Research and innovation challenges for resource recovery and circular economy

Workshop proceedings




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Resource Recovery from Waste | NERC Science of the Environment | E·S·R·C Economic & Social Research Council | Department for Environment Food & Rural Affairs

Executive Summary

With the Resource Recovery from Waste (RRfW) programme[1] drawing to a close, a workshop was held on 18 March 2019 with the aim of identifying the research and innovation spaces where further investments in resource recovery and circular economy could make a valuable contribution. 32 participants attended the workshop and 6 responded to the survey, spanning disciplines and sectors (academia, industry, policy).

The workshop asked participants to identify research challenge areas, building on previous work by RRfW. To encourage broad thinking, participants were asked to think about challenges associated with each of the life-cycle stages of: Design, Take, Make, Use, Dispose, Store and Natural Reserves.

Three new challenge areas were identified, which were: Global circularity; Contributing to a low-carbon economy; and Resource security and productivity. These join the previously identified challenge areas of: Designing out waste; Human behaviour; New business models; Developing the policy landscape; Better metrics to measure multi-dimensional values; Circular bio-economy; Land- and marine-based renewables; Waste processing processes and technologies; Better data gathering; and Energy and circular economy.

Individual challenges (sub-challenges) were prioritised via voting. Out of the top five sub-challenges, the first two related to 'Designing out waste', more specifically improving durability, reuse, repair and remanufacturing rates. The next three fell within 'Human behaviour', concerning changing consumption patterns, public appreciation of natural reserves, and public acceptance of 'waste-based' products respectively. However, most sub-challenges could be linked to multiple challenge areas, highlighting the multi-disciplinary and interconnected nature of the research and innovation space ahead.

During the workshop, solution directions were proposed for the top two sub-challenges for each stage of the life-cycle and prioritised by voting. The prioritised solution directions fall within the following themes:

- **Changing consumption systems:** Improving resource efficiency and preparing for a low-carbon society, addressing how to change consumer behaviour and developing material/product passports/labelling.
- **Resource repositories and resource recovery systems:** Processing or temporarily storing materials with the aim to recover all resources for further use or safe return to natural bio/geo/chemical processes.
- **Business model innovation:** Circular economy business models that promote longer lasting products that facilitate reuse, repair and upgrade/remanufacturing, and better design linked to EPR.
- **Material and product data systems:** Insight into natural capital and anthropogenic ores, tracking the value of materials/components through supply chains. Quality guarantees, information provision.

If we are to successfully tackle these next research and innovation challenges for resource recovery and circular economy, we will need to join across sectors, disciplines and research councils to deliver change.

[1] The Resource Recovery from Waste (RRfW) programme was a £7m investment by NERC, ESRC and Defra, which envisions a circular economy in which waste and resource management contribute to clean growth, human well-being and a resilient environment. The programme ran from 2014 to 2019.

Front cover image credits: Two women standing on escalator: rawpixel.com via pexel.com. Hands holding soil, orchid in grassland and truck on rubbish dump: Shutterstock images 272597318, 313195265 and 169420184 respectively.

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1. Introduction

With the £7m NERC, ESRC and Defra funded Resource Recovery from Waste (RRfW) programme due to finish in 2019, a workshop was held in March 2019 to map remaining research and innovation challenges for resource recovery and circular economy.

1.1 The Resource Recovery from Waste programme

RRfW 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 research and knowledge exchange in support of a paradigm shift in the recovery of resources from waste, driven by environmental and social benefits rather than by economics alone.

RRfW strived to meet 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.

Key outcomes of RRfW include: technologies and approaches to recover resources from industrial, mining and organic wastes; novel assessment tools to optimise the value created in resource recovery systems across multiple domains (economic, technical, environmental and social); and recommendations for the transition to a circular economy based on academic, government and industry perspectives.

Read more about RRfW's research and knowledge exchange activities and radical findings in the end-of-programme brochure on the RRfW website[2].

1.2 Workshop aims and objectives

Following 5 years of research and innovation by RRfW, various challenges are remaining and these were further explored at a workshop held on 18 March 2019 in Swindon with representatives from across the RRfW network and UKRI (Appendix 1) to discuss where further investments could make a valuable contribution.

The workshop identified and prioritised research and innovation challenges, serving the dual objective of:

1. Providing NERC with details about the big questions on resource recovery and circular economy to inform business cases by NERC to secure funding from UKRI.
2. Providing details for RRfW to propose a NERC Highlight Topic[3].

[2] https://resourcerecoveryfromwaste.files.wordpress.com/2019/05/rrfw_programme_brochure_web_spreads.pdf
[3] https://nerc.ukri.org/research/portfolio/strategic/topics/

2. Methods

2.1 Data collection

This section details the participants who gave input into the workshop results and gives an overview of the workshop programme and activities.

2.1.1 Participants

The workshop was attended by 32 participants with another 6 taking part via an accompanying survey (Figure 1). Representatives from the six RRfW projects and key partners in industry and government were invited, alongside contacts from UKRI. Please find a full list of participants in Appendix 1.

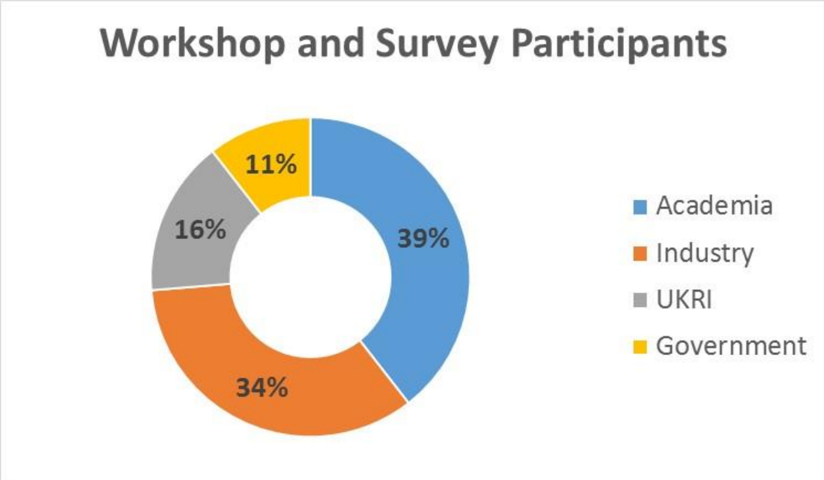

Figure 1: Participants in workshop and survey on research and innovation challenges in resource recovery and circular economy.

2.1.2 Workshop programme

During the workshop, and in the survey, participants systematically mapped and prioritised research and innovation challenges, followed by proposing solution directions and estimating the required scale of investment (Table 1).

Time	*Activity*
12:00	Lunch
12:30	Welcome by NERC.
12:45	Workshop introduction.
12:50	Participant introductions.
12:55	Introducing RRfW and major challenge areas.
13:15	Challenge mapping.
14:10	Prioritise challenges.
14:25	Break.
14:55	Mapping solution directions.
15:40	Prioritise solution directions.
15:55	Estimate investment scale.
16:10	Next steps and close.

Figure 2: Overview of workshop programme

2.1.3 Challenge mapping

The challenge mapping session started with an introduction of remaining challenges already identified by RRfW (Section 3.1) to prevent duplication of effort. Participants were encouraged to take a whole-system perspective based on the lifecycle of materials and products as published in Velenturf *et al* (2019)[4]. Each lifecycle stage was considered as a major challenge area (Design, Take, Make, Use, Dispose, Store and Natural Reserves) within which the participants were asked to map sub-challenges (Figure 3). Participants spent seven minutes at each table and were then asked to move to the next table. During the process participants were mixed to limit bias and maximise networking opportunities.

At the end of the challenge mapping exercise, participants were allocated 10 votes (using sticky dots) each to select the most urgent sub-challenges. This was a free-flowing activity during which participants could cast their votes on any of the tables. The top two, and in case of a tie the top three, of sub-challenges at each table were selected for the next session.

Figure 3: Participants mapped challenges at each lifecycle stage of materials and products.

2.1.4 Solution directions

Participants were asked to propose solution directions for the prioritised sub-challenges, spending 5-6 minutes at a table before moving on in rotation to the next. For example, if a sub-challenge would be the energy requirement of recycling processes then a solution direction could be the development of new technologies that are less energy intensive, or to promote more reuse, repair and remanufacturing to reduce energy demand for the processing of products that are at end-of-use.

Solutions directions were prioritised with a second sticky dot exercise, asking participants to cast 5 votes to select the solutions with the highest potential to result in economic, social and environmental benefits for the UK.

2.1.5 Investment scale

The last activity at the workshop constituted of estimating the investment required for prioritised challenge-solution combinations, ranging from very small (innovation) projects <£50k; smaller projects <£300k; large projects <£1m; programmes <£5M; and strategic programmes >£5M.

[4] Velenturf, A.P.M., Archer, S.A., Gomes, H., Christgen, B., Lag-Brotons, A.J., Purnell, P. (Under review) *Circular Economy and the Matter of Integrated Resources.*

2.1.6 Survey

For those unable to attend the workshop, a survey was prepared. Based on the challenge areas previously identified by RRfW (see section 3.1), participants were asked to respond to the following questions:

1. **Identification of major challenge areas:** Are any major research and innovation challenge areas missing from this list? If so, please give details. [Subsequent questions gave space to address areas identified in this step for subsequent sub-challenges / solution directions]
2. **Identification of sub-challenges**: Please identify sub-challenges for the major challenge areas listed; for example, for the major challenge 'energy and circular economy' a sub-challenge may be the energy requirement of recycling. Please highlight in bold your highest priority sub-challenge for each major challenge.
3. **Identify solution directions for priority sub-challenges:** For the prioritised sub-challenges, please suggest solution directions. For example, a solution for the energy requirement of recycling could be to develop new technologies that are less energy intensive, or to promote more reuse, repair and remanufacturing to reduce energy demand for the processing of products that are at end-of-use.
4. **Identify environmental, social and economic benefits:** Out of the solution directions identified in question 3, please highlight which ideas (max. 10) that you think are most likely to yield the most environmental, social and economic benefits and what those benefits may be.
5. **Any further comments:** Please share any further comments you have on the priorities for the research and innovation agenda going forward for resource recovery and circular economy.

2.2 Data analysis

All data were transcribed in Word. Identified individual challenges (sub-challenges) were prioritised by votes and those attracting at least one vote were extracted. Sub-challenges that repeated or substantially overlapped were combined. The sub-challenges were then grouped into major challenge areas and sub-challenges ordered within these based on overall number of votes (see Appendix 2, Table 1). Survey data were reviewed and used to either supplement the workshop outputs, or expand with additional challenges/sub-challenges: no weighting (votes) were assigned to survey results.

The challenge areas and sub-challenges identified from these entries are presented below (Section 3.2: Challenge areas identified from workshop and survey; Section 3.3: Research and innovation sub-challenges).

For prioritised research sub-challenges identified at the workshop, workshop participants were asked to suggest solution directions. Solution directions were prioritised at the workshop; those receiving more than 1 vote were extracted, grouped into themes and ordered within these themes by number of votes (Appendix 3, Table 2). Survey data were reviewed and used to supplement the workshop outputs (Appendix 3, Table 3).

Workshop participants were further asked to identify the scale of investment required for prioritised solution directions and under which funding body remit the research would fall. Where more than one estimate of investment was given, a range of required investment is presented (Appendix 3, Table 2).

Solution direction themes are summarised and presented below (Section 3.4: Solution directions).

3. Results

3.1 Challenge areas identified previously by RRfW

Prior to the workshop, a number of research and innovation challenge areas were identified through the work of the RRfW programme and from sessions/feedback at the RRfW conference 2019[5]. These are summarised as:

- **Designing out waste**: Interventions are needed at all levels to design out waste: materials, design, consumer preferences, repair/recycling infrastructure, policy/standards/labelling.
- **Human behaviour**: We need a better understanding of how human behaviour influences uptake of circular economy practices and how this can be improved.
- **New business models:** Operationalising service and sharing business models. Better understanding of circular economy infrastructures, industrial synergies and investment landscape. Interface with policy.
- **Developing the policy landscape**: Understanding the practices of resource use and developing interventions that work with these.
- **Better metrics to measure multi-dimensional values**: To help integrate the creation of social and environmental benefits from resource efficiency into policy.
- **Circular bio-economy:** Develop strategies for resource recovery in terms of bioeconomy, fuels, chemicals and heat. Soils as a resource: construction, remediation, agricultural.
- **Waste processing processes and technologies:** Aim at processing complete waste matrices, recovering all resources and leaving zero waste residue. Particular challenges remain for textiles, metals, plastics, construction wastes, waste wood/fibre and organic material.
- **Better data gathering**: 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.
- **Energy and circular economy:** Invent, scale up and industrialise processes using CO2, more affordable low-carbon energy solutions; upgrade pyrolysis. Circular economy approaches for low-carbon energy infrastructure. Environmental aspects of decommissioning.
- **Land- and marine-based renewables**: Interface with the circular economy. [This category was merged with circular bio-economy going forward].

3.2 Challenge areas identified by workshop and survey

The following additional challenge areas were identified from the workshop and survey responses:

- **Global circularity**: This challenge area acknowledges we are part of a global system and that circularity extends across borders. Markets for primary and secondary resources are global, and need to be tackled in this context. Similarly, developing countries need to combine addressing public health and environmental issues (climate change mitigation /plastics entering the ocean) with moving towards a circular economy; efforts in this direction would also address UN SDG and benefit the UK.
- **Contributing to a low-carbon economy**: Resource recovery offers a huge potential to contribute towards building a low-carbon economy. We need to lower barriers to behavioural change, engaging and empowering the public to lower carbon footprints. Embedded emissions should be made apparent. [The

[5] https://rrfw.org.uk/results/events/resource-recovery-from-waste-conference-2019/

original energy and circular economy category was determined to fit within this category and removed as a separate category going forward].

- **Resource security and productivity**: Identifying the greatest resource risks (scarcity and critical resources) and the greatest opportunities to increase circularity and resource productivity.

The research and innovation challenges identified recognise the need to move up the waste hierarchy and develop systems that reduce consumption and increase circularity, with resource recovery being a step transition to a circular economy. They also recognises the contribution that resource recovery and circular economy can make to GCRF, UN sustainability goals, climate change agenda, resource security and productivity.

3.3 Research and innovation sub-challenges

Designing out waste [59 votes]

Interventions are needed at all levels to design out waste: materials, design, consumer preferences, repair/recycling infrastructure, policy/standards/labelling.

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 further 'designed out' of the economy through improved durability and recyclability of products.

Component and materials passports are needed to address quality for reuse, to give more confidence and acceptability for use of secondary and recovered components/materials. During the transition to reduced waste, a whole systems approach should be adopted to ensure that the correct circular economy infrastructure is in place to adapt to design changes e.g. increased use of compostable packaging.

Sub-challenges:

- Improving durability, reuse, repair and remanufacturing rates
- Component and materials passports
- Transition to circularity – infrastructure changes

Human behaviour [56 votes]

We need a better understanding of how human behaviour influences uptake of circular economy practices and how this can be improved. This includes understanding current consumption patterns, relationship between consumption and design, and opportunities to challenge these status quo. We need to understand people's perception of waste-based products and take action to increase the legal, industry and customer acceptance of these products. We need to understand how to engage the public and businesses with appreciating the value of natural reserves and increasing a sense of responsibility for their resource use. Similarly, how do the public view potential circular economy activities such as resource storage or landfill mining – public and political support will be necessary to avoid 'not-in-my-backyard' response.

Sub-challenges:

- Changing consumption patterns
- Public appreciation of natural reserves
- Public acceptance of 'waste-based' products
- Public perception of resource storage and landfill mining

New business models [31 votes]

New business models are needed to underpin a circular economy, from take back systems to operationalising service and sharing business models. We need to gain a better understanding of circular economy infrastructures, industrial synergies, investment landscape, and how businesses can transition to zero waste operations and reduce the pressure for over production/consumption.

A persistent challenge is managing the support of and collaboration between stakeholders in the supply chain, (secondary) material processors, product designers, retailers, consumers, and waste managers, which is necessary to implement circular economy. Practical guidance to facilitate circular economy in supply chains is underdeveloped. A particular knowledge gap constraining this further is the lack of business models that can capture economic as well as social and environmental benefits from circular economy practices.

Sub-challenges:

- Take back systems
- Develop business landscape for use of by-products
- Transition to zero disposal
- Decentralised infrastructure
- Co-location and/or industrial synergies
- Change business model to reduce over production
- Move to service economy
- Circular business models in the context of SME's

Developing the policy landscape [26 votes]

The policy landscape should be developed based on an understanding of the practices of resource use and determining interventions that work with these, including understanding the effectiveness of fiscal tools. Focus should be on the higher levels of the waste hierarchy and supporting high value products from waste to re-enter the value chain.

Sub-challenges:

- Make "take" unattractive by taxing resource use / incorporating externalities
- Identifying regulatory and other barriers to greater circularity and resource productivity, and finding solutions
- Promote sustainable resource extraction
- Developing system solutions

Better metrics to measure multi-dimensional values [24 votes]

Better and consistent metrics, indicators and criteria need to be developed to measure environmental, social and economic values, to help integrate the creation of net-environmental and social benefits from resource efficiency into government and industry practice. 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) and achieve the UN Sustainable Development Goals.

Sub-challenges:

- Change measure of economic accounting
- Better metrics and data management for natural reserves
- Resource recovery metrics to be collected
- Make LCA fit for purpose

- Understanding the direct costs of litter

Circular bio-economy [22 votes]

Develop strategies for resource recovery in terms of bioeconomy, fuels, chemicals and heat, developing capacity to process own bio-waste rather than export it e.g. as a fraction of MSW/RDF. Need to establish clear priorities of recycling routes for given materials to maximize value. Soils should be treated as a resource, rather than waste or hazard, to encourage resource recovery and reuse and innovative deployment in construction, remediation, agricultural. Interface of land and marine based renewables with the circular economy.

Sub-challenge:

- Retain valuable ('waste') bio-resources
- Soil management and reuse
- Algae-based economy

Global circularity [16 votes]:

This challenge area acknowledges we are part of a global system and that circularity extends across borders. Markets for primary and secondary resources are global, and need to be tackled in this context. Similarly, developing countries need to combine addressing public health and environmental issues (climate change mitigation /plastics entering the ocean) with moving towards a circular economy; efforts in this direction would also address UN SDG and benefit the UK. New business models are required with a focus on the 'informal sector' and local community entrepreneurs.

Sub-challenges:

- Global citizens with global standards and responsibilities for resources
- Global demand and excessive consumption/waste.
- Future CE thinking for developing countries.
- Modelling the local to global
- Development of low-cost waste recycling and processing technologies
- Integrating the informal sector.
- Reducing the weight of plastics entering the oceans.

Waste processing processes and technologies [16 votes]

The aim should be to process complete waste matrices, recovering all resources and leaving zero waste residue. Particular challenges remain for textiles, metals, plastics, construction wastes, waste wood/fibre and organic material.

Landfill mining of legacy landfills should be comprehensively assessed covering resource potential, waste stability/preservation, hazards and public acceptability of developing such technologies. Future resource storage infrastructure should be designed with similar considerations in mind, understanding how to preserve, contain and recover value in the future. Design innovation is needed to ensure the usability of resource recovery systems and avoid misuse undermining intended benefits. Similarly, a new mentality is needed to see design opportunities in what are currently considered problems, e.g. harvesting CO_2. New waste segregation technologies, such as robotics, are needed especially for recovery of critical materials. Reprocessing technologies need to be scaled up, including biorefinery approaches to recovery resources from dilute concentrations. When returning resources back to the environment, we should have an understanding what this means for overall levels and also scope for enhancing the environment e.g. remediation leading to increased biodiversity.

Sub-challenges:

- Landfill mining
- Design innovation
- Maintain levels of natural reserves
- Resource storage infrastructure
- Waste segregation technologies and recovery of critical materials
- Scale up of reprocessing technologies
- Integrated biorefining to added value productions from waste resources

Contributing to a low-carbon economy [14 votes]

Resource recovery offers a huge potential to contribute towards building a low-carbon economy. We need to lower barriers to behavioural change, engaging and empowering the public to lower carbon footprints. Embedded emissions should be made apparent via labelling and impacts of consumption made tangible e.g. through a personal carbon allocation. There should be a move from 'dispose' to stockpile storage where recycling solutions are not immediately available, looking for opportunities to decarbonise, recover resources and enhance natural capital.

Energy should look to both invent, scale up and industrialise processes using CO_2 and continue to develop more affordable sustainable low-carbon energy solutions. Circular economy approaches should be developed for low-carbon energy infrastructure and the environmental aspects of decommissioning addressed. There is a need to understand alternative models of energy generation and how investments in these is supported by different incentive regimes.

Sub-challenges:

- Eco-labelling to cover embodied energy
- Make the impacts of consumption tangible
- Decarbonise and recover
- Impacts of CE and resource productivity on natural capital
- Understand impact of different incentive regimes on investment for renewable energy
- Understanding role of the hydrogen
- Distributed generation

Better data gathering [10 votes]

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. For wastes for which there are currently no viable solutions to return materials to the economy and that need to be stored, data systems need to be put in place to allow for efficient monitoring and future access.

Sub-challenges:

- Traceability of wastes
- Data for storage

Resource security and productivity [3 votes]

Recovering resources and reducing the demand for resources, by improving resource productivity, will greatly increase our resource security for critical materials for which we are currently 100% importers. There is a need to identify the greatest resource risks (scarcity and critical resources) and the greatest opportunities to increase circularity and resource productivity.

- Resource security
- Increase resource productivity
- Understand impacts of Resource and Waste Strategy commitments on secondary materials
- Identification of strategically important materials for targeted development of resource recovery technology

3.4 Solution directions

Two prioritised challenge areas (or three where there was a tie) from each life-cycle stage (Figure 3) were selected in order to develop solution directions. These challenge areas were:

- Incentivise sustainable resource use (TAKE)
- Tax take, make take un-sexy (TAKE)
- Longer lasting products designed for end-of-life / remanufacturing (MAKE)
- Ecodesign labels and standards to include materials and embodied energy (MAKE)
- Traceability of waste (collection/separation/quality/value) (DISPOSE)
- Take-back systems (to manufacturers/suppliers) (DISPOSE)
- Behaviours & social practices, consumption patterns (USE)
- Repair, skills, availability, cost (USE)
- From soil remediation to resource recovery promoting innovation & reuse (STORE)
- Stop waste exporters – develop new systems for storage and recovery of materials (STORE)
- Better metrics & data management (NATURAL RESERVES)
- Appreciation by public of natural reserves (NATURAL RESERVES)
- Poor communication to public/business: Knowledge, awareness, responsibility (NATURAL RESERVES)
- Customer acceptance of waste based products (DESIGN)
- Design for full chain, design out waste (DESIGN)

The overarching solution directions themes are summarised as follows, the number in brackets indicate the cumulative votes for related solution directions:

Changing consumption systems [32]:

Drive change towards alternative consumption systems; Impact on resource efficiency and low-carbon society; Societal preparation for a circular and low carbon economy including understanding social/policy drivers/barriers for changing consumer behaviour, communication/ awareness raising; Material and product passports, labelling.

<u>Sub-solution directions:</u>

- Carbon tax/Personal Carbon Allowance
- Environment impact labelling on all products so that people understand the environmental implications
- Need to understand the material requirements of different "systems of consumption" and how changing economic direction and social change can deliver a low material/carbon society
- Need to expose absurd consumption behaviours
- "Recycled" new product may not be as good as primary material – trade-off

<u>Survey results:</u>

- The food and health care sectors a priority, since so much of the material they use is single use

- Addressing human behaviour, both to present waste for collection and to separate wastes to facilitate resource recovery
- Packaging design to aid recycling and prevent littering
- Researching what successfully motivates people not to fly tip
- Simple LCA and LCSA apps, for sustainable design and allowing people to calculate the environmental impact of their daily activities (like driving, eating red meat, etc.)

Resource repositories and resource recovery systems [31]:

Move from residual waste storage to storage of specialist wastes. The focus is still on bulk volumes, but the aim is recovery of all matter including aggregates and soils, in accordance with material quality standards and in a planned manner via resource recovery systems. Acceptance of general public for such storage systems is crucial. No materials should be disposed of as all potentially contain value. However, some materials will temporarily become unusable (for economic, technical or environmental reasons) and will require treatment, storage in repositories, associated inventory systems, and retrieval mechanisms and markets. The ultimate aim at all times is to recover the materials either for further use in production-consumption systems or for the safe return to natural bio/geo/chemical processes.

Sub-solution directions:

- Standards for storage
- Planning for long-term
- Public acceptability of managing wastes
- Remediating a value added component of the soil that can be extracted for higher value use
- Evidence to demonstrate benefits of recycling / reuse etc v. mining natural materials
- Need for real world demonstration

Survey results:

- Rigorous, systematic and holistic LCA and LCSA for waste standardisation
- New chemical, biological, pyro and physical processes for separating materials; Robotics for waste segregation
- Tools and processes to apply biorefinery approach in practice
- Processing critical materials
- Low-cost waste recycling and processing technologies suitable for use by local entrepreneurs in developing (and developed) countries

Material and product data systems [31]:

Insight into natural capital and anthropogenic ores, and everything in between in the production-consumption system. Material/ product tracking the value of materials and components as they move through supply chains. Quality guarantees, information provision. This challenge underpins and ties together all the others. Without data we cannot know what the current situation is or understand the impact of interventions, measuring progress and success.

Sub-solution directions:

- Consumer facing product embodied impact labelling
- Zero loss manufacturing systems
- Mandatory EDOC / Using digital technologies e.g. IOT, big data
- Smart cities – open data on resource movements in/around and out of cities
- Real time waste data nationally and beyond

- Residual wastes - Changes in composition as function of processes
- Need real time data flows of all materials
- Better evidence and data for communications. Public perception
- Need for a national capability in resource flows, economic flows and environmental pressures

Survey results:

- Further development of material tracking
- Model required volumes of equipment / material needed to meet energy transition/climate change targets
- Improved measurement and modelling of plastics leakage into rivers and the sea. Identify points of intervention to mitigate or prevent loss of value
- Knowledge sharing and learn from shortcomings and failures

Business model innovation [20]:

Circular economy business models; Better design linked to EPR; Facilitation of collaboration such as through a "Circular Economy Network" offering a business support; Moving up the waste hierarchy to identify the business models to promote longer lasting products that facilitate reuse, repair and upgrade/ remanufacturing.

Sub-solution directions:

- Service based business models
- Materials passport for all products
- EPR by default
- Collaborating between stakeholders across supply chain

Survey results:

- New business models, with a focus on the 'informal sector' and local community entrepreneurs
- Rigorous, systematic and holistic LCA and LCSA for sustainability
- Understanding the advantages and disadvantages of fiscal measures and encouraging market forces as opposed to direct regulation around design of product

Full details on the suggested solution directions can be found in Appendix 3.

4. Next steps

This report brings together the current research and innovation priorities for resource recovery and circular economy as identified by participants of the workshop and survey. The results will be shared with NERC and other research funders to inform them of research and innovation needs in this area.

Based on the workshop data a NERC highlight topic on the integration of restoration and enhancement of natural capital into circular economy was developed by the RRfW programme coordination team and submitted to NERC in May 2019. It proposes a highlight topic that promotes a shift from waste management to resource stewardship through the development of controlled storage and resource recovery systems, designed to deliver net-environmental gains. If you are interested to collaborate on this funding idea then RRfW would like to hear from you, please find our contact details on the RRfW website.

The workshop and survey results highlight that there is considerable research and innovation required to support realising the full benefits of resource recovery and circular economy. The challenges identified underlines the need for whole system approaches, crossing disciplines and sectors, and bringing the public on-board to drive political will and behaviour change.

The urgency with which we need to move from a destructive linear economy to a sustainable circular economy means that we need to reach for transformative change. This will only be possible by working together across research council remits and with full engagement of all actors and stakeholders. While the Resource and Recovery from Waste programme is itself drawing to a close, we leave a large and well connected research community able to address these urgent challenges. The RRfW community continues to evolve and we welcome new collaborations. Please get in touch to collaborate with us on the challenges and opportunities outlined in this report.

We thank all workshop and survey participants for their time and effort to share their insights. We are grateful for the support from NERC in the organisation of the workshop, which was funded by NERC, ESRC, and DEFRA for RRfW via grant NE/L014149/1.

Appendix 1: Workshop participants and survey respondents

The following people participated in the workshop on research and innovation challenges for resource recovery and circular economy or responded to the accompanying survey.

Name	Surname	Organisation	Workshop / Survey
John	Barrett	University of Leeds	Workshop
Margaret	Bates	CIWM	Workshop
Ian	Burke	University of Leeds	Workshop
Scott	Bryant	Zero Waste Scotland	Survey
Richard	Dinsdale	University of South Wales	Workshop
Mark	Fitzsimons	University of Plymouth	Workshop
Jenny	Ford	Materials in Mind	Workshop
Libby	Forrest	Environmental Services Association	Workshop
Siddharth	Gadkari	University of Surrey	Workshop
Catherine	Gilmore	BBSRC	Workshop
Stuart	Hayward-Higham	SUEZ Recycling and Recovery UK	Workshop
Beth	House	NERC	Workshop
Tammy	Johnson	Office for National Statistics	Workshop
Juliet	Jopson	University of Leeds	Workshop
Rachel	Lombardi	International Synergies	Workshop
Lynne	Macaskie	University of Birmingham	Workshop
Will	Mayes	University of Hull	Workshop
Sophie	Parsons	IOM3	Workshop
Shyeni	Paul	EPSRC	Workshop
Phil	Purnell	University of Leeds	Workshop
Helen	Randell-Sly	STFC	Workshop
Deborah	Sacks	Department for International Trade	Survey
Jhuma	Sadhukhan	University of Surrey	Survey
Devin	Sapsford	Cardiff University	Workshop
Danielle	Sinnett	University of the West of England	Workshop
Claire	Spooner	ESRC	Workshop
Gerard	Stephens	Materials Processing Institute	Workshop
Nina	Sweet	WRAP	Workshop
Bernie	Thomas	Resource Futures	Workshop
Mike	Tregent	Environment Agency	Workshop
Anne	Velenturf	University of Leeds	Workshop
Amy	Vitale	NERC	Workshop
Allan	Walton	University of Birmingham	Survey
Jim	Wharfe	Environmental Consultant	Workshop
David C.	Wilson	Imperial College London / CIWM	Survey
Andrew	Woodend	Defra	Survey
Miying	Yang	University of Exeter	Workshop
Eileen	Yu	Newcastle University	Workshop

Appendix 2 Challenges and sub-challenges

Table 1 Challenges and sub-challenges, combined workshop and survey results

Challenge	Sub-challenge	Votes	Explanation
Designing out waste	Improving durability, reuse, repair and remanufacturing rates	41	Products to be designed for durability and to be upgradable, repairable, allow for disassembly and component re-use, providing transparent inventory. Tensions between designing for innovation and longevity/durability to be addressed. Re-use and repair to be made more acceptable to consumer, supported by necessary skills and systems. Whole system approach to increase reuse/upgrade/repair without causing systems failure.
	Component and materials passports	9	Component and materials passports are needed to address quality assurance for reuse, to give more confidence and acceptability for use of secondary and recovered components/materials. Standards should be developed for remanufacturing and recertification for use. Materials passports should be made more widely applicable, including certification of alternative raw materials.
	Transition to circularity – infrastructure changes	9	During the transition to reduced waste, a whole systems approach should be adopted to ensure that the correct circular economy infrastructure is in place to adapt to design changes e.g. increased use of compostable packaging. Just in time processes and transition technology are needed to ensure resources go straight back into make/use. Design manufacturing processes should be made adaptable to making new products to prevent future capital lock down.
Human behaviour	Changing consumption patterns	18	Understanding current consumption patterns (practices, imagery, norms, values), relationship between consumption and design, and opportunities to challenge these (loan not own). Textiles and ‘fast fashion’ particularly of interest
	Public appreciation of natural reserves	18	Need to understand how to engage public and businesses with understanding the value of natural reserves so they have more knowledge (e.g. options for reprocessing), awareness and feel more responsibility for their resource use. Includes education against disposal and keeping value within the UK.
	Public acceptance of ‘waste-based’ products	13	Legal/industry/customer acceptance of ‘waste-based’ products should be addressed e.g. by developing secondary resource design standards. Determine routes to drive more sustainable consumer choices, such as marketing campaign / celebrity endorsement.
	Public perception of resource storage and landfill mining	7	Need to understand and address public perception of resource storage and landfill mining as there is a potential ‘not in my backyard’ response to developing resource ‘stores’. Implications for planning processes and legislation should also be understood.

Challenge	Sub-challenge	Votes	Explanation
Waste processing processes and technologies	Landfill mining	6	Need a comprehensive assessment of the resource potential of legacy landfills, including waste stability, preservation, hazards and containment (leachate leakage): are landfills 'bad' or 'safe, distributed storage'? The legal/industry/customer acceptance of landfill mining should be addressed.
	Design innovation	4	Need more innovation on design from wastes, taking into consideration usability e.g. are environmental credentials undermined by inappropriate use? Design mind set to change from problem (CO_2 in atmosphere) to opportunity (CO_2 stock waiting for us to harvest).
	Maintain levels of natural reserves	4	Understanding natural reserve levels, especially when we 'return' resources. Look for scope for enhancements, designing in improvements such as supporting biodiversity.
	Resource storage infrastructure	2	Understanding design criteria for resource storage sites. Need to consider: size & location, leakage, duration, management, responsibility for shared storage, separation, risk and understanding waste flows (data management).
	Waste segregation technologies and recovery of critical materials	Survey	Need to develop systems for product segregation, particularly robotics. Similarly, develop processes and technology to recover critical materials, in particular rare earth magnetic materials and elements in batteries (Co, Li, Ni). Should aim to achieve a high degree of waste separation down to component parts with a high purity of each material.
	Scale up of reprocessing technologies	Survey	Lab processes exist for reprocessing of many materials. The market and economics of these technologies needs to be understood, focusing efforts on fundamental innovation in multi-scale simulation (e.g. molecular through meso to unit process) supporting sustainable engineering systems.
	Integrated biorefining to added value productions from waste resources	Survey	Hybrid processing (e.g. biochemical, electrochemistry, and steam or supercritical water extraction) with high intensification opportunities should be advanced to the right scale as these can comply with stringent environmental standards and recover resources from dilute concentrations.
New business models	Take back systems	10	Development of take back systems with onus on manufacturer/supplier. Need to reduce complexity for this system and design/manufacture with take-back in mind.
	Develop business landscape for use of by-products	8	Need to understand how to incentivise creation of local value from by-products e.g. symbiosis, or seed new industries. Standard on quality of recycled products required to allow solid investment and make the most sustainable source the most attractive (3rd party verification/certificate). Match supply with demand to prevent unnecessary storage/ degradation/loss (links to regulation/legislation).
	Transition to zero disposal	4	Need to determine what business need to do and when for transition to zero disposal: transition periods, economics and financing, decommissioning.

Challenge	Sub-challenge	Votes	Explanation
	Decentralised infrastructure	3	Need to understand how we can move to a service industry: What are the pulls? Who are the champions?
	Co-location and/or industrial synergies	2	How can local authorities, waste management companies, high value industries and reprocessing industries work together to support a regional ecosystem?
	Change business model to reduce over-production	2	Need to understand how to reduce over-production e.g. responding to demand rather than predicted amounts, or make less but deliver same service (service model).
	Move to service economy	2	How do we move to a service economy delivering service and function (will change with time) rather than products and goods.
	Circular business models in the context of SME's	Survey	What circular economy challenges and opportunities are associated with SMEs, and how can SMEs be supported to engage with this agenda.
Better data gathering	Traceability of wastes	9	Need to make waste easier to collect, separate, and sort, improving the quality and traceability of waste. Should be linked to value exploration of waste.
	Data for storage	1	Need to understand the data needs for resource storage including how to keep data of storage locations up to date and ongoing monitoring (e.g. leakage into surrounding soils).
Better metrics to measure multi-dimensional values	Change measure of economic accounting	9	Move away from GDP and towards full resource accounting that includes measures of environmental and social progress in addition to economic.
	Better metrics and data management for natural reserves	8	Develop metrics and data management for natural reserves. How should natural reserves be valued? Risk of economisation/commodification. Monetise natural reserves - finance and economic models.
	Resource recovery metrics to be collected	4	Current metrics are not collected with resource recovery in mind – need to refocus data collection e.g. carbon lock-up. Metrics must work at right scale – global versus local impacts.
	Make LCA fit for purpose	3	Life cycle assessment (LCA) needs to be made easier to use and findings standardised for communication with all stakeholders. The study undertaken, assumptions and scenario descriptions should be made transparent to all stakeholders. Need to understand trade-offs between multi dimensions/ease of understanding/usefulness with metrics.
	Understanding the direct costs of litter	Survey	Develop better estimates of direct costs of litter (local authority level costs, including street cleansing, enforcement, comms etc.). e.g. are there models to allocate costs from aggregate data (e.g. from MHCLG).

Challenge	Sub-challenge	Votes	Explanation
Developing the policy landscape	Make “take” unattractive	16	Investigate policy tools to discourage over use of resources. Options could include taxing resource use, or by incorporating externalities to ensure the true cost of the design is reflected in the price. The economic costs of passing cost onto the consumer vary in scale e.g. between fashion and power plant construction.
	Identifying regulatory and other barriers to greater circularity and resource productivity, and finding solutions	6	Understand and tackle regulatory barriers to the use of secondary resources, making it equivalent to primary resources. Policy/funding needs to support more integrated and sustainable systems. Need to understand the effectiveness of fiscal tools, in particular the way in which EPR impacts on material use and will change as it is introduced in a greater range of materials. Can reducing waste be incentivised by making ‘waste’ very expensive?
	Promote sustainable resource extraction	2	Understand how we can transition to clean, sustainable ‘take’ process. Need to slow ‘taking’ and develop policy to make ‘clean’ options a viable choice.
	Developing system solutions	2	Need to design system solutions and work through market, legislation/regulation, risk/reward. PFA has various uses – local context gives local solution, but which solution is optimal and could be encouraged? No modulated fee – IPR over EPR.
Energy and circular economy	Understand impact of different incentive regimes on investment for renewable energy	Survey	Recommendations for best approach to incentivise renewable energy and their implications for resource efficiency. Incentivise material recovery before energy recovery: aim for pre-processing for valuable pharmaceutical and chemical recovery (only 5-10% of waste by mass) before energy recovery. This will also help in cleaner energy production.
	Understanding role of the hydrogen	Survey	Expect future to be a mix of large-scale electrification, supported by roll-out of hydrogen production via renewable-powered electrolysis. Understand how resource recovery technology could contribute to the hydrogen revolution and how best to realise this.
	Distributed generation	Survey	Understand effectiveness of policies driving production to the smaller scale near and on-site generation technologies in reducing fossil fuel usage.
Land- and marine-based renewables	Algae-based economy	2	
Circular bio-economy	Retain valuable (‘waste’) bio-resources	12	Need to develop mixed capacity (AD, pyrol., gasification, compost) to process own bio-waste, understanding how to best balance the system and retain technical value. Develop biorefinery approach to establish clear priorities of recycling routes i.e. processing for biopharmaceuticals provides the highest value, conversion into gas/fuel least value.
	Soil management and reuse	8	Need to encourage reuse and innovative deployment of soil, current default is to treat as waste and/or hazard. SPF landscape decision. Construction of soil using waste materials.

Challenge	Sub-challenge	Votes	Explanation
Resource security and productivity	Resource security	2	Understand resource risks, including scarcity and critical resources.
	Increase resource productivity	1	Understand the greatest opportunities for more circularity and resource productivity. In particular, how this can be achieved through reuse, remanufacturing, and behavioural change i.e. make less and use less in making better things.
	Understand impacts of Resource and Waste Strategy commitments on secondary materials	Survey	Understand impacts of Resource and Waste Strategy commitments on secondary materials, particularly impacts of greater recycling on markets for secondary materials.
	Identification of strategically important materials for targeted development of resource recovery technology	Survey	Develop a matrix of products, materials, challenges and current recover rates in order to identify and prioritise development of processes to tackle the most challenging materials where the material itself is strategically very important. Li-ion batteries from EVs and energy storage systems and composite materials (e.g. vehicle bodywork, wind turbine blades etc.) should be included in the "hard to deal with" list of materials.
Contributing to a low-carbon economy	Eco-labelling to cover embodied energy	6	Standards/eco-labelling should be developed to capture resource use and embedded emissions embodied in the product itself, as well as energy usage, so consumers can make an informed choice
	Make the impacts of consumption tangible	5	Understand impacts of consumption. How can this be made tangible to consumers e.g. through personal carbon allocation?
	Decarbonise and recover	3	Move from 'dispose' towards stockpile storage, looking for opportunities to decarbonise and recover resources.
	Impacts of CE and resource productivity on natural capital	Survey	Impacts of CE and resource productivity on natural capital, including carbon emissions.
Global circularity	Global citizens with global standards and responsibilities for resources	4	Understanding ownership, use, liability and responsibility for the commons. How can we develop global citizens with global standards and responsibilities, global ownership certificate?
	Global demand and excessive consumption/waste	4	Address global demand for materials, imports, exports and excessive consumption. How can we drive innovation to reduce demand for primary resources? Better data gathering, could include using earth observation data to remotely monitor waste hotspots.

Challenge	Sub-challenge	Votes	Explanation
	Future CE thinking for developing countries	4	How can developing countries lead the world for circular economy? Look for ways to leap-frog natural infrastructure stereotype for developing countries e.g. mobile phones in Africa replaced need for hardwired telecoms with commensurate savings.
	Modelling the local to global	4	Develop model of natural reserves/critical raw materials at national, regional and global scales, including geospatial geo-referencing mapping. Trends are towards global governance model as opposed to markets with single global currency. Nationalism of the 'take' boundaries it creates is most likely to fail to meet challenges of uneven distribution/resource conflict etc. High level market model with balance trading between city/regions can also balance ecological footprints.
	Development of low-cost waste recycling and processing technologies	Survey	Low-cost waste recycling and processing technologies suitable for use by local entrepreneurs, to extend the SDGs addressed to include lifting people out of poverty (SDG1) and providing sustainable livelihoods (SDG8).
	Integrating the informal sector.	Survey	New business models, with a focus on the 'informal sector' and local community entrepreneurs. Developing the policy landscape, with a focus on extended producer responsibility and on integrating the 'informal sector'.
	Reducing the weight of plastics entering the oceans.	Survey	Addressing human behaviour, both to present waste for collection and to separate wastes to facilitate resource recovery. Improved measurement and modelling of plastics leakage into rivers and the sea; and understand better the dissipation of value when materials, and products at the end of life, become waste in developing countries. Identify points of intervention to mitigate or prevent loss of value.

Appendix 3 Summary of Solution directions

Table 2: Solution directions determined at workshop

The life cycle stage that the original sub-challenge was identified in is presented in the left hand column. The solution direction includes the sub-challenge and solution direction, separated by a colon i.e. Sub-challenge: solution direction. Votes indicates the number of sticky dot votes assigned to prioritise solution directions; only solution directions receiving two or more votes are presented. Solution directions were mapped onto funding body remits: NERC (Natural Environment Research Council), ESRC (Economic and Social Research Council), EPSRC (Engineering and Physical Sciences Research Council), BBSRC (Biotechnology and Biological Sciences Research Council), I-UK (Innovate UK). The estimated scale of investment required is given in pounds sterling (millions).

Life cycle	Solution direction	Votes	NERC	ESRC	EPSRC	BBSRC	I-UK	Invest-ment
Changing consumption systems [32]								
Take	Tax take: Carbon tax/Personal Carbon Allowance	7						£1m
Make	Ecodesign labels and standards to include materials and embodied energy: Environment impact labelling on all products so that people understand the environmental implications	5	X	X				£0.3 - £1.5m
Use	Behaviours & social practices, consumption patterns: Need to understand the material requirements of different "systems of consumption" and how changing economic direction and social change can deliver a low material/carbon society	8		X	X		X	£1 - £5m
Natural Reserves	Communication to public/business - Knowledge, awareness, responsibility: Need to expose absurd consumption behaviours	7		X				£0.25 m
Design	Customer Acceptance of waste based products: "recycled" new product may not be as good as primary material – trade-off	5		X		X	X	£5m+
Resource repositories and resource recovery systems [31]								
Store	From soil remediation to resource recovery promoting innovation & reuse: Standards for storage	9	X	X	X	X		£1-4m

Life cycle	Solution direction	Votes	NERC	ESRC	EPSRC	BBSRC	I-UK	Invest-ment
Store	Stop waste exporters – develop new systems for storage and recovery of materials: Planning for long-term	9	X	X	X			£5m+
Store	Stop waste exporters – develop new systems for storage and recovery of materials: Public acceptability of managing wastes	4		X				
Store	From soil remediation to resource recovery promoting innovation & reuse: remediating a value added component of the soil that can be extracted for higher value use	3						£2m
Natural Reserves	Appreciation by public of natural reserves: Evidence to demonstrate benefits of recycling / reuse etc v. mining natural materials	4	X	X	X	X		£2m
Natural Reserves	Communication to public/business - Knowledge, awareness, responsibility: Need for real world demonstration	2						
Business model innovation [20]								
Make	Longer lasting products designed for end-of-life / remanufacturing: Service based business models	7		X	X		X	£1-£5m
Use	Repair, skills, availability, cost: Materials passport for all products	5			X		X	£0.3 - £1m
Dispose	Take-back systems: EPR by default	6			X		X	£0.4m
Dispose	Traceability of waste: Collaborating between stakeholders across supply chain	2						
Material and product data systems [31]								
Take	Incentivise sustainable resource use: Consumer facing product embodied impact labelling	3	X	X			X	£0.4 - £1m
Make	Ecodesign labels and standards to include materials and embodied energy: Zero loss manufacturing systems	3					X	

Life cycle	Solution direction	Votes	NERC	ESRC	EPSRC	BBSRC	I-UK	Invest -ment
Dispose	Traceability of waste: Mandatory EDOC / Using digital technologies e.g. IOT, big data	6			X		X	£1m
Dispose	Traceability of waste: Smart cities – open data on resource movements in/around and out of cities	2						
Dispose	Traceability of waste: Real time waste data nationally and beyond	2						
Dispose	Traceability of waste: Residual wastes -Changes in composition as function of processes	2						
Store	Stop waste exporters – develop new systems for storage and recovery of materials: Need real time data flows of all materials	2						
Natural Reserves	Communication to public/business - Knowledge, awareness, responsibility: Better evidence and data for comms. Public perception	2						
Natural Reserves	Better metrics & data management: Need for a national capability in resource flows, economic flows and environmental pressures	9	X	X	X			£8m+

Table 3: Solution directions proposed by survey respondents

Solution direction data from survey (Question 3) condensed for brevity. Also includes some answers to Question 4 (Out of the solution directions identified in question 3, please highlight which ideas that you think are most likely to yield the most environmental, social and economic benefits and what those benefits may be), where these were judged to be additional solution directions.

Research challenge	Solution direction
Resource repositories and resource recovery systems	
Design out waste	Rigorous, systematic and holistic LCA and LCSA for waste standardisation.
Waste processing processes and technologies	Robotics [for waste segregation]
Waste processing processes and technologies	New chemical, biological, pyro and physical processes for separating materials. For magnets we have developed a hydrogen based route.
Waste processing processes and technologies	Mass education by user friendly integrated biorefinery philosophy embedded tool enabling sustainable designs
Energy and circular economy	Learn to prioritise from biorefinery approaches (see the definition of biorefinery above, but also needs practitioners’ expertise to apply in practice)

Research challenge	Solution direction
Land- and marine-based renewables	Apply biorefinery concept to recover the following: • Recovery of therapeutic, pharmaceutical and healthcare ingredients. • Sugar extraction. • Protein extraction (essential amino acids). • Recovery of minerals, salts and nutrients.
Circular bio-economy	No single technological solution. But take a holistic process engineering design approach to apply biorefinery in practice.
Resource security and productivity	Critical materials. There are huge environmental benefits to processing these materials and massive economic impacts on the supply chain.
Changing consumption systems	
Design out waste	The food and health care sectors should be a priority here, since so much of the material they use is single use and justified on health grounds. Comparison goods can be more easily designed for repair and re-manufacturing, and it is likely to be marketing reasons that mean this doesn't happen – these need to be tackled through converse marketing, or regulation.
Design out waste	Packaging design to aid recycling and prevent littering - would bring environmental and social benefits
Human behaviour	Researching what successfully motivates people not to fly tip? - social as well as environmental benefits, via helping to raise well being
Human behaviour	Simple LCA and LCSA mobile apps, which allows people to calculate the environmental impact of their daily activities (like driving, eating red meat, etc.)
Human behaviour	Mass education by user friendly LCA and LCSA embedded tool enabling sustainable designs
Business model innovation	
New business models	Must be supported by rigorous, systematic and holistic LCA and LCSA for sustainability
Developing the policy landscape	Understanding the advantages and disadvantages of fiscal measures and encouraging market forces as opposed to direct regulation around design of product would be very useful in the UK context. A mixture of regulation and fiscal measures will be needed.
Developing the policy landscape	Should be long term supported by roadmap supported by rigorous, systematic and holistic LCA and LCSA
Material and product data systems	
Better data gathering	Material tracking projects are being developed currently and seem to be the best way forward at present.
Better data gathering	Knowledge sharing and learn from shortcomings and failures
Better data gathering	From an energy transition/climate change strategy perspective, the required energy sector shift to meet specific targets should be reasonably well known through forecasting/models (e.g. TIMES etc.), so this should allow some approximation of the likely volumes of equipment and material that need to be installed/removed in the coming decades. Examples include: number of low-carbon heating systems that will need to be installed/gas boilers removed, building fabric improvements, wind turbine erection and repowering etc.
Better metrics to measure multi-dimensional values	Understand true potential of rigorous, systematic and holistic LCA and LCSA

Research challenge	Solution direction
Contributes to all four categories above	
Global circularity	Reducing the weight of plastics entering the oceans. Current best estimates suggest that extending waste collection to all people, and eliminating open dumping and open burning, would more than halve the quantity of plastics entering the oceans. Sub-directions when pursuing this overall solution direction would include most of those below. • Addressing human behaviour, both to present waste for collection and to separate wastes to facilitate resource recovery. • Low-cost waste recycling and processing technologies suitable for use by local entrepreneurs, to extend the SDGs addressed to include lifting people out of poverty (SDG1) and providing sustainable livelihoods (SDG8). • New business models, with a focus on the 'informal sector' and local community entrepreneurs. • Better data gathering. Specifics here include improved measurement and modelling of plastics leakage into rivers and the sea; and the application of CVORR to understand better the dissipation of value when materials, and products at the end of life, become waste in developing countries. Identify points of intervention to mitigate or prevent loss of value. • Developing the policy landscape, with a focus on extended producer responsibility and on integrating the 'informal sector'.