Developing technology, approaches and business models for decommissioning of low-carbon infrastructure

Workshop proceedings

February 2018

Authors: Phil Purnell, Anne Velenturf, Paul Jensen, Nick Cliffe, Juliet Jopson

UNIVERSITY OF LEEDS Resource Recovery from Waste Innovate UK

Contents

1. Introduction 2
1.1 Aims and objectives 2
1.2 Participants 2
1.3 Report outline 3
2. Opening presentations 5
2.1 UK Research and Innovation 5
2.2 E^{4}LCID: Engineering, Economic and Environmental Envisioning for Low-Carbon Infrastructure Decommissioning 6
2.3 Lessons learned from oil & gas decommissioning 7
3. Parallel sessions to understand sectors 8
3.1 Offshore wind 8
3.2 Onshore wind 10
3.3 Solar PV 12
3.4 Electric vehicles 12
3.5 Other sectors of relevance to low-carbon development 14
4. Cross-sectoral challenges 15
4.1 Design for durability and recycling + Availability critical materials 15
4.2 Extending infrastructure lifetime: O&M + Repowering 16
4.3 End-of-life management: Logistics + Resource recovery 16
4.4 Business opportunities and challenges 16
4.5 Policy-related challenges 17
4.6 Environmental challenges 17
4.7 Other challenges 17
5. Conclusions and recommendations 19
5.1 Key research issues 19
5.2 Updates for E^{4}lcid 21
5.3 Checklist Industrial Strategy Challenge 22
Appendix A: Participants 23
Appendix B: E^{4}LCID: Engineering, Economic and Environmental Envisioning for Low-Carbon Infrastructure Decommissioning 24
Appendix C: Workshop evaluation 27

1. Introduction

This workshop was organised to gain a better insight into the issue of the decommissioning and resource recovery of low-carbon infrastructures. To maximise values created from low-carbon infrastructures, they must be designed for durability, decommissioning and resource recovery. This will avoid a repeat of the £300Bn+ bills facing the taxpayer for the decommissioning of nuclear and North Sea oil infrastructure, enable the recovery of critical materials required for low-carbon components and infrastructure and, importantly, contribute to UK materials security. Meeting this challenge requires the development of disruptive new science, technology and industry business models in a sector where there is a distinct global need and development opportunities, but little experience or expertise.

1.1 Aims and objectives

This workshop identified and detailed industry and research challenges, discussed current best practice and gauged the demand for new solutions regarding the resource efficient maintenance and end-of-life management of low-carbon infrastructure and technologies. The outcomes presented in this report will shape a research programme led by the University of Leeds and will be used to deepen our understanding of the potential for industry-led innovation funding under the Industrial Strategy Challenge Fund[1]. The workshop objectives were to:

- Introduce opportunities for innovation funding and participation in a multi-million research programme starting in 2018.
- Identify and detail research challenges around the end-of-life management and eventual decommissioning of low-carbon infrastructure.
- Facilitate networking and collaboration for research and innovation projects.

1.2 Participants

The workshop was held on 16 January 2018 in Leeds. The workshop attracted 37 registrations from academia, business, government and catapult organisations, of which 34 participated in the event (Figure 1). A full list of participants is included in Appendix A. Additionally, 18 further individuals from several prominent organisations operating in the area of renewables and/or other areas of low-carbon development declared an interest in the workshop but, unfortunately, could not attend the event; these individuals have stated a desire to stay involved in the development of projects and where possible their contributions were taken on board ahead of the workshop[2].

The stated interests of the participants are shown in Figure 2, with offshore- and onshore wind being of most interest to the group, followed by electric vehicles and solar PV. Participants also indicated a large number of other interests in relation to decommissioning of low-carbon infrastructure; these included recycling (of batteries and other components as well as composite materials), circular economy, oil and gas decommissioning, etc.

[1] https://www.gov.uk/government/collections/industrial-strategy-challenge-fund-joint-research-and-innovation
[2] This report includes results from conversations with Zero Waste Scotland, Knowledge Transfer Network, Offshore Wind Innovation Hub, and Composites UK.

Figure 1: There were 34 participants representing universities, companies, governmental organisations and catapults.

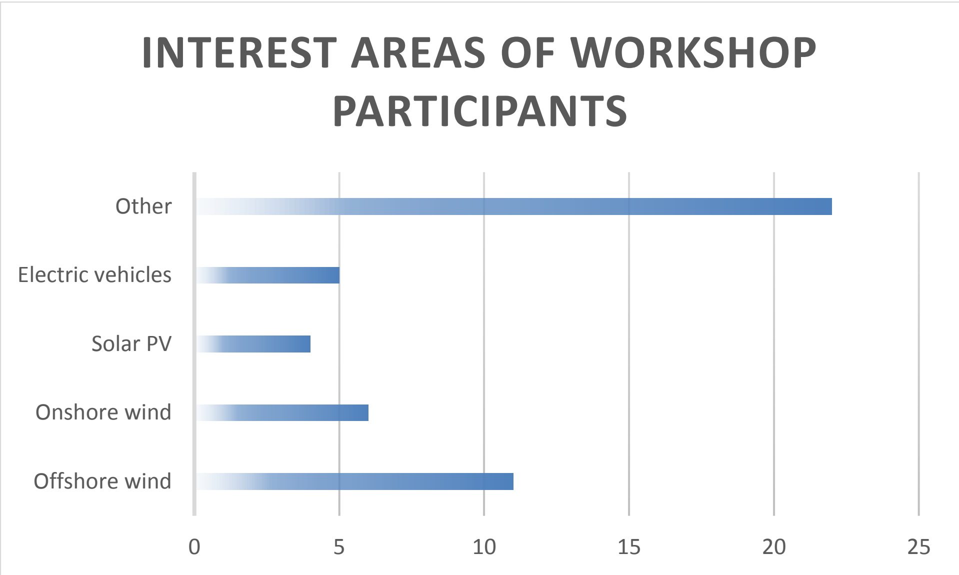

Figure 2: Participants indicated all relevant sectors of their interest at registration.

1.3 Report outline

The workshop consisted of three sessions (Table 1). Section 2 provides an overview of the first of the sessions, including presentations by keynote speakers. Section 3 summarises discussions held in parallel sessions on offshore wind, onshore wind, solar PV, and electric vehicles. Section 4 presents cross-sectoral challenges that were identified by attendees. Section 5 concludes the report, with key challenges on the decommissioning of low-carbon infrastructure and recommendations for future academic- and industry-led projects presented.

Table 1: Workshop programme

12:00	Networking lunch
13:00	Opening by workshop facilitator *Welcome, household announcements and session introduction* Welcome by Nick Cliffe, Innovate UK *Frame the workshop and introduce funding opportunities and the Industrial Strategy Challenge Fund* Grant proposal introduction by Phil Purnell, University of Leeds *Outline the proposed research programme* Quentin Fisher, University of Leeds *Oil and gas decommissioning, lessons learned* Workshop programme introduction by workshop facilitator *Introduce further workshop programme and challenge areas session*
14:00	Parallel sessions for the sectors: - Offshore wind - Onshore wind - Solar PV - Electric vehicles
15:15	Coffee and tea break
15:45	Feedback presentations from parallel session facilitators Introduction of challenge areas session by workshop facilitator
16:15	Identifying cross-sectoral challenge areas
17:00	Feedback presentations on cross-sectoral challenges Overview of main workshop findings and next steps by Phil Purnell, University of Leeds
17:30	Close

2. Opening presentations

Three opening presentations kicked off the workshop, the slides are available on the RRfW website[3].

2.1 UK Research and Innovation

Nick Cliffe started by reiterating that materials security was one of the top concerns of industry and that the workshop was timely in addressing this theme.

He then went on to give a greater insight into the funding landscape in the UK. In April 2018 the new body "UK Research and Innovation" will be launched. It brings together the seven UK research councils, Innovate UK and a new organisation, Research England, working closely with its partner-organisations in the devolved administrations[4].

The Industrial Strategy Challenge Fund (ISCF)[5] aims to bring together the UK's world leading research with business to meet the major industrial and societal challenges of our time, as part of the government's £4.7 billion increase in research and development over the next 4 years. The focus is on challenges where the UK has a world-leading research base and companies ready to innovate, and where a large or fast-growing and sustainable market is evident.

In April 2017, approximately £1bn was announced for 6 challenges up until 2020/21. The most relevant challenges are 'Clean and flexible energy' and 'Robotics and artificial intelligence'. Other challenges are: Healthcare and medicine, Driverless vehicles, Manufacturing and materials of the future (highly relevant to circular economy), and Satellites and space technology.

The Industrial Strategy White Paper has announced £725m for a second wave of challenges. This includes the topic areas of 'Prospering from the energy revolution' and 'Transforming construction' that are highly relevant to this proposal. For example, the Faraday Battery Challenge[6] has been launched. Recyclability is one of the eight areas of automotive battery technology that needs to be addressed. In terms of where we are and where we want to be, a useful example is lithium battery power packs. Currently, somewhere between 10% and 50% of these are recycled or reused, whereas the proposed target is 95% by 2035.

Nick concluded that to prove the importance of addressing the decommissioning and resource recovery from low-carbon infrastructures challenge, it is crucial to collect the following evidence:

- A potential global market that could be created or disrupted by new innovation which is potentially large, or fast growing and sustainable
- That accelerating advances in this field can generate significant social and economic benefits
- That the UK has capabilities to meet market needs in terms of research strength and business capacity
- Of a business commitment to work with government to achieve this; and
- That government support will make a difference

[3] www.rrfw.org.uk
[4] https://www.ukri.org/
[5] http://www.rcuk.ac.uk/funding/iscf/
[6] https://www.gov.uk/government/collections/industrial-strategy-challenge-fund-joint-research-and-innovation#faraday-battery-challenge:-clean-and-flexible-energy

2.2 E[4]LCID: Engineering, Economic and Environmental Envisioning for Low-Carbon Infrastructure Decommissioning

Phil Purnell introduced the draft proposal E[4]LCID (Appendix B). In his introduction, he noted that 2017 is the first year that North Sea oil has been a net drain on the public purse; this is mainly due to decommissioning costs that will eventually total around £25Bn. Estimates of the historical and future cost to the taxpayer of nuclear decommissioning range from £97Bn - £222 Bn. The purpose of the E[4]LCID proposal is to engineer our new low-carbon infrastructure to avoid these public costs.

Oil, gas and nuclear decommissioning face a mixture of challenges. Engineering challenges include the scale and complexity of decommissioning, the harshness and inaccessibility of locations, and lack of initial design for deconstruction. Economic challenges pertain to a lack of financial and fiscal planning, impacts on the public purse (the State acting as 'decommissioner of last resort'), and loss of jobs and associated welfare costs. Environmental challenges are about preventing catastrophic environmental damage (particularly regarding nuclear), disruption of established ecosystems, and returning sites to their 'natural' state.

These challenges may also apply to low-carbon infrastructures. Low carbon infrastructures and associated technologies include for example on/offshore wind, energy storage, solar PV, electric vehicles, and other infrastructures such as wave and tidal; also consider grid-, resource recovery- and heat network infrastructures. These infrastructures are relatively new and there is still the opportunity to design-in options to extend infrastructure lifetime through preventative and corrective maintenance, reuse of components, repowering, and ultimately decommissioning and resource recovery.

Two additional problems confront low-carbon infrastructure compared to other infrastructure: 1) The extensive use of composites for which there are no recycling routes and 2) The use of critical materials of which we are 100% net importers.

A review on the decommissioning and resource recovery of offshore windfarms[7] estimated that the costs of decommissioning will be 4-5 times higher than estimated, calculations are characterised by a high degree of uncertainty and total decommissioning costs were estimated between £1.3 and £4.9Bn in the period 2021-2034 with a similar bill to follow in the shorter period 2035-2040[8]. Crucially, cost estimates *exclude the recycling costs*. Current decommissioning plans suffice with vague statements such as "The possibility of recycling material and/or reuse of plant elements will be considered" and "It is intended that the vast majority of all elements of the offshore windfarm will be taken back to land for reuse and recycling."

Glass-fibre reinforced polymer (GRP) recycling in the UK currently remains limited to small volumes of in-house activity with 1 SME recycling carbon fibre reinforced polymer (CFRP) (Composites UK). This capacity needs to be increased; a typical large onshore windfarm can now have 140 turbines equalling 8000 tonnes of GRP/CFRP[9]. In terms of critical materials, 140 turbines contain more than

---

[7] Anne Velenturf, Paul Jensen and Phil Purnell (2017) Resource recovery for low carbon infrastructure: Offshore wind turbine decommissioning and resource recovery. Internal report.
[8] Groundhog Day for Decommissioning? The Case of the Offshore Wind Industry; https://www.researchgate.net/publication/320895827_Groundhog_Day_for_Decommissioning_The_Case_of_the_Offshore_Wind_Industry
[9] https://www.energy-uk.org.uk/energy-industry/lighting-up-britain/whitelee-wind-farm.html

100 tonnes of rare earths (2-3% of current UK per annum consumption). Linking this to electric vehicles, rare earth metal demand will approach 20% of supply by 2020; Stock of lithium/rare earth metal in scrap will exceed current supply by 2020/2040. Moreover, in the electric vehicle sector the demand for cobalt and lithium will exceed supply by 2020.

Recycling and recovering these materials will pose economic, business, social, (geo)political, institutional, environmental, organisational/logistical and technical challenges (Figure 3). Current decommissioning plans include insufficient detail on this; while this is a problem, it is also a massive business opportunity given the coming global competition for these materials and their recycling and recovery processes.

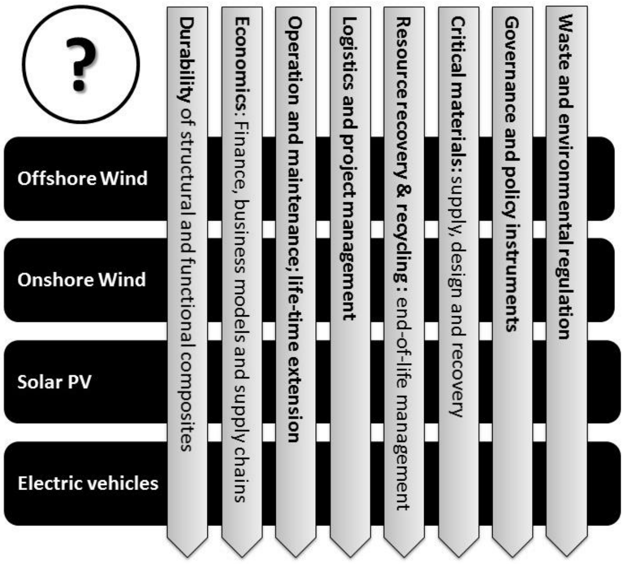

Figure 3: Overview of proposed sectors and cross-sectoral challenges that were critically assessed at the workshop.

With this workshop we will gain a better insight into the challenge of decommissioning and resource recovery of low-carbon infrastructures and associated technologies, including:

- Scope: breadth and depth; programme or projects; what's missing? (Figure 3)
- Partners: stakeholders and expertise; who else do we need?
- Old vs new; what's been done already (TRL, i.e. Innovate vs RCUK), what's novel?
- Tensions, how do we manage conflicting interests?

2.3 Lessons learned from oil & gas decommissioning

Quentin Fisher outlined the 'lessons learned' from decommissioning in the oil and gas industry, which could be summarised as 'think ahead'. Infrastructure should be designed with decommissioning in mind and the potential for reuse of components should be assessed at an early stage. Decommissioning plans should be continually reassessed throughout the life of a project. Technical studies should be undertaken early, especially with regard to ground conditions both technical (e.g. the amount of overburden to be removed) and ecological (e.g. assessing what the pre-installation ecology is, so that one has a baseline for a 'return to natural state'). Early stakeholder engagement is essential because building up well-working relations takes time. Final costs for oil and gas decommissioning have been three to five times greater than the initial estimates.

3. Parallel sessions to understand sectors

Four parallel sessions were organised focusing on: offshore wind, onshore wind, solar PV and electric vehicles. Participants were free to join the session most relevant to them.

In each session the programme proposal 'E^{4}LCID' (Appendix B) was discussed to ensure all important elements would be included (Figure 3). The following questions were covered, in order of priority:

1. **Given the experiences with decommissioning oil and gas as well as nuclear infrastructure, what are your fears/concerns for decommissioning low-carbon infrastructure?**
2. **What are the anticipated benefits for companies and UK plc?**
3. **How can we ensure that the research outcomes will benefit companies and UK plc?**
4. Gauge the scope of the challenges and solutions needed. What is the state of current solutions, is any laboratory work needed, do we need entirely new technologies or are solutions available and just need upscaling?
5. What is the scale of the challenges and amounts of monetary resources needed?
6. Long-term future perspective – which materials are we likely to need for the sectors discussed and/or low-carbon infrastructure in the future? Are they the same as the materials used now? To what extent is resource security an issue?
7. Funding source – which of the identified challenges are best funded by research councils for academic-led projects and which by Innovate UK for industry-led projects?
8. Are there any other sectors that should be included in the proposed research programme, in addition to offshore- and onshore wind, solar PV and electric vehicles?

The following sections summarise the answers to these questions for as far as they were covered.

3.1 Offshore wind

Q1: Given the experiences with decommissioning oil and gas as well as nuclear infrastructure, what are your fears/ concerns for decommissioning low-carbon infrastructure?

Concerns were raised that at current rates, recovery of the materials would nowhere near cover the cost of decommissioning; there is insufficient plants (e.g. jack-up and other support vessels) to carry out the task and there are no facilities for reprocessing the recovered material. Materials need to be better categorised, as does the degree to which properties (and hence values) are reduced with time and by the decommissioning process. Existing decommissioning plans are vague and based on the assumption that reverse engineering will be applied. Regulation relating to the robustness of decommissioning plans and budgets are weak. The benefits of decommissioning need to be made clear, and contrasted with the damage done to the 'new' ecology that grows around the installations[10] [cf. Prof. Fisher's presentation: often, in oil and gas sector, no baseline surveys of the pre-installation ecology were performed so no one knows what 'return to nature' looks like]. Some decommissioning issues are specific to sectors e.g. onshore has no problem with cranes but it does with transport (big blades are hard to transport over land), while for offshore the reverse is true.

[10] See: Smyth et al. (2015), Renewables to Reefs? Decommissioning Options for the Offshore Power Industry. *Marine Pollution Bulletin* 90(1-2):247-258. https://doi.org/10.1016/j.marpolbul.2014.10.045

Suitable locations for storage and deconstruction/recycling/remanufacturing of components is a pressing issue. This is exemplified by the likes of the Humber which, both on the north and south banks, lacks quays and port facilities able to accept larger vessels and turbine materials, yet it is at the heart of the largest installation developments. There is a lack of joined up thinking on where the economically and environmentally best location for such activities should take place.

Q2. What are the anticipated benefits for companies and UK plc?

Decommissioning followed by recycling 'on-site' would provide more jobs for site operatives at end-of-life; this requires the development of new skills. Research and innovation into how to dismantle installations without cranes would provide useful technical export expertise (notably there is now a vessel operating out of Norway that can take complete turbines out to sea and bring them back in one piece). Additionally, UK companies are in a good position to provide legal, financial and project management expertise that may be exportable, not least transferring lessons learned from oil and gas infrastructure decommissioning. All elements of the (international) decommissioning and resource recovery supply chain need to be further established; further research and innovation is needed including into recycling technologies. The majority of the material is steel for which there is an established market but supply chains for other materials still need further development; could these be 'piggy backed' on steel recycling infrastructure?

Q3. How can we ensure that the research outcomes will benefit companies and UK plc?

Addressing technical, economic and business issues around recycling of composite materials would benefit UK plc. The competitive advantage of UK-based facilities needs to be carefully considered; should the industry focus on: lower cost or higher quality, i.e. why would companies choose the UK over other countries? How can the UK become the decommissioners of choice, rather than Denmark or Germany; we need to win a 'race to the top' or 'race to the bottom'. Alternatively, regulation could direct decommissioning and recycling to UK markets. However, recycling in the UK could be more expensive than other countries, posing a competitive disadvantage for such 'locally recovered' materials in an international market setting. The value of recovered materials and presence of markets requires more research. Ensuring that robust inventories of materials are kept – what is out there and when is it coming back – will be crucial to success[11]. Could the UK reimagine floating offshore wind technology by capitalising on its presumed simpler routes to decommissioning?

Q4. Gauge the scope of the challenges and solutions needed. What is the state of current solutions, is any laboratory work needed, do we need entirely new technologies or are solutions available and just need upscaling?

There are a number of challenges, in order of appearance from design to resource recovery: The complete windfarm including the turbines need to be designed with decommissioning and resource recovery in mind. More work is urgently needed on how the composite and functional materials degrade, for example via laboratory research. Additionally, new vessels need to be developed to facilitate transport of decommissioned components. Further research and action must go towards the development of markets for recovered materials, to ensure the components have a value rather

[11] For an indication of components used in a windfarm, see https://www.thecrownestate.co.uk/media/5408/ei-km-in-sc-supply-012010-a-guide-to-an-offshore-wind-farm.pdf

than giving them away for free or even at a cost to the operator. Finally, the focus should be on more robust decommissioning plans and regulation – including financing i.e. who pays and through which business model, responsibilities for components, decommissioning and recovery, and risk management for the government in case companies fail to meet their legal obligations[12].

3.2 Onshore wind

General observations

Discussion was focussed more on governance than technology. Now was seen as a good time to focus on opportunities to develop solutions and associated skills. Key issues include knowledge and resource security, liabilities (i.e. who is responsible) and ownership of inventory (materials, components); raising questions around the governance of decommissioning and resource recovery. The lack of knowledge regarding durability of composites was highlighted; decommissioning problems may be on us sooner than we think.

Q1: Given the experiences with decommissioning oil and gas as well as nuclear infrastructure, what are your fears/ concerns for decommissioning low-carbon infrastructure?

A focus on opportunities, not 'big numbers' fear, and small targeted projects that can grow into business opportunities was suggested. The timing for research is perfect because: a) The next round of onshore wind will be subsidy free and this changes the mechanisms and business models, and b) We are still in a place where influencing the design of infrastructure [to promote materials recovery] is possible. If research can show the value of recovered materials, then this would provide a motivation for recovery. A more granular focus on how each component has a value and thus provides business opportunities [for recovery] is required. Sites retain value because of e.g. grid connections; site infrastructure is built to last 50-100 years. Whether this remaining value of site infrastructure can be capitalised on, depends on the decision whether to repower the windfarm or whether to return it to its natural state.

Such decisions will be shaped by governance processes, which are complex; waste and smaller windfarms are devolved matters while large infrastructure projects are centrally governed. This also raises questions around who is responsible for providing funding and support, if any. Further differences between small and large operators pertain to their ability to prepare for decommissioning and gather the required skills, where large companies have a distinct benefit. Generally, the capacity and the skill is not there yet to deal with decommissioning coherently. Skills gaps exist in the reverse logistics of taking a turbine apart but also to solutions for land-transport of very large components. Industry has not yet worked out how to dismantle infrastructure and make money, largely because the materials are not seen as having a value; although a few operators do sell components and/or whole turbines to Eastern Europe and the developing world.

[12] Relating to several of the points made on the weakness of planning, and UK Plc having to aim to be the cheapest or the best decommissioner, there is a suggestion that a decommissioning standard should be developed. This could be an add-on to the new BSI 8001 Circular Economy standard or something new and dedicated to low-carbon infrastructure (or, simply, large scale renewables, such as wind).

The waste management industry was purported as the designated industry to recover critical raw materials. As well as the headline materials (rare earth metals, copper etc)[13] there is also a pending shortage of carbon fibre for blade production. Current recycling processes produce fibres that are too short and ca. 70% virgin carbon fibre must be used in new blades. The decommissioning and resource recovery of wind turbines benefits from relatively good quality information around the inventory being commissioned and the timing of its anticipated end-of-life, which is a distinct benefit compared to other resource recovery business cases; however, there are still challenges as there is tacit knowledge about the fine detail of materials used in the turbines and alterations made during the operation and maintenance of a windfarm. Such issues can be solved by components being marked with their composition, and their anticipated lifetimes. Additionally, there are uncertainties around the ownership of sites and windfarms, plus extended producer responsibility of component manufacturers; and consequently it is not clear who carries the responsibility for which costs associated with decommissioning and resource recovery. This poses a governance challenge which needs to be addressed. Finally, a warning from the WEEE industry: rare earth materials are ignored in order to get at the other metals. The carbon benefits of recovering e.g. neodymium need to be emphasised, this will significantly impact on the business case for government action.

Q2. What are the anticipated benefits for companies and UK plc? / Q3. How can we ensure that the research outcomes will benefit companies and UK plc?

The need to capture tacit, detailed knowledge of the inventory was reiterated, to provide resource security. This information needs to be captured now; it is unlikely that manufacturers or windfarm operators would be able to tell you what materials were in a 15+ year old turbines as technology has iterated several times. Other materials with potentially harmful emissions effects (e.g. SF_6) are monitored; these monitoring and reporting systems could be repurposed. The waste management industry needs to reposition itself within the supply chain; this will add jobs in the manufacturing sector. The opportunities to realise cost savings should be emphasised. Radical business models such as leasing of materials (or rather their function *a la* Rolls Royce) will also rely on good inventory.

The skills position in the UK – lots of STEM graduates – needs to be seen as a positive, and job/training opportunities need to be front-and-centre when talking to government. To stimulate skills, the benefits to companies (e.g. £7 for every £1 invested in training) should be emphasised and the government needs to give signals that the skills are needed; we also need to define what 'wind turbine skills' are, e.g. to 16-year olds[14]. Welsh legislation (Well-being of Future Generations) provides a useful lever to help reposition these social benefits. The NIMBY issue is still strong; current approaches do not really offer incentives to the public and so anti-wind lobbyists fill the gap.

---

[13] Vidal et al (2013) predict that demand for base metals such as iron, copper and aluminium in the renewables industry will soar well-beyond volumes that can be sustainably supplied without more circular economy practices https://www.nature.com/articles/ngeo1993

[14] Several studies have suggested that there are existing training schemes and skills in the market place to fulfil the needs of the wind energy industry, particularly regards technicians who were suggested to be largely High Voltage Electrical/Mechanical Engineers with specialist experience and training in 'Working at Heights', 'Working in Confined Spaces', 'Remote Working HSE' and, for offshore, 'Marine Safety' (Survival at Sea) training. See, for example, http://www.thecrownestate.co.uk/media/389763/owic-uk-offshore-wind-supply-chain-review-opportunities-barriers.pdf and Paul D. Jensen (2015), *Skills Support for Regional Growth: An Analysis of SMEs in the Engineering Sector*. York, North Yorkshire and East Riding Enterprise Partnership. For the wider needs of the wind industry, also see: TCE (2010), Your Career in Offshore Wind Energy. London, UK: The Crown Estate.

Lessons could be learned from e.g. the Netherlands, where community incentives are clear. Such social and community benefits need to be integrated into new business models. Further research into business models is also required to explore the potential of product service systems for turbine components.

A better mutual understanding of how companies can contribute to academic research is required; resources, timescales etc. Conferences could be better designed for this purpose. Including regulators in the process is difficult, particularly when they hold the key datasets; not least because several regulators are involved each with very specific interests and there is no top-level view from Government.

3.3 Solar PV

[NB: there were very few external attendees at this session].

Q1: Given the experiences with decommissioning oil and gas as well as nuclear infrastructure, what are your fears/ concerns for decommissioning low-carbon infrastructure? / Q2. What are the anticipated benefits for companies and UK plc?

No real issues other than concern over continued supply of critical raw materials (indium, gallium etc).

Q3. How can we ensure that the research outcomes will benefit companies and UK plc?

We need an inventory: how much PV is installed? It is more dispersed compared to other low-carbon infrastructure such as wind. Presumably those managing feed-in tariff must have data; can we access this to answer this question? How much competition and diversity is there in this sector? How do the panels degrade; is it the supporting components (e.g. glass cover) or do the core semiconductors degrade? If only the former, what are the economics of fixing the panels versus renewing them?

3.4 Electric vehicles

Q1: Given the experiences with decommissioning oil and gas as well as nuclear infrastructure, what are your fears/ concerns for decommissioning low-carbon infrastructure?

There is too much focus on new powertrains and not enough on materials substitution e.g. the whole-life environmental impacts of using aluminium versus steel. Also, the focus is on operational, not embedded emissions: both need to be considered. The word ‘decommissioning’ may not be appropriate for electric vehicles, it is more like continuous recycling. There is a trade-off between car safety and design for recycling; similar to wind- and solar PV, although there the focus is on durability. Who carries responsibility for the recycling of car batteries is not clear and the battery-ownership and governance of the recycling process needs to be investigated. This needs to happen in conjunction with an assessment of on-going business model innovation in the car manufacturing and transport sector. The scale of the recycling challenge could decrease in the future; the impact of lower car sales (a general decrease in car use as predicted by the ‘Mobility as a Service’ model [Transport Systems Catapult]) needs to be taken into account. How will the anticipated reduced car consumption impact on the demand for recycling and for the recycled materials? There are further geopolitical issues pertaining to the shipping of cars elsewhere for recycling; while there are also challenges around recycling cars in the UK while car components are manufactured elsewhere in the world. How will legislation impact 'cross boundaries' e.g. must an electric vehicle that is registered in the UK be recycled there, even if imported [in whole or part]? There is no obvious lodestone of success with regard to recycling; a focus on individual materials tends to dominate.

Q2. What are the anticipated benefits for companies and UK plc?

Job creation: Magnet systems / hard drives could see recovery of 95-98% of rare earth metals, but there are no manufacturers in the UK who would use this to put it back into magnets or other electronic elements. This means that it would be necessary to sell abroad as the supply chain currently is not all in the UK. Addressing this would provide an opportunity to develop jobs in UK for resource recovery, even if the manufacture is abroad (but having both locally would be better). Transport costs and exchange rate both add costs to recycling of magnets and could be avoided by manufacturing locally. High-value high-tech jobs from manufacturing magnets/ batteries/ laptops/ mobile phones – could be linked with the resource.

Geopolitical security: Value chain mapping shows lots of geopolitical problems with shipping recovered resources elsewhere. A strong point of the E^4LCID proposal is that it addresses these issues. We could avoid being held to ransom by e.g. China who have the largest supply of these elements.

Industry competitiveness: changes in business models e.g. leasing batteries could create new industries. WEEE regulations have driven new industry; remanufacturing laptops etc. This is analogous to what we need for lithium batteries. How would the business model work? Scale, security of supply for recycling, and joining up supply chain so that manufacture and recycler are linked in closed loop, would stimulate the business. Who would reuse batteries? This could be a whole new industry in itself, e.g. link to solar power storage on domestic scale rather than industrial.

Environmental impact: current resource procurement and shipping of recyclates incurs large environmental impact here and abroad.

Q3. How can we ensure that the research outcomes will benefit companies and UK plc?

Building a UK supply chain that maximises one of those values [Q2] will be essential. Future projections will need to take into account changes in values of waste streams, such as likely in the case of for example cobalt and lithium. We also need to look for clashes where there is demand in different sectors e.g. knee implants are 65% cobalt, so do we use limited cobalt supplies for knees or batteries?

Q4. Gauge the scope of the challenges and solutions needed. What is the state of current solutions, is any laboratory work needed, do we need entirely new technologies or are solutions available and just need upscaling?

Polyesters are already being recycled and are easy to take out of vehicles. If we need to look at all the materials in a vehicle, is there any value in co-locating? Much more efficient to separate and process in one place rather than sending different components elsewhere; similar to other low-carbon sectors, there is a need to research the integrated of disassembly and resource recovery infrastructures. Cherry picking may be a problem, with some bits being wanted but others less desired. The current supply chain means that there is nowhere (in the UK) for a wrecked electric car to be taken for recycling, and facilities internationally are still only test-beds. Automation will be possible once standardisation is introduced; states/politics bring in standardisations. The demand for recycling technologies needs to be critically examined in the light of potential reduced car consumption.

Q5. What is the scale of the challenges and amounts of monetary resources needed?

An analysis of the car industry now, which is global and has huge economies of scale, will need to address the political economy in which this new resource recovery will work in order to have uptake.

3.5 Other sectors of relevance to low-carbon development

The current programme proposal (Appendix B) focuses on onshore- and offshore wind, solar PV and electric vehicles. During conversations ahead of the workshop and during the event itself, a number of additional sectors were suggested which we should consider in the development of a research programme or series of projects:

- Heating infrastructure and closely linked upgrading of the building stock as part of the decarbonisation agenda.
- Grid infrastructure, this includes infra for electricity, gas, heat etc which needs to be: a) Either relocated with evolving infrastructures, for example as coal-fired power stations are closed and wind- and solar farms are commissioned, or b) Upgraded to be able to convey alternative fuels etc, consider for example hydrogen, next generation airplane fuel, etc.
- Resource recovery/ circular economy infrastructure itself, as the scale and services offered by the current waste management industry must change to facilitate the recycling of low-carbon infrastructures and associated technologies.
- Future low-carbon technologies not yet deployed at a large scale such as wave and tidal energy, where we can still include realistic decommissioning and resource recovery planning up-front.
- Bioenergy, for example infrastructure generating heat from bio-wastes/ by-products.
- Include/ combine with a project on the decommissioning of oil and gas infrastructure, to delve further into the lessons learned and enable transfer of knowledge to low-carbon infra sectors.

4. Cross-sectoral challenges

With this activity we aimed to identify cross-sectoral challenges, which will enable us to prepare a coherent research programme. Moreover, we strived to gauge the scope of the cross-sectoral challenges and potential solutions, and whether this needs to be taken forward in academic- or industry-led projects. Merging the cross-sectoral challenges outlined in Figure 3 for logistical reasons, six areas were explored at the workshop:

1. Design for durability and recycling + Availability critical materials
2. Extending infrastructure lifetime: Operations & Maintenance + Repowering
3. End-of-life management: Logistics + Resource recovery
4. Business opportunities and challenges
5. Policy-related challenges
6. Environmental challenges

In addition, space was made available to voice other challenges that did not fit into any of the areas mentioned above.

Participants were asked to identify specific challenges within the listed challenge areas and to add their ideas to a table of results drawn on a flipchart (Table 2).

Table 2: Format used to capture cross-sectoral challenges.

Challenge area				
Challenge	**Offshore Wind**	**Onshore Wind**	**Solar PV**	**Electric vehicles**
E.g separation of composites into raw materials that can be used in new components	*Yes/ No (add details and solutions if any).* *Industry/ academic led.*	*Yes/ No (add details and solutions if any).* *Industry/ academic led.*	*Yes/ No (add details and solutions if any).* *Industry/ academic led.*	*Yes/ No (add details and solutions if any).* *Industry/ academic led.*
Etc.				

4.1 Design for durability and recycling + Availability critical materials

Materials criticality was seen as an issue for all sectors. In addition to the normally invoked suite of critical raw materials (rare earth metals, lithium, cobalt), copper and aluminium should be added for offshore wind and electric vehicles.

Design for recycling applied across sectors. For the wind sectors, ease of transport was highlighted. For solar PV, accounting for the value of the functional materials was noted. For electric vehicles, reversible joining techniques and their durability were noted.

Design for durability, disassembly and performance (and the tension thereof) was noted for both wind sectors (similar trade-offs were noted for electric vehicles in the parallel sessions). The unknown long-term ageing behaviour of composites and the potential for using self-healing materials was of concern. Design standardisation was seen as a cross-cutting issue (with analogies in designing battery space in electric vehicles), with lessons to be learned from the car industry.

4.2 Extending infrastructure lifetime: O&M + Repowering

Repurposing and repowering with better technologies cut across all sectors. Kinetic storage (for wind), voltage control (for solar PV) and the use of electric vehicle batteries for grid storage both during and after working life were specifically mentioned. However, repowering of electric vehicles was not seen as likely. The unknown lifetimes of materials was also seen as applicable to all sectors, with degradation rates for second-life batteries singled out. The promotion of reuse over recycling and design for remanufacture was also ubiquitous, as was investigation of 'short life – easy decommissioning' paradigms for design.

Improved monitoring and early repairs was seen as a key issue for wind and solar PV sectors.

Health and safety issues related to maintenance were seen as critical in wind, but not other sectors. Robotic 'smart' turbines that could 3D print blades onsite were mentioned, as was holistic control of windfarms to reduce wear and increase life.

4.3 End-of-life management: Logistics + Resource recovery

Materials availability, accessibility and flows was seen as a cross-cutting issue. Particular challenges were transport for offshore wind (and onshore wind transport challenges were mentioned in the parallel sessions), and the split responsibilities for e.g. batteries and the rest of the vehicle was raised for electric vehicles. Related to this, inventory was also seen as a cross-cutting opportunity (in the case of wind) and challenge (in the case of solar PV and electric vehicles), i.e. how much material, what it is, what can be reused and the capacity of the market.

Valuing the technology and materials (presumably understanding the value over and above the market value in order to decide on a recovery route) was seen as an issue for wind and electric vehicles, while for solar the scrap material was not seen as valuable. The possibility of creating new recovery infrastructure was seen as essential for wind and solar PV, while for electric vehicle funding should be concentrated on adapting existing infrastructure to cope with electric vehicles.

4.4 Business opportunities and challenges

Servitisation (business models based around provision of service, rather than ownership of products, components and materials) was seen as the primary cross-cutting issue for research. This in addition to business model innovation challenges mentioned in all parallel sessions.

Stakeholders with vested interests that could hinder business development were highlighted as an issue for wind and possibly solar PV. The high capital cost of infrastructure and decommissioning, and clarifying 'who pays' and related subsidies to support secondary material value were seen as issue in wind and electric vehicles, but not for solar PV as the technology is scalable (although we note that despite apparent solution in the market, these have not fulfilled this scalability potential). Exploring direct reuse to recover value (mainly of batteries) was seen as important for solar PV and electric vehicles. The UK's expertise in financial and legal services was seen as being a key driver for developments in wind and solar PV, but not electric vehicles.

4.5 Policy-related challenges

The only cross-cutting issue identified for this challenge were issues around consumer demand and providing consumers with information on CO_2/greenhouse gas emissions and energy demand. The relationship was simple for wind and solar PV (i.e. directly related to energy demand) but more complex for electric vehicles (where the embodied-operational emissions balance is different, and use of electric vehicles in rural areas will be challenging).

Other general issues raised included: end-of-life management based on circular economy principles; recovery of rare-earth components; classification of electric vehicle batteries as hazardous waste (specifically, safety of DIY repairs and road traffic accidents); how standards can stifle innovation; environmental impact assessment and legislation; long- versus short-term financial issues; and embedding lifecycle approaches in commercial decisions.

4.6 Environmental challenges

Biodiversity was seen as a cross-cutting challenge: birds and marine life for offshore wind, birds and bats for onshore wind, vegetation for PV and potential increased roadkill (cf. less noise) for electric vehicles.

Environmental standards for mining of key materials in the country of origin was also seen as important across the board.

Sustainability assessments for decommissioning were seen as important for offshore wind. The impact of greenhouse gases used in switchgear for wind was also mentioned, but these are being phased out. Whole-system views and associated trade-offs were mentioned in the context of electric vehicles (e.g. aluminium reduces waste and hence operating emissions, but increases embodied emissions). Others factors to be included when assessing lifecycle impacts holistically were the impact on land use patterns of solar PV, and assessing whether recovering resources might actually increase pollution by disturbing waste deposits (e.g. oil drill chips) for offshore wind was highlighted.

The treatment of waste from mining and valuing the environment in business models were given as general issues.

4.7 Other challenges

A large number of additional challenges were raised at the workshop and beforehand through conversations with interested stakeholders who could not make it to the workshop. These challenges need further assessment to determine their relevance as cross-sectoral challenges and inclusion in the research programme or other projects:

- Data and digitisation; Information systems and big data, need to capture material flows and their characteristics.
- Collaboration between problem ‘causers’ and ‘solvers’; Governance challenges related to transparency, or lack thereof, of changing ownership structures over time; related to contract management, extended producer responsibility, and regulation plus its implementation via central government or devolved administrations.

- Sustainability assessment integrating environmental, economic, social and technical values; using alternative metrics for appraisal and evaluation.
- Upskilling (particularly for offshore wind and electric vehicles) – as discussed in the onshore wind parallel session.
- Reduced consumption and demand management.
- Radical system change and disruptive technology.
- Better economic theory.
- Risk management.
- Reuse of components in other sectors such as turbine blades in conservation, batteries from cars in household applications, etc.
- Trade-offs between sectors, if materials used in one sector then less available for other sector for lifetime of product/component – requires strategic prioritising of allocating (near) critical raw materials (also raised in the parallel session on electric vehicles).
- New material design (this can probably be integrated with the theme on durability); trade-off between design for durability and design for recoverability (as raised in especially the off-/onshore wind parallel sessions).
- Changing future demand – e.g. due to climate change (but also reduced consumption) and effects of weather patterns impacting on durability of infrastructures.
- New logistics/ transport means such as ships, mobile or temporary infrastructure for duration of decommissioning and resource recovery operation (link to end-of-life logistics theme).
- Integration of decommissioning and resource recovery infrastructure, such as having resource recovery infrastructure located where components can be transported too within monetary and planning constraints; and after resource recovery, integration with present manufacturing infrastructure/ sectors in the UK or elsewhere.
- Reducing production waste/ lean manufacturing when manufacturing low-carbon infra from primary or secondary resources.

5. Conclusions and recommendations

5.1 Key research issues

The presented analysis highlights the following eight research issues as being central to all stakeholders' perception of the problems facing decommissioning of low-carbon infrastructure.

1. **Value and critical materials**: Making the business case for resource recovery from low-carbon infrastructure will require that recovered materials, components and products are correctly valued (in addition to estimating the costs of decommissioning and resource recovery with a greater certainty). In particular, the hidden value in recovering critical materials – i.e. the environmental and resource security benefits – must be costed into valuations. This will require supporting regulation. When these materials are correctly valued, design interventions for recycling (e.g. modular design, reversible joining) will follow more easily (while bearing in mind other design challenges around e.g. durability and safety). The suite of materials considered critical should be widened, to include carbon fibre, aluminium and copper as well as the usual rare-earths, lithium and semiconductor materials.
2. **Resource recovery infrastructure**: There is a chronic shortage of resource recovery infrastructure. This includes infrastructure that enables extending the lifetime of whole infrastructures or the components therein (and thereby extending the functional lifetime) and repowering of sites, as well as the complete decommissioning and recycling of components and materials. The latter requires fixed facilities (recycling plants) and mobile plant (cranes, vessels, temporary processing facilities ahead of land-transport). Many of the materials used have no current recycling facilities; there is nowhere in the UK to recycle an electric vehicle, and composites are currently not recycled. The size of many low-carbon infrastructure components also creates logistical and storage problems. However, the UK is well-placed to build on its existing infrastructure for e.g. vehicle recycling, steel recycling, ports; new infrastructure could be co-located with these. Developing this would give the UK a competitive advantage, attracting imports for recycling, but the capital cost is high and there will be new challenges around the integration of infrastructures both within the resource recovery sector and across sectors (such as transport, manufacturing, energy). It is also important that the British resource recovery sector is competitive in an international context, and stays in tune with changing demand for (recovered) materials.
3. **Inventory**: Knowledge of the stock of materials in our current low-carbon infrastructure is limited, with wide variability between sectors. The materials intensity of e.g. wind turbines, electric vehicles is not widely known with any accuracy except in isolated cases, but must be pieced together from secondary sources. Moreover, we only have an indirect understanding of the system-wide rate or timing of flows in (new installations) and flows out (end-of-life components). Research is required to solve this; labelling components with their material contents, using solar PV installation data to estimate stocks and flows of semiconductor materials, assessing the materials intensity of old and new systems. Without this data, the value in (1) above cannot be predicted and business models cannot be formulated.
4. **Durability**: There is very little data on how materials, components and products degrade in service. This poses challenges to predict exactly when installations will need to be replaced, impacting on (3) above. This is particularly true for composites materials, but also for components and products e.g. when a solar PV degrades, is it the glass cover, the supports or the core semiconductor materials that degrade? Knowing degradation at the materials,

component and system level allows repowering or refurbishment procedures to be drawn up, adding further time-dependent knowledge on likely materials in- or out-flows from the system. Monitoring the behaviour of materials, components and products in-service is a crucial aspect of this.

5. **Whole-system analysis**: Making decisions regarding decommissioning requires trade-offs between economic, social, technical and environmental costs and benefits to be evaluated. We currently have neither the metrics nor the models to do this effectively. For example, light-weighting electric vehicles by using aluminium greatly reduces operational emissions, but increases embodied emissions. Using solar PV to generate electricity reduces CO_2 emissions but changes patterns of land use. Consumers and stakeholders need clear information on these trade-offs in order that they can make informed decisions regarding demand reduction.
6. **Skills and expertise**: On a positive note, UK plc have learned a lot from oil and gas decommissioning and this should give us a head-start in planning low-carbon infrastructure decommissioning. We also have excellent STEM graduates who should be ready to enter this field. We also have deep expertise in the legal and financial issues that will surround decommissioning. We need to work out how these skills can be harnessed to prevent poor decommissioning. We need to define e.g. what a wind turbine engineer is, and what (s)he needs to learn. This will require greater collaboration between (higher) education institutes and industry. We also need to reposition waste management as part of the materials supply chain, with knowledge on the future flows and values of materials that can move responsively to market and geopolitical drivers of materials availability. All this will lead to the creation of new, highly skilled jobs.
7. **Policy, regulation and legislation**: The markets required to support all the above points will take time to emerge. In the meantime, regulation will be required to drive the right behaviour, clarify ownership of the issues on decommissioning and resource recovery, and reduce risks. We need to formalise responsibility for materials and components along the supply chain, not allowing manufacturers to 'pass the buck' at end of life. International regulation will be required to address cross-border issues, such as the assigning of responsibility along the supply chain for the environmental and social impact of mining in the country of origin. Policy should promote materials security, especially in a post-Brexit world, that ensures we have the materials to deliver a low-carbon future at the right price and the right time. It should also prevent those with vested interests from impeding resource recovery during decommissioning, and ensure that the cost is not borne by the taxpayer as decommissioner of last report. Existing plans in this respect are weak and generic.
8. **Economics and business models**: The transformative potential impact – positive and negative – of new business models needs to be investigated. In particular, a move towards 'leasing of service' rather than 'ownership of materials' should be explored (such as regional ownership of infrastructure). The relationship between legislation and business models also needs to be explored; new business models have emerged as a result of WEEE regulations and we can learn from those. Additionally, new collaborative business models need to be developed to close the loop. Many business models require that the scale and security of supply (derived from studies in 1, 3 & 7 above) are predictable and supported by agreed pipelines of activity. Many of these will require a new approach to the economics of infrastructure that includes social, environmental and technical, as well as financial analysis, and understands the political economy of low-carbon infrastructure systems.

5.2 Updates for E^{4}lcid

This workshop provided further insights into the research challenges around the decommissioning and resource recovery of low-carbon infrastructures and associated technologies.

Broadly, the consensus on issues in 5.1 map onto the cross-cutting research challenges identified in the original proposal but with some repositioning. Durability, Economics and Business Models, Policy Regulation & Legislation, and Critical Materials remain as priorities. Our original focus on operation and maintenance has been repositioned across Durability (via monitoring), and Infrastructure; the issues surrounding logistics and project management are now included in Infrastructure and Expertise. However, the workshop has identified two new areas of investigation: Inventory, and Whole System Analysis that will now take a much higher priority in the forthcoming proposal.

The support for a programme, rather than project-based approach was clear in order to retain a ‘whole systems’ perspective. However, there are some issues surrounding the inclusion of electric vehicle in an ‘infrastructure’ project. While we always made it clear that the proposal covered infrastructure and supporting low-carbon technologies, the narrative needs to be strengthened to justify doing this. We will need to explore with electric vehicle stakeholders the extent to which issues surrounding e.g. critical materials and recycling can be covered in this programme proposal, and perhaps what areas of enquiry might be moved to a supporting project proposal.

The relative importance of the sectors included in the programme needs reconsideration. Different approaches can be taken to the analysis of the most relevant sectors. For example, selecting proposal to analyse the sectors with the greatest relevance to the UK economy and/or for which decommissioning challenges are expected to arise within the next 10 years will be different from a proposal where we aim to learn from sectors that are furthest ahead with decommissioning with a view to apply best-practice to emerging energy infrastructures.

Our stakeholder coverage was broadly representative of the sectors discussed. Engagement from the solar PV community was low and this needs to be addressed, although this was seen as the least problematic sector overall. Engagement with the oil and gas decommissioning industry was seen as important, as it is clear there are powerful lessons to be learned from the decommissioning of offshore petrochemical installations. Nuclear decommissioning was seen as too specific to be as important in this regard, but some engagement will be useful and several attendees had the necessary contacts. Broadening of the stakeholder base is an ongoing process for any project of this type and we will continue to do this.

Conflicting interests were mentioned several times, and addressing these has been explicitly incorporated into 5.1 (7) above.

It seems clear that most of what was proposed was ‘new’ and mostly suitable to be addressed through academic research in close collaboration with relevant companies.

5.3 Checklist Industrial Strategy Challenge

The workshop evidence and outputs suggest that the area is suitable for further exploration and consideration for developing a challenge programme for consideration by the Industrial Strategy Challenge Fund (ISCF)[15].

The ISCF provides funding and support to UK businesses and researchers and is part of the government's £4.7 billion increase in research and development over 4 years to 2021. It is designed to ensure that research and innovation takes centre stage in the UKs Industrial Strategy.

For decommissioning of and resource recovery from low-carbon infrastructure there does appear to be a large potential global market that could be created or disrupted by innovation, although the workshop highlighted that the scale of the opportunity is currently unknown and requires research to model and quantify. Given the current uptake and global 'switch' to low carbon infrastructure innovation in this area could also give the UK an advantage in a market which is potentially large, or fast growing and sustainable.

The UK also benefits from its business expertise and investment in decommissioning of North Sea oil and gas infrastructure and nuclear decommissioning.

The growth and productivity opportunity provided by the current transition to electric vehicles has already been recognised by the ISCF – with funding made available for projects and activity related to end-of-life solutions for EV batteries from the *Faraday Challenge*, the level and scope of this investment will need to be considered in developing thinking on challenge fund potential for decommissioning of low-carbon infrastructure. The Wave 2 ISCF challenge *Prospering from the energy revolution* recognises that countries all over the world are moving to renewable low-carbon energy, with investment more than doubling over the last decade. This challenge focuses on smart systems which link energy supply, storage and use, and join up power, heating and transport to increase efficiency dramatically rather than decommissioning but does recognise that energy infrastructure will undergo significant change over the coming decades.

Further research to better understand the potential scale of the opportunity and the scope of the technical and economic challenges is needed in order to assess the potential of this area for ISCF funding, in addition the level of business engagement and appetite to innovate in this area must also be better understood.

[15] See https://www.gov.uk/government/collections/industrial-strategy-challenge-fund-joint-research-and-innovation

Appendix A: Participants

First name	Surname	Affiliation
Petros	Aristidou	University of Leeds
Martin	Atkins	Green Lizard Technologies
Andrew	Brown	University of Leeds
Jonathan	Busch	University of Leeds
Nick	Cliffe	Innovate UK
George	Cobb	SSE
Alan	Colledge	Cawleys Hazardous Services
Lee	Davies	Defra
Pietro	Di Modica	ORE Catapult
Andrew	Dickson	ALL NRG
Quentin	Fisher	University of Leeds
Helen	Forsyth	University of Leeds
Arjan	Geveke	BEIS
Ali	Ghanbarzadeh	University of Leeds
Sam	Haig	Axion Consulting
Ged	Hall	University of Leeds
Stephen	Hall	University of Leeds
Oliver	Heidrich	Newcastle University
David	Hobson	Axion Consulting
Eleni	Iacovidou	University of Leeds
Diletta Colette	Invernizzi	University of Leeds
Paul	Jensen	University of Hull LHDI
Mark	Jolly	Cranfield University
Adrian	Jones	Welsh Government
Juliet	Jopson	University of Leeds
Jeremy	Laycock Campbell	University of Leeds
Edward	Morell	Seren Technologies Limited
Roberts	Proskovics	ORE Catapult
Phil	Purnell	University of Leeds
Steve	Smith	ECOBAT
Jon	Steel	National Composites Centre
Alan	Tinline	ABP
Anne	Velenturf	Resource Recovery from Waste
Liu	Yang	University of Strathclyde

Appendix B: E^{4}LCID: Engineering, Economic and Environmental Envisioning for Low-Carbon Infrastructure Decommissioning

Challenge statement: We must design our low-carbon infrastructure for durability, decommissioning and the recovery of valuable resources. This will avoid a repeat of the £300Bn+ bills facing the taxpayer for the decommissioning of nuclear and North Sea oil infrastructure, enable the recovery of critical materials required for low-carbon components and infrastructure and, importantly, contribute to UK materials security. Meeting this challenge requires the development of disruptive new science, technology and industry business models in a sector where there is a distinct global need and development opportunities but little experience or expertise.

1. Project rationale

The UK nuclear power and North Sea oil sectors developed with little thought for the impact of decommissioning and taxpayers are now faced with colossal bills. Nuclear clean-up is estimated at £3Bn p.a. with a total cost of up to £219Bn[16]. Meanwhile, North Sea oil decommissioning is a net drain on the public purse of £400m p.a., estimated at £75Bn in total[17]. These high costs are incurred through interacting factors in three domains:

- **Engineering:** e.g. the scale and complexity of decommissioning, involving millions of tonnes of materials and hundreds of complex installations; harshness and inaccessibility of locations (particularly for offshore oil and gas) and a lack of initial design for deconstruction.
- **Environmental:** the need to prevent potentially catastrophic environmental damage associated with poor waste management (particularly in the case of nuclear); disruption of ecosystems established during decades of operations and difficulty in returning sites to their 'natural' state.
- **Economic:** a lack of financial and fiscal planning and foresight applied to eventual decommissioning; impacts on the public purse incurred by the implicit role of the state as 'decommissioner of last resort'; loss of jobs and associated welfare and retraining costs.

We are about to embark on the exponential growth of new low carbon infrastructure (LCI) – onshore and offshore wind turbines, solar energy farms, bulk electrical storage facilities and associated technology (AT), in particular electric vehicles (EV) given the plans to ban IC-engined cars by 2040[18,19]. Current LCI decommissioning plans (e.g. those mandatory for offshore wind[20]) are formulaic, generic and lack context and details on recycling routes, financial risk and, in many cases, environmental impact. Two additional factors pertinent to LCI can be identified that could further exacerbate eventual decommissioning issues.

---

[16] https://www.gov.uk/government/publications/nuclear-provision-explaining-the-cost-of-cleaning-up-britains-nuclear-legacy/nuclear-provision-explaining-the-cost-of-cleaning-up-britains-nuclear-legacy

[17] https://www.carbonbrief.org/analysis-north-sea-industry-cost-uk-taxpayers-396m-2016?utm_content=buffer16954&utm_medium=social&utm_source=twitter.com&utm_campaign=buffer

[18] http://www.bbc.co.uk/news/uk-40723581

[19] https://www.gov.uk/government/publications/clean-growth-strategy

[20] https://itportal.beis.gov.uk/EIP/pages/files/orei_guide.pdf

LCI components and AT rely on mixed materials and composites: glass- and carbon-polymer composites used for turbine blades, ceramic chemically doped photovoltaic crystals in solar panels, and electric vehicle and grid storage battery cells. These currently cannot be efficiently and safely recycled on an infrastructural scale and the potential for future decommissioning impacts owing to material disposal is high. The deterioration rates of these materials, i.e. their condition with regard to contamination, weakening or dissipation into the environment with time, is also poorly understood.

LCI&AT components also rely on 'critical' materials. Notable, rare-earth metals are required for permanent magnets in direct drive high-performance motors and generators required by EVs and wind turbines. EVs and grid storage batteries both require lithium and cobalt. Solar panels require indium, gallium and germanium[21]. Demand will outstrip supply, aggravated by competition from other industries and countries[22]. *Recycling technologies for these materials are extremely limited. These critical materials must be designed into the system such that the functional components they enable can be recovered, refurbished and reused where possible.* Non-availability of these materials would have significant national economic and political consequences in a low-carbon future.

2. Transformational research required

Engineering: to develop 'design for recovery' techniques that prioritise whole life system-of-system issues, such as repowering and decommissioning. **Science**: to develop and scale-up recycling/recovery processes to protect both the UK's natural environment and her national material security. **Economics**: to establish business models and political structures that avoid the enormous impact on the public purse exemplified by nuclear/oil sector decommissioning and create opportunities for UK PLC. **Logistics**: shipping (recovery of offshore components), waste management (storing/reprocessing of large volumes of end-of-life materials), manufacturing (skills and supply chains for recovered critical materials and new technologies).

Example research questions may include:

- How do we recycle or reuse 100-ton scale composite components? What post-decommissioning applications could they satisfy? How can we prevent these materials ending up in landfill?
- How do we recover critical materials from infrastructure? – e.g. rare earths from wind turbine magnets and EV motors, lithium and cobalt from EV and grid storage batteries, indium from PVs – to protect both the environment and UK materials security?
- How do we redesign infrastructure components to strike a balance between technical efficiency in service, ease of refurbishment and decommissioning, and recovery or reuse of key materials and components?
- How do we design financial instruments that include the (long term) costs of decommissioning in (short term) development investments, and avoid the cost being borne by future taxpayers as with nuclear and North Sea oil? How can circularity of resource use be built into the long-term business models?

[21] https://ec.europa.eu/growth/sectors/raw-materials/specific-interest/critical_en
[22] https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/417822/PU1798_Valuing_Infrastructure_Spend_-_lastest_draft.pdf p32 box 4.D

- What are the effects on the recoverability/recyclability of materials of operating in harsh (offshore) environments? How do these materials deteriorate?
- What will the effect of decommissioning on the habitats, biodiversity and ecosystems developed around installations? How will the recovery of the large quantities of materials used in LCI not currently abundant in our infrastructure affect the environment?
- What will be the impact of social, political and economic changes (e.g. Brexit, Industrial Strategy, austerity, increasingly stringent global environmental regulations, pursuit of UN Sustainable Development Goals, the rise of developing nations, responses to climate change etc.) on how decommissioning plans should be designed and delivered?

We propose investigating four sectors: **offshore wind, onshore wind, solar PV** and **electric vehicles**. In addition, we have initially identified eight cross-cutting research areas pertinent to all the sectors:

1. Durability of structural and functional composites in demanding environments
2. Operation and maintenance (including robotics and automated systems)
3. Resource recovery, including end-of-life management and recycling technologies
4. Critical materials supply, design and recovery (resource security)
5. Repowering and eventual decommissioning logistics and project management
6. Finance, business models, supply chains and resource markets
7. Governance and policy instruments for low-carbon and circular economies
8. Waste and environmental regulation protection

At the workshop, we will ascertain demand for innovative and new solutions for these sectors and crosscutting areas, and identify any further areas of investigation. Given the criticality of developing low-carbon infrastructure that is operationally robust, easily refurbished, recoverable and reusable, this research presents significant potential early mover business opportunities. As such, we particularly welcome the input and participation of industry stakeholders. In collaboration with interested parties, all information collected at the workshop will be used to detail the proposed project's funding application.

3. Impact

The potential for UK prosperity is two-fold. First, this is a global problem that is not being addressed and so the potential to develop exportable industrial processes and skills is very high. As one of the 'first mover' countries in LCI, we can develop a highly lucrative skill-set that will be attractive to the new economic giants of the future (e.g. BRIC countries). While we have extensive knowhow on decommissioning of existing infrastructure that could be applied, this is held by a limited number of skilled, ageing workers, all of whom are fully committed. This research could unlock public and private investment in a new cohort who can export their skills. These exports are not limited to technical skills; developing financial products, aligned with fiscal and regulatory issues, which provide for decommissioning costs will also be attractive. Secondly, designing for decommissioning will avoid costs comparable to the North Sea and nuclear cases, saving the taxpayer's purse hundreds of billions of pounds. Designing for recovery will ensure that the valuable and critical materials contained in the LCI stock will remain available for use in the UK, protecting our materials security and the long-term economic viability of LCI.

Appendix C: Workshop evaluation

Feedback questions

1. **How would you rate the event?**

	Very Good	*Good*	*OK*	*Poor*	*Very Poor*
Workshop programme					
Relevance for your organisation					
Networking opportunities					
Organisation					

2. **Has the workshop been useful for you? Yes/ No, please give details.**

3. **Would you be interested to be actively involved in the programme proposal "*E^4LCID*: Engineering, Economic and Environmental Envisioning for Low-Carbon Infrastructure Decommissioning" led by the University of Leeds?**

Role	*Yes*	*Maybe*	*No*
Academic research partner			
Continue to co-create proposal			
Join steering committee			
Provide letter of support			

4. **Would you be interested to be actively involved in industry-led projects on the development of technologies, approaches and business models for decommissioning and/or resource recovery of low-carbon infrastructure?**

Role	*Yes*	*Maybe*	*No*
Lead a project			
Partner on a project			

5. **Are there any further comments or suggestions that you would like to share?**

Evaluation results

Response rate: 24%

How would you rate the event?

Workshop programme	Good/ Very good
Relevance for your organisation	Good/ Very good
Networking opportunities	OK/ Good
Organisation	Good/ Very good

Interested to be active in INDUSTRY-LED PROJECTS on the development of technologies, approaches and business models for decommissioning and/or resource recovery of low-carbon infra:

75% INTERESTED TO LEAD A PROJECT

100% WOULD PARTNER ON INDUSTRY-LED PROJECT

Learning points:

"A lot of insightful discussion was had but more perspective and experience from industrial stakeholders would have been good"

"Target some key solar PV stakeholders for the next workshop"

*Role**
Academic research partner – 88%
Continue to co-create proposal – 100%
Join steering committee – 75%
Provide letter of support – 75%

**Participants that answered yes or maybe.*

On average 85% interested to be actively involved in the programme proposal "*E[4]LCID*: ENGINEERING, ECONOMIC AND ENVIRONMENTAL ENVISIONING FOR LOW-CARBON INFRASTRUCTURE DECOMMISSIONING" led by the University of Leeds

"As an industry it has allowed us to feed directly into the research topic so that the outcome will be applicable to our business and the issues we are facing now and in the future."

"The workshop provided a good insight into challenges associated with circular economy."

100% USEFUL WORKSHOP