TECHNOLOGY INNOVATIONS IN THE CIRCULAR ECONOMY

Insights and evidence from the NICER Programme

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CE-HUB
UKRI National Interdisciplinary Circular Economy Research

NICER PROGRAMME

University of Exeter

UK Research and Innovation

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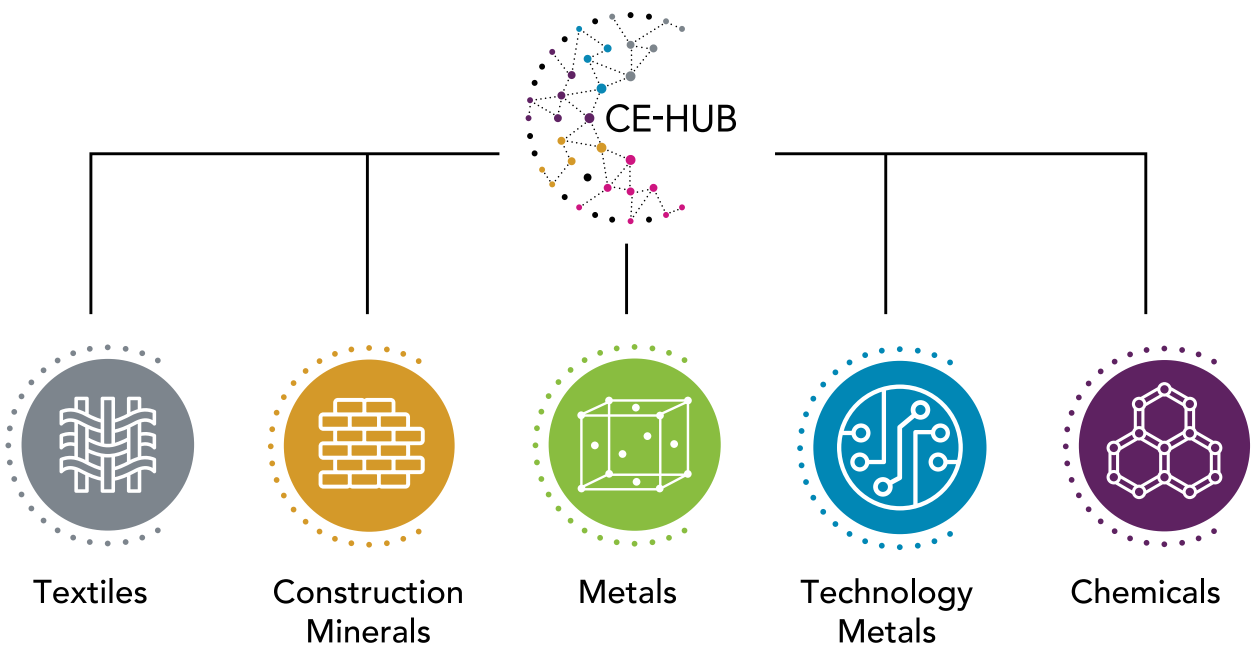
About the National Interdisciplinary Circular Economy Research Programme

The National Interdisciplinary Circular Economy Research (NICER) programme is a £30 million four-year investment from UKRI and the Department for Environment, Food & Rural Affairs (DEFRA) to deliver the research, innovation and evidence base needed to move the UK towards a circular economy. Launched in January 2021 and comprising initially of 34 universities and over 150 industrial partners, NICER is made up of five Circular Economy Research Centres each focused on a specialty material flow, and the coordinating CE-Hub:

- The National Interdisciplinary Circular Economy Research Hub (CE-Hub), led by the University of Exeter
- The Textiles Circularity Centre (TCC), led by the Royal College of Art
- The Interdisciplinary Circular Economy Centre for Mineral-based Construction Materials (ICEC-MCM), led by University College London
- The National Interdisciplinary Centre for the Circular Chemical Economy (CircularChem), led by Surrey University
- The Interdisciplinary Circular Economy Centre for Technology Metals (Met4Tech), led by the University of Exeter
- The Interdisciplinary Centre for Circular Metals (CircularMetal), led by Brunel University London

NICER is the largest and most comprehensive research investment in the UK Circular Economy to date. It has been delivered in partnership with industrial organisations from across sectors and DEFRA to ensure research outcomes contribute to the delivery of industrial implementation and government policy. A core aim of the programme is growing the Circular Economy community through a significant programme of outreach and collaboration.



About the NICER Insight Reports series

The objectives of the NICER programme are to:

1. Accelerate understanding and solutions to enable circularity of specific resource flows,
2. Provide national leadership, coordinate and drive knowledge exchange across the programme as a whole and with policy, consumer, third sector and business stakeholders,
3. Ensure research is embedded with stakeholders by involving businesses, policymakers, consumers and society, the third sector, and other affected groups and communities at every part of the programme.

The transition towards a UK circular economy requires a whole system approach. This means that, in addition to accelerating knowledge at the resource and sector level, there are a number of agnostic system level enablers or drivers that can be applied to accelerate adoption at scale. The purpose of the NICER Insight Report Series is therefore to highlight learning from across the NICER Programme in relation to these system wide enablers.

Technology Innovations and the Circular Economy: Insights and Evidence from the NICER programme

The UKRI NICER programme has been extremely successful in generating new technologies (and enhancing existing ones) of the type that will be paramount in the planning and execution of a variety of steps towards ensuring that our future material world is more circular in nature and therefore more sustainable. This Insights Report summarises the wide array of technology innovations developed over the course of the NICER programme across all material sectors described below, briefly explains the potential for their real-world impact on Circular Economy activity, and signposts the reader to where they can find further information on these innovations.

The five material flows focussed on in this programme are Metals (primarily high-volume use metals such as aluminium and steel); Technology Metals (such as those used in digital devices, batteries, solar panels, magnets etc); Mineral-based Construction Materials (e.g. aggregate, cement, brick, plasterboard, stone and glass); Chemicals (primarily olefins, such as ethylene and propylene); and Textiles (with a focus on turning bio-waste into renewable materials that can be used in textiles).

1. Products should be designed with sustainability in mind, using durable materials and planning for end-of-life recovery

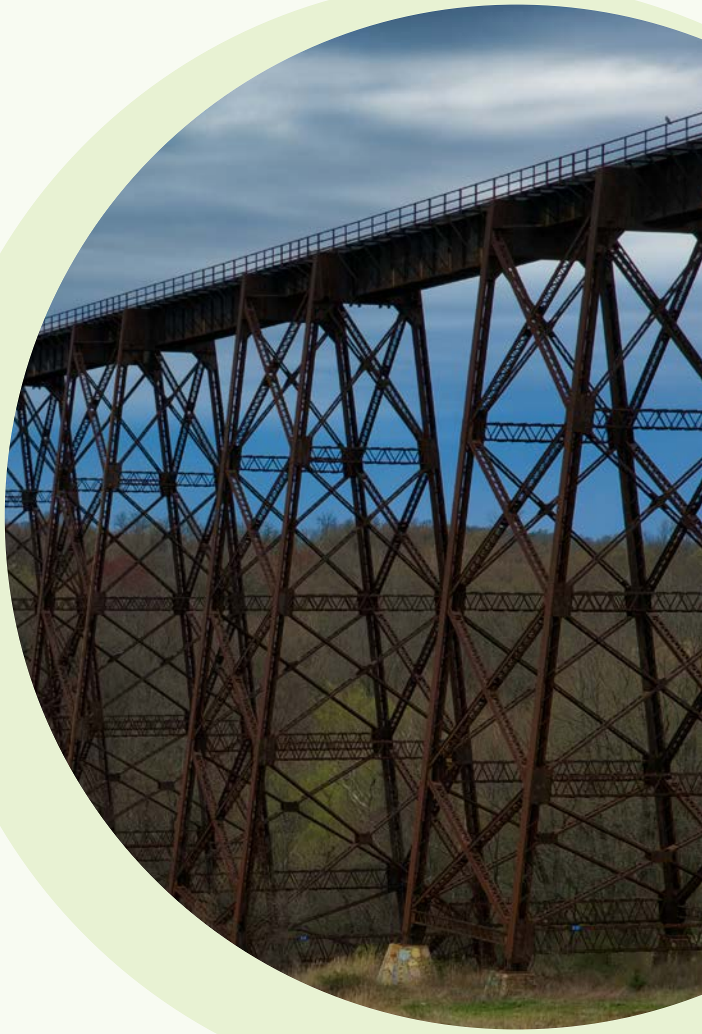
Ensuring that a product design incorporates sustainable principles will help to minimise environmental impact, which can in turn make it more economically viable as well as socially responsible. Lifecycle assessment, material selection, design for disassembly and end of life strategies are all principles that can be considered as part of a sustainable design process. Design strategies that have been considered over the course of the NICER programme include the following:

- **The 'Circular Business Models for Metals Report'** describes how 20 archetypical circular business models can be applied and enable each of the 12 circular metal visions Circular Metal Visions 2050. As a result, 65 circular metal business strategies were defined. Each strategy can be used to **support organisations in the metal value chain to engage circular metal business model solutions.** Circular Business Models for Metals Navigating the Transition- Pathways to a Circular Metal Economy in the UK
- **Design for Deconstruction & Reuse Lightweight Infill Walls.** Lightweight exterior infill walls are built between floors of primary structural frames to provide building façades. Lightweight exterior infill walls are becoming increasingly common in building construction in the UK due to their easy construction, lightness, and low cost. The design of lightweight infill wall systems will lead to **specifiers designing infill walls for reuse, as well as new industries emerging to facilitate reuse**. More information can be found here and here and also here.
- **Multisensory Virtual Reality** - Farfalla is a Virtual Reality (VR) experience that immerses consumers in the future of retail, empowering them to see themselves contributing to textile circularity. Through hands-on activities, users explore bio-based textiles in a multisensory environment, fostering learning and optimism. To innovate with multisensory immersion in storytelling, UCL has integrated smell and sound to the VR experiences, **which make this a highly engaging and memorable experience, which are very important in meaning-making and behaviour change.** Further information can be found here.
- **The Circular Shirt Builder (CSB)** is a physical apparel configurator designed to engage consumers in the co-creation of modular garments, specifically shirts. It uses a modular shirt as a reflective tool that combines traditional tailoring elements with modern modular design principles. Our study shows that consumers who go through this experience **acquire a heightened awareness of their own design preferences while learning and valuing the manufacturing process of clothing**. Further information can be found here.
- **Electromyography (EMG) bracelets** were used, along with a custom-built application, to collect data on hand gestures used to evaluate the properties of textiles. This new technology and the resulting dataset enhance the integration of interactive technologies in consumer experience design. Additionally, it **contributes to a better understanding of how consumers select textiles**. More information can be found here and here.
- Supporting **UK biomaterial start-ups** through access to advanced materials research - in innovative bio-based processes and advanced textile fabrication technologies - in the TCC Materials Library, Circular Materials Design Toolkit, Design of Use catalogue, and funding with the TCC network. Apparel brands were able to rethink their value chains by adopting circular design strategies that extend the life of materials and to creatively differentiate themselves in cooperative design.

2. Material specification can be enhanced in order to facilitate superior properties and performance

Technologies leading to enhanced properties of materials can directly impact on durability, performance and sustainability of products incorporating these materials, as well as conferring economic benefits. Other advantages can include enhanced recyclability of specific materials, helping to reduce waste and conserve natural resources. Examples of technologies developed throughout the NICER programme which could lead to improvements in material manufacturing (and in some cases have already done so) are provided below:

- **High performance and consistency Grain refiner** for Al-Alloys. Revolutionizing Metal Refining: Al-Ti-B Grain Refiner Efficiency Soars from 40% to 95%. This, for the first time, has overcome the inconsistency problem associated with Al-Ti-B grain refiners and will confer significant economic benefits in the casting industry. It will also **enormously enhance the ability to recycle aluminium alloys effectively without reducing quality, i.e. without low value down-cycling**. Further information can be found here.
- **AR Biofibre Explorer** - TCC repurposed Augmented Reality (AR), a popular technology commonly used in fashion retail to enhance sales, and applied it to promote circular economy principles. Specifically, we used AR to improve consumer awareness of biobased materials. The Biofibre Explorer is an AR application designed to showcase the fabrication process of TCC-biobased circular textiles. It visually demonstrates the wet spinning method used to produce regenerated cellulose, enhanced by haptic feedback, **providing users with an interactive and engaging way to understand the value of bio-based materials**. Further information can be found here.
- Development of **novel melt spinning and jet casting processes** for the production of Alloys and Rare Earth Permanent Magnets (REPMs) **enables better microstructure control and therefore improved properties and performance meaning magnetic materials can be manufactured from recycled materials more effectively**. Further information can be found here.



3. Utilisation of production methods that can lead to reduced energy use and/or cleaner methods of energy production can in turn contribute to net-zero goals

Reduction of energy use during material production and development of cleaner energy production methods are key steps towards achieving net-zero goals. This principle can be applied at any point through the value chain, from sustainable sourcing through transportation, energy-efficient manufacturing, to product lifecycle management. The specific innovations developed as part of the NICER programme relate to production of green hydrogen using aluminium, and electrochemical reduction of CO_2, both of which will contribute to the UK's decarbonisation goals.

- Method of **producing green hydrogen using aluminium**. Producing green hydrogen using the reaction of liquid aluminium with water steam, and an embodiment of this method. The method is based on the surface reaction of water with Al to produce hydrogen that is first dissolved in liquid Al and then extracted from it using ultrasonic cavitation or vacuum. Hydrogen production using the reaction of aluminium with water is important from the viewpoint of Net Zero challenges as it is emission-free. **The benefits are both environmental and societal.** Moreover, as aluminium and water are abundant on Earth, **this way of hydrogen production may become the mainstream in future energy harvesting**. Green hydrogen production using the reaction of liquid aluminium with water vapor has benefits over the use of solid aluminium and water solutions as follows: **larger energy stored in liquid aluminium; higher rate of reaction; relative simplicity in removing the reaction products; and alumina as the by-product that can be returned directly to the electrolysis cycle**. Further information can be found here.
- **Electrochemical reduction of CO_2** - Electrolysis technology that can convert carbon dioxide emissions from industries into valuable chemicals and fuels more efficiently. The University of Liverpool and Loughborough University have developed a highly efficient CO_2 electrolysis technology that converts industrial carbon dioxide emissions into valuable chemicals and fuels using a bipolar membrane electrolyser. Achieving over 50% efficiency, this innovation can transform CO_2 into products like carbon monoxide, aiding in the creation of various chemicals. Supported by UK research funding and industry partnerships, the technology aims to reduce fossil fuel reliance and promote a circular economy, thus **contributing to the UK's decarbonization goals and enhancing sustainable chemical production**. Further information can be found here, here and also here.

4. Technologies resulting in extension of life of in-use materials lead to a longer lifespan and therefore reduced need for mining and consumption of primary materials

Enhanced durability of materials as well as the ability to be able to both detect and repair fatigue-impacted materials during service will greatly enhance the length of their service life, in turn leading to increased sustainability and reduced waste. Extension of in-service life is a key step towards creating a circular economy. An excellent example of new technology developed to address this as part of the NICER programme is described below.

- **Electrical Resistivity Measurements and Non-linear Ultrasound Measurements in Metals:** These diagnostic methods have been enhanced within the project to detect not just large cracks but also finer microstructural changes such as persistent slip bands and variations in dislocation density from the earliest fatigue cycles. The enhancement of these techniques allows for earlier and more precise detection of potential issues, facilitating interventions that can preemptively address fatigue before it leads to significant damage. This adaptation of EPT specifically for these applications marks a significant innovation, deviating from traditional uses. The ability to diagnose metal fatigue and rejuvenate metallic components during service can **extend their service life by a factor of 3**; such service life extension is expected to be more significant with further development of more effective technologies. A fully developed Metal Health Service will provide a solid foundation **for transforming the current product-based metals industry to a largely service-based industry**. Further information can be found here.

5. Reclamation of materials post-use through recycling, composting, or remanufacturing reduces our reliance on new resources

Improved recovery of post-use materials is one of the key areas that will enable us to move towards a more circular economy. Increased recovery of materials will lead to increased recycling as well as greater use of those materials in remanufacturing processes. The NICER programme has developed a variety of tools and technologies which will facilitate improved recovery of materials, in turn leading to a reduced need for raw materials and a decreased environmental impact in these areas.

- Method for **monitoring the in-service use of heavy-duty off-road vehicles** that will identify its level of wear and tear at the end of life. This method identifies the sensors that have to be mounted on a vehicle, the type of signal processing that has to be carried out on the signal and how the vehicle was used (terrain, load level and experience of driver). The method is able to predict to a greater than 95% certainty how the vehicle was used and therefore the wear and tear on the vehicle. **Being able to identify its wear and tear at the end of life will help to decide its post-end of life processing, whether it is reuse, remanufacture or recycling**. Further information can be found in the Royal Society publication here.
- **Ultrasonic technology for releasing and recovering metals from lithium-ion battery waste**. This has been applied to production scrap where the electrodes have been separated and it works well but it is less efficient for shredded material. For this waste stream thermal processing followed by sieving is very effective at material recovery. **Recovery rates for materials are now >96% for NMC > 98% for graphite and ca. 98% for lithium salts**. More information can be found here.
- Development and commercialisation of **Hydrogen Processing of Magnet Scrap (HPMS)** technology. This technology effectively demagnetises and segregates the Rare Earth alloy from the magnet containing scrap, significantly increasing the rate and efficiency of separation, delivering significant savings in operating costs and giving a pure and indigenous supply of rare earth alloy. **This can then be manufactured into new REPMs with a 90% energy saving when compared to those from primary sources**. Further information can be found here.
- Efficient **recycling of metals from solar cells** using catalytic etchants. Development of selective etchants, eutectic solvents, brines and anti-solvents to target specific metals also promotes selective leaching thereby improving recovery. Further information can be found here.
- **Solvent swelling process for recovering heavy metals from X-ray protective garments**. A project has been run with SF Xray in Belfast where end of life X-ray garments have been recycled using a green solvent mixture to release the embedded bismuth and antimony. This has been optimised on a 1 kg scale to demonstrate that the recycled material is as effective at stopping X-rays as the original material. The collaborators are **setting up a logistics model to turn a large-scale linear economy into a circular process**. Further information can be found here.
- Development of **debondable adhesives** - Device architecture and bonding techniques are the most challenging in design for recycling. The adhesives used in the structure hinder disassembly and maintenance. Incorporating adhesives that can debond when an external stimulus is applied can **improve the efficiency of recycling process**. Further information can be found here.

6. Technologies using more accurate sorting and separating techniques can aid the recovery process in their ability to identify specific waste materials

Correctly identifying materials post-use can greatly aid in their transition to being reused or remanufactured. This reduces the amount of waste sent to landfill, increases the quality of recycled products, and reduces the demand for raw materials. The below example of improved technology for steel scrap sorting uses a computer vision-based detection method with semi-supervised learning, and will facilitate increased volumes of steel recycling.

- A **computer vision-based object detection method** for domestic steel scrap sorting has been developed to facilitate the sorting process. This method identifies various materials on a moving conveyor belt, such as steel, copper, and fabrics. The object detector labels bounding boxes around detected objects and assigns corresponding class labels. As a data-driven approach, it necessitates high-quality annotated data. We have meticulously annotated over 1 million object instances to train the detector. Despite this effort, a significant amount of data remains unannotated. To leverage this unannotated data, we employ semi-supervised learning. By using flow-warped features to enhance the consistency of pseudo-labels generated from unannotated frames, we achieve better performance when training on both annotated and unannotated data compared to using only annotated data. This development in semi-supervised steel scrap object detection allows computer vision-based methods to be more widely applicable in different environments, as they require less annotated data to achieve satisfactory performance. **This development will lead to increased volumes of steel recycling.** Further information can be found here.

7. Production of new material from waste leads to extension of product/material life by upcycling or refurbishing, creates new value and reduces environmental impact

Utilisation of waste materials for regeneration is a powerful tool which helps conserve resources and reduce environmental impact. This can involve recycling of solids and chemicals, repurposing of materials, and development of new materials from biowaste. These innovative technologies collectively help to promote resource efficiency.

- Development, in partnership with Constellium, of **high recycled content exceptionally low carbon aluminium extrusion alloy technology** for use in automotive applications particularly for battery enclosures, side sills and crash management systems. Blended scrap alloy formulations optimised through digital systems to meet final compositional requirements, and to minimise the resultant embodied CO2 content of the cast, then **provide industry leading low embodied CO2 aluminium alloy components with equivalent performance to those produced from primary grade aluminium**. Further information can be found here and here.
- **Hydrogenolysis of polymers for selective chemical recycling of plastics**. The University of Liverpool created nanostructured Ru/CeO2 catalysts to break down plastic (polypropylene) more efficiently, saving both material and energy. Collaboration with the Cardiff University team revealed these catalysts work better than standard mixtures due to the small Ru clusters. Our catalysts successfully turned post-consumer polypropylene into useful liquids, demonstrating they can handle real waste. We were able to reduce the cost of the catalyst by substituting nickel for ruthenium, making the process more affordable and efficient. Our nanostructured catalyst enables **transformation of plastic waste into chemical building blocks, reducing costs and energy use**. Further information can be found here.
- **Bio-material start-ups** collaborating with Cranfield University/TCC to develop next generation fibres from agricultural waste using novel manufacturing processes; and using a novel solution-dyeing method to dye commercial cotton fabrics using natural dyes. Outcomes will lead to **a reduction in food landfill waste; improvement of natural dyes to be able to replace synthetic dyes; minimisation of the need for pre-treatment techniques, which tackles heavy metal pollution**. Read more here.
- **Bio-process for recycling of biowaste**. By transforming waste into new biobased materials, the intention is to **add value to end of life waste materials and produce circular materials that can then be designed to re-enter the material stream as high value textiles**. The University of York has established a collaboration with Bamboo Clothing Ltd (BAM) to **demonstrate the proof of concept to optimise the biobased process and scaling up of this technology**. Further information can be found here and a case study here.
- **Advanced hydrothermal processing routes for chemicals from biomass and wastes**. Loughborough University is exploring hydrothermal liquefaction (HTL) as a pre-treatment for fractionating wet biomass and wastes into different product fractions that can be further upgraded into olefins and other resources flows. We have developed a safe, low-cost and industrially applicable magnetite catalyst supported on activated carbon that can be magnetically retrieved from the solid and reused multiple times without regeneration. The FeOx/C catalyst improved the bio-oil yield by nearly 20% when compared to the uncatalyzed reaction for the HTL of draff. This reusable catalyst **boosts biomass conversion and paves the way for low-cost sustainable resource recovery**. Further information can be found here and also here.

8. Data-related technologies enable tracking of economic implications and access to data on material flows and design considerations

The possibilities opened to the world of circular economy through utilisation of data-related technologies are vast. The NICER programme has leveraged data-related-technologies to understand how different policy and economic decisions might affect CE scenarios, as well as for the exploration of geomodels, and the creation of databases that can be used to enhance sustainability, reduce costs and improve efficiency, thus benefitting the environment as well as supporting economic growth and innovation.

- **Pathways to a Circular Metal Economy** in the UK and globally. A global economic model helps to evaluate ex-ante the implications of different economic, decarbonisation and circular economy policies on the global steel and aluminium industries. The integrated modelling framework in which material flow analysis for steel and aluminium is combined with an economic model will **enable the tracking of effects of policy changes on monetary and physical flows at the same time.** The updated integrated steel model has enabled scenarios such as the use of different policy options to increase reuse of steel scrap in the UK to be tested, as well as the **economic implications of subsidies to iron ore, subsidies to primary production, and subsidies to secondary production.** Further information can be found here.

- The first sub national **(Spatial) Regional Computational General Equilibrium Model of macroeconomic impacts** of CE interventions was developed to evaluate regional implications of circular economy measures in the UK construction industry. This model enables us **to quantify the economic impacts of 50% efficiency gains in 1) The cement sector and 2) The ready-mix concrete sector.** Further information can be found here.
- **Circular economy geomodel** for granite-related mineralisation and wastes in Cornwall. New circular economy geological models have been developed for exploration of lithium, tin and tungsten ore deposits in Cornwall, integration of co-products and renewable energy, re-use of waste, development of the downstream value chain and recommendations to improve the planning and regulatory environment. This has been used as the first case study testing the UN Resource Management System as **a framework for sustainable development**. More information can be found here and a case study here.
- **Geomodel for large-scale and artisanal copper and cobalt recovery from mine wastes** in the Zambian Copperbelt. A new geomodel comparing large-scale and small-scale (artisanal) mining of wastes (tailings, overburden, slag) in the Zambian Copperbelt to recover copper and cobalt, and develops circular economy scenarios from this comparison to **reduce waste and protect the environment**. More information can be found here.

- **Toolbox for sustainable metal recycling** for improved metal recovery from end-of-life products Toolbox of recovery Technologies includes Ultrasonic delamination which separates active materials in LiBs (lithium-ion batteries) enabling short-loop recycling to manufacture new electrodes. Metal recovery can be enhanced by electrocatalytic dissolution of metal using specific redox catalysts. Combining both techniques can improve delamination time and efficiency. Development of selective etchants, eutectic solvents, brines and anti-solvents to target specific metals also promotes selective leaching thereby improving recovery. The toolbox of tailored processes to extract and recycle technology critical metals efficiently and in a sustainable manner from various wastes which have a complex architecture of inorganic, organic materials and metals has the following impacts:
  - Minimizes inefficiencies observed in current processes.
  - Improves metal recycling rates by mitigating losses.
  - Reduces energy consumption.
  - Curtails emissions of hazardous substances like gases, dusts, and chemicals.
- **Mapping embedded flows of technology metals** in the whole value chain of products including pre-manufacturing stages. Estimating consumption (current and future), recovery, repurposing, and end-of-life flows of embedded flows of technology metals in products. Further information and related publications can be found here and here. Case study also found here.
- **CE Data observatory**. The NICER CE data observatory is a data-science led approach to model, visualise and demonstrate proof of value from application of CE interventions across all material-product-sectoral areas of policy and industry interest. The CE-DO aims to **provide a focal place for data on material flows and stocks alongside linked economic and impact dimensions**.
- We developed an **innovative model and software to analyse quantitative data on effort of participation in co-design**. This technology measures the level of physical and cognitive effort consumers are willing to invest in a co-design activity, helping to **better understand the level of complexity an effective co-design activity should take**.
- **Bayesian material flow analysis model.** BaMFA can help to **optimise data collection practice and efficiency** including identifying poor data availability, quality, and granularity. Further information can be found here and here.

This Insights report emphasises the technological developments from all the centres within the NICER programme with the mutual aim of creating closed-loop systems, reducing waste and contributing to sustainability and Net Zero objectives.

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