selectively separate different metals. With 80% of waste in the chemical industry a result of solvents,[38] the scope for their use is significant. Bio-inspired DESs based on sugars, alcohols and glycerol are under development for metal electrodeposition, metal extraction, catalysis, and materials processing.[39,40] The University of Leicester is exploring these solvents as part of the Faraday Institution's ReLiB project.[41]

- **A range of other chemistries are needed beyond novel solvent systems in order to more effectively recover CRMs from waste**. This may include integrated approaches such as the chemical pre-treatment of materials (eg chlorinating an oxide for dissolution) or electrochemical oxidation.[42,43]
- **The separation of battery components, such as the removal of polymer adhesives between cells, currently requires the use of toxic and hard-to-dispose-of solvents**. Furthermore, the chemistry of these adhesives is often not shared by manufacturers. Debondable polymers that can be disassembled to a monomeric state while remaining unsusceptible to hydrolysis during operation, could offer an alternative, as do reversible adhesives more generally.[44]
- **New battery manufacturing, recommissioning, and disassembly processes**. Some battery manufacturers, such as the Chinese company BYD, are implementing strategies such as automated battery manufacturing and modular cell assembly without the use of adhesives.[45] Both the Faraday Institution's ReLiB project and the DeMoBat project in Germany are also developing the robot-assisted dismantling of batteries and motors for electric vehicles.[46] More effective processes for the recommissioning of battery cells for reuse need to be developed.
- **Advances in process intensification can boost the commercial-scale recovery of CRMs from batteries**.[47] Examples include advances in electrocatalysis, diffusion dialysis systems, and countercurrent leaching.[48,49]



4.2 Electric vehicles

Scientific and technological challenges

As with batteries, securing future material supplies to feed the UK's electric vehicle manufacturing base is of critical importance. The recovery of CRMs from domestic secondary raw material flows is an important part of this effort and can help to alleviate the challenges of supply bottlenecks and price volatility that are often associated with primary raw materials.

A range of end-of-life challenges exist for electric vehicles with respect to their design, manufacture and the suitability of recycling methods that are typically employed. The handling of these vehicles at end-of-life is important in terms of minimising total life cycle emissions and reducing overall environmental impact. Appropriate dismantling of vehicles also allows for the safe removal of both hazardous and valuable materials (such as batteries, refrigerant gases, engines, tyres and electronic components).[50]

Participants highlighted the need for a greater recycling capacity in the UK and a reduction in waste exportation, as waste processed in low- and middle-income countries represents a source of pollution in these countries and a loss from the UK's economy and manufacturing base. Key points raised included:

- **Undesirable end-of-life processes often involve the mechanical processing or shredding of an entire vehicle, resulting in the loss of valuable materials that are often present in only small amounts.** These techniques maximise value from bulk materials only and lead to the cross-contamination of material streams, reducing the value of recovered materials. Materials and components – such as metals, polymer composites, and electronics – should instead be separated for reuse in manufacturing or further processing, while vehicles should be designed to make battery removal and replacement easier.
- **The design of technologies should be future-proofed** by considering the lifetimes of systems and infrastructures in place and expected societal or technological trends (such as models that predict future modes of vehicle use). Such trends may dictate the scientific or technological innovation needed, such as the required range of batteries or the favoured form of transport.[3]

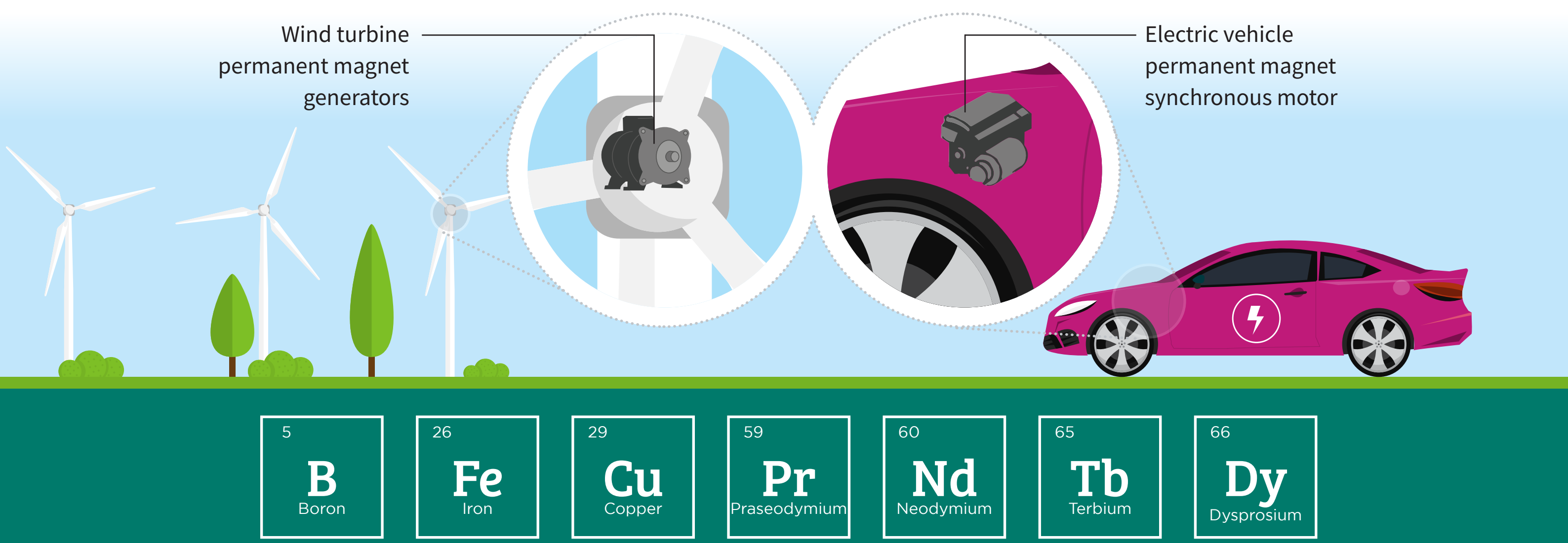
Specific examples and opportunities

Participants highlighted the following examples of best practice and future opportunities:

- **Improved extraction or disassembly processes developed by chemical scientists and engineers should be shared with product designers** to ensure the successful employment of these end-of-life processes in industry. For example, researchers at the University of Birmingham are exploring the deconstruction of fibre reinforced composites to reclaim carbon fibres for reuse.[51]
- **Physical separation methods such as the shredding of materials results in considerable losses of CRMs before chemical processing and recovery begins**. These CRMs are contained in relatively small quantities (in comparison to the entire vehicle) and are lost as dust during the shredding process. New disassembly routes need to be developed to avoid this alongside an assessment of where to deploy chemical or physical separation processes to enable maximum recovery. Product design that facilitates disassembly can also negate the need to shred products at end-of-life.
- **Circular business models for the sale and use of vehicles**. River Simple manufactures energy and resource efficient hydrogen-powered electric cars and sells mobility as a service via subscription, retaining ownership of the cars and the materials used to construct them.[52] Considering the circular lifetime of products more generally, participants advocated for strengthened incentives for car manufacturers, such as comprehensive right to repair legislation, extended producer responsibility (EPR), and strict end-of-life design standards for products.
- **While funding and collaboration incentives are in place for electric vehicle battery recycling, they are less established for magnet recycling (such as those recovered from electric motors)** and are currently driven by EU partnerships. Participants reported difficulty in retaining involvement in these partnerships since the UK's departure from the EU. They also noted that magnet feasibility studies are particularly challenging to conduct if manufacturers are not based in the UK, and that magnet manufacturing typically occurs in countries with ore processing capabilities and reserves, such as China.
- **The energy requirements of a material recovery process can be considerable** and in some cases can exceed that of sourcing from new feedstocks. Comprehensive life cycle assessment (LCA) needs to be carried out to understand these energy requirements. In some cases, these can be alleviated by the introduction of new technologies, the utilisation of clean energy, or by focusing on reuse to preserve function over longer timeframes.
- **Technologies are also under development for the targeted mobilisation and recovery of CRMs from legacy landfills, industrial sites and other waste sources**. These techniques are capturing valuable metals – such as platinum group metals expelled from automotive catalysts – while decontaminating waste to prevent pollution risks. Removing CRMs from polluted organic waste can also support the production of alternative fertilisers that help to lock carbon into soils.[53]

Figure 2: Elements commonly found in wind turbines and electric vehicles[54]

Wind turbine generators and electric vehicle synchronous motors both contain permanent magnets that use a range of elements in their construction. The following list is not exhaustive but demonstrates a permanent magnet's reliance on elements that may be scarce or used in high volume.



4.3 Wind power

Scientific and technological challenges

Wind turbines use a range of materials and components in their construction, ranging from steel to composite carbon and glass fibre resins for turbine blades (that are particularly challenging to recycle[55]) to rare earth metals such as neodymium or dysprosium for the permanent magnets of turbine generators.[56]

The efficiency of wind turbine end-of-life processing is in part determined by the ease with which CRMs can be recovered from them and the barriers to recycling that might exist.[57] As this technology evolves, greater emphasis will be placed on extending product lifetimes to bolster reliability and performance, and this may influence the end-of-life strategies that need to be employed. With 60,000 tonnes of wind turbine blades reaching their end-of-life in the next two years,[58] this ever-growing challenge requires action across the entire supply chain. Participants highlighted a number of suggestions:

- **To successfully handle low carbon infrastructure and technologies at end-of-life, the roles and responsibilities of stakeholders throughout entire product lifecycles must be clearly defined**. Compared to more mature sectors such as that of the automotive, stakeholders in the wind sector are often reportedly unaware of the circular economy opportunities that exist. In offshore wind, for example, there is a high untapped potential for the reuse, repurposing and remanufacturing of materials and components. Opportunities include the reprocessing of turbine blades into secondary raw materials by companies such as Procotex (in Belgium) that produce milled and chopped fibres,[59] or Renewable Parts Ltd (in Scotland) who repair and refurbish wind turbines.[60]
- **The full lifetime cost of new technologies must be factored into energy infrastructure decisions** and metrics should be developed to quantify the materials saved over the entire lifetime of a technology as a result of circular design choices.[61] While a variety of life cycle assessment (LCA) tools and international materials databases containing comprehensive datasets exist, participants noted a lack of regulation and standardisation. In addition to LCA, lifecycle sustainability assessment (LCSA) was highlighted as a tool that takes economic, environmental, and social impact into account.[62]

Specific examples and opportunities

- **To fully understand the upper lifespan of wind turbines and engines,** manufacturers should seek to understand the reasons behind a loss in a wind turbine's performance, which might be the oxidation of components or a result of design and construction choices. It was noted that the lifespan of neodymium in components is particularly important to consider.
- **The development of business cases for the recycling of composite materials is needed to identify potential markets**. For example, the Offshore Renewable Energy (ORE) Catapult's financial forecasting specialists assess opportunities for recycling into multiple industries and supply chains to identify if components can be reused before stripping them of their materials.[63] The ORE Catapult also works with companies to develop new technologies and leverage government support. Their work with Greenspur Renewables, for example, seeks to develop permanent magnet generators that use ferrite instead of neodymium to alleviate raw material concerns.[64]
- **Financial and legislative support should be provided to wind turbine operators to alleviate economic barriers to recycling** which should promote the reuse and recycling of turbine components instead of sending to landfill.
- **Recycling processes, such as those under development at the University of Birmingham,[65] need to be developed and scaled up in the UK** to shift reliance away from primary raw materials.

5 Enabling factors

The scientific and technological challenges faced in the sustainable and circular use of CRMs in batteries, electric vehicles and wind power do not exist in isolation and participants highlighted a number of enabling factors that should also be taken into consideration.

Factors that were identified and are explored in this section include collaborations, regulation, incentives, and business models.

5.1 Collaborations

Collaborations across industry and academia offer opportunities to address the challenges of resource recovery and circularity and should take a whole system approach. Participants identified a number of collaborative opportunities:

- **Those between chemical scientists and engineers** in areas such as the metrology of critical materials, solvatometallurgical processing, the automated dismantling of products, and the improved formation of components such as glues, binders and laminated plastics.
- **Across entire supply chains for a given technology or group of technologies**. This may include mining and material processing, product design, extended use, disassembly and 'high quality' materials recovery (ie secondary raw materials of equal value to their primary source). Closed-loop recycling should be enabled rather than the downcycling of materials (the recycling of a material into one of lesser value[66]). Global research to tackle these issues is ongoing and should be considered.[3]
- **Partnerships with product designers that consider the disassembly and recovery of CRMs from technologies and their components at end-of-life**.

From discovery research to application

Regardless of the technology, the long journey from discovery research to application can be aided by interdisciplinary engagement between industry and academia. Examples range from Innovate UK's Catapult network[67] (established to promote R&D through business-led collaboration between scientists and engineers to exploit market opportunities) to Swansea University's M2A doctoral training model that provides an industry supervisor to offer industry exposure to students and to make sure that research projects are relevant to the needs of industry.[68] The EPSRC project, 'A Sustainable Circular Economy for Offshore Wind', also supported the development of ORE Catapult's Circular Economy for the Wind Sector Joint Industry Project.[57]

Within the battery development space, the Faraday Institution's ReLiB project at the University of Birmingham was established to explore the sustainable management of lithium-ion batteries when they reach the end of their useful life in electric vehicles.[41] Furthermore, the new UK Research and Innovation (UKRI) Circular Economy in Technology Metals hub, led by the University of Exeter (supported by Birmingham, Manchester, Leicester and the British Geological Survey), is one of five new UKRI Interdisciplinary Circular Economy Centres across the UK dedicated to exploring how the reuse of waste materials can deliver huge environmental benefits and boost the UK economy.[69]

Collaborations can also allow different sectors to learn from one another and to translate best practice into new areas. Participants considered the urban mining sector, this being the process of recovering rare earth metals from discarded WEEE.[6]

- **Urban mining techniques should be further developed, funded and applied to technologies such as WEEE, batteries and the electronic components in electric vehicles**. Knowledge can be translated from other sectors, such as advances in the mechanisation of ore mining or the marketisation of waste outputs by oil refineries (eg the former waste product tar). This could allow opportunities, such as the extraction of gold and rhodium from catalysts, to be scaled up.[70] Such techniques should be developed with their full environmental impact taken into consideration and will require financial investment.

5.2 Regulation

Though many of the challenges discussed in this report rely on action from manufacturers, waste management companies and other industry partners, action is also needed from legislators and policymakers. For example:

- **Waste management approaches should consider the entire lifecycle of chemicals, not just the carbon and energy implications of waste**. Tensions between chemicals and circular economy regulation (such as the need to phase out toxic chemicals that may be critical to a material's function) should be addressed by legislation that safely manages pollutants at end-of-life. For example, legislation should make sure that waste containing flame retardants that cannot be easily reclaimed is safely disposed of or reused.[71]
- **Adequate 'polluter pays' legislation is lacking across many industries in the UK**. The introduction of both new policy and enforcement to prevent the release of waste to the environment by industry is needed. This will become increasingly important as CRMs are extracted from new waste streams, such as in the management of wastewater.
- **The use of materials tracking systems can help in the management of materials across their entire lifecycle, identify sources of CRMs, and help materials to stay in circulation for longer**. Combining the national waste tracking system with the National Materials Datahub, for example, could create a powerful tool to identify the fates of CRMs in the UK, as well as viable secondary resources for their extraction. Furthermore, a similar approach to material safety data sheet (MSDS) principles could be used to help handlers of technologies to consider a material's impact on health and safety. Data submitted to the Department for Environment, Food & Rural Affairs (DEFRA) for compliance with UK REACH chemical regulations and Restriction of Hazardous Substances (RoHS) guidance could also help to inform such a system if concerns regarding commercial sensitivity can be overcome. This has been a primary goal of Topolytics Ltd in their efforts to develop a national waste tracking system.[72]
- **Right to repair legislation should be expanded in its scope to include more products and ensure that they can be more easily disassembled, upgraded and repaired when components fail**.

Participants also noted that in cases where regulation applies to low carbon infrastructure, complex and dynamic ownership structures mean that it might not always be clear to whom the regulation applies.

5.3 Incentives

Incentives are needed to increase the UK's processing capability of technologies at end-of-life to shift the sourcing of CRMs away from mining and towards waste.

- **The UK has one of the highest consumption rates of WEEE in the world, representing a rich potential secondary raw materials reserve**.[2] The production of superior quality secondary raw materials or products should be encouraged, supported by appropriate infrastructure, as the less desirable downcycling of materials is often incentivised by markets. Investment can be encouraged and justified by pooling end-of-life materials and technologies from a range of low carbon sectors.
- **Legislative actors such as the Environment Agency, who license recyclers, have the scope to promote and reward circularity**, establish rules of best practice and identify centres of excellence. Modulated compliance fees for WEEE was identified as recent progress in this area.
- **The majority of consumers are unaware of the valuable materials contained within their products**. An Ipsos MORI survey of over 2,000 people investigated knowledge and behaviours around WEEE as part of the Royal Society of Chemistry's Elements in Danger campaign. It highlighted that the majority of people are unaware of the valuable materials contained within their electronic devices, contributing to a propensity to store devices indefinitely or to neglect recycling.[4] Consumers should be incentivised to responsibly dispose of the products that they own, by being provided with information about how they can recycle their products and the value of the resources contained within them.

5.4 Business models

Economically viable materials markets are critical for the success of new end-of-life processes and can be supported by legislation or incentives. For example:

- **Proposed updates to the EU Batteries Directive legislation will remove barriers to recycling by banning materials that are particularly hazardous, deleterious to recycling processes, or increase the cost of disposal significantly.**[25]
- **Economic incentives, such as deposit return schemes (DRS), are needed to encourage the return of waste technology to appropriate stakeholders**. Other mechanisms, such as the secure data wiping and curbside collection of WEEE, have also been employed.

For new recycling business models to be successful, they often need to be deployed at scale, depending on the technologies and methods that are used.

- **Experience can be translated from the more established aluminium and steel recycling industries**. However, participants noted that alternative hydrometallurgical processes can be installed at lower capacity with lower capital cost and more easily expanded as required.
- **Where industries are not yet established, legislative incentives should encourage markets for secondary raw materials and support industries that are managing this transition**. Examples of support include infrastructure establishment, new jobs and staff training, sector-enabling funding, forward-looking research and innovation in this area, and strategic collaborations across supply chains.

6 Conclusion

A transition from a linear to a circular economy is key to a sustainable future for batteries, electric vehicles, and wind power. Delivering a decarbonised future based on these technologies will require sector-wide innovation and collaboration spanning both industry and academia.

The chemical sciences are actively contributing solutions for the more sustainable use of Critical Raw Materials so that they can be recovered from waste and retain their value. Through applied and discovery research, chemical scientists are identifying further challenges that need to be solved, though support and incentives are needed to accelerate this and to translate innovation in the lab to commercial application.

Furthermore, there are a number of opportunities for collaboration between chemical scientists, engineers and designers, through which circular approaches to CRM usage and recovery can be translated into action. A shift to circular design, use and disassembly should be simultaneously encouraged as this will play a key role in supporting the scaling of CRM recovery and sustainable waste management practices.

We hope that this report demonstrates the role that the chemical sciences has to play in society's transition from a linear to a circular economy, especially with regard to the management of low carbon technologies at their end-of-life and in the delivery of a decarbonised future.

7 Participants

This report is a summary of views and insights from roundtable discussions that took place in March 2021. It forms part of the Royal Society of Chemistry's ongoing efforts to gather evidence on the technical challenges and opportunities faced by chemical scientists and their collaborators in the area of sustainability.

The report was written by Dr Ross Jaggers of the Royal Society of Chemistry and does not represent the views of any individual participant.

During this event, Professor Emma Kendrick, University of Birmingham, and Eoin Bailey, Celsa Steel UK, shared their perspectives ahead of a series of discussion sessions facilitated by members of the Royal Society of Chemistry staff. The following individuals contributed to these discussions, which form the basis of this report:

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- Professor Carlo Burkhardt, Pforzheim University
- Dr Rhys Charles, Swansea University
- Dr Matthew Davies, Swansea University
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- Professor Colin Herron, Zero Carbon Futures
- Professor Eva Hevia, University of Bern
- Dr Vicky Hilborne, University College London
- Professor Jason Love, University of Edinburgh
- Dr Stephen Mudge, Norwegian Institute for Air Research
- Dr David Owen, Treatchem Ltd
- Professor Herman Potgieter, Manchester Metropolitan University
- Professor Phil Purnell, University of Leeds
- Dr Andy Rees, Welsh Government
- Ronald Schoff, Electric Power Research Institute
- Claire Spooner, Engineering and Physical Sciences Research Council
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