Tackling End-of-Life Challenges in Wind Infrastructure: Innovations, Insights, and Future Research Pathways

Workshop report

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Location: University of the West of England City Campus at Arnolfini, 16 Narrow Quay, Bristol BS1 4QA

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Table of Contents

The challenge

As the global shift towards renewable energy accelerates, the end-of-life challenges for wind infrastructure are becoming increasingly significant. Since the 1990s, the UK has installed 11,000 onshore wind turbines, contributing to a global total of approximately 400,000. These installations have played a crucial role in energy decarbonisation. However, the sustainability of this capacity raises important questions about the long-term management of wind infrastructure, including the replacement of original equipment, repowering with new turbines, and the handling of materials generated by these processes. Such challenges require the bringing together of cross-disciplinary expertise to identify and address the end-of-life challenges for wind infrastructure: challenges around replacement, repowering, removal and the creation of circular economies for redundant components.

The workshop

Organised by Dr Carla De Laurentis as part of a funded project at the University of the West of England[1] and in collaboration with Prof Richard Cowell from Cardiff University and Dr Rebecca Windemer from Regen, the workshop aimed to bring together wind energy professionals, policymakers, and scholars from the fields of energy transitions, circular economy, and related disciplines to share emerging innovations, identify barriers and enablers, and explore business models, policy instruments, and innovations necessary for the sustainable management of end-of-life wind energy infrastructure. .

The workshop contributed to the launch of the Wind Energy End of Life Observatory (WEELO), a collaborative initiative from UWE, Cardiff University, and Regen. The workshop featured keynotes presentations giving international and UK perspectives on end of life issues for wind infrastructure followed by shorter expert insights on current innovative approaches to managing potential end-of-life problems. The presentations were followed by roundtable discussions to exchange knowledge, foster collaboration, and drive forward the sustainable management of wind infrastructure.

This report provides a brief summary of the event.

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[1] Vice Chancellor's Early Career Researcher Development Award entitled: 'Exploring waste management opportunities and challenges from end of life of on-shore wind infrastructure in the UK'

The agenda:

11.00: Registration and coffee 11.30: Welcome and introductions 11.45: End of life of wind infrastructure: International and UK perspectives 13.00: Lunch and networking 13.45: Short Presentation Session: Innovations and expert insights and Roundtable discussion (1) 15.00: Comfort break 15.15: Short Presentation Session: Innovations and expert insights and Roundtable discussion (2)

The participants

The workshop brought together 28 people from industry, research sectors, governments and non-governmental organisations and regulators. Organisations represented included:

Organisations	
Carleton University	Savills
Resource Futures	University of Birmingham
Universita' di Udine	ReWind
Leeds University	Cardiff Metropolitan University
DESNZ	University College Cork (UCC)
University of Leeds	Wardell Armstrong/ SLR
University of Nottingham	University College Cork
Thrive Renewables	Regen
National Composites Centre	Cardiff University
Ecotricity	RWE
Octopus Energy	UWE
UCL	Offshore Renewable Energy Catapult
Munster Technological University	

Photo: Participants

Focus areas

Participants discussed the challenges and current innovative approaches to managing the end-of-life of wind infrastructure and ways forward within three focus areas:

- Lessons from the UK and international context on some aspects of end of life of wind infrastructure
- Identifying the decommissioning landscape and expert insights into key areas relevant to the end of life of wind infrastructure (e.g. repowering, regulations, decision-making influencing end of life- carbon savings, financial and material challenges for circular approaches to end of life
- Challenges and knowledge gaps in end of life of wind infrastructure and how these could be addressed.

Lessons from International and UK Perspectives on some aspects of end of life of wind infrastructure

The event started with the session on "End of Life of Wind Infrastructure: International and UK Perspectives". This provided valuable insights into the diverse approaches and lessons learned from different international contexts and the UK.

Prof Colin Mackie from the University of Nottingham discussed ***the use of decommissioning bonds in England's onshore wind sector***. The presentation offered an opportunity to provide a closer look at the challenges associated with the cost of decommissioning and to provide an overview of what it has been done to ensure developers/owners can fund their decommissioning and site restoration responsibilities. A recognised means of enhancing the prospect of decommissioning and site restoration is for developers/owners to provide a 'bond' (or security) to the local planning authority, with it being released upon the satisfactory performance of the decommissioning and site restoration. Bonds are used as guarantee that if the developer/owner defaulted on their obligations, the local planning authority could access the funds to complete the works. The presentation, building on an original empirical study of 275 onshore wind projects in England between 1990 and 2022, provided an insight on how decommissioning bonds were (or were not) used. In contrast to offshore wind (governed by the Energy Act 2004), there is no energy-specific legislative framework for decommissioning and site restoration of onshore wind in England. Instead, planning decision-makers must utilise their general planning control powers under the Town and Country Planning Act (TCPA) 1990. Bond provision achieved using planning conditions and planning obligations was found to be relatively rare, being present in only 15.6% of projects (43 of 275). Moreover, the use of bonds covered a narrow cost range, namely the 'net decommissioning and site restoration cost'- this is the difference between two estimates provided by the developer prior to consent being granted i) the decommissioning and site restoration costs per MW of installed capacity/per turbine and ii) the infrastructure's salvage value (e.g. the second hand value of metal) per MW of installed capacity/per turbine. This approach might be problematic as developers might underestimate their decommissioning and site restoration costs, overestimate the infrastructures scrappage or resale value or, most likely, do both affecting the effectiveness of the bonds. A number of lessons were shared by the presenter:

1. Bonds must guarantee performance of decommissioning and site restoration.
2. Granular detail of the costs that arise upon, and following, decommissioning and site restoration is needed to ensure better cost estimates;
3. The role of salvage value and whether the salvage value of the retired infrastructure ought to be permitted to be used to lower the value of the bond to be provided by the developer/owner;
4. Making publicly available information on bond levels and submitted cost estimates.

In concluding, our first speaker suggested that the ability to pay is something that should be at the heart of the claimed reversibility of onshore wind projects in planning policy.

Dr Kathrin Kramer, a Circularity and Sustainability Advisor, explored ***second-lifecycle and end-of-life opportunities for wind turbines in Denmark and Germany***. The presentation draws from her study, that sought to better understand how sustainable and resilient circular supply chains can be developed along the entire lifecycle of a wind turbine. The significant scale of decommissioning efforts in both Germany (since 2000, ~3,600 MW and ~4,500 turbines) and Denmark (since 1998, 830 MW and 3,195 turbines were decommissioned) were used to reflect the ongoing challenges and opportunities in managing the end-of-life of wind infrastructure. In Denmark, 72.1% of the fleet is older than 20 years; in Germany 27.7% is older than 20 years and the research showed in both countries, decision to decommission (with or without repowering) or to continue operation depended on several technical, legal/regulatory, economic and organisational factors. The presentation discussed how different circular economy pathways were taken for decommissioned assets. A common circular economy pathway in both countries consisted of a second lifecycle for the whole turbine; in Denmark 60.1% of decommissioned assets were exported to second hand markets and in Germany 46%. The presentation also discussed the circular supply chain processes that exist in the two countries suggesting that, while the observed processes were relative similar in both, differences appeared at the actor level. Not every actor responsible for decommissioning considered every circular economy pathway, with most decommissioning companies considering the option to export the turbines, and a comparatively limited number considering the refurbishment of turbines prior export. The decision-making process in post-decommissioning supply chains was also considered, highlighting that among the factors that influence circular economy pathway, there are regulatory requirements, decommissioning standard (or the lack thereof), logistical hurdles, available time window, preferences for certain turbine types and availability of spare parts.

Lessons drawn from the presentation to elicit discussion included:

- More empirical data on circular economy pathways is needed together with further evidence on what factors are influencing decision-making among stakeholders.
- It is important to conduct further research on the technological and economic feasibility of second-lifecycle applications and the cascade of circular strategies for both installed and future wind turbine types and their components.
- Traceability and Transparency is also an important issue to consider as traceability systems and digital product passes can ensure transparency in material flows.

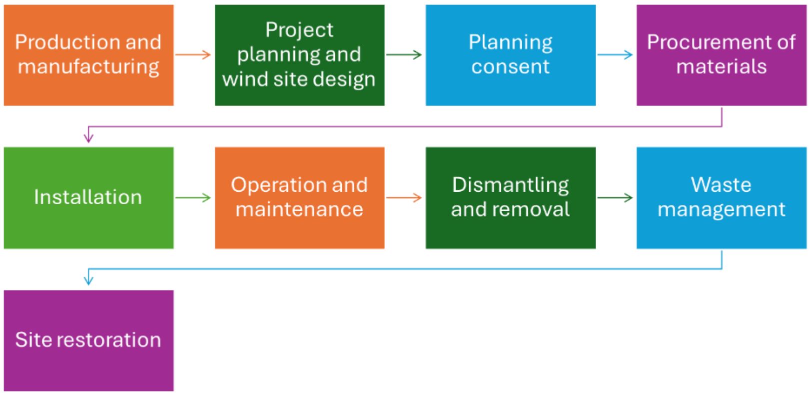
Dr Vesna Jaksic from Munster Technological University presented an ***Irish case study on the repurposing of wind turbine blades***, showcasing practical solutions for reusing these components and reducing waste. The presentation introduced the EU-funded EirBLADE (National REposItory of Decommissioned Wind Turbine BLADEs), a national database of wind turbine blades. The database was developed to address the challenges that repurposing blades might encounter. Persistent challenges are: the lack of asset databases with information that could support blade acquisition from different actors (e.g. recyclers); the complex geometry of blades; the lack of protocol/ standards for condition rating, material profiling and structural capacity evaluation. To address these, the national database was created to provide detailed information on blade age, condition, decommissioning dates, and structural properties. Together with visual inspection and condition rating system the database is the first to specifically address second-life applications for blades. The database also allows for exploring details of blades models in use in wind farm sites in Ireland, the lengths, the location and the decommissioning timelines. Via an inspection tool, there are opportunities to assess wind turbine blades, provides condition ratings and damage scoring in order to issue a 'fitness repurposing' report that can be used to aid second-life applications. Examples of successful blade reproposing in Ireland were shared: i.e. the Blade Bridge's footbridge created for the *Midleton to Youghal Greenway* and three pieces of street furniture, commissioned by Mayo County Council in September 2023, for the opening of the *Achill Greenway*. There are a number of potentials for this application considering that approximately 2323 turbines will be decommissioned in Ireland by 2038. The presenter highlighted the different range of expertise of those involved, including academics, civil engineers, architecture and design experts as well as collaborative research networks and external funding bodies. The presentation highlighted the relevance of data sharing and the information needed to develop effective repurposing strategies for decommissioned and current wind turbine infrastructure.

Together these presentations provided a valuable opportunity to hear from international and the UK contexts on progress in addressing end of life issues and some of the barriers and enabling strategies for managing the end-of-life phase of wind infrastructure. They also underscored the critical importance of cross-border collaboration and knowledge sharing in addressing the complex challenges associated with wind infrastructure decommissioning and repurposing.

Identifying the decommissioning landscape and expert insights

The second part of the workshop started with an exercise to identify the participants position in a pre-defined decommissioning landscape. Participants were asked to identify the area that their work resonate with the most and to use this as an opportunity to briefly discuss why they have chosen that specific area (see Figure 1). The decommissioning landscape was identified by the organisers as following:

Figure 1: Decommissioning landscape



These were chosen by the team to identify some of the key areas and phases in the end of life of wind infrastructure. Reality is more complex than this simple linear figure (Figure 1). For instance, decommissioning is also relevant at the time of installation as well as at the end of life, as there might be issues related to tooling and the relevant tools for dismantling. Operation and maintenance were included to reflect the importance of maintenance to extend the life of the assets but also to reflect that not all decommissioning occur at the end of life of a wind site- for instance some decommissioning might occur due to malfunctions and in case of turbines/ components' fire. Under the waste management categories, participants were also asked to think more broadly around the waste hierarchy.

The exercise also encouraged participants to identify where in the ecosystem they sat and to draw arrows to show where their interests reached. Moreover, participants were asked to explain whether they are contributing concrete outcomes and practices (area on the top of the thread) or innovation potential (area on the bottom of the thread). Figure 2 below captures the results from one of the groups.

Figure 2: Positioning participants in the decommissioning landscape

This exercise was punctuated with five expert insights. The presentations focussed on the issues of repowering, regulations for circular use of end of life of wind infrastructure, carbon emissions generated or saved by decommissioning and their relevance to decision-making, the challenges of financing circularity in wind energy end of life and the challenges of wind turbine materials *vis-a-vis* the potential to re-use it for civil engineering.

List of expert insights and presentations

Repowering Windfarms – A Summary of Pros & Cons (Paul Evans from Wardell & Armstrong, Part of SRL)

Regulations to Ensure Sustainable Circular Use at End-of-Life (RESCUE) (Keri Vaughan, ORE Catapult

ReWind: Exploring Carbon Effective Solutions for Wind Turbine Decommissioning (Matthew Geraghty, DNV/ RE-Wind)

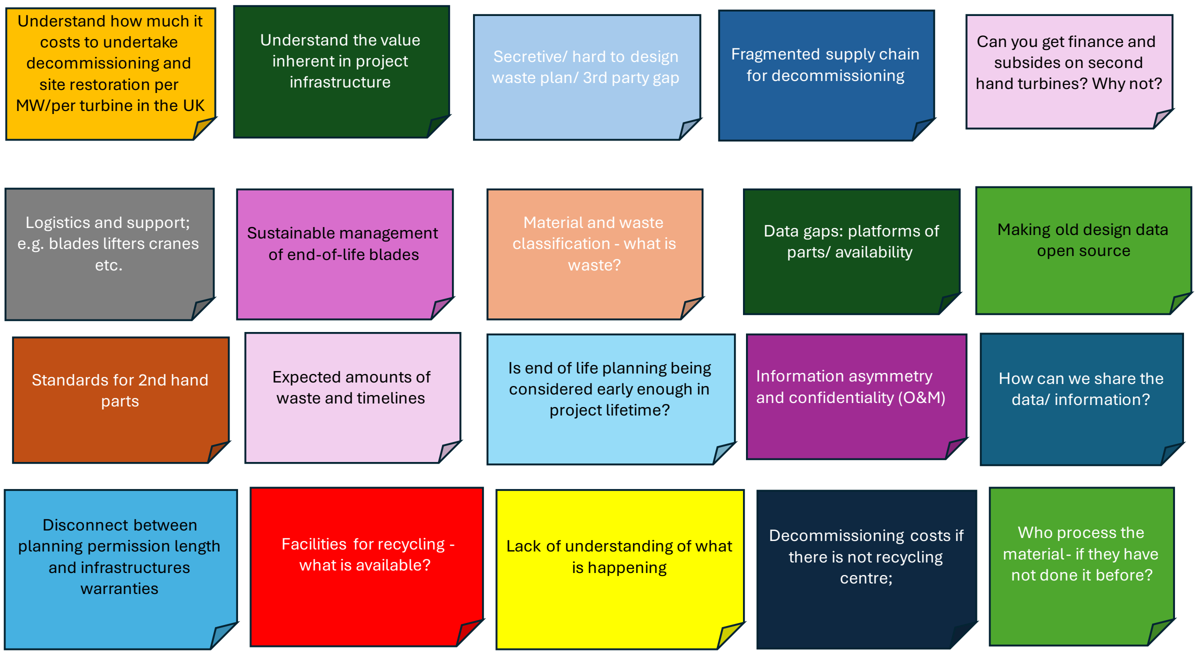
Compliance Bonds to Finance Circularity in Wind Energy, Peter Deeney, University College Cork

Punks, puddles and pigeon poo: open challenges in sustainable infrastructure materials, Patrick Barry

Challenges and knowledge gaps in end of life of wind infrastructure

The presentations were used to prompt round table discussions where participants could delve deeper into the topics, ask questions, and share their thoughts. The roundtable discussions were focussed on i) exploring some examples of the current practices and innovation that are emerging in management of the end-of-life of wind infrastructure, using the experts' presentations as a jumping off point and ii) identifying the knowledge gaps and challenges in the decommissioning landscape.

Figure 3 Knowledge gaps and challenges



As highlighted in Figure 3, a number of knowledge gaps and challenges were identified. These are clustered around the following:

- ***Planning and decommissioning***: do we consider end of life of wind assets early enough in a wind project timeline? Are the planning requirements adequate to address end of life (e.g. bonds, warranties, decommissioning plans and regulations)?

- ***Data access and data availability***: there are a number of issues associated with confidentiality and data availability in many areas of the decommissioning ecosystem; these revolve around questions on how to share sensitive or confidential data on materials and components between stakeholders (especially third parties) while managing information asymmetry;

- ***Fragmentation of supply chain***: There are inherent challenges in decommissioning wind infrastructure, including the involvement of multiple contractors and subcontractors with unclear roles. Due to the lack of evidence and case studies on already completed decommissioned projects, there is often a lack of best practices (e.g. standards) for dismantling and material processing capabilities;

- ***Decommissioning costs:*** decommissioning can be a costly process with a number of factors affecting decommissioning costs. These include salvage values, restoration bonds, and the influence of a "smash and grab" culture, whereas operators or contractors might prioritise high-value materials. Yet there are also other elements that could affect those costs. Some of the decommissioned wind turbines have entered the second-hand markets; therefore, any intervention to facilitate the re-use of second-hand turbines might ultimately affect the cost of decommissioning; yet not all old turbines will be effectively sold in second-hand markets- especially if these are poorly maintained. The cost of decommissioning will also be affected by spare parts availability and second-hand parts standardisation. Furthermore, there will also be cost implications for decommissioning- e.g. transport- when no recycling centres are available nearer the sites.

The presentations and the roundtable discussions helped participants to gain a better understanding of the decommissioning ecosystem, identify critical knowledge gaps, and explore the benefits of collaborative, cross-disciplinary research efforts. In particular, they provided an opportunity to delve into the following:

- Understand the current state of knowledge and the key issues in the decommissioning ecosystem.
- Identify gaps in knowledge and discuss what kind of research is needed to fill these gaps.
- Highlight the advantages of a multi-disciplinary approach to understanding and addressing the practical challenges in the field.

Concluding remarks

The workshop aimed at building and strengthening connections across wind energy professionals, policymakers, and scholars to address the complex challenges of the end of life of wind infrastructure. It also offered an opportunity to highlight emerging innovative approaches to managing the end-of-life of wind infrastructure, including repurposing wind turbine blades and exploring second-lifecycle opportunities in different countries. The workshop supported a better understanding of the wind energy decommissioning ecosystem and provided a platform for sharing and developing ideas. The workshop also focussed on sharing the work that the Wind Energy End of Life observatory (WEELO) is doing and the potential benefit of further developing this cross-disciplinary collaboration. An extended invitation was made to participants to join this collaborative work and actionable steps were identified to align with the development of the Observatory. The suggested actionable steps were the following:

1. Consolidate data on decommissioned projects, best practices, and policy frameworks in support of the sustainable decommissioning and recycling of wind turbines;
2. Investigate what is happening in other industries at end of life such as aerospace and other renewables and learn from cross-industries examination;
3. Develop a knowledge repository to facilitate addressing data gaps and produce open access research;

4. Advocate for the need to consider end of life of wind infrastructure as early as possible in the life cycle of wind energy infrastructure and advocate for policy incentives for circularity;
5. Continue the focus on cross-sectoral collaborations and activities, avoiding duplication and encouraging new ideas around how to address the challenges identified.

This report is built around the discussions and insights shared during the workshop, highlighting the collaborative efforts needed to advance the sustainable management of wind infrastructure.