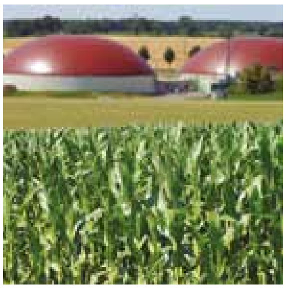
RESOURCE RECOVERY FROM WASTE

February 2019







A five year research programme, 2014 – 2019, funded by the Natural Environment Research Council, Economic and Social Research Council and Department for Environment, Food and Rural Affairs.

NERC SCIENCE OF THE ENVIRONMENT

E·S·R·C ECONOMIC & SOCIAL RESEARCH COUNCIL

Department for Environment Food & Rural Affairs

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> **"The £7M Resource Recovery from Waste programme addressed the strategic challenge of bringing the exploitation of renewable and non-renewable natural resources and the generation of wastes within the Earth's environmental limits.**

FOREWORD

Strategic purpose

The £7M Resource Recovery from Waste programme addressed the strategic challenge of bringing the exploitation of renewable and non-renewable natural resources and the generation of wastes within the Earth's environmental limits. The programme delivered strategic science in support of a paradigm shift in the recovery of resources from waste, driven by benefits to the environment, from air and water quality to soils and biodiversity, and human health rather than by economics alone.

The six projects of the Resource Recovery from Waste programme strived to meet the global challenges on natural resource use through an interdisciplinary twin-track approach of finding new ways to use existing natural resources coupled with new approaches to extract further use from waste materials, including:

1. Considering technical, environmental, health and social dimensions of value, in addition to economic value, when designing resource recovery processes.
2. Understanding how waste production is part of a wider system of production; analysing the effects of new approaches and technologies in terms of time (e.g. effect on future outputs or impacts) and space (e.g. where impacts arise in systems divorced geographically from the intervention).
3. Incorporating scientific and engineering findings into outputs that will deliver impacts on e.g. business models, policy-making, regulatory frameworks, consumer perception and behaviour, established methodologies such as ecosystem services, and standards or codes of practice.

On behalf of the funders, I would like to extend my thanks to all of those who have engaged so effectively with the Resource Recovery from Waste programme. Bringing together such diverse disciplines and perspectives to tackle a highly complex problem is difficult and challenging, but this programme has made great strides in advancing our knowledge and understanding of the circular economy, and hopefully paving the way for further research and innovation in this space.

Dr Beth House
Head of Research,
Earth and Energy Sciences, NERC

Delivering radical change

Resource Recovery from Waste aspires to a circular economy in which waste and resource management contribute to clean growth, human well-being and a resilient environment. Achieving a circular economy will require radical changes in how resources are extracted, transformed through design, production and consumption, and treated, recovered and recycled when products reach their end-of-use.

A sustainable circular economy must respect environmental limits and safeguard social standards. Different technologies, business practices and government interventions have been suggested to help the transition towards a circular economy; the costs, benefits and trade-offs of each must be assessed and compared via a 'systems of systems' approach in order to select the best pathway to sustainable circularity.

Realising a circular economy requires transformative economic, social and environmental actions from people across society. Resource Recovery from Waste brought together a diverse set of projects on secondary mining, soil restoration, technologies to recover all materials from mixed waste flows, and approaches for whole-system design and sustainability assessment. A community of researchers from engineering, environmental and social sciences, and business schools has emerged. Organisations from government to industry and the third sector co-created responses and embedded them in policy and business activities. This has produced the radical new visions, approaches, tools and technologies in response to the global challenge of resource management presented on the following pages.

The circular economy can be within our grasp – but only if we reach out together.

Prof Phil Purnell
Convenor of Resource Recovery from Waste,
University of Leeds

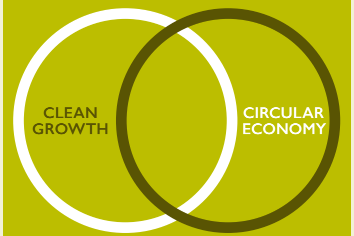
KEY THEMES

ECOSYSTEM STEWARDSHIP

our economy and society depend on and actively shape the environment.

BEYOND CARBON

resource efficiency can reduce carbon emissions in the UK by more than 50% by 2032.

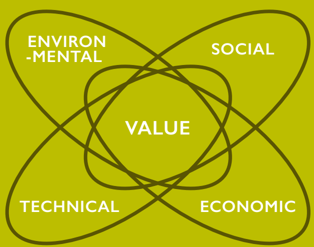


HUMAN WELL-BEING

circular economy can significantly contribute to UN Sustainable Development Goals.

MULTI-DIMENSIONAL VALUE

creating environmental, social, technical and economic value from waste.

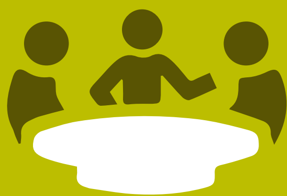


RESOURCE RECOVERY FROM WASTE

covered a wide range of themes.

CO-PRODUCING SOLUTIONS

working with academia, industry, policy makers and the public to develop solutions.



MIXED PRODUCTION WASTES

recovering resources from bulk industrial wastes.

HARNESSING BIOLOGY

developing new low-energy biological approaches to separate metallic and organic materials.

ZERO WASTE RESIDUE

designing resource recovery systems to use 100% of waste materials.

RADICAL IDEAS AND EXCITING DISCOVERIES

Resource Recovery from Waste set out to contribute to radical change in waste and resource management. The highly diverse themes, people and projects brought together in the programme offered a fertile context within which the following radical ideas and exciting discoveries emerged.

There are thousands of valuable resource hubs in the UK alone. Our legacy of landfilled industrial, municipal, metallurgical and mining wastes are valuable resource hubs that contain important elements for clean growth, many of which are currently 100% imported into the UK.

Capitalising on the resource potential. Regulation should shift away from a primary focus on waste treatment to also embrace the economic, social and environmental opportunities associated with resource recovery.

Integrated technologies for integrated resource flows. Many resource flows and products contain tightly-bound mixtures of biological and 'technical' materials, and the concentration of materials targeted for recovery can be low. A new generation of technologies has been developed that enables the integrated recovery of minerals and metals, biomass and/or aggregates while generating power, treating wastewater and/or restoring soils and land.

Extended carbon benefits of resource recovery. Resource efficiency is the single greatest potential contributor to decarbonisation of the UK economy. Moreover, bioelectrochemical technologies can turn CO_2 into chemical feedstock, while alkaline residues can become carbon sinks through resource recovery processes.

Low-impact, low-energy, low-cost. The integrated design of many RRfW processes optimises the use of waste materials, power, heat and even 'waste-light', while external energy input and costs are reduced. The use of waste-based components in resource recovery systems helps to further limit costs and enhance technology effectiveness. Integrated systems require sponsors to overcome the 'silo' approach and be prepared to share both risks and benefits.

Extreme recovery. Technologies tested in the lab and/or field proved to be extremely effective with recovery rates of targeted materials of 95-99%. 'Second life' use of recovered materials into value products has been shown in case histories, removing some of the barriers to change.

Bio-related technology for targeted recovery. Technologies incorporated the selection and use of microbes that are naturally responsible for the mobilisation of resources such as precious- and base metals. Conversely, neo-nanoparticles with catalytic properties for resource recovery or green chemical synthesis can also be engineered with the help from microbes and integrated into systems for resource recovery.

Quality matters. Waste management should focus on enhancing the quality of resources recovered and reused rather than the mass or volume of material processed. Large volumes of waste are sometimes unavoidable, such as with acid mine drainage, but value can be extracted from the majority of these wastes by focusing on the qualitative characteristics of all the materials they contain.

Multidimensional value. A major barrier to recovering materials is the lack of methods that can account for creation of value in social, environmental and technical domains, in addition to economic aspects; we have developed a framework that can address this.

There are multiple types of circular economies. There are different types of circular economy that can be realised, in which different positive (benefits) and negative (impacts) values are created. The economic, social, environmental and technical values that are created and destroyed in circular economy scenarios should be assessed and integrated into decision-making processes.

Circular economy is an engine for value redistribution. Monetary benefits generated through the preservation of technical value of materials and products should be used for the creation of net environmental and social gains, and this is a stepping stone to the ideal situation in which the creation of social and environmental benefits through better resource use are rewarded economically.

“The highly diverse themes, people and projects brought together in the programme offered a fertile context within which the following radical ideas and exciting discoveries emerged.”

WORKING TOGETHER BY DESIGN

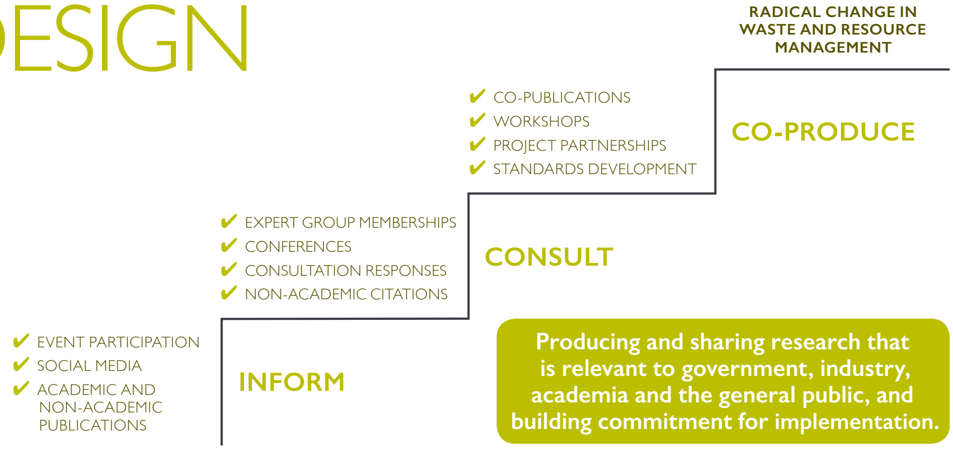


Figure 1. Stepped engagement strategy for RRfW programme.

Engagement strategy

RRfW aimed for radical change in mentality and practices for resource and waste management. Programme activities were shaped by an engagement strategy to deliver on this ambitious impact (Velenturf & Purnell 2017).

Stakeholders from within and outside RRfW were invited to take part in a series of activities ranging from informing to consulting and the co-producing of research and other outputs (Figure 1). This added to the socio-economic relevance of our on-going research; preparations of a diverse set of research outcomes in formats useful for academia, governmental, industry and general public; and generated commitment for uptake of research outputs by key organisations in positions able to implement change.

Building a Resource Recovery from Waste community

Creating responses to interdisciplinary problems such as those posed by the circular economy and resource recovery from waste requires not only collaboration between academic disciplines, but co-creation of research questions and agendas with stakeholders from across society. One of the key achievements of the programme is the creation of such a network of about 100 academics and over 300 stakeholders, which remains ready and able to deliver RRfW solutions (see RRfW website 'About Us: Network and RRfW Community' for more details).

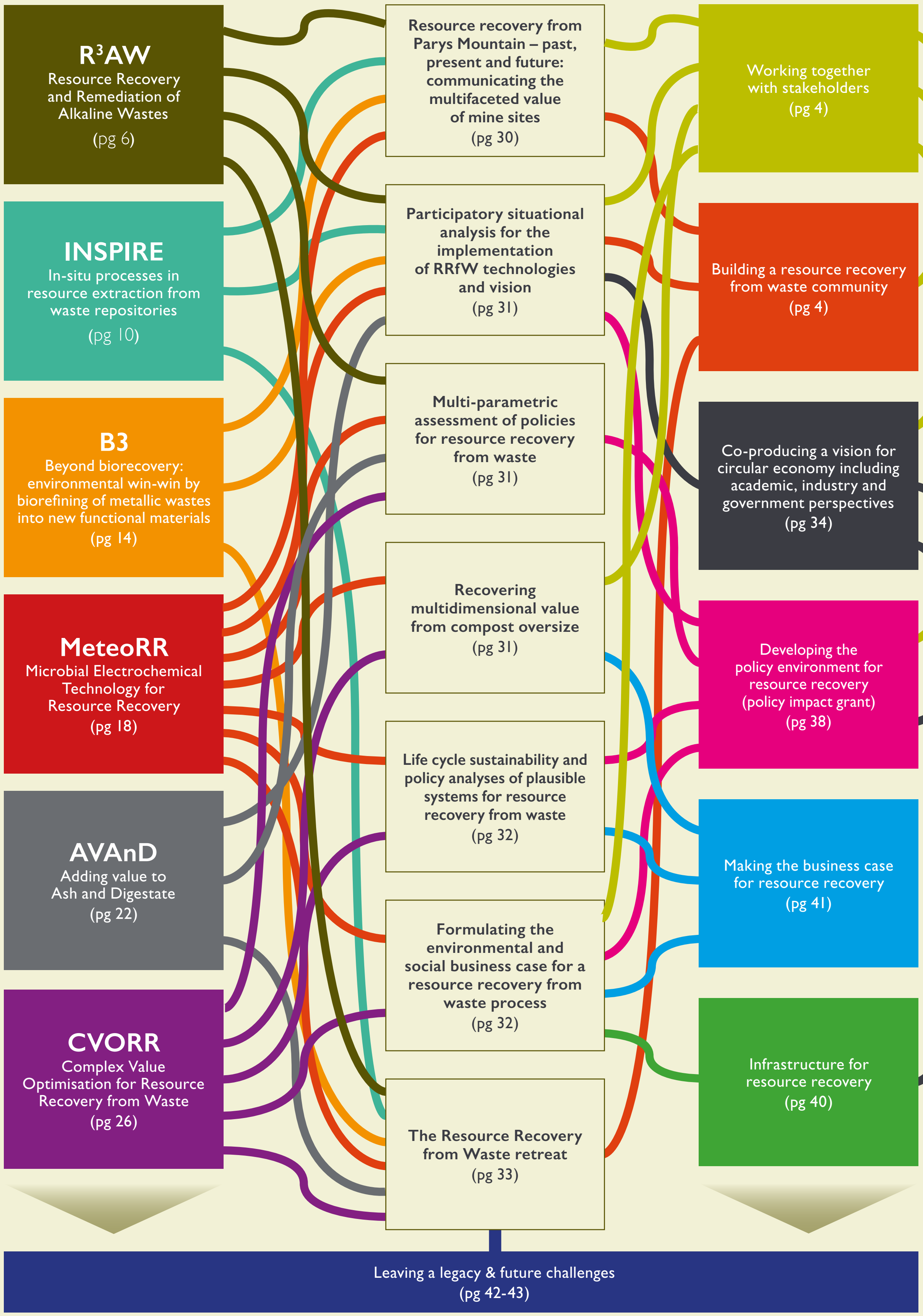
A programme coordination team brought together 6 projects across 15 universities and deployed an overarching body of work to integrate research outcomes and deliver on the strategic objectives (see Foreword). A community of researchers working in the space of resource recovery from waste was assembled through collaborations initiated by the coordination team, through knowledge exchange at conferences, social media and newsletters, mini-projects raised by researchers from across the programme, and researcher exchanges between the RRfW projects. A writing retreat catalysed the production of a book from the whole RRfW consortium and launch of a special issue in the Frontiers research journal (see 'The Resource Recovery from Waste retreat').

The reach of the RRfW network was expanded through knowledge exchange with over 20 like-minded research programmes and other organisations. RRfW messages were shared via activities that engaged thousands of people mainly through the hosting of, and participating in, over 60 events, over 50 academic articles, and numerous non-academic publications and other communications such as our blogposts, newsletters and social media activity. The total number of people reached by RRfW research is larger with the inclusion of activities of individual projects.

Changes in the governance system are crucial for implementing a circular economy. RRfW made a particular effort towards engagement and impact in policy and regulation through a series of activities:

- A conversation with governmental bodies was started with the co-creation of a vision and approach to realise a circular economy (see 'Visions for a Circular Economy') and this built a network across government and informed an agenda for further engagement.
- A series of workshops across the UK was held to formulate technology- and place-specific policy recommendations (see 'Participatory situational analysis for the implementation of RRfW technologies and vision').
- RRfW contributed to numerous government meetings and consultations, helping to shape future policy and regulation with our research outcomes.
- A policy impact grant and impact acceleration account capitalised on the momentum and policy-relevant outcomes from RRfW producing 2 policy and practice notes and discussing our recommendations at numerous meetings, while expanding our network to over 200 people in government, NGOs and industry bodies (see 'Developing the policy environment').

RESOURCE RECOVERY FROM WASTE PROGRAMME OVERVIEW



R^{3}AW

Resource Recovery and Remediation of Alkaline Wastes

> **"Over two billion tonnes of alkaline residues are produced each year from a range of globally-significant production and disposal processes."**

UNIVERSITIES OF HULL, LEEDS, CARDIFF, HUDDERSFIELD, NEWCASTLE AND THE OPEN UNIVERSITY

Over two billion tonnes of alkaline residues are produced each year from a range of globally-significant production and disposal processes. These include slags and residues from steel and alumina production as well as ashes from waste incineration. Such by-products are increasing in volume on a global basis and can pose environmental risks, such as water pollution from highly alkaline leachates containing toxic metals and metalloids (e.g. arsenic, chromium and vanadium), dust generation at disposal sites, and challenges for rehabilitating waste depositories into productive land given the extreme initial chemical conditions.

At the same time, alkaline residues can be enriched in a range of elements and minerals critical to future green technologies, for example vanadium, lithium and cobalt, which are increasingly used in mobile and static energy storage batteries. Recovery of elements like vanadium, which are environmental pollutants, would also make the residue safer for bulk reuse e.g. as aggregate. Furthermore, alkaline residues which are typically the product of high temperature processes, are enriched in silicate and oxide minerals that can take in atmospheric carbon dioxide when they are weathered. As such, there are a range of potential economic, environmental and social benefits that could be reaped from these major global waste streams.

Working to address this dual problem and opportunity, R^{3}AW has advanced our understanding of the geochemical processes controlling the release of critical elements like vanadium from steel slag, highlighting the potential environmental risks of uncontrolled disposal of slag and how these can be minimised. We transposed standard water treatment technologies to extremely alkaline waters for the first time and demonstrated how we can recover elements of interest, with over 95% recovery efficiency for vanadium from both steel slag and bauxite processing residue leachates (see 'Vanadium - pollutant or resource?').

Extensive field studies on the management of highly alkaline waters demonstrated the physical structures and biological communities that can promote lowering of pH in alkaline waters towards regulatory limits. A field pilot test at Scunthorpe demonstrated the effectiveness of reedbeds in buffering waters and crucially there is no evidence that exposing aquatic plants to extremely alkaline pH increases risk of uptake of potentially ecotoxic elements such as chromium and vanadium in field conditions. Our field investigations have also provided clear evidence that the full benefits of legacy steel and iron wastes for atmospheric carbon uptake are not currently being realised (see 'Sequestering atmospheric CO_2 in slag'), while long term assessment of bauxite residue rehabilitation has highlighted the effectiveness of low-cost amendments in developing functioning soils (see 'Bauxite residue rehabilitation').

In addition, we conducted over 20 in-depth interviews with key producers in the steel slag production, management and after-use chain, and ran a workshop at the former Redcar Steelworks on opportunities for resource recovery with participation from industry, regulators, academia and local communities. This work highlighted key challenges that need to be overcome for new resource recovery technologies for steel by-products, particularly due to inflexibility in regulation driven primarily by environmental protection, as well as complex liability issues with long-standing downstream user agreements and changing ownership of sites (see 'Building a circular economy in the European context').

Recommendations based on the R^{3}AW research are already informing operational environmental management of leachates and residue disposal areas with project partners, as well as contributing to policy debates on resource recovery and development of circular economy theory.

Vanadium – pollutant or resource?

Vanadium is present in high volume industrial alkaline wastes such as steel slag and bauxite processing residue (red mud) from alumina generation. R[3]AW has shown that vanadium can be leached from these residues in disposal areas and is most commonly in its most toxic (pentavalent form) downstream of slag and red mud disposal sites, posing significant environmental risk.

However, vanadium is also increasingly vital for green technologies and was added to the European Union Critical Raw Material list in 2017. Vanadium has traditionally been used in high-strength steel alloys but emerging uses in redox flow batteries – for large scale renewable energy storage – are leading to rapid increases in global demand.

Our research suggested that 43% of the annual global production of vanadium could be recovered from alkaline wastes, such as steel slag, red mud, fly ashes from coal energy production, and construction and demolition waste. We have also demonstrated for the first time how soluble vanadium can be recovered from steel slag and red mud leachates using traditional water treatment technologies (ion exchange resins) adapted for extremely alkaline conditions.

While this shows promise in terms of environmental protection, our data suggest it is unlikely such a recovery mechanism would be viable for vanadium recovery on economic grounds alone currently. However, materials like steel slag would be safer for bulk afteruses (e.g. as aggregate) after this vanadium is leached. Where opportunities for resource recovery can offset environmental remediation costs, there may be compelling combined economic and environmental cases for intervention.

Further reading: Hobson *et al.* (2018); Gomes *et al.* (2018a); Watt *et al.* (2018); Gomes *et al.* (2017b); Hobson *et al.* (2017); Gomes *et al.* (2016a); Gomes *et al.* (2016b)

Figure 2: Highly alkaline bauxite processing residue leachate after the Ajka red mud spill in Hungary (2010): vanadium was a key pollutant present in the waters at the site

Figure 3: Calcium carbonate deposits downstream of the former Consett Steelworks – the end product of slag leaching and atmospheric CO_2 uptake

Sequestering atmospheric CO_2 in slag

During the process of steel-making, iron ore is mixed with limestone or dolomite and heated to extremely high temperatures. The end results are steel and slag, a waste mixture of calcium and magnesium silicates and oxides. Around 500 million tonnes of slag are produced globally each year.

As the slag minerals weather, when in contact with rainwater, the resulting alkaline solutions react with atmospheric carbon dioxide (CO_2) and form calcium carbonate – one of the most stable forms of carbon (Figure 3). This reaction offsets some of the greenhouse gas emissions associated with steel production.

In R[3]AW we investigated the carbon balance of some of the largest slag heaps in the UK at the former Consett Steelworks. We measured the volume of the slag mounds by geophysical mapping and compared this with four decades of water chemistry data to calculate how much calcium carbonate has precipitated. Our results showed that less than 1% of the potential atmospheric carbon uptake has been realised in the mounds, nearly four decades after the steelworks closed.

This implies that uncontrolled deposition of slag in mounds or waste depositories does not efficiently promote carbon sequestration – a major potential value of these industrial leftovers. Ongoing research in a related project is investigating how we can engineer both new and historical slag deposits to encourage atmospheric carbon uptake.

Further reading: Mayes *et al.* 2018.

Bauxite residue rehabilitation

During alumina production from bauxite ore, one to two tonnes of residue are produced for every ton of product. Despite bauxite residue containing potentially valuable metals it currently has no commercially viable bulk reuses and is commonly stored in vast purpose-built bauxite residue disposal areas.

Waters interacting with untreated bauxite residue can have pH values up to 13, have elevated concentrations of sodium, and contain toxic elements such as aluminium, arsenic and vanadium.

Establishment of protective vegetation cover at bauxite residue disposal areas is therefore often resource intensive and involves importing large volumes of topsoil. Adding smaller volumes of organic matter, such as spent compost, and gypsum directly to the residue has been proposed as a much cheaper method to achieve revegetation. However, doubts remained about the long-term efficacy of this approach.

Data from organic matter amended bauxite residue plots deposited 20 years ago showed that the surface treatments lower alkalinity and salinity, and thus produce a substrate more suitable for seedlings. The reduction of pH leads to much lower aluminium, vanadium and arsenic mobility in the treated residue, with beneficial effects extending passively 20-30 cm below the original amendment.

We have also showed that the positive rehabilitation effects are still maintained after two decades due to the establishment of an active and resilient biological community. This treatment was estimated to provide cost savings of over £2M to site closure plans at just one bauxite residue disposal area, with additional environment benefits in terms of reduced transport CO_2 emissions and alternative uses for organic wastes.

Further reading: Bray *et al.* (2018).

> **“**
> Despite bauxite residue containing potentially valuable metals it currently has no commercially viable bulk reuses.

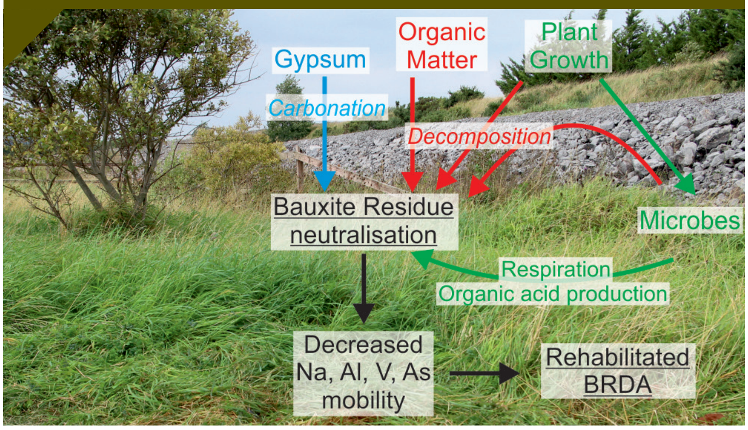


Figure 4: Grassland developed over bauxite processing residue

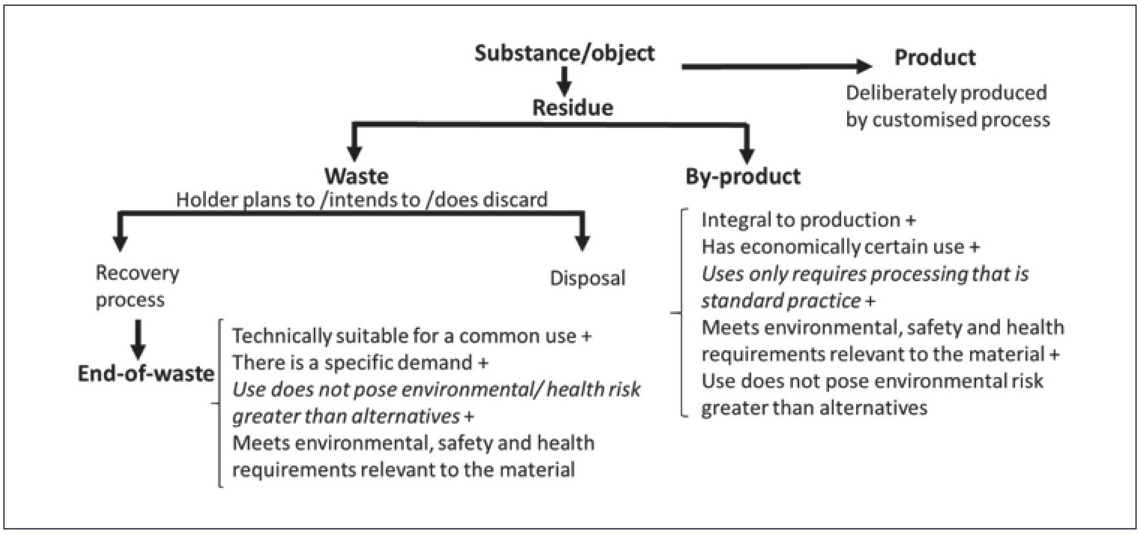


Figure 5. Diagrammatic representation of the requirements for establishing whether a given material is legally a waste in the light of criteria for establishing by-product or end-of-waste status. Based on the WFD (2008); EC JCR (2008) and ECDG Guidance (2012). From Deutz *et al.* (in press) in *Resource recovery from Wastes: Towards a Circular Economy* Edited by L. E. Macaskie, D. J. Sapsford, W.M. Mayes, RSC.

Building a circular economy in the European context

Looking at how R³AW outcomes can be applied in practice revealed the complexity created by evolving layers of regulation. While the EU circular economy strategy only dates from 2015, the strategy is building on policies that have been evolving since the 1975 Waste Framework Directive. These policies cover a wide range of activities related to the production process, management of residues, incentivising the use of secondary materials and disincentivising disposal.

The potential for regulations to have counter-productive effects has been recognised by the EU. Over the past decade, there have been efforts to reduce barriers to recovery that have inadvertently been instituted by earlier efforts to ensure that residues were disposed of without harm to the environment. The 2008 and 2018 Waste Framework Directives therefore discuss how to define terms such as end of waste and by-products. However, the definitions are not straightforward. They include safeguards against the generation of inadvertent environmental impacts and also require an actual, not just potential, market for the recovered material. The status of a given substance is therefore strongly context dependent.

Even with regulatory encouragement to consider recovery, stakeholders were more concerned for the much stronger regulatory signals around environmental protection. The Best Available Techniques reference note for the steel industry governs residue disposal as well as production processes. The implementation of innovative approaches would be facilitated by specifying the outcome rather than the technology.

Further reading: Deutz *et al.* (2017); P. Deutz *et al.* (in press), in Resource recovery from Wastes: Towards a Circular Economy Edited by L. E. Macaskie, D. J. Sapsford, W.M. Mayes , RSC.

> “While the EU circular economy strategy only dates from 2015, the strategy is building on policies that have been evolving since the 1975 Waste Framework Directive.”

INSPIRE

IN Situ Processes In Resource Extraction from waste repositories

UNIVERSITIES OF CARDIFF, WARWICK AND THE WEST OF ENGLAND

> "Societies have disposed of vast quantities of industrial, municipal, metallurgical and mining waste into the ground."

Societies have disposed of vast quantities of industrial, municipal, metallurgical and mining waste into the ground, this has resulted in the geological storage of an enormous amount of material that could be a potential resource if sustainable recovery technology can be developed to recover them. Therefore, instead of considering these waste repositories to be a legacy waste issue and a long-term liability, with the right science and technology a paradigm shift can be made possible so that waste repositories are viewed as 'resource hubs' for potential future recovery.

The INSPIRE project, which took inspiration from *in situ* leaching applied in the mining industry, was focussed on technology that can be applied whilst the waste materials lie *in situ*, thus avoiding the need to actively mine the material (with its commensurate costs and energy consumption) and thereby minimise ecological and environmental impacts of resource recovery. The fundamental geoscience research questions that underpins this is 'How can we understand and manipulate the *in situ* biogeochemistry of the waste within the geological repository to recover resource?' An ancillary question that arose was 'How can we better define the multifaceted meaning of resource recovery in the context of different waste repositories?'

The INSPIRE project used a multi-pronged approach to break these questions down into the following areas:

- Determining the effectiveness of inorganic, organic and biotechnological liquids for selective leaching of metals and minerals (lixiviants) and recovery of elements from wastes.
- Identifying, isolating and/or stimulating microbial species native to waste repositories for the purposes of resource recovery and waste valorisation.
- Gaining an understanding of, and technological control of key flow phenomena at the micro- to macro- scale in waste repositories.
- Examining nanotechnology applications in *in situ* recovery
- Developing a better understanding of the multifaceted resource potential value of UK waste repositories and their suitability for *in situ* processing.

Further reading: Sinnett (in press); Crane & Sapsford (2018c); Crane & Sapsford (2018b); Warwick *et al.* (2018); Crane & Sapsford (2018d); Chen *et al.* (2018); Peppicelli *et al.* (2018); Crane & Sapsford (2018a); Roberts *et al.* (2017); Crane *et al.* (2017); Sapsford *et al.* (2017); Rashid *et al.* (2017)

The project contributed key conceptual advances for *in situ* recovery, and a series of environmental science and technology advancements. Key conceptual developments focus on further developing the sustainability rationale for an *in situ* approach to resource recovery, including the development of a taxonomy of terminology including both 'direct' and 'indirect' *in situ* recovery. Specific environmental science and technology key findings, outcomes and developing themes from the research include the following:

Microbial 'wealth' in wastes

Resource recovery may be enacted or enabled through biostimulation of *in situ* microbial populations (for example see 'Accelerating gas generation from landfill waste'). These studies together with modelling have shown that it might be possible to (i) increase peak gas yields (i.e. recovery of methane) (ii) reduce the long-term methane emissions (and therefore greenhouse impact) and (iii) decrease the timeframe for landfill stabilisation (opening up land resource recovery). INSPIRE research has also demonstrated the potential for biostimulation of microbial consortia within iron-oxide and jarosite-bearing wastes for enhanced metal recovery and in wastewater treatment applications.

Flow behaviour and manipulation

INSPIRE research has elucidated the potential for electrokinetics to be applied to resource recovery from industrial and mining wastes. The work has shown that electrokinetics is effective at not only transporting metals through low-permeability wastes but also enhanced resource recovery through making some waste fractions less recalcitrant. As such electrokinetics is likely to be a key technology in application to resource recovery from many waste repositories.

We have also investigated potential barriers for containment of leachates and lixiviants from resource recovery systems and as part of seepage-control systems. In particular, a method to estimate wall thickness for cutoff walls was developed based on a decoupling method of the horizontal (advective) and dispersive components of contaminant fluxes through the wall; this offers a practical approach which provides sufficient accuracy for design. Also we have developed models of flow diversion due to biomass accumulation and validated these against experimental results.

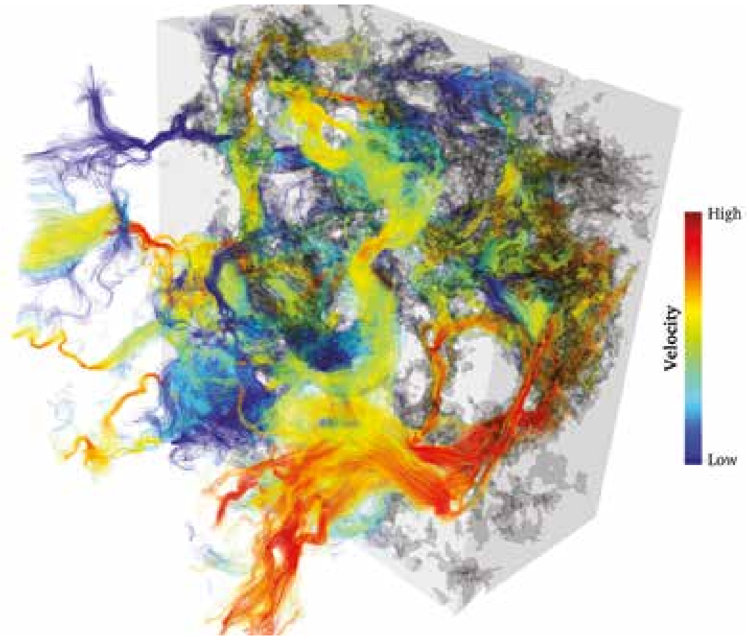


Figure 6. Modelled pore water velocities though tortuous micropores of waste material

Novel lixiviants

Lixiviants are liquids that selectively leach metals or minerals of interest, but not all are suitable for *in situ* resource recovery. INSPIRE research has demonstrated the applicability and viability of methanesulfonic acid and citric acid in mobilising metals from wastes and also in enhancing electrokinetics. These organic acids, which comprise a biodegradable conjugate base, have the potential for developing more environmentally safer *in situ* leaching technology.

> **INSPIRE research has characterised the multifaceted nature of the resource 'value' of mine waste sites**

Nanotechnology applications

INSPIRE research also examined the role of nanoparticle technology both from the perspective of applying engineered nanoparticles for resource recovery but also on recovering metals directly as potentially higher-value nanoparticles. As part of this, INSPIRE researchers formulated a new paradigm for the 'precision mining' of metals from different media, and demonstrated the concept using selective uptake and release of copper and rare earth elements from mine drainage onto nano zerovalent iron and diatomite supported nano zerovalent iron. Furthermore work has gone into development of synthetic non-aggregating magnetic nanoparticle specifically for capture of silver from the environment.

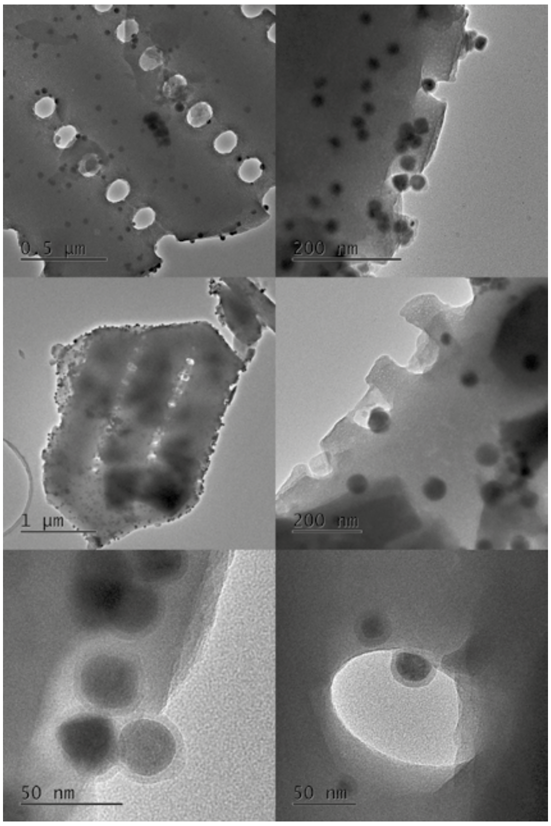


Figure 7. Nano zerovalent iron loaded onto diatomite for precision mining of copper from mine water

Multifaceted value

INSPIRE research has characterised the multifaceted nature of the resource 'value' of mine waste sites, including for the first time estimates of the total quantity of metals in many large mine waste piles in England and Wales. It has also highlighted the cultural and ecological resources, and planning context associated with former mining landscape and how these could all influence resource recovery. This multifaceted value has been further explored through community engagement and touring museum exhibits to boost understanding of the problem (see 'The cultural and environmental value of former mining landscapes' and 'Resource recovery from Parys Mountain: communicating the multifaceted value of mine sites').

Figure 8: Parys Mountain, Wales, has been a site of copper mining since the Bronze Age, reaching its peak in the 18th Century. It is now designated a site of biological special scientific interest.

The cultural and environmental value of former mining landscapes

There are around 5,000 former metal mines in England and Wales. Such sites have often been abandoned for many decades, allowing unusual habitats to develop and providing an important connection with our industrial heritage. In this project, we examined the scale of the protections associated with former metal mines, using geographical information systems. We found that 84% and 51% of metal mines in England and Wales, respectively, are co-located with areas protected for their ecological, geological or historical significance. Some designations, for example, ancient woodlands, are coincidental to mining and may benefit from resource recovery combined with remediation activities. However, many others, such as Sites of Special Scientific Interest, only exist due to previous mining activities and may be adversely affected by resource recovery or other disturbance.

We also visited six areas in England and Wales with a history of metal mining and ran workshops in each location. Here we asked 38 residents to sort a series of statements based on how much they resonated with their opinions and preferences. The statements covered a range of opinions on the mining legacy, its value and long-term management, with a particular focus on the potential for metal recovery from wastes. Analysis revealed different perspectives on the mining heritage. All placed a high value on the cultural and ecological value of this heritage, however, they differed in their priorities for long-term management. For example, emphasis was placed on either nature conservation, cultural heritage, water quality or the opportunity for job creation through reworking the mines. The views of local people are nuanced; they value their mining heritage but opinion is split on the most effective way to manage these sites, especially where there is an impact on water quality.

This research suggests that there is a tension in the long-term management of sites, which should be considered when assessing the potential for, and desirability of, resource recovery.

Further reading: Sinnett (in press); Crane *et al.* (2017)

Accelerating gas generation from landfill waste

The breakdown of woody material, cardboard and food waste in landfill sites is limited by the rate of breakdown of lignin, an aromatic polymer found in lignocellulose in plant cell walls and woody materials that is very resistant to microbial breakdown. If the rate of biodegradation of the landfill contents could be enhanced, then the release of methane from landfill sites – which provides gas for commercial or private energy generation – would be accelerated, and the time needed for reuse of the land should be reduced, both of which would be valuable for commercial landfill operators, and for regional town planning purposes.

Tim Bugg and his group at the University of Warwick isolated 11 new bacterial strains from landfill soil that can break down lignin. Four of these strains, when added to landfill soil containing lignocellulose, show 5-10 fold enhancement in release of gas – mainly methane – in small scale trials and half litre experiments using commercially available compost (see Figure 9). These results show that bacterial lignin degraders found in landfill soil, which don't need oxygen (anaerobic), can be used for *in situ* delignification and enhanced gas release in soil containing lignocellulose.

Professor Bugg notes that "it's very interesting that these bacteria can work under virtually anaerobic conditions, as previously it was thought that lignin degradation was always an aerobic [oxygen using] process, whereas methane production is via anaerobic bacteria. We would like to understand how this is working at the molecular level, and we hope that this might have application for treatment of lignocellulosic wastes".

Further reading: Rashid *et al.* (2017)

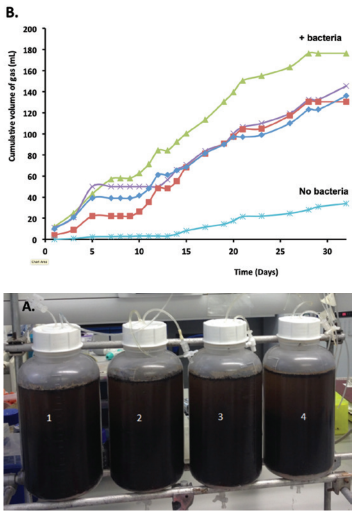


Figure 9: Investigation of effect of lignin-degrading bacteria on the anaerobic digestion of commercially available compost.

B3

Beyond biorecovery: environmental win-win by biorefining of metallic wastes into new functional materials

UNIVERSITIES OF BIRMINGHAM, BANGOR AND EXETER AND CATSCI LTD

The use of microbial processes to recover metals from wastes and scrap is well known. On the other hand, bacteria can deposit metals in such a way as to be able to use the biomaterial in useful reactions, bypassing commercial refining. The goal of the 'biorefinery' concept of B3 was to illustrate this circularity in four systems involving precious metals, base metals, rare earth elements and uranium.

Many wastes contain a range of these metals vital to our 21st century technologies. Recovering such resources from wastes can help to conserve dwindling primary reserves, reduce energy use and pollution associated with their extraction and refining, and by biorefining, minimise the need for commercial refinery processes.

Hence, the B3 project used a range of microbiology-approaches to recover metallic resources from such diverse wastes as mine tailings, electronic and metallic scraps, furnace linings, used car catalysts (and road dust that contains precious metals shed from the catalysts during use) and jewellery manufacturing waste, as well as base metals (copper, zinc) from acid mine drainage.

B3 set the goal to go beyond biorecovery by converting these resources directly into high value materials, such as bio-nanoparticles, which have applications in green chemistry, catalysis, low carbon energy, environmental protection and potentially in photonics.

Chemical leaching methods were applied to the wastes to generate metal solutions which were treated with metal-reducing and mineralising bacteria to separate and retain the metals of interest, sometimes more than one per waste. The enriched solids can be delivered back into refineries or, within B3, bio-refined directly into new bio-nanomaterials. The project also envisaged local 'supply chains' to make useful materials from locally-sourced wastes.

Focusing initially on the platinum group metals, the project demonstrated new approaches to create bionanomaterials for catalysis, environmental and energy applications (see 'Biorefining of metallic wastes into new nanomaterials'). Bimetallic bio-nanoparticles made generically from road dust, in collaboration with Toronto City Council, were shown to be effective in *in situ* catalytic upgrading of heavy oil from the Athabascan oil sands in Alberta. Normally *in situ* application could not use precious metals, such as platinum and palladium, in a once-through process due to economics and critical resource dispersion. B3 has shown the recovery of the otherwise-lost precious metals from road dust (and scraps) using bacteria to make low grade, effective, biologically-based nanoscale sacrificial catalysts. The biorefined catalysts were comparably effective to commercial catalysts in heavy oil upgrading, with less fouling via accumulated 'coke' (Omajali *et al.* 2017). A Life Cycle Analysis showed major economic benefits. For carbon neutral alternatives to fossil oils, pyrolysis oil from biomass (wood/algae) can produce comparable liquid fuels after upgrading via the bio-neo-catalyst for onward refinery (Kunwar *et al.* 2017). Production of biofuels from thermal treatment of biomass can generate by-product streams, such as 5- hydroxymethyl furfural (5-HMF). Bimetallic bio-neocatalysts upgraded 5-HMF into 2,5-dimethyl furan, a 'drop in fuel' that can be used directly in diesel or petrol engines.

> **The B3 project also developed biorefining techniques for the recovery of rare earth elements (REE) from uranium mine waste.**

B3 have also advanced biorecovery methods to apply to acidic and metal-rich effluents from mine wastes. The team developed a combined approach of bioleaching and biorefining to extract and recover metals, and showed that this could yield considerable economic benefits at both copper mine sites investigated, as copper could be selectively recovered. The leftover bacteria were then used in 'second life' to make metallic catalysts in lieu of purpose-grown bacteria, outperforming the latter in upgrading 5-HMF obtained from cellulose breakdown, where commercial catalyst for this purpose was ineffective against waste-derived 5-HMF. In parallel, excess hydrogen sulfide from the bioremediation process was used to manufacture zinc sulphide quantum dots. B3 is currently developing these zinc sulphide quantum dots for use in photobioreactors for algal growth systems, bringing them closer to real world application. (see 'Biorecovery of mine waste and making zinc quantum dots'). Large scale growth of algae is attractive as a biomass resource grown from carbon dioxide and sunlight. Wet algal biomass is easily processed thermochemically to give fermentable feedstock for bio-hydrogen or bio-ethanol production, plus 5-HMF by product as above.

The B3 project also developed biorefining techniques for the recovery of rare earth elements (REE) from uranium mine waste, separating out the REE components from uranium and thorium, which can be onwardly-used in nuclear fuels. The rare earth elements are recovered as nanophase mineral phosphates using a biofilm immobilised on foam in a flow-through column. By controlling the flow rate into sequential bio-columns B3 has optimised the separation of rare earth elements, uranium and thorium in such a flow through system (see 'Biorefining rare earth elements, uranium and thorium'). Some REE phosphates are known catalysts, e.g. for clean adipic acid production, avoiding use of toxic chromium (Cr(VI)) and providing a clean technology route to nylon production. The biomaterials are currently being tested for their catalytic activity.

Taking all these strands together, the B3 project has been successful in demonstrating that using biological approaches to recovery of resources from waste has the potential not only to conserve limited resources, but by bio-refining these directly into high value products, such recovered resources can be used to support the green technologies of the future.

"Acidic and metal-rich effluents that form in mine wastes (e.g. tailings) can cause acute environmental problems, polluting locally and downstream."

The UK has no natural sources of PGMs but significant levels are found in secondary waste materials such as furnace linings, road dusts, and electronic scrap.

Biorefining of metallic wastes into new nanomaterials

The six platinum group metals (PGMs) are platinum, palladium, ruthenium, rhodium, iridium and osmium. Valuable for their resistance to corrosion and oxidation, high melting points, electrical conductivity and catalytic activity, these elements have wide industrial applications and their high demand coupled with relative scarcity results in high prices. Their extraction from primary ores is particularly environmentally-damaging, resulting in large spoil heaps and high energy consumption.

The UK has no natural sources of PGMs but significant levels are found in secondary waste materials such as furnace linings, road dusts, and electronic scrap. Researchers on the B3 project at the University of Birmingham used bacteria to recover these elements from wastes and turn them into high quality catalysts. Incoming soluble metal is trafficked into the bacterial cells where the metal ions are reduced by hydrogenases to create metallic seeds (Figure 10). The seeds then catalyse deposition of more metal abiotically to form nanoparticles with high catalytic activity. Only the initial step is metabolism-dependent; and the team has shown that, once seeded, metallised cells can remove PGMs from even *aqua regia*, required to solubilise noble metals in secondary wastes (Murray *et al.* 2017a). The nanoparticles are made atom by atom, guided by bio-scaffolds, which confers particular crystal shapes and hence reaction specificity and selectivity. The project has shown that the biorefined metal nanoparticles catalytic and fuel cell activity can exceed that of pure metals e.g. power output (fuel cells) or product selectivity (alkyne hydrogenation) (Macaskie *et al.* 2017b). Working in partnership with CatSci Ltd selected B3 neo-catalysts biofabricated from wastes are being evaluated against commercial catalysts for validation in commercial reactions to factor into several Life Cycle Analysis case histories.

Further reading: Murray *et al.* (2017a); Murray *et al.* (2018a); Gomez-Bolivar *et al.* (2018); Omajali *et al.* (2018); Macaskie *et al.* (2017b).

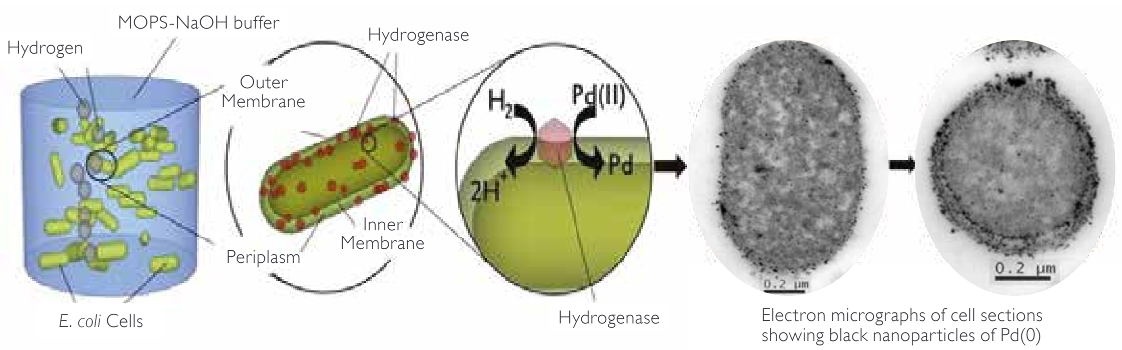
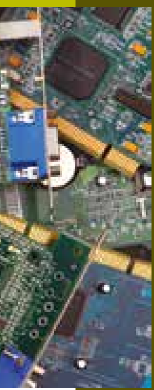


Figure 10: Biofabrication of palladium catalysts by bacteria. The small black particles shown in cell sections by electron microscopy are the nanoparticle catalysts.



Biorecovery of mine waste and making zinc quantum dots

Acidic and metal-rich effluents that form in mine wastes (e.g. mineral tailings) can cause acute environmental problems, polluting locally and downstream. But the low concentrations of metals in the effluent has meant that it was not economic to recover the metals. B3 has been working to overcome this by biologically accelerating the leaching of metals from copper mine wastes using bacteria that oxidise metal-bearing ores to release metals, along with making dilute sulphuric acid. Other bacteria can reduce sulphate to make hydrogen sulphide (H_2S). The soluble copper in leach liquors is then selectively precipitated as copper sulphide (CuS) by using the biogenic hydrogen sulphide (H_2S) produced by these bacteria. Using this combined approach to extract and recover metals was estimated to have considerable economic benefits at both mine sites investigated.

The H_2S is produced as an off-gas for metal recovery but excess H_2S is produced. This was used to make zinc sulphide (ZnS) quantum dots, value-adding to low-value zinc by making a material used in photonics. Quantum dots can absorb light and reemit at a different wavelength and could increase the efficiency that light is used for photosynthetic biotechnology (e.g. growing algae for bio-oil production or to supply bacterial cultures with trace nutrients). Normally only certain light wavelengths are absorbed by photosynthetic pigments and the rest is wasted; quantum dots can help by converting 'waste' light and emitting it at favourable wavelengths for optimum photosynthesis.

The B3 team have shown that biogenic ZnS quantum dots produced as a by-product from the metal recovery process behaved identically to chemically produced ZnS quantum dots. In addition, by 'tuning' the synthesis of the quantum dots the team could match the absorbed light to the solar light wavelengths that penetrate through the atmosphere and the light emitted by the quantum dots to the absorption wavelength of chlorophyll. This can be used to increase the efficiency by which light is used for photosynthetic biotechnology e.g. growing algae for bio-oil and hydrogen production. Using commercial reference quantum dots, tests established that algal productivity was boosted by 2.5-fold using this approach. B3 is currently developing these zinc quantum dots for use in photobioreactors for algal growth systems, bringing them closer to real world application.

Further reading: Falagan & Johnson, 2016; Falagan *et al.* (2017); Murray *et al.* (2017b); Stephen *et al.* (2017); Murray *et al.* (2018b).

Biorefining rare earth elements, uranium and thorium

Rare earth elements (REEs) are not rare per se but difficulties lie in their refining - a technology developed almost exclusively in China who controls over 90% of global REE supply and hence prices/availability. As a consequence alternative REE supplies, and resource-efficiency in existing ones, are urgently sought. REE importance lies in their often non-substitutable applications in magnet and electronics technologies (e.g. in hybrid cars or neodymium magnets, which are vital to wind turbine operation), and as catalysts.

REEs very often occur as by-products of 'winning' other metals e.g. the Elliott Lake uranium site in Canada contains REEs plus residual uranium in waste tailings, while thorium co-occurs in many REE minerals and is an inevitable co-product of their refining. Thorium has few applications (other than as a fuel in some nuclear reactor designs) but uranium use in the nuclear industry is ubiquitous and expanding globally. A dual upgrading of uranium / thorium tailings becomes attractive if the co-recovery of REE can be realised without radioactive contamination.

The REE can be recovered as phosphates using a biofilm immobilised on foam in a flow-through column. Uranium and thorium phosphates are also bio-recovered, although more slowly. Hence, by controlling the flow rate through sequential bio-columns B3 has demonstrated separation of REE (very rapidly, at a fast flow rate), uranium (more slowly) and thorium (at a very slow flow rate) in such a flow through system. This relies on the chemistry of the metal phosphate precipitation process, with a 'slower to precipitate' metal (UO_2^{2+}) having insufficient residence time at high flow rates (which are suitable for $REEPO_4$ recovery). Th^{4+} does not exist in solution and a small amount of citrate is needed to suppress hydrolysis and colloidal $Th(OH)_4$ formation which occurs in water. The citrate reduces Th(IV) availability and retards thorium phosphate formation significantly, making a triple separation possible (Macaskie *et al.* 2017a). Addition of ammonium ion to the thorium-removing column promotes formation of the less soluble ammonium salt of thorium phosphate which accelerates its removal in the third column.

Further reading: Macaskie *et al.* (2017a).

MeteoRR

Microbial Electrochemical Technology for Resource Recover from wastewater

> **"The demand for mineral and energy resources is increasing rapidly due to a growing world population and growing economies."**

UNIVERSITIES OF NEWCASTLE, MANCHESTER, SURREY AND SOUTH WALES. COLLABORATIONS WITH GLASGOW UNIVERSITY, PENN STATE UNIVERSITY, THE UNIVERSITY OF GHENT, HARBIN INSTITUTE OF TECHNOLOGY, CHINA, AND MULTIPLE INDUSTRY PARTNERS.

The demand for mineral and energy resources is increasing rapidly due to a growing world population and growing economies. But mineral and energy resources are currently largely obtained from finite geological deposits. Therefore developing more sustainable routes to these resources is of utmost importance.

Industrial, municipal and agricultural wastewaters are potential sources of metals and chemical salts, acids and bases, and energy from oxidising organic matter in the wastewater. Conversely, untreated wastewater can be harmful to people, other living organisms, and the environment: organic compounds can harbour microbial pathogens which cause disease, whilst heavy metals can be toxic and adversely affect fragile ecosystems. However, conventional extraction methods are not technically or economically feasible due to the low concentrations and highly complex mixtures of materials in such wastewaters.

Bioelectrochemical technologies have the potential to overcome these problems by combining wastewater treatment with energy generation and resource recovery (see 'Bioelectrochemical systems'). Organic carbon in waste generated by humans alone amounts to 60 to120 gCOD/person/day (COD – chemical oxygen demand, is a measure of the level of organic compounds in wastewater). At an energy content of 14.7 kJ/gCOD (Heidrich *et al.*, 2011) and with 6.8 billion people this translates into about 600 – 1200 TWh/yr available for bioelectrochemical technologies to tap. Additionally, using BES to convert the greenhouse gas carbon dioxide (CO_2) to valuable organic feedstock chemicals has the additional environmental benefit of helping to combat global climate change caused by greenhouse gas emissions.

Using BES therefore offers a net environmental benefit from wastewater treatment and an economic and environmental upside of using a waste stream for high value product recovery (Foley *et al.* 2010), offering economic incentives for industry to adopt clean technologies as part of the circular economy.

The MeteoRR project has been working to develop BES technologies for the recovery of pure metals or valuable chemicals with market value from wastewater containing organic, metal and CO_2 pollutants. This has led to advancements in the use of BES for a range of different applications. In particular, the team at Newcastle University have collaborated with an industry partner to recover copper and produce formate and hydrogen from malt whisky wastewater (see 'Malt whisky wastestreams: recovering copper, energy, heat and carbon'). Team members at the University of Manchester have demonstrated that copper nanoparticles with novel catalytic activity can be produced from copper in solution by some metal-reducing bacteria (see 'Microbial metal recovery from industrial waste) and scaled up BES have been developed by our partners at the University of South Wales (see 'Upscaling Bioelectrochemical Systems for metal recovery'). Our collaborators at the University of Surrey are using Life Cycle Sustainability Assessment (LCSA) to determine, not only the economics of our resource recovery from waste processes, but also their net environmental benefit. Such LCSA enable the comparison of BES with conventional methods of waste treatment, helping support the case to industrialists, policy makers and regulators on the viability of microbial electrochemical systems for the treatment of wastewater as part of the circular economy.

Further reading: Daghio *et al.* (2018); Shemfe *et al.* (2018c); Feito *et al.* (2018); Shemfe *et al.* (2018b); Shemfe *et al.* (2018a); Sadhukhan *et al.* (2018); Cruz Viggi *et al.* (2017); Sadhukhan & Matinez-Hernandez (2017); Kim *et al.* (2017); Daghio *et al.* (2017); Sadhukhan (2017a); Boghani *et al.* (2017); Sadhukhan (2017b); Song *et al.* (2016); Ng *et al.* (2016); Boghani (2016) ; Sadhukhan *et al.* (2016); Daghio *et al.* (2016); Premier *et al.* (2016)

Bioelectrochemical systems

In bioelectrochemical systems (BES), wastewater containing organic chemicals is fed into a chamber where the organics are broken down by bacteria into CO_2, protons and electrons. In the process, the electrons are transferred to a positively charged electrode (the anode) where they move through an external circuit to the negatively charged electrode (cathode). The BES can be configured in a number of ways, depending on the desired output (see Figure 11). In a microbial fuel cell, these electrons combine with oxygen at the cathode and electricity is generated. Alternatively, in a microbial electrolysis cell, the electrons can be combined with protons (hydrogen ions) at the cathode to produce hydrogen, combined with metal ions to recover pure metals, or added, with protons, to CO_2 to produce valuable organic feedstock chemicals such as formate or methanol.

For microbial electrolysis cells, small amounts of externally supplied electricity may be required for hydrogen production and CO_2 conversion to organic feedstock chemicals.

For metal recovery the required additional electricity depends on the metal being processed. The different cathode reactions in BES may require chemical or biological catalysts at the cathode to make them work.

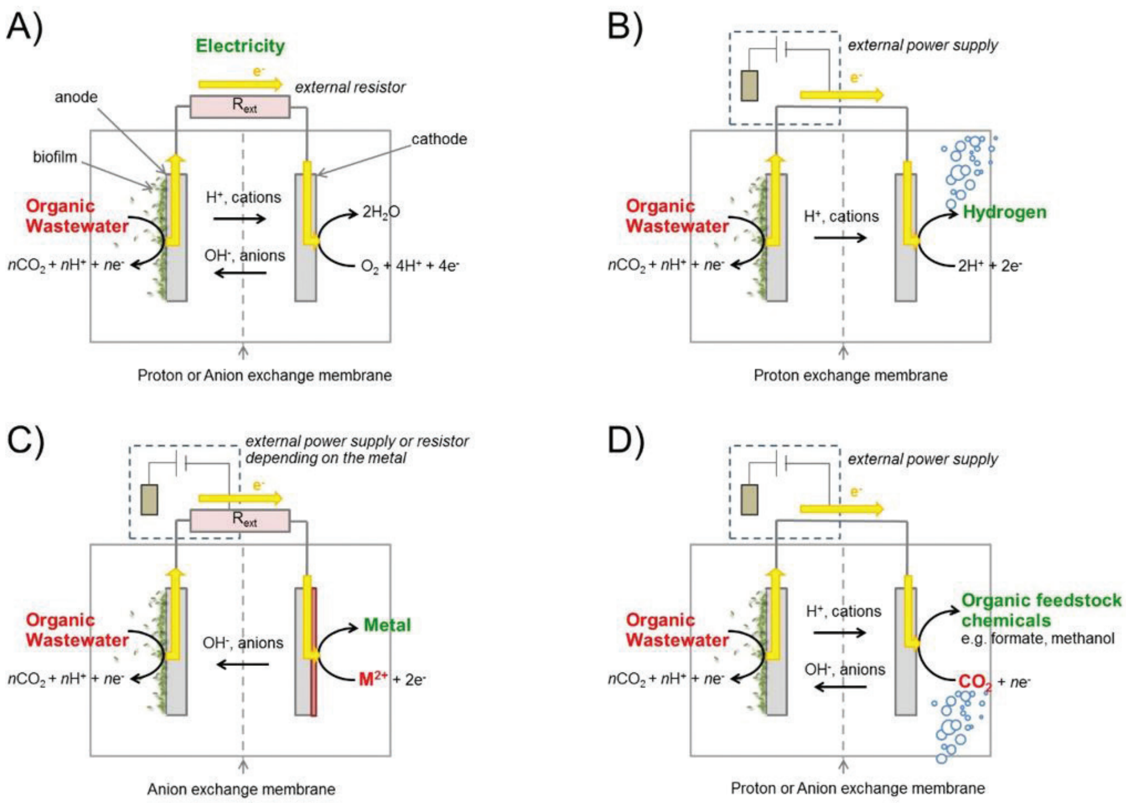


Figure 11: The diagram above explains the operation of BES for electricity generation (A), hydrogen recovery (B), metal recovery (C), and CO_2 conversion to valuable organic feedstock chemicals (D). Wastes are highlighted in red and resources in green.

Malt whisky wastestreams: recovering copper, energy, heat and carbon

The Scotch whisky industry generates £4 billion in export revenues annually and employs around 40,000 people in the UK. Despite the massive economic impact of the industry it is built on rather humble raw materials: malt whisky is produced essentially from water, barley and yeast. The production process leads to a range of by-products that are often seen as wastes, but increasingly their value as a resource is being recognized. The by-products include draff, pot ale, spent lees, wash water, CO_2, and low grade heat at 40°C. Conventional technologies for resource recovery from wastes exist but have low efficacy, high start-up or operating costs and low selectivity. Research from MeteoRR and EPSRC-funded LifesCO$_2$R projects at Newcastle University are leading to the development of an integrated waste management system using new and existing technologies to recover copper, energy and heat (Figure 12).

Gasification is a mature technology for the treatment of biomass. Building on this, the integrated system (Figure 12) being uses an indirectly heated pyrolytic gasification (I-HPG) process that could produce 100 MWh of electrical energy per week from 100 t of draff. Spent lees contain dissolved copper ions which are leached from the copper still used in malt whisky production. The copper needs to be removed from distillery wastewater to avoid pollution, and the energy generated from draff gasification can be used to recover copper from spent lees using a copper reducing bioelectrochemical system (Cu BES). Organic compound in the waste can be oxidized on the anode of a BES and drives the copper recovery on the cathode. The rest of the energy could be used to produce formate from the waste CO_2 generated in the whisky production process using an electrochemical cell (CO_2EC). Hydrogen, which can also be produced using bioelectrochemical cells, could be fed in the I-HPG to recover the energy.

Although currently the process requires some addition of energy (ca. 391 MWh/100t draff), this could be reduced with more efficient catalysts for electrochemical CO_2 conversion to formate, being developed in the LifesCO$_2$R project. With such development the system could be competitive with existing technologies for energy cogeneration from draff, which requires wood chips, and biofuel generation using the Acetone Butanol Ethanol (ABE) fermentation.

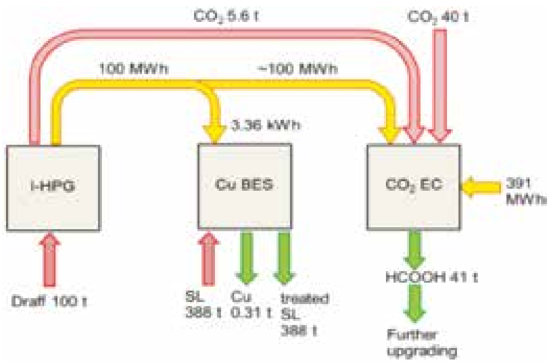
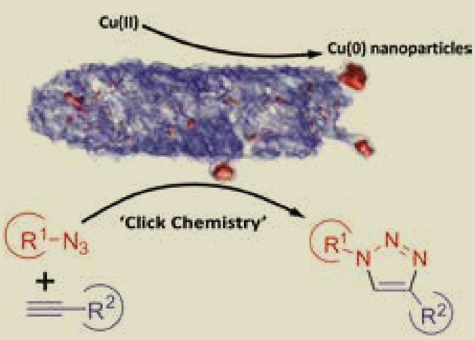


Figure 12: Integrated process design overview with weekly mass and energy flows. External energy is required for the system to operate. The integrated system removes all draff, treats all the spent lees (SL), recovers copper and removes all CO_2 producing formic acid and hydrogen as by-product.

Microbial metal recovery from industrial waste

Microorganisms offer a potentially simple, cost-effective and green process for recovering metals from industrial waste streams in the form of valuable nanomaterials. Copper is of particular interest due to its abundance in various waste streams and its wide ranging applications as a catalyst. In this project, we demonstrated that the metal-reducing bacterium, *Shewanella oneidensis*, a bacterium able to colonise microbial fuel cells, was able to recover copper from solution as metallic copper nanoparticles which could be easily separated from solution. These nanoparticles are catalytically active towards a range of 'click chemistry' reactions, commercially important reactions with applications in drug discovery and bio-conjugation.

This work led to a successful BBSRC award which is continuing to develop the efficiency and applications of this technology. A similar microbiological process was also applied to copper-containing distillery waste water, resulting in complete removal of copper from solution in less than one minute. This technology allowed for simple, efficient recovery of the copper, which could then be applied and reused as a click chemistry catalyst. These microbial processes highlight the potential for biotechnology to convert waste metals into commercially valuable and industrially important nanocatalysts. A recent EPSRC / BBSRC knowledge exchange award is supporting the development of this technology with a commercial partner from the Scottish whisky sector, to investigate its potential for scale-up and on-site applications.



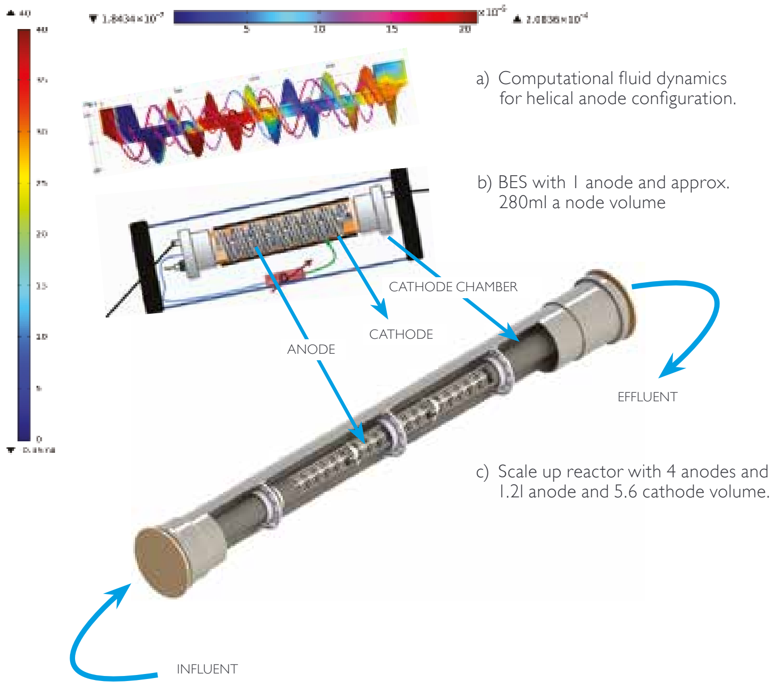
Further reading: Kimber *et al.* (2018)

Figure 13: Three-dimensional representation of *Shewanella oneidensis* cell (purple) with copper recovered from solution in the form of catalytically active nanoparticles (red). The scheme at the bottom represents a range of click chemistry reactions catalysed by these bionanoparticles.

Upscaling Bioelectrochemical Systems for metal recovery

Scale up is a vital component of taking new concepts from the laboratory to practical application. However, increasing the size of the BES is not straightforward, as with increased volumes the systems tend to be less efficient due to significant increase in internal resistances. Consideration should be given to reactor designs that are both robust and easily manufactured.

To recover copper, a tubular arrangement of BES (Figure 14) is a promising design strategy for scale up as it has the ability to maintain the spatial distribution between electrodes whilst increasing the total reactor volumes. In addition, various anode/cathode geometries can also be used to enhance the fluidic mixing to increase mass transfer and avoid the development of dead zones within the tube, Figure 14a. Further, there is the possibility of the deployment of continuous manufacturing processes such as extrusion, lamination etc. which may be used to increase system performance (depending upon the application). These systems can also be easily modularised with the individual reactors being connected in series/parallel (Figure 14 b and c). The soluble copper concentration in the various effluent streams is generally less than 30 mg/L which makes its recovery difficult, ineffective and energy intensive when using traditional methods. However, BES is capable of recovering about 99% metal from low metal containing waste streams while simultaneously treating organic waste at the anode chamber. Scaling up BES may need more extensive planning and research before commercial implementation but the technology holds great promise to enable research based systems to be placed in an industrial context.



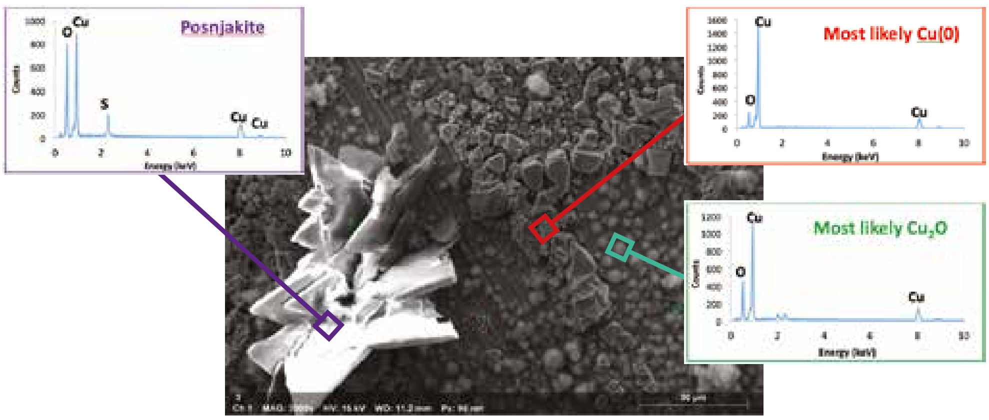
a) Computational fluid dynamics for helical anode configuration.

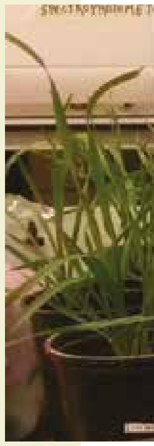
b) BES with 1 anode and approx. 280ml a node volume

c) Scale up reactor with 4 anodes and 1.2l anode and 5.6 cathode volume.

Figure 14: Surface plot showing acetate concentration (mol min-1) on helical side wall and streamlines showing fluid flow (b) One reactor module containing 1 anode and 1 cathode which can be scale up to (c) multiple anode and cathode assembly in one reactor system

Figure 15: Shows the characterisation of recovered copper deposit forms in a scale up reactor





AVAnD

Adding Value to Ash and Digestate: Developing a suite of novel land conditioners and plant fertilizers from the waste streams of biomass energy generation.

LANCASTER UNIVERSITY, STOPFORD ENERGY & ENVIRONMENT, THE JAMES HUTTON INSTITUTE AND AQUA ENVIRO

Soils provide support and regulate fundamental processes, including food production, water supply and carbon storage, known as ecosystem services. However, intensive agricultural practices have resulted in soil degradation, posing a threat to these essential life-supporting services. There is strong scientific consensus that healthy soils are essential to the maintenance of human civilisation, with growing recognition from public bodies and governments that soil is not just a country's greatest source of wealth but it is a country's life.

One of the key challenges related to soil health is the need to move away from linear approaches, where essential nutrients and organic matter are transferred from agricultural soils to food consumers, in many instances finally ending up as waste. This linear system has led to a chronic depletion and worldwide geographical unbalances of macro-nutrients, especially phosphorus and nitrogen, leading many agricultural soils to be increasingly dependent on industrially produced nitrogen and mined phosphorus fertilisers to maintain crop productivity. Whilst agricultural management is clearly one of the cornerstones for sustainability, alternative materials able to supply and replenish soil nutrients and organic matter is another crucial step.

The AVAnD project focussed on improving the circularity of nutrients in the agrifood system by developing approaches to returning nutrients extracted through food production and forestry back to agricultural land. Bioenergy can be produced from waste organic materials including food, farm and forestry wastes. By-products of bioenergy processes present an opportunity to reduce pressure on natural resources, whilst addressing some of the challenges facing agriculture, energy generation, and waste disposal.

The AVAnD project looked at the waste products from anaerobic digestion (digestate) and thermal biomass combustion (ash). Anaerobic digestion is the microbially mediated breakdown of organic matter without oxygen to form natural gas (methane) along with a nitrogen and carbon rich by-product known as digestate. Digestate use as alternative fertiliser is becoming increasingly common, however it does not necessarily provide the essential ratio of macro-nutrients for crop nutrition and can be bulky to transport from area of production to areas of agricultural demand.

Therefore, the novel aspect of the AVAnD approach was to examine whether blends of digestate and ash could provide complementary nutrient profiles and enhance the value of digestate as a soil conditioning product.

Whilst both ash and digestate have been utilised separately as fertiliser and/or soil conditioners the biological and chemical interactions following application of blends of these materials to land, and the implications for crop productivity and for ecosystem function, were unknown. The AVAnD project addressed this by:

- Assessing the effect of ash addition on physicochemical parameters of the resulting ash-digestate blend including dewaterability, nutrient partitioning and pathogen survival.
- Examining the effects of blends of ash and digestate on crop productivity and nutrition.
- Examining the effects of the blends on soil physiochemical properties and biological function.
- Investigating the legislative barriers and opportunities to utilising blends of bioenergy by-products in agriculture.

The effects of blends of ash and digestate were examined at both short term scales (6 weeks under greenhouse conditions) and longer term (over a full growth cycle in field conditions).

KEY FINDINGS FROM THE AVAnD PROJECT INCLUDE:

- Whilst ash addition did not improve physical digestate characteristics, such as dewaterability, it did promote pathogen die-off when used in unpasteurised digestates.
- Digestate and biomass ash blends performed as well or better than inorganic fertilisers of nitrogen and phosphorus in both glasshouse and field trials using winter wheat (see 'Crop productivity: bioenergy by-products versus synthetic fertilisers').
- No negative effects on soil biota - earthworms and microbial activity - were observed with the level of fertiliser addition used in the field and glasshouse trials (see 'Impact of bioenergy by-products on soil health').
- Microbial respiration under the digestate-ash blend regimes led to a gain in soil carbon, in other words more carbon was added to the soil than was lost through respiration. This is in contrast to inorganic fertilisers where the net carbon balance is negative (see 'Impact of bioenergy by-products on soil health').
- Regulatory barriers remain for the use of fertilisers produced from some waste materials but the incoming revisions to the EU fertiliser directive looks to promote more simple regulation around recycling of nutrients (see 'Fertilisers from bioenergy waste and 'end of waste' regulations').

Figure 16: Commercial anaerobic digestion plant converting organic waste into methane for energy and digestate

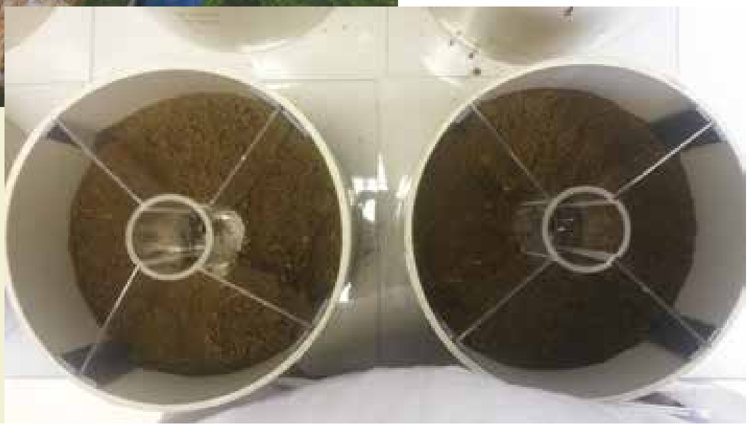
Crop productivity: bioenergy by-products versus synthetic fertilisers

Crop performance is one of the most important aspects when looking to replace or supplement the use of synthetic inorganic fertilisers. In short-term glasshouse experiments, we examined how four different anaerobic digestate-biomass ash blends impacted the initial stages of wheat growth, including a comparison with conventional practices (inorganic fertilisers). We used a fully comparative design, which meant that the benefits of mixing different ash fractions and digestate types (food/crop-based) as well as using them separately could be tested. Given the importance of soil in plant responses, these trials were performed using two contrasting soil types (neutral and acidic soil).

Glasshouse trials using winter wheat demonstrated that:

- Digestate and ash blends performed as well as inorganic fertiliser in early plant growth stage.
- Whether ash addition had a beneficial effect on plant performance depended on ash fraction and digestate characteristics.
- In the acid soil, crop performance significantly improved with the addition of ash, thus highlighting the potential for ash and digestate-ash blends to provide both fertilising and soil conditioning (liming effect) properties.

After these trials, the most promising blends were carried through to field trials, using the same materials (ash/digestate; neutral soil; winter wheat). This experiment was performed in large mesocosm where winter wheat was grown from seed to harvest to assess crop productivity. The aboveground biomass results obtained mirrored those from the glasshouse, with similar performance observed between ash/digestate blends and the inorganic fertiliser.



> "In addition to increasing the circularity of nutrient cycling from bioenergy by-products in agri-food systems, a key aim of the AVAnD project was to examine their impact on soil health."

Impact of bioenergy by-products on soil health

In addition to increasing the circularity of nutrient cycling from bioenergy by-products in agri-food systems, a key aim of the AVAnD project was to examine their impact on soil health. Wastes and by-products could act as fertilisers but potential detrimental effects associated with their use, for example on soil properties or human health, must also be assessed. Extensive work has been performed to demonstrate that digestate meeting a quality protocol (PAS 110) is safe to use on agricultural land. The AVAnD project used PAS 110 digestates and ash containing levels of heavy metals below those specified for other materials currently used on agricultural land, such as poultry litter ash and sewage sludge.

The effects of ash-digestate blends on soil biota were examined using application rates based on major nutrients (nitrogen and phosphorus), in accordance with best agriculture practice. The project examined the effects of the additions on:

- Earthworm toxicity and avoidance
- Soil microbial activity and biomass
- Soil microbial community composition

In general terms, the results suggested no detrimental effects of the digestate-ash blends on earthworms and soil microbial activity. In fact, in the short term assays earthworm weight increased when digestate was used as a fertiliser addition on its own, although toxic effects were observed at higher levels of digestate-ash blend. Microbial respiration assays demonstrated the benefit of adding a carbon-rich fertiliser compared to a nutrient only inorganic fertiliser. Digestate-ash blends stimulated microbial respiration and carbon dioxide production to a similar extent as the inorganic fertiliser. However, the net carbon balance of the soil actually increased with the blend (i.e. more carbon added to the soil than was lost through stimulated respiration), unlike with inorganic fertiliser where the net carbon balance is negative.

Fertilisers from bioenergy waste and 'end of waste' regulations

The combination of a non-waste product (PAS 110 digestate) with biomass ash waste from the thermal combustion process to produce fertilisers and soil conditioners posed a regulatory challenge. Mixing these two materials results in the creation of a new waste rather than a marketable product regardless of the agronomic benefits demonstrated. The regulation around what can be applied to productive land is necessarily risk averse in order to avoid contamination of the environment and our food chain. However, in order for the nutrient and soil conditioning potential of wastes, such as biomass ash, to be realised greater flexibility in the route from waste to fertilising product may be required.

By following prescribed Quality Protocols it is possible for residues from certain bioenergy processes to achieve 'end of waste' resulting in them being viewed as marketable products, for instance digestate and poultry litter ash. The limitation of this approach is illustrated when considering the use of biomass ash as a fertilising product either alone or in combination with digestate. Despite having similar characteristics to poultry litter ash in terms of agronomic value and potential contaminant load, biomass ash will be considered a waste because the feedstock and production process do not match those of a Quality Protocol.

Current 'end of waste' procedures have facilitated the transfer of resources previously perceived as waste back into the economy. However, they are rigidly defined and focus on the waste type rather than on the resource potential of the materials. Adopting a more flexible approach, such as that set out in the revisions for the European Union Fertiliser Directive, in which the characteristics of the final 'waste' is relevant as opposed to the production process, could help promote more innovative alternative fertiliser production.

"The regulation around what can be applied to productive land is necessarily risk averse in order to avoid contamination of the environment and our food chain.

"Raw materials are currently so cheap that resource recovery does not create economic value; yet at the same time the volume of wastes created is overwhelming planetary systems."

CVORR

Complex Value Optimisation for Resource Recovery from Waste

UNIVERSITY OF LEEDS

Raw materials are currently so cheap that resource recovery does not create economic value; yet at the same time the volume of wastes created is overwhelming planetary systems. In the 19th century, waste management legislation was introduced to protect public health, creating social value by preventing disease. Later a requirement was added to create environmental value by preventing environmental damage. More recently, retaining finite resources in the technosphere is the focus of the circular economy, helping preserve the technical value of materials i.e. the properties and quality that render them useful to society.

Interactions within resource recovery systems involve all four domains of value. For example, strict EU targets for reusing and recycling waste electronic and electrical equipment (WEEE) necessitate expensive facilities making it difficult to recover costs and so WEEE is sent to less economically developed regions. Here, it may be recycled in poorly regulated facilities with lower environmental and labour welfare standards. Thus avoiding economic and environmental impacts in the EU may create social and environmental impacts elsewhere. The resource recovery sector is riddled with such trade-offs, yet there are no assessment methods that allow these to be evaluated across the economic, environmental, social and technical domains (Figure 17).

CVORR has developed a framework to help account for multi-dimensional costs and benefits in resource recovery from waste (RRfW) systems that cross geographical, political and sectoral boundaries, and which vary with time (see 'The CVORR framework'). It can help provide decision makers with the evidence to design better RRfW regulations that prevent off-shoring of impacts, or swapping impacts in one sector for larger ones in another, or cause stockpiles of low-quality recyclates. A key part of this is integrating analysis of economic flows with material flows to identify business models permitting firms to operate, and their interaction with technical and environmental values. It explicitly requires that RRfW is not just considered as an 'end of pipe' treatment process at the waste-generation point, but includes upstream (e.g. product design) and downstream (e.g. secondary resource markets) analysis.

Our key case study has been of the interlinked electricity generation, steel production and concrete manufacture industries, in which by-products from the first two are used as purportedly low-carbon inputs for the third. As all three global sectors seek to decarbonise, CVORR has shown that complex technical and economic interactions between them cause counter-intuitive effects that will influence their decarbonisation strategies (see 'The concrete – electricity generation – steel manufacture system'). We have also looked at national and global plastics recycling, and relationships between the formal and informal recycling sectors to help develop the CVORR methodology (see 'Recycling plastics').

KEY ACHIEVEMENTS OF THE PROJECT INCLUDE:

- A simple 'how-to' guide for CVORR framework, including multi-dimension metrics selection.
- CVORR has provided input into Defra's Resource and Waste Strategy, particularly on new metrics that move towards quantifying resource productivity.
- RRfW and waste management businesses have expressed interest in applying CVORR to their current business models and potential future modifications, highlighting CVORR as an adaptable approach.
- CVORR is making impact internationally: it is being applied in Buenos Aires to unravel how the informal recycling sector might improve plastic recycling, investigating food sovereignty in co-produced research with East African smallholders, and evaluating the impact of using 'door to door' recyclable collectors in Mumbai (see 'Recycling plastics').
- Integration of CVORR with the HMG 'Green Book' guide for evaluating infrastructure spending is under way in collaboration with policy makers in various government departments, launched at a House of Commons event in November 2018.
- The CVORR approach is being used in other projects: impact acceleration grant working with Defra on plastic packaging system assessment in England to help identify and remove policy barriers and promote good recycling practice; iCASP 'Green-Blue Infrastructure' project will use CVORR framework to look at natural landscaping in urban areas; and analysis of recycling in Brazil as part of a Marie Curie Fellowship.
- Approaches from CVORR are being included in a new MSc level module "Circular Economy and Resource Recovery from Waste", putting the University of Leeds among the few leading academic institutions in the UK delivering teaching modules focused explicitly on 'circular economy'.

Further reading: Iacovidou et al. (2019b); Millward-Hopkins *et al.* (2018a); Millward-Hopkins *et al.* (2018b); Hahladakis and Iacovidou (2018); Hahladakis *et al.* (2018a); Hahladakis *et al.* (2018b); Iacovidou *et al.* (2018); Iacovidou *et al.* (2017a); Iacovidou *et al.* (2017b); Iacovidou *et al.* (2017c)

> **"The CVORR approach is being used in other projects: impact acceleration grant working with Defra on plastic packaging system assessment in England to help identify and remove policy barriers and promote good recycling practice.**

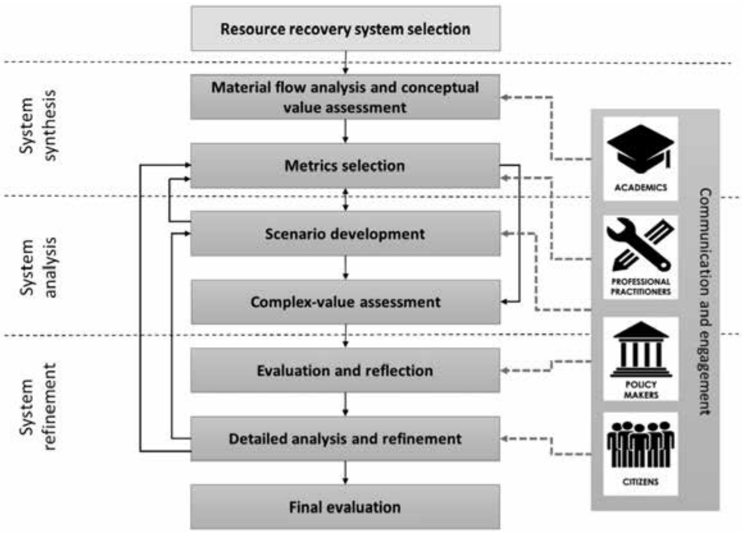


Figure 17: Initial framework for complex value optimisation for resource recovery (CVORR) (Iacovidou *et al.* 2017b).

> **"The CVORR framework is an approach to complex value analysis."**

The CVORR framework

The CVORR framework is an approach to complex value analysis (Figure 17). In the synthesis stage, an initial model of the mass flows of resources through the system of interest is constructed. System boundaries are examined closely to include all processes upstream and downstream of the waste generation point that interact physically, socio-politically or economically with the main system; the 'system of systems' approach. Where this is not possible, the impact of inflows from 'background' systems can be captured by using embodied values (e.g. embodied carbon for energy or material inflows) but the interdependence between the background and foreground systems must be explicitly analysed. It is important that the global nature of the systems is recognised (e.g. offshoring) as power relations between countries become evident that are buried if we work at too narrow a scale.

Each mass flow is then associated with metrics that capture technical, economic, social and economic value (benefits and impacts). Of particular importance are how changes in technical value drive changes in other domains. A suite of metrics specific to the system under study is selected; the CVORR project has classified over 200 metrics, and is developing a systematic metric selection process that takes into account the values of stakeholders and external contexts such as the UN Sustainable Development Goals. This is in contrast to previous analysis methods that collapse all types of value into one (e.g. economic in natural capital or ecosystem services approaches) or consider a single domain of value and/or a 'one size fits all' suite of metrics (e.g. Life Cycle Analysis, LCA). Thus stakeholders are able to refer to whichever values matter to them at each and every system stage.

The CVORR framework has uncovered a second set of five metric classifications. These are based on whether quantities: are conserved (e.g. mass, energy) or can be created or destroyed (monetary value); are transferred via material (calorific value of coal) or non-material (electricity) flows; change according to the functioning of the foreground (substance concentration) or background (policy change) system; or transfer value according to physics or chemistry (contamination) or accounting conventions (embodied CO_2). Discrepancies between these types of metrics render previous methods mutually incompatible (e.g. LCA and cost-benefit analysis). Correcting this to allow simultaneous analysis of social, environmental, economic and technical value generation is CVORR's most powerful asset.

At the analysis stage, scenarios are developed that compare 'business as usual' with interventions intended to promote a given outcome. External factors driving change – regulatory, cultural, political etc. – and power relations between the key actors must also be made explicit using a 'systems of provision' approach. The mass flow model is then altered accordingly and the resultant changes in multidimensional value compared.

At the refinement stage the model and system are re-examined in the light of initial findings. Trade-offs in value (e.g. conversions between different types of value) are assessed and the stakeholders associated with each identified; who wins and who loses? Do the metrics reflect the motivations of all stakeholders? Do the system boundaries need to be changed to include critical background processes? Can more equitable trade-offs be identified? The model is then adjusted accordingly and the analysis repeated; this iterative process is continued until a stable analysis is obtained and reported using multi-criteria decision analysis techniques.

Analysis of the UK system suggested that: only about 16% of the plastics collected by local authorities actually finds its way to reprocessors.

The concrete – electricity generation – steel manufacture system

Cement production accounts for about 90% of the carbon dioxide (CO_2) emissions associated with concrete manufacture. Pulverised fly ash (PFA) recovered from coal-burning power stations can be used to replace up to approximately 50% of the cement. Since PFA is considered 'zero carbon' (the CO_2 emitted during its production is normally attributed to the electricity produced) this is a popular way of reducing the carbon footprint of concrete. However, as electricity producers switch to burning biomass to reduce their own carbon footprint, the PFA chemistry changes, making it unsuitable for use in concrete. Thus, a low carbon intervention in one system could potentially impact carbon reduction strategies in another, driven by a change in the technical value (i.e. quality) of the PFA.

A CVORR analysis of this simple system of systems used three further metrics; CO_2 emissions (environmental), profits in each sector (economic) and deaths caused by work accidents and particulate pollution (social). The results show that the net change in environmental value depends on the response of the actors and the embodied carbon (eCO_2) associated with biomass and PFA. If biomass is allocated low eCO_2 then the environmental benefits in electricity production offset the environmental costs in construction. If PFA is imported, then whether any net gains are made depends entirely on the eCO_2 allocated to the PFA. Economic gains fall as ash disposal costs rise, and importing PFA from countries with lower safety standards may effectively offshore social costs (i.e. deaths) although mortality is dominated by particulate pollution.

Recycling plastics

We have looked at many plastics recycling systems both in the UK and internationally. Analysis of the UK system suggested that: only about 16% of the plastics collected by local authorities actually finds its way to reprocessors; separation of plastics by householders decreases the total amount of plastic collected for recycling per household (although it may improve the quality of that collected); and nearly a third of local authorities report insufficient or incorrect data that cannot be included in the analysis, suggesting that data reporting needs to be simplified.

Our analysis of informal waste picking in Mumbai showed that increased segregation of plastics increased not only the amount of plastics collected but created thousands of new jobs. It also offered the potential to increase the incomes of the waste pickers and reduced CO_2 emissions from plastics burning. This highlights the importance of geography and economics to such technical analyses (Figure 18).

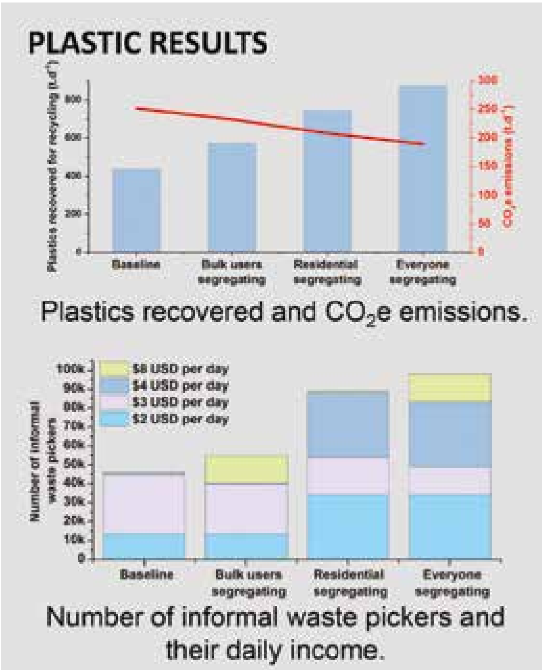


Figure 18: Plastics recovered and economic outcomes achieved in Mumbai as a function of segregation scheme. (Cottom *et al* (2019) Circular South Cities. Conference poster).

PULLING TOGETHER

In addition to the main projects of R³AW, INSPIRE, B3, MeteoRR, AVAnD and CVORR, the Resource Recovery from Waste programme also included a series of smaller mini-projects. These acted to pull together and exploit scientific synergies between different RRfW projects, and support the integration of research between our academic and non-academic project partners. Mini-projects addressed the gap between applied and basic research, and applied research and industrial practice.

Resource recovery from Parys Mountain: communicating the multifaceted value of mine sites

The UK's mining heritage generates significant income through tourism. Many former mining areas have cultural destinations and events that celebrate this aspect of our industrial heritage. We collaborated with a selection of these venues to showcase findings from the RRfW programme. Working across the INSPIRE, B3, MeteoRR and R³AW projects, display materials, including posters and a board game, were developed which enabled direct engagement of stakeholders and the general public.

The team exhibited at King Edwards Mine (Camborne, Cornwall) during the International Mining Games; a prestigious and historic mining event to commemorate the global mining legacy. The displays received a positive response and Copper Kingdom (Parys Mountain), Silver Mountain Experience (Aberystwyth), and Heartlands (Camborne, Cornwall) are now using our displays as part of their permanent exhibits. These activities allowed us to reach several thousand people over a period of a few months, and the permanent displays have created a lasting legacy for RRfW to reach a wider and bigger audience.

Participatory situational analysis for the implementation of RRfW technologies and vision

In order to promote resource recovery and resource efficiency as part of the transition towards the circular economy, we need to understand how such a change in waste and resource management could be achieved.

To address this, RRfW hosted four one-day workshops between October 2017 and April 2018, spread across Northern Ireland, Scotland, Wales and England. The 53 participants included representatives from academia, government, industry and NGOs. Each workshop focused on a different technology area from the RRfW programme.

The workshops asked stakeholders to identify the diverse legislative areas that need to be integrated and aligned to support resource recovery, the barriers and drivers for this, which actors are able to realise changes in governance, and the actions they should take. The insights captured were then used to inform RRfW's recommendations to government (Velenturf et al 2018c, also see 'Developing the policy environment'). The workshops facilitated a two way conversation, with an average of 98% participants saying they had learned new things and 58% saying they would be making changes in practice as a result of participating in the workshop.

Multi-parametric assessment of policies for resource recovery from waste

Sustainability assessment of resource recovery from waste is an important prerequisite for informed and sound decision-making. Life Cycle Sustainability Assessment (LCSA) has been developed to support this process, yet its use is still constrained by the difficulty of identifying the most relevant impact parameters.

This gap was addressed by a team drawing from R³AW, CVORR, MeteoRR and AVAnD. They further developed LCSA for resource recovery from waste based on a parameter identification approach that uses the political, economic, social, technological, environmental and legal (PESTEL) analysis, using anaerobic digestion of source-separated food waste as a case study (Iacovidou *et al.* 2017a). The approach can summarise key interdependencies, trade-offs and provides a wider understanding of the political and legal context, all important in extending the implementation of LCSA towards the right direction.

This mini-project also fed into the RRfW policy recommendations (see 'Developing the policy environment').

"Compost oversize, a predominantly woody fraction left over from the composting process, could be suitable for use as a fuel.

Recovering multidimensional value from compost oversize

Compost oversize, a predominantly woody fraction left over from the composting process, could be suitable for use as a fuel. However, stringent end-of-waste regulations and contamination with non-organic and potentially toxic materials, make compost oversize difficult to process. The result is that most is stockpiled, combusted in inappropriate facilities or sent to landfill, leaving its value unrealised.

The mini-project used the CVORR approach to assess alternative compost oversize management options. The study found that, from environmental and social perspectives, gasification was a better option for compost oversize management compared to incineration and stockpiling. However, for this to be economically and technically feasible the contamination of the compost oversize needs to be reduced; from the point where waste is placed into the bin, with householders' taking increased responsibility for separating their waste, to local councils and waste companies having sufficient funding for implementing waste management and checking green waste quality upon receipt at the composting site, and capacity to support enforcement of regulations (Iacovidou et al. 2019a).

Life cycle sustainability and policy analyses of plausible systems for resource recovery from waste

A software tool for techno-economic and sustainability analysis of resource recovery technologies for circular economy (TESARREC™) has been developed at the University of Surrey (MeteoRR team) and is proceeding towards commercialisation. Initially focused on bioelectrochemical systems (Shemfe *et al.* 2018b), TESARREC™ will be expanding its capability to evaluate sustainability and design of a wide range of wastewater treatment, resource recovery from waste and (bio)remediation technologies for valorisation of waste streams into added value products.

TESARREC™ has uniquely embedded life cycle sustainability assessment (LCSA) encompassing (environmental) life cycle assessment (LCA), (economic) life cycle costing (LCC) and social LCA (SLCA) methodologies, in accordance with the ISO 14040, 14041, 14044 and 26000 standards, to address an important market need by enabling firms to easily design and simulate sustainable process configurations and systems topologies including new innovations for reducing environmental footprints of their waste management facilities. TESARREC™ resolves an unmet market-need leading to benefits to both users and the environment.

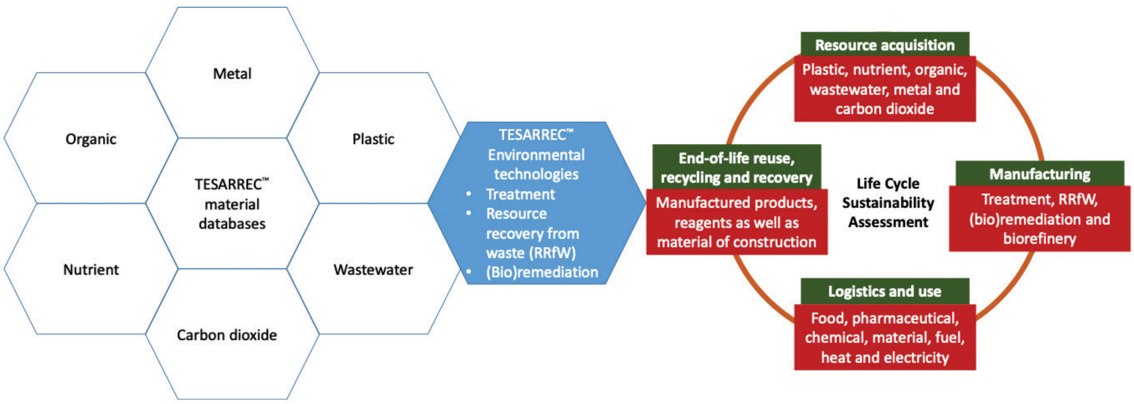


Figure 19. Concept for TESARREC™ software tool for techno-economic and sustainability analysis for resource recovery technologies.

Formulating the environmental and social business case for a resource recovery from waste process

Mechanical Heat Treatment (MHT) is used to separate a mixed municipal solid waste streams into component parts via a range of mechanical and thermal treatments, such as autoclaving. Autoclaving uses steam and pressure to break down the organic waste, for example from labels on bottles or single-use coffee cups, into a sanitised fibre fraction (the now clean glass or plastic can be further sorted for recycling).

Currently these sanitised fibres are used in combustion process to generate power, a low-value application. Hence it is of interest whether there is the potential to produce fibres for higher value applications. A review was undertaken of the trends driving change in the composition and volume of residual municipal solid waste in the UK, and the evolution of the waste infrastructure, including MHT technology. Initial analysis of various economic scenarios identified that there are a number of potential routes for higher value applications for fibres from MHT that would benefit from further research.

The Resource Recovery from Waste retreat

A writing retreat was held in Penzance, Cornwall, in November of 2017 with the aim of bringing together RRfW partners for the production of shared publications, developing and strengthening the RRfW network. Participants included representatives from all RRfW projects.

The retreat supported progress towards RRfW programme level achievements, namely the development of the Resource Recovery from Waste book ('Resource recovery from Wastes: Towards a Circular Economy' Edited by L. E. Macaskie, D. J. Sapsford, W.M. Mayes, to be published by The Royal Society of Chemistry) and the '[Resource Recovery from Waste' research topic (special issue) on the Open Access platform "Frontiers"](). It also served as a platform of knowledge exchange and collaboration between individuals and projects, including providing a space to push other mini-projects forward.

The retreat was valuable in enabling the formulation of a more coherent set of RRfW publications. Relations between RRfW researchers were strengthened, offering a valuable basis for further research collaborations.

"A writing retreat was held in Penzance, Cornwall, in November of 2017 with the aim of bringing together RRfW partners for the production of shared publications."

VISIONS FOR A CIRCULAR ECONOMY

The Resource Recovery from Waste (RRfW) programme aimed to facilitate radical change in waste and resource management in the UK by establishing the much-needed relations between the goal of a sustainable circular economy and the development of resource recovery technologies, policies and business models that will be required to get there.

To achieve this, RRfW catalysed collaboration between actors in industry, government and academia in order to co-produce visions of a desirable future and practical steps for its implementation. Outcomes of the engagement with each of the target groups are presented here (Academic, Government and Industry perspectives).

The circular economy is often presented as a singular option, but our co-creation process identified that UK thought leaders in academia, government and industry aspire to three different types of circular economy: a 'closed loop' economy primarily reliant on energy recovery which is being implemented now; a future where wastes are prevented by designing them out of the economy; and resource recovery from waste as a transitional stage (Figure 20).

Figure 20: Circular economies identified by the RRfW co-creation process: current economy reliant on energy-from-waste; transition including resource recovery; and future zero waste circular economy.

Academic perspective

ECOSYSTEMS, PLANETARY BOUNDARIES & WELLBEING

Healthy ecosystems are essential for human well-being, providing the 'ecosystem services' of provisioning (e.g. food), support (e.g. nutrient cycling), regulation (e.g. water quality) and culture (e.g. parks); degrading them infringes on multiple human rights. 12 out of the 17 UN Sustainable Development Goals contain targets for improving waste and resource management, requiring radical industrial and social changes in order to stay within planetary boundaries that define the 'safe operating space' for humanity. Four of the nine boundaries have already been crossed, for: climate change; biogeochemical loading such as biologically active nitrogen; biodiversity loss; and land use. Our current extraction, production, use and waste of resources has driven this boundary crossing; for example, over half of industrial CO_2 emissions are attributable to processing primary materials. Transforming waste and resource management will help change these self-destructive pathways.

SCIENCE, TECHNOLOGY AND ECONOMICS

The paradox of over-exploiting limited resources whilst generating 22 billion tonnes of waste annually – the linear 'take-make-use-dispose' economy – could be resolved by moving to a circular economy, where resources are kept in use for as long as possible to generate value then recovered and reused, instead of allowing their value to dissipate into waste. Moving to a circular economy would have multiple benefits. Reduced extraction of new resources reduces emissions of CO_2, and water and energy consumption. Increased reuse and recycling increases resource supply-chain security and economic activity. To approach circularity will require new science and technology; not just 'end-of-pipe' treatment to recycle wastes but also changes in design and manufacturing that make products more amenable to being reused, dismantled and/or recycled. Supply chains need to be redesigned to prevent value of materials in four dimensions – technical, environmental, social and economic – from leaking into waste during product life cycles. Economic models and regulation that take account of all four dimensions of value (not just financial value) must be co-designed to support the emergence of new business models that help firms achieve circular operation.

REBALANCING: PARTICIPATORY ACTION RESEARCH

This shift in thinking requires academia to engage across the supply chain (designers, manufacturers, consumers, waste processers) and with politicians, regulators and NGOs who support markets and drive changes in practices. Participatory governance is a flexible engagement process that can range from informing, to listening, consulting, co-producing, co-deciding and full autonomy, bringing a diversity of expertise to solve problems and generate commitment. Academia can adopt these techniques through participatory action research, creating conditions in which scientific progress can lead to societal impact. We have used this approach via an engagement strategy including building a strategic network of organisations with power to drive change; dissemination of our research via written academic- and non-academic media; inviting contributions from government and business to on-going research; active membership of government and industry groups; and hosting conferences, workshops and other meetings to share our research and identify new needs.

Further reading: Velenturf & Purnell (2017).

"Moving to a circular economy would have multiple benefits.

Government perspective

We compared the outcomes of perspectives from governmental waste and resource specialists with the Governments' published strategies for a circular economy, resource recovery, and waste management in England, Wales, Northern Ireland, and Scotland. They broadly agreed on a vision of a circular economy that maximises the value of materials by keeping them in the economy for as long as possible, moving away from end-of-pipe approaches and instead designing durability and recyclability into the economy. Parts of this vision have already been incorporated in policy and regulation but with large differences across the four nations (see Table 1). Coherence across the UK is driven by EU directives; as Brexit looms, this coherence is likely to deteriorate further unless concerted policy action is taken by BEIS, Defra and their devolved counterparts. Recommendations include:

- Measuring progress and collecting data in terms of technical, social and environmental values in addition to economic;
- Secondary resource markets should be supported through incentives and regulation;
- Policy interventions should enable innovation across waste processing technologies, business models, product design, and data collection/analysis;
- A whole-system approach to analysis should be adopted but translated into specific actions for key departments;
- A long-term and predictable resource efficiency policy framework is required;
- Promote infrastructure that preserves the functional qualities of materials that contribute to industrial productivity through reuse and recycling, rather than just energy-from-waste infrastructure.

Themes	W	NI	S	E
Integrating economic with social and environmental values				
Radical change in economic theory and practice	Green	Orange	Orange	Red
Progress redefined to include social and environmental factors	Green	Green	Orange	Orange
Maximise environmental, social and economic value created from resources	Green	Red	Orange	Red
Internalise or integrate environmental, social and economic metrics	Orange	Red	Orange	Red
Supporting secondary resource markets				
Decoupling: consumption from economic growth; environmental, social and economic metrics	Green	Green	Green	Red
Keep materials in economy as long as possible	Green	Orange	Green	Orange
Incentivise/regulate emerging secondary resource markets	Green	Green	Green	Green
From supplier-led to demand-led markets	Green	Orange	Red	Red
Enabling innovations				
Business model innovation vs. business as usual with improved recycling technology	Green	Orange	Green	Orange
Material and product design including end-of-life options	Green	Green	Green	Green
Digitisation enabling recycling, but growing e-waste	Orange	Red	Green	Orange
Whole system approach identifying key intervention points				
Move away from end-of-pipe approaches and higher up the waste hierarchy	Green	Orange	Green	Orange
Decarbonisation+ has to include waste and resource management	Green	Orange	Green	Orange
Enable CE through (decentralised) waste infrastructure	Green	Red	Green	Red
Whole system approach but identify key intervention points for targeted action	Green	Green	Green	Orange
Realise radical change through engagement of government, industry, academia and general public				
	Green	Orange	Orange	Orange

Table 1: Comparative analysis of key themes distilled from government specialists' personal view and formal government visions, strategies, and plans for circular economy, resource recovery, and/or waste management (published documents) for Wales (W), Northern Ireland (NI), Scotland (S) and England (E). Green = included; orange = partly included and red = not included in formal government documents.

Further reading: Velenturf *et al.* (2018a)

“Many businesses have adopted circular economy principles.”

Industry perspective

Many businesses have adopted circular economy principles. RRfW involved companies and professional bodies from across several industries to envision what waste and resource management would ideally look like in 30 years, and to identify the key barriers, opportunities and actions for realising such vision. The industrial view largely aligned with that of academia and government. A list of actions was identified for industry in order of importance:

1. Embed extended producer responsibility into corporate social responsibility policy.
2. Contribute to policy development, especially by providing data on stocks and flows of primary and secondary resources.
3. Design products and materials to enable them to retain their economic, technical, social and environmental value as long as possible i.e. prioritise resource productivity.
4. Innovate to increase resource security, e.g. by using secondary resources or finding higher-value outlets for unavoidable wastes.
5. Innovate business models to embed circular economy within companies.
6. Promote behaviour change by educating staff and consumers about resource recovery.

Although industry can take a lead in the transition towards a circular economy, they identified a wide range of policy and regulatory barriers that government should remove by providing a clear long-term vision and strategy, improved regulation and implementation capacity, innovation support, and investment. Industry saw a role for academia in supporting the transition by undertaking blue-sky research necessary to deliver breakthrough change, but applied and industrial research needs to be better linked in order to commercialise these breakthroughs.

Further reading: Velenturf & Purnell (2018).

DEVELOPING THE POLICY ENVIRONMENT

The RRfW programme has assessed the political and regulatory challenges to adopting new resource recovery technologies, processes and systems. Multiple industrial, commercial and governmental commentators expect resource recovery (as part of the transition towards a circular economy) to deliver billions of pounds of financial savings for businesses and create tens of thousands of high-quality jobs. It will improve the UK's resource security by protecting access to critical strategic materials.

Resource recovery has enormous potential to reduce the environmental impacts of linear resource use (particularly the CO_2 emissions associated with primary resource production which account for ~40% of total emissions) and would also provide social benefits through better jobs, less litter and empowered communities. Despite these clear benefits, the transition remains slow and the current policy landscape is a major barrier. The long-term aims of UK policy in this area should be to create an economy, environment and society capable of realising these benefits across generations and borders. In order to achieve this, RRfW makes the following overarching policy recommendations.

Integrate assessment of multi-dimensional costs and benefits into decision making

Resource recovery business cases rest on the generation of social, environmental and technical costs and benefits as well as those in the economic dimension. While in some cases these costs and benefits can be converted to economic values or 'monetised', in many cases they cannot and this should not preclude them from analysis. The incorporation of multi-dimensional values (and metrics to measure them) into decision-making needs to occur at the highest level of government. Understanding technical value – the functional characteristics of products and materials that provide their utility – and its interaction with other dimensions of value is critically important; a focus on quality as well as quantity. The Treasury needs to build on Green Book guidance to include monetised and non-monetised values on economic, environmental, social and technical aspects. The system wide costs, benefits and net gain across multiple domains of value can then be used to inform decision-making and investment. Avoiding the subjective conversion of all measurements into e.g. money or carbon equivalents will aid transparency. This requires new data collection and analysis systems that enable comparison of different units of measurement e.g. profit (money), human life expectancy (years), air quality (diverse emissions), recycled contents (proportion secondary material in unit product) and secondary resource quality. Such a model has been developed by the CVORR project at the University of Leeds. By incorporating values that account for social and environmental net gain into (economic) growth forecasting models the sustainability of policies can be better assessed.

Collect data on stocks and flows of material quantity and quality

Poor data availability, quality and coherence are known issues in measuring resource flows, particularly for recovered materials. It stems from data only being collected in response to individual regulatory targets driven by public health or environmental legislation, rather than specifically for resource recovery, preventing effective policy-making and investment. Better data must be collected for the express purpose of calculating the quantities and qualities of stocks and flows of primary and secondary resources within our economy. Scotland has made an excellent start, measuring the nation's bio-refining potential, which gives an insight into the effort needed to design, populate and capitalise on a UK National Materials Database. Material flows need to be measured from point of extraction/production, through fabrication, use and end-of-life options, so that a full life cycle overview is available for all products. The regular assessment of supply chain scenarios for these products provides opportunities for continuous improvements in the transition towards a more sustainable, high-value circular economy.

Launch Office for Resource Stewardship to coordinate government action

The UK government needs to develop a stable policy framework on resources and waste, evaluated at strategic intervals but with underlying long-term targets that future governments can retain, to maximise multi-dimensional values of materials and products and minimise impacts at end-of-use. Circular economy policy and regulations across the UK nations are diverse, currently driven by varying desires to comply with EU directives. After leaving the EU, a strategy is needed to keep approaches to waste, resource efficiency and circular economy sufficiently coherent across the UK nations to maintain stability and give confidence to investors and companies operating in the resources and waste sector.

To deliver this approach, the government needs to both take a whole systems perspective to managing resources and wastes but also identify key intervention points. Developing holistic, integrated, yet targeted policies requires collaboration across government departments. For instance, resource efficiency targets (under Defra) could contribute significantly to decarbonisation (under BEIS); vice versa, climate targets could incorporate resource efficiency. An Office for Resource Stewardship could formalise collaboration between government structures such as Defra, BEIS, NIC and the EA. It should monitor stocks and flows of primary, secondary and critical resources, carry out multi-dimensional value assessments in priority sectors, and advise on cross-departmental interventions for circular economy. This implies a change in governance culture around circular economy, from a focus on health and environment at the 'end of pipe' stage to include economic and technical aspects throughout the supply chain.

An Office of Resource Stewardship would enable three important measures to support a sustainable circular economy:

- Promote diverse investment in infrastructure and innovation that optimises retention of the technical value of materials and products, and preserve UK resource security (especially of materials required to implement the Clean Growth Strategy e.g. lithium, cobalt and rare earth metals for which we are 100% importers). Quality, as well as quantity, of recyclates should be a priority.
- Create a 'level playing field' for primary and secondary materials by integrating environmental and social costs into their price, through a differential tax on the primary resource content of materials and products manufactured, imported and/or traded in the UK informed by extended producer responsibility principles. This would encourage design for reuse, repair and recycling.
- Harmonise regulation to ensure that residues created by new resource recovery processes can be returned to the economy, by promoting dialogue between regulators, policy makers, business and research to establish where resource recovery is technically and economically viable, the barriers in place and the environmental and social implications of regulatory change.

Knowledge, skills and infrastructure for a circular economy

A "Circular Economy Network" should be established to build a comprehensive programme of business support, disseminating essential circular economy knowledge and skills to companies throughout the UK. The Resources and Waste Strategy could catalyse the network, which also aligns with objectives in the Industrial and Clean Growth Strategies, delivering cross-departmental benefits. This would facilitate industries in developing resource efficient (e.g. zero waste) sustainable supply chains, and embed practices such as waste minimisation, innovative circular business models, the uptake of clean technologies, and industrial symbiosis.

Policy notes

These overarching policy recommendations amalgamated with technical findings from our research resulted in two more specific policy notes. 'The organic waste gold rush' (Marshall *et al.* 2018b) discusses how the use of organic waste in the bioeconomy can contribute towards the UK's strategic goals of clean growth and resource security. Policy and regulations should encourage industrial synergies and increase the diversity of resources recovered from organic waste. 'Making the most of industrial wastes' (Marshall *et al.* 2018a) examines how mining and manufacturing wastes contain metals such as vanadium, cobalt, lithium and rare-earth elements necessary for clean technologies. The current regulatory framework was not designed with the circular economy in mind and policies will need to become more integrated to make the most of the resource potential of industrial wastes.

Further reading: Deutz *et al.* (2017); Iacovidou *et al.* (2017b); Semple *et al.* (2017); Velenturf and Purnell (2017); Velenturf *et al.* (2018a)

INFRASTRUCTURE FOR RESOURCE RECOVERY

The British waste management sector retains a focus on public health and environmental protection concerns and our legacy infrastructure is struggling to adapt to a new resource productivity paradigm.

Is our current and planned waste and resource recovery infrastructure ready to deliver a circular economy and associated benefits? RRfW research concludes that it isn't and making it so will require radical interventions.

The British waste management sector retains a focus on public health and environmental protection concerns and our legacy infrastructure is struggling to adapt to a new resource productivity paradigm. Two key deficiencies can be identified: in data (see 'Developing the policy environment') collected only in relation to specific (EU) regulations; and in public infrastructure investment because in many cases the narrow targets under this legislation (e.g. % diversion of organic waste from landfill) have been 'met' so no further investment need is perceived.

The data problem is that little of it is mutually compatible and double counting is widespread. Without reliable data on mass flows (and their ability to provide stable income streams) it's not possible to reliably predict the gap between capacity and requirements, which impedes strategy and investment. This is reflected in the lack of diversity in the National Infrastructure Plan, where at least 80% of solid waste investment is in Energy from Waste plants, creating an infrastructure that paradoxically relies on the continued creation of waste. Burning waste for energy destroys technical value and removes materials from the supply chain. In a truly circular economy this should be a last resort, not the dominant technology. Options with greater power to reduce resource extraction and associated CO_2 emissions such as reduction, repair and reuse are under-promoted. Driving a change from waste treatment to waste prevention will require responsibility for end-of-life resources to not just be perceived as the remit of the waste management industry, but include the entire supply chain; designers, manufacturers, retailers, users and material reprocessors.

'Closing the loop' to move from the current focus on waste treatment to the circular economy will require political leadership and public investment, including the establishment of an Office for Resource Stewardship (see 'Developing the policy environment') to work with the National Infrastructure Commission to establish a diverse resource recovery infrastructure that protects national interests by enforcing efficient use of materials, preventing waste and encouraging reuse and recycling. As the UK embarks on a new industrial strategy and world trade relations, we should reimagine the resource recovery industry as an engine for sustainable growth at home and a crucible from which we export the science, technology and services required for a global circular economy.

Further reading: Purnell (2017)

MAKING THE BUSINESS CASE FOR RESOURCE RECOVERY

If resource recovery is to be adopted as part of the transition towards a circular economy, government and businesses need to understand how they would benefit from this change: in other words, a compelling business case is required. The RRfW programme enlisted the help of resource recovery experts from academia, industry and government as part of the Resource Recovery from Waste 2017 annual conference. We asked them to identify drivers, barriers and actions for the adoption of resource recovery, and 37 themes were identified that can act as a list of aspects for future business cases. The themes fall between the old economic paradigm (that economic growth will find a way out of the complex issues associated with resource overexploitation and waste generation) and the newer paradigm, where multi-dimensional i.e. economic, social and environmental challenges need multi-dimensional solutions. Resource recovery should support multi-dimensional growth in which the better use and preservation of technical qualities of materials and products drives the partial redistribution of economic values to the creation of social and environmental net-gains.

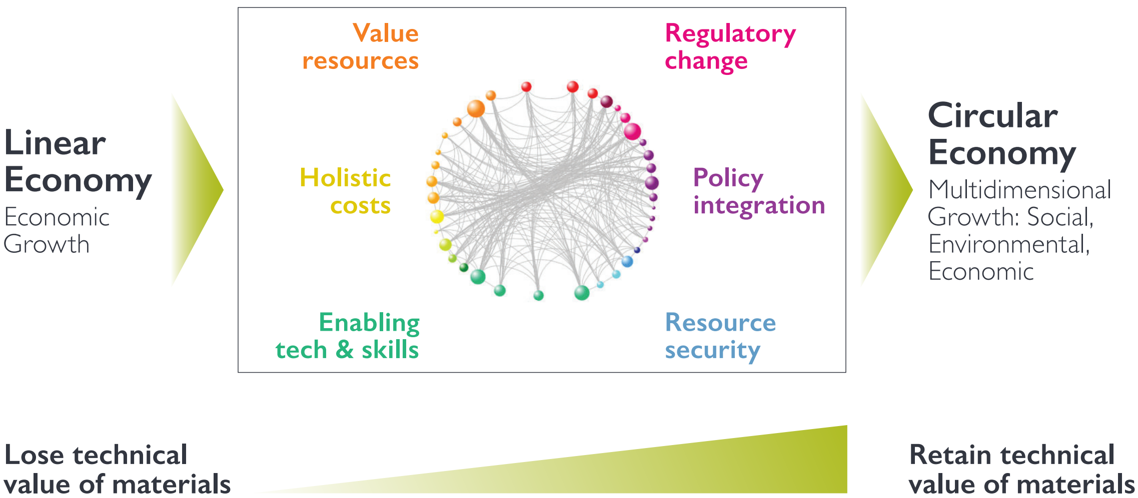


Figure 21. Key nodes of action for transition to Circular Economy

Using the full list of 37 themes for any single business case would be unwieldy, and so network analysis determined which themes were most interconnected and could thus act as key intervention points (Figure 21). These were:

1. Expanding the types of values (benefits and costs) considered from mostly economic costs to also include environmental, social and technical values ('Value resources', 'Holistic costs')
2. Elucidating governmental aspects such as 'Regulatory change' and 'Policy integration'.
3. Promoting 'Enabling technologies & skills' and 'Resource security'.

These key intervention points function as an umbrella for formulating business cases for resource recovery and are likely to encompass associated benefits regarding the other themes too. For instance, arguments for valuing resources are likely to promote change in business models, including external impacts as a fairer reflection of true cost, and opportunities for low-carbon growth. In turn, how we value resources is likely to depend on the policy and regulatory landscape. Writing full business cases for resource recovery (addressing the total net benefit) will require the integration of evidence from across disciplines and sustained research efforts (see 'Future challenges').

Further reading: Velenturf & Jopson (2019)

LEAVING A LEGACY

The aims of RRfW – to achieve a circular economy through radical changes in how resources are extracted, used, recovered and recycled – will remain in place after the formal programme has finished. The legacy of RRfW is to provide resources that can help continue to further these aims.

We have established a community of academics and research professionals with a unique set of skills and expertise that cross traditional academic boundaries to address the real-word challenges facing the resource recovery sector. This community of about 100 environmental scientists, engineers and economists has deeply engaged with many resource recovery actors including government departments and agencies, waste producers, waste and resource management companies and various trade associations. Thus we have also established a network of over 300 stakeholders who have helped us co-create both research outcomes and new research questions. This new RRfW community can thus provide both theoretical advice and practical evidence for industry and policymakers charged with delivering a circular economy. Many of our research professionals have gone on to take up permanent academic positions, fellowships, and positions at the interface between industry and government, both in the UK and abroad.

We have significantly progressed the state-of-the-art in resource recovery research, with almost 100 peer-reviewed publications spanning: new resource recovery and waste treatment technologies; theoretical frameworks, metrics and models for assessing the value of resource recovery, stocks and flows of plastics in the technical and natural environment; exemplars of cooperative research methods; analyses of academic, industrial and governmental attitudes and concerns; and infrastructure and policy reviews and recommendations. This body of work will form the basis for developing the resource recovery processes of the future.

We have drawn together these diverse outputs into a series of briefing papers, policy and practice notes, an edited book (to be published by The Royal Society of Chemistry) and a journal special issue (Frontiers Research Topic 'Resource Recovery from Waste') which we firmly expect to become standard references in the field and provide the starting point for design of outreach and educational programmes. We have also engaged broadcast media, featuring in a number of national and international transmissions e.g. on the role of plastics in society (BBC Radio 4 'Plastic Fantastic' series, first broadcast May 2018).

We have produced a series of policy recommendations. As well as publishing these in traditional forms, we have engaged with policy-makers in numerous ways to help further disseminate the findings of RRfW, including: presentations at House of Commons events; engaging in committee work with government departments and agencies shaping waste and resource policy; and contributing to guidance for the Green Book, Industrial Strategy, and new frameworks, metrics and evidence for the Resources and Waste Strategy.

The RRfW programme has also helped to create new research projects that will directly advance the aims of the programme. These include:

- investigations into the ability of waste slags from iron and steel production to remove CO_2 from the atmosphere (see Greenhouse Gas Removal in the Iron and Steel Industry, NE/P019943/1)
- new partnership-based approaches to building a circular water economy in Africa (see RECIRCULATE: Driving eco-innovation in africa: capacity-building for a safe circular water economy, ES/P010857/1)
- bio-electrochemical technologies to convert CO_2 into liquid fuels using energy from biomass and wastewater (see Liquid Fuel and bioEnergy Supply from CO_2 Reduction, EP/N009746/1) and for use as sensors in wastewater treatment (see ToOLTuBES: Toxicity & Organic Load Tracking using BioElectrochemical Systems, BB/R005613/1)
- formulating fertilisers and land conditioners from bioenergy waste (see ISCF WAVE 1 AGRI TECH: Formulating novel fertilisers and land conditioners from bioenergy wastes, BB/R021619/1).

FUTURE CHALLENGES

The Resource Recovery from Waste programme has made significant steps in supporting the radical change needed in waste and resource management landscape for a transition to a circular economy. But challenges still remain.

- A persistent challenge is managing the support of and collaboration between the stakeholders – materials processors, product designers, retailers, consumers, waste managers and secondary material processors – necessary to implement circular economy. Practical guidance for each is underdeveloped, especially with regard to accessing the benefits of a circular economy. Supply chains should be integrated to connect waste producers and users.
- Product design paradigms need to rank the ability to upgrade, repair, dismantle and recover materials equally with economic, aesthetic or technical performance. Wastes can be 'designed out' of the economy through improved durability and recyclability of products.
- Waste processing processes and technologies need further development, aimed at processing complete waste matrices, recovering all resources and leaving zero waste residue. Particular challenges remain for textiles, metals (faster acting leaching technologies), plastics (methods for separation, recognition and recycling), and construction wastes (recovery processes for bulk aggregates).
- Business models exist that contribute to solving global sustainability issues but need to be communicated and operationalised for firms along the supply chain. These can only be implemented with a better understanding of circular economy infrastructures and their relations to wider industry, via UK Research and Innovation.
- Data on the quantities, quality, and location in time and space of materials, resources and wastes needs to be coherently collected at local, regional and national scales. The use of digital and data technologies such as blockchain could make data collection, management and assessment more secure and reliable, and less costly and onerous.
- Better and consistent metrics, indicators and criteria need to be decided upon to measure environmental, social and economic values, to help integrate the creation of social and environmental benefits from resource efficiency into government and industrial policy. Consistent use of these metrics would also aid the development of strategies to implement international governance to preserve planetary boundaries (beyond climate change and carbon).
- Energy solutions: invent, scale up and industrialise processes using CO_2, more affordable low-carbon energy solutions; upgrade pyrolysis oil to enable wider use

"A persistent challenge is managing the support of and collaboration between the stakeholders.

BIBLIOGRAPHY

Boghani (2016). Control of microbial fuel cell voltage using a gain scheduling control strategy. Journal of Power Sources. 322, 106-115. doi:10.1016/j.jpowsour.2016.05.017; Open Access.

Boghani *et al.* (2017). Reducing the burden of food processing washdown wastewaters using microbial fuel cells. Biochemical Engineering Journal. 117, (Part A), 210-217. doi:10.1016/j.bej.2016.10.017; Open Access.

Bray *et al.* (2018). Sustained bauxite residue rehabilitation with gypsum and organic matter 16 years after initial treatment. Environmental Science & Technology. 52 (1), 152-161. doi:10.1021/acs.est.7b03568, Open Access.

Chen *et al.* (2018). Decoupled Advection-Dispersion Method for Determining Wall Thickness of Slurry Trench Cutoff Walls. International Journal of Geomechanics. 18 (5), p.06018007. Open Access Abstract.

Crane & Sapsford (2018a). Selective formation of copper nanoparticles from acid mine drainage using nanoscale zerovalent iron particles. Journal of Hazardous Materials. 347, 252-265. doi:10.1016/j.jhazmat.2017.12.014, Open Access.

Crane & Sapsford (2018b). Sorption and fractionation of rare earth element ions onto nanoscale zerovalent iron particles. Chemical Engineering Journal. 345, 126-137. doi.org/10.1016/j.cej.2018.03.148, Open Access.

Crane & Sapsford (2018c). Towards Greener Lixiviants in Value Recovery from Mine Wastes: Efficacy of Organic Acids for the Dissolution of Copper and Arsenic from Legacy Mine Tailings. Minerals, 8(9), 383. doi:10.3390/min8090383, Open Access.

Crane & Sapsford (2018d). Towards "Precision Mining" of wastewater: Selective recovery of Cu from acid mine drainage onto diatomite supported nanoscale zerovalent iron particles. Chemosphere, 202, 339-348. doi:10.1016/j.chemosphere.2018.03.042, Open Access.

Crane *et al.* (2017). Physicochemical composition of wastes and co-located environmental designations at legacy mine sites in the south west of England and Wales: Implications for their resource potential. Resources, Conservation and Recycling. 123, 117-134. doi:10.1016/j.resconrec.2016.08.009; Open Access.

Cruz Viggi *et al.* (2017). Bridging spatially segregated redox zones with a microbial electrochemical snorkel triggers biogeochemical cycles in oil-contaminated River Tyne (UK) sediments. Water Research 127, 11-21. doi:10.1016/j.watres.2017.10.002; Open Access.

Daghio *et al.* (2016). Anodes Stimulate Anaerobic Toluene Degradation via Sulfur Cycling in Marine Sediments. Applied and Environmental Microbiology 82, 297-307 doi:10.1128/AEM.02250-15; Open Access Abstract.

Daghio *et al.* (2017). Electrobioremediation of oil spills. Water Research 114, 351-370. doi:10.1016/j.watres.2017.02.030; Open Access Abstract.

Daghio *et al.* (2018). Anode potential selection for sulfide removal in contaminated marine sediments. Journal of Hazardous Materials. 360, 498-503. doi.org/10.1016/j.jhazmat.2018.08.016; Open Access from 16 Aug 2019.

Deutz *et al.* (2017). Resource recovery and remediation of highly alkaline residues: A political-industrial ecology approach to building a circular economy. Geoforum, 85, 336-344. doi:10.1016/j.geoforum.2017.03.021, Open Access.

Ding *et al.* (2016). Role of an organic carbon-rich soil and Fe(III) reduction in reducing the toxicity and environmental mobility of Chromium(VI) at a COPR disposal site. Science of the Total Environment. 541, 1191-1199. doi:10.1016/j.scitotenv.2015.09.150, Open Access.

Fagbohungbe *et al.* (2015a). High solid anaerobic digestion: operational challenges and possibilities. Environmental Technology & Innovation. 4, 268-284. doi:10.1016/j.eti.2015.09.003; Open Access abstract.

Fagbohungbe *et al.* (2015b). The effect of substrate to inoculum ratios on the anaerobic digestion of human faecal material. Environmental Technology and Innovation. 3, 121-129. doi:10.1016/j.eti.2015.02.005; Open Access abstract.

Fagbohungbe *et al.* (2016). Impact of biochar on the anaerobic digestion of citrus peel waste. Bioresource Technology. 216, 142-149. doi:10.1016/j.biortech.2016.04.106; Open Access abstract.

Fagbohungbe *et al.* (2017). The challenges of anaerobic digestion and the role of biochar in optimizing anaerobic digestion. Waste Management, 61, 236-249. doi:10.1016/j.wasman.2016.11.028; Open Access abstract.

Falagan & Johnson (2016). Acidithiobacillus ferriphilus sp. nov.: a facultatively anaerobic iron- and sulphur-metabolising extreme acidophile. International Journal of Systematic and Evolutionary Microbiology 66: 206-211, doi: 10.1099/ijsem.0.000698, Open Access.

Falagan *et al.* (2017). New approaches for extracting and recovering metals from mine tailings. Minerals Engineering. 106, 71-78. doi:10.1016/j.mineng.2016.10.008, Open Access.

Feito *et al.* (2018). Applicability of a PEDOT coated electrode for amperometric quantification of short chain carboxylic acids. (2018). GC. Sensors and Actuators, B-Chemical. 255 (1), 712-719. doi:10.1016/j.snb.2017.08.033; Open Access Abstract.

Gomes *et al.* (2016a). Alkaline residues and the environment: A review of impacts, management practices and opportunities. Journal of Cleaner Production, 112, 3571-3582. doi:10.1016/j.jclepro.2015.09.111, Open Access.

Gomes *et al.* (2016b). Vanadium removal and recovery from bauxite residue leachates by ion exchange. Environmental Science and Pollution Research. 23(22), 23034-23042. doi:10.1007/s11356-016-7514-3, Open Access.

Gomes *et al.* (2017a). Hydraulic and biotic impacts on neutralisation of high-pH waters. Science of the Total Environment. 601, 1271-1279. doi:10.1016/j.scitotenv.2017.05.248, Open Access.

Gomes *et al.* (2017b). Removal and recovery of vanadium from alkaline steel slag leachate with anion exchange resins. Journal of Environmental Management, 187, 384-392. doi:10.1016/j.jenvman.2016.10.063, Open Access.

Gomes *et al.* (2018a). Options for managing alkaline steel slag leachate: a life cycle assessment. Journal Cleaner Production. 202, 401-412. doi.org/10.1016/j.jclepro.2018.08.163, Open Access.

Gomes *et al.* (2018b). Recovery of Al, Cr and V from steel slag by bioleaching: Batch and column experiments. Journal of Environmental Management. 222, 30-36. doi: 10.1016/j.jenvman.2018.05.056, Open Access.

Gomez-Bolivar *et al.* (2018). Characterization of palladium nanoparticles produced by microwave-injured bacteria with enhanced catalytic activity Proc 19th Int Microscopy Congress 9-14 Sept 2018, Sydney, Australia. Open Access Abstract.

Hahladakis & Iacovidou (2018). Closing the loop on plastic packaging materials: What is quality and how does it affect their circularity? Science of the Total Environment. 630, 1394-1400. doi:10.1016/j.scitotenv.2018.02.330, Open Access.

Hahladakis *et al.* (2018a). An overview of chemical additives present in plastics: Migration, release, fate and environmental impact during their use, disposal and recycling. Journal of Hazardous Materials. 344, 179-199. doi:10.1016/j.jhazmat.2017.10.014, Open Access.

Hahladakis *et al.* (2018b). Post-consumer plastic packaging waste in England: Assessing the yield of multiple collection-recycling schemes. Waste Management. In press. doi:10.1016/j.wasman.2018.02.009, Open Access.

Hobson *et al.* (2017). Mechanism of vanadium leaching during surface weathering of basic oxygen furnace steel slag blocks: a microfocus x-ray absorption spectroscopy and electron microscopy study. Environmental Science & Technology. 51 (14), 7823–7830. doi:10.1021/acs.est.7b00874, Open Access.

Hobson *et al.* (2018). Behaviour and fate of vanadium during the aerobic neutralisation of hyperalkaline slag leachate. Science of The Total Environment. 643, 1191-1199. doi:10.1016/j.scitotenv.2018.06.272, Open Access.

Hodkin *et al.* (2016). Coprecipitation of ^{14}C and Sr with carbonate precipitates: The importance of reaction kinetics and recrystallization pathways. Science of the Total Environment. 562, 335-343. doi:10.1016/j.scitotenv.2016.03.192, Open Access.

Iacovidou *et al.* (2017a). A Parameter Selection Framework for Sustainability Assessment. Sustainability. 9(9), 1497. doi.org/10.3390/su9091497, Open Access.

Iacovidou *et al.* (2017b). A pathway to circular economy: Developing a conceptual framework for complex value assessment of resources recovered from waste. Journal of Cleaner Production. 168, 1279-1288. doi: 10.1016/j.jclepro.2017.09.002, Open Access.

Iacovidou *et al.* (2017c). Metrics for optimising the multi-dimensional value of resources recovered from waste in a circular economy: A critical review. Journal of Cleaner Production, 166, 910–938. doi:10.1016/j.jclepro.2017.07.100, Open Access.

Iacovidou *et al.* (2018). Technical properties of biomass and SRF co-fired with coal: Impact on multi-dimensional resource recovery value. Waste Management. 73, 535-545. doi:10.1016/j.wasman.2017.07.001, Open Access.

Iacovidou *et al.* (2019a). Multi-dimensional value assessment of compost oversize production and management from open air composting. Resource Recovery from Waste. Open Access.

Iacovidou *et al.* (2019b). Quality of resources: A typology for supporting transitions towards resource efficiency using the single-use plastic bottle as an example. Science of the Total Environment. 647, 441-448. doi:10.1016/j.scitotenv.2018.07.344.

Johnson *et al.* (2017). Emerging Trends and New Frontiers in Community Operational Research. European Journal of Operational Research. In press. doi:10.1016/j.ejor.2017.11.032, Open Access.

Kim *et al.* (2017). Anodic electro-fermentation of 3-hydroxypropionic acid from glycerol by recombinant *Klebsiella pneumoniae* L17 in bioelectrochemical system. Biotechnology for Biofuels. 10, 199. doi:10.1186/s13068-017-0886-x, Open Access.

Kimber *et al.* (2018). Biosynthesis and Characterization of Copper Nanoparticles Using *Shewanella oneidensis*: Application for Click Chemistry. Small. In press, published online Jan 2018. doi: 10.1002/smll.201703145, Open Access.

Kunwar *et al.* (2017). Nanoparticles of Pd supported on bacterial biomass for hydroprocessing crude bio-oil. Fuel. 209, 449-456. doi:10.1016/j.fuel.2017.08.007, Open Access.

Macaskie *et al.* (2017a). Biotechnology Processes for Scalable, Selective Rare Earth Element Recovery. Rare Earth Element, Dr. Jose Edgar Alfonso Orjuela (Ed.), ISBN 978-953-51-3402-2, Print ISBN 978-953-51-3401-5. InTech, doi:10.5772/intechopen.68429, Open Access.

Macaskie *et al.* (2017b). Metallic bionanocatalysts: potential applications as green catalysts and energy materials. Microbial Biotechnology. 10, (5), 1171–1180. doi:10.1111/1751-7915.12801, Open Access.

Macaskie, Sapsford & Mayes (Editors). Resource recovery from Wastes: Towards a Circular Economy. Green Chemistry Series. In press. Royal Society of Chemistry.

Marshall *et al.* (2018a). Making the most of Industrial Wastes: strengthening resource security of valuable metals for clean growth in the UK. RRfW Policy and Practice Note. Resource Recovery from Waste.

Marshall *et al.* (2018b). The organic waste goldrush: optimising resource recovery in the UK bioeconomy. RRfW Policy and Practice Note. Resource Recovery from Waste.

Mayes *et al.* (2016). Advances in understanding environmental risks of red mud after the Ajka Spill, Hungary. Journal of Sustainable Metallurgy. 2(4), 332-343. doi:10.1007/s40831-016-0050-z, Open Access.

Mayes *et al.* (2018). Atmospheric CO_2 Sequestration in Iron and Steel Slag: Consett, County Durham, United Kingdom. Environmental Science and Technology. 52 (14), 7892-7900. doi: 10.1021/acs.est.8b01883, Open Access.

Midgley *et al.* (2017). What is Community Operational Research? European Journal of Operational Research. In press. doi:10.1016/j.ejor.2017.08.014, Open Access.

Millward-Hopkins *et al.* (2018a). Fully integrated modelling for sustainability assessment of resource recovery from waste. Science of the Total Environment. 612, 613-624. doi:10.1016/j.scitotenv.2017.08.211, Open Access.

Millward-Hopkins *et al.* (2018b). Resource recovery and low carbon transitions: The hidden impacts of substituting cement with imported 'waste' materials from coal and steel production. Global Environmental Change. 53, 146-156. doi:10.1016/j.gloenvcha.2018.09.003, Open Access.

Murray *et al.* (2017a). A novel biorefinery: biorecovery of precious metals from spent automotive catalyst leachates into new catalysts effective in metal reduction and in the hydrogenation of 2-pentyne. Minerals Engineering. 113, 102-108. doi:10.1016/j.mineng.2017.08.011; Open Access abstract.

Murray *et al.* (2017b). Biosynthesis of zinc sulphide quantum dots using waste off-gas from a metal bioremediation process. RSC Adv. 7, 21484-21491. doi:10.1039/C6RA17236A, Open Access.

Murray *et al.* (2018a). Biorefining of platinum group metals from model waste solutions into catalytically active bimetallic nanoparticles. Microbial Biotechnology. 11(2): 359–368. doi:10.1111/1751-7915.13030, Open Access.

Murray *et al.* (2018b). Enhancement of photosynthetic activity by quantum dots application. In Nonmagnetic and Magnetic Quantum Dots. Ed V.N.Stavrou. InTech Publications, Rijeka, Croatia, Chapter 9. ISBN 978-953-51-3959-1

Ng *et al.* (2016). A multilevel sustainability analysis of zinc recovery from wastes. Resources, Conservation & Recycling. 113, 88-105. doi:10.1016/j.resconrec.2016.05.013; Open Access.

Omajali *et al.* (2017). *In situ* catalytic upgrading of heavy oils using dispersed bio-nanoparticles supported on Gram positive and Gram negative bacteria. Applied Catalysis B: Environmental. 203, 807-819. doi:10.1016/j.apcatb.2016.10.074, Open Access.

Omajali *et al.* (2018). Probing the viability of palladium-challenged bacterial cells using flow cytometry. J Chem Technol Biotechnol. In press. doi.org/10.1002/jctb.5775

Peppicelli *et al.* (2018). Changes in metal speciation and mobility during electrokinetic treatment of industrial wastes: Implications for remediation and resource recovery. Science of The Total Environment. 624, 1488-1503. doi:10.1016/j.scitotenv.2017.12.132, Open Access.

Premier *et al.* (2016). Reactor design and scale-up. In Microbial electrochemical and fuel cells: Fundamentals and applications (Scott, K., and Yu, E. H., Eds.), Elsevier, Woodhead Publishing. ISBN: 978-1-78242-375-1, Open Access abstract.

Purnell (2017). On a voyage of recovery: a review of the UK's resource recovery from waste infrastructure. Sustainable and Resilient Infrastructure, doi:10.1080/23789689.2017.1405654 Open Access. Published online: 08 Dec 2017

Rashid *et al.* (2017). Delignification and enhanced gas release from soil containing lignocellulose by treatment with bacterial lignin degraders. Journal of Applied Microbiology. 123, (1), 159–171. doi: 10.1111/jam.13470; Open Access from 16 Jun 2018.

Riding *et al.* (2015). Harmonising conflicts between science, regulation, perception and environmental impact: The case of soil conditioners from bioenergy. Environment International. 75, 52-67. doi:10.1016/j.envint.2014.10.025; Open Access abstract.

Riley & Mayes (2015). Long-term evolution of highly alkaline steel slag drainage waters. Environmental Monitoring and Assessment. 187, (7), 1-16. doi:10.1007/s10661-015-4693-1, Open Access.

Roberts *et al.* (2017). Changes in Metal Leachability through Stimulation of Iron Reducing Communities within Waste Sludge. In Solid State Phenomena (262, 269-272), 22nd International Biohydrometallurgy Symposium. Trans Tech Publications. doi:10.4028/www.scientific.net/SSP.262.269, Open Access Abstract.

Sadhukhan (2017a). Microbial electrosynthesis. Encyclopedia of Sustainable Technologies. Elsevier. Pages 455–468. eBook ISBN: 9780128047927. doi:10.1016/B978-0-12-409548-9.10151-4 (Science Direct)

Sadhukhan (2017b). Special Issue editorial-Sustainable availability and utilisation of wastes. Sustainable Production and Consumption, 9, 1-2. doi:10.1016/j.spc.2017.01.002.

Sadhukhan & Matinez-Hernandez (2017). Material Flow and Sustainability Analyses of Biorefining of Municipal Solid Waste. Bioresource Technology. 243, 135-146. doi:10.1016/j.biortech.2017.06.078; Open Access from 19 May 2019.

Sadhukhan *et al.* (2016) A Critical Review of Integration Analysis of Microbial Electrosynthesis (MES) Systems with Waste Biorefineries for the Production of Biofuel and Chemical from Reuse of CO_2. Renewable and Sustainable Energy Reviews. 56, 116-132. doi:10.1016/j.rser.2015.11.015; Open Access.

Sadhukhan *et al.* (2018). Role of bioenergy, biorefinery and bioeconomy in sustainable development: Strategic pathways for Malaysia. Renewable and Sustainable Energy Reviews. 81, (Part 2), 1966-1987. doi:10.1016/j.rser.2017.06.007; Open Access.

Sapsford *et al.* (2017). *In Situ* Resource Recovery from Waste Repositories: Exploring the Potential for Mobilization and Capture of Metals from Anthropogenic Ores. Journal of Sustainable Metallurgy. 3, (2), 375–39. doi:1–18. doi:10.1007/s40831-016-0102-4, Open Access.

Semple *et al.* (2017). Resource Recovery: linking renewable energy, waste management and sustainable agriculture. Government Office for Science report From waste to resource productivity: Evidence and case studies page 42. Open Access pdf.

Shemfe *et al.* (2018a). Chapter 11: Bioelectrochemical Systems for Biofuel (Electricity, Hydrogen, and Methane) and Valuable Chemical Production. Green Chemistry for Sustainable Biofuel Production, Dr Veera Gnaneswar Gude (Ed.). ISBN: 9781771886390, E-Book ISBN: 9781315099354, Apple Academic Press.

Shemfe *et al.* (2018b). Life cycle, techno-economic and dynamic simulation assessment of bioelectrochemical systems: A case of formic acid synthesis. Bioresource Technology. 255, 39–49. doi:10.1016/j.biortech.2018.01.071, Open Access.

Shemfe *et al.* (2018c). Social Hotspot Analysis and Trade Policy Implications of the Use of Bioelectrochemical Systems for Resource Recovery from Wastewater. Sustainability, 10(9), p.3193. doi.org/10.3390/su10093193, Open Access.

Sinnett (in press). Going to waste? The potential impacts on nature conservation and cultural heritage from resource recovery on former mineral extraction sites in England and Wales. Journal of Environmental Planning and Management. doi:10.1080/09640568.2018.1490701 Open Access.

Song *et al.* (2016). Maximum Power Point Tracking to Increase the Power Production and Treatment Efficiency of a Continuously Operated Flat-Plate Microbial Fuel Cell. Energy Technology. 4, (11), 1427–1434. doi:10.1002/ente.201600191

Stephen *et al.* (2017). Advances and bottlenecks in microbial hydrogen production. Microbial Biotechnology. 10, (5), 1120–1127. doi:10.1111/1751-7915.12790, Open Access.

Stewart *et al.* (2018). Hydration of dicalcium silicate and diffusion through neo-formed calcium-silicate-hydrates at weathered surfaces control the long-term leaching behaviour of basic oxygen furnace (BOF) steelmaking slag. Environmental Science and Pollution Research. 25 (10), 9861–9872. doi:10.1007/s11356-018-1260-7, Open Access.

Velenturf & Jopson (2019). Making the business case for resource recovery. Science of The Total Environment. 648, 1031-1041; doi:10.1016/j.scitotenv.2018.08.224 (Published online: 18 Aug 2018). Open Access.

Velenturf & Purnell (2017). Resource recovery from waste: Restoring the balance between resource scarcity and waste overload. Sustainability, 9 (9), 1603; doi:10.3390/su9091603 Open Access.

Velenturf & Purnell (2018). Delivering Radical Change in Waste and Resource Management: Industry Priorities. Resource Recovery from Waste. (Published online: 26 Sept 2018). Open Access.

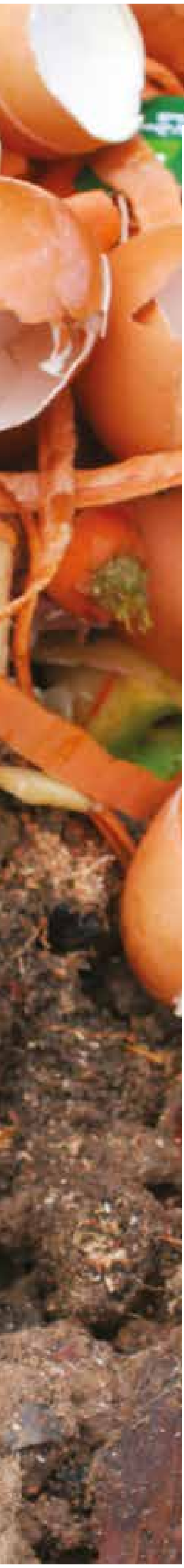
Velenturf *et al.* (2018a). Co-producing a vision and approach for the transition towards a Circular Economy: Perspectives from Government Partners. Sustainability, 10, 1401; doi: 10.3390/su10051401 Open Access.

Velenturf *et al.* (2018b). Evolution of Mechanical Heat Treatment for resource recovery from Municipal Solid Waste in the UK. Resource Recovery from Waste. Resource Recovery from Waste. Open Access.

Velenturf *et al.* (2018c). Participatory Situational Analysis: How can policy and regulation support resource recovery? Synthesis workshop report. Resource Recovery from Waste. Open Access.

Warwick *et al.* (2018). Altered chemical evolution in landfill leachate post implementation of biodegradable waste diversion. Waste Management and Research. doi.org/10.1177/0734242X18785723, Open Access.

Watt *et al.* (2018). Vanadium: A Re-Emerging Environmental Hazard. Environmental Science and Technology, Doi:10.1021/acs.est.8b05560.



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In addition, we would like to acknowledge all those involved in the Resource Recovery from Waste programme projects and mini-projects, including non-academic partners, for the hard work and dedication that made the outcomes reported in this brochure possible. A full list of partners and RRfW researchers are provided on the RRfW website: 'About Us': Network and RRfW Community.

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