Engineering X

Safer End of Life for Offshore Wind Infrastructure

Workshop report, November 2024

Royal Academy of Engineering

LR Foundation

Contents

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Executive summary

Climate change poses one of the greatest threats to human safety and the environment. To mitigate its effects, we must reduce our reliance on fossil fuels and transition to cleaner energy sources.[1] Offshore wind has a key role to play in achieving net zero targets and its rapid growth in recent years has brought much-needed green energy. However, this progress also raises challenges – one of which is ensuring that the emergent asset base of offshore wind is dealt with safely and sustainably when it reaches the end of its design life.

To initiate critical conversations on this topic, Engineering X convened a workshop of interregional and cross-sector stakeholders in London on 16–17 May 2024. Participants identified challenges for safety at the end of life for offshore wind infrastructure and ways to address them. Discussions took place around three focus areas: (1) technology and infrastructure, (2) circularity, and (3) regulation. This report details the key stakeholders and findings identified during the workshop, and calls for urgent action on the priority recommendations made. The sheer scale and amount of work required to ensure a truly safe and sustainable end of life for offshore wind infrastructure was evident throughout the workshop discussions. Issues with the current system, significant blocks, and a targeted set of 39 recommendations for action (see Appendix A) were raised.

Key findings

Across all discussions, four themes for action emerged. The workshop's key findings (see also Section 4) call on the sector to:

1. **coordinate and work together for safe, sustainable, and effective end-of-life management** that is mindful of impacts worldwide and contextual differences
2. **address gaps in regulation by developing more appropriate and agile regulation while ensuring international coherence** which allows for appropriate planning and the development of safe and sustainable approaches
3. **proactively develop international circular end-of-life supply chains that engage and prepare suppliers** in existing and emerging offshore wind markets
4. **advance full-circle technology and processes for end of life implemented by a well-trained workforce** that can monitor, maintain, replace, and dismantle components safely.

Key stakeholders

The key stakeholders (see also section 3) who must take action on these findings include:

- governments and regulators, who set the direction and develop regulations
- offshore wind manufacturers, developers, and operators, who plan and execute the end-of-life process
- researchers, who provide evidence to guide both regulatory and industry actions
- non-profit organisations, who champion social and environmental responsibility
- others with vital perspectives, including those from the end-of-life supply chain, financial stakeholders, and communities impacted by offshore wind projects.

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The key findings represent substantial challenges that require all stakeholders to work together with urgency. From the workshop, priority recommendations for action on each of these findings have emerged (see also section 5).

Priority recommendations for action

1 **Launch a global, inclusive working group** – a neutral body to establish an inclusive, international working group that can raise awareness across the sector, convene stakeholders, set benchmarking targets, and coordinate activities across regulation, supply chains, and technological developments for safe and sustainable end-of-life processes for offshore wind.

2 **Develop international and national standards** – a neutral body to convene cross-sector actors to cocreate a framework that can be adopted by regulators. National regulators in countries with established or emerging offshore wind infrastructure will embed the framework in their respective national regulation. At the international level, the international regulatory bodies responsible will be identified and the importance of end of life raised with them.

3 **Collaboratively map and forecast end-of-life material flows** – industry and research to jointly map end-of-life materials. First, assess when and what minimum volumes are likely to emerge, in order to inform investment, scaling, and timelines. Then, reach out to end-of-life suppliers to prepare logistically and develop the skills and workforce needed (ports, vessels, and resource management sector).

4 **Maximise learning by coordinating pilots and gaps** – cross-sector actors to build on initiatives to map existing technologies, approaches, and pilots, and then coordinate and share learning from piloting efforts. Meanwhile, develop and train the workforce for decommissioning processes.

Given the enormous scale, diminishing timelines, and categorical urgency of end-of-life projects, we must act swiftly and collaboratively to ensure the safe and sustainable management of offshore wind infrastructure at the end of its design life. Insights from the workshop show what the sector can do, where to start, and who should lead – the time for action is now.

This work forms part of the wider Engineering X Safer End of Engineered Life programme's focus on enhancing safety in the decommissioning of offshore infrastructure and ships.

1. Introduction

1.1 The challenge

Offshore wind structures are designed and built for a certain lifetime, currently 20 to 25 years.[2] What happens to the structures at the end of their planned design life poses complex challenges, including several concerning safety. These safety challenges range from dismantling large structures offshore and transporting them to shore, to the risks of exporting potentially hazardous waste or second-hand parts from mature offshore wind markets to other geographies, often lower- and middle-income countries. The latter regions may also be less well equipped to manage the materials safely.

End-of-life safety challenges for offshore wind such as these have received little attention to date. With a growing number of ageing farms, by 2035 over 3.5 gigawatts of offshore wind turbines will come to the expected end of their design life – and future decommissioning waves will be even bigger.[3]

In other industries, such as oil and gas and shipping, the costs of a lack of proper planning and consideration of end of life can be significant with regard to human safety and the environment. Shipping is an acute example: 70% of ships are decommissioned on three beaches in South Asia and the process disproportionately affects workers and nearby communities (see also Spotlight 1.1, below).[4]

As installed offshore wind capacity is accelerating and markets are emerging worldwide, what can be done differently in this sector to mitigate safety and environmental risks at the end of life?

Spotlight 1.1 | Learning from the shipbreaking sector

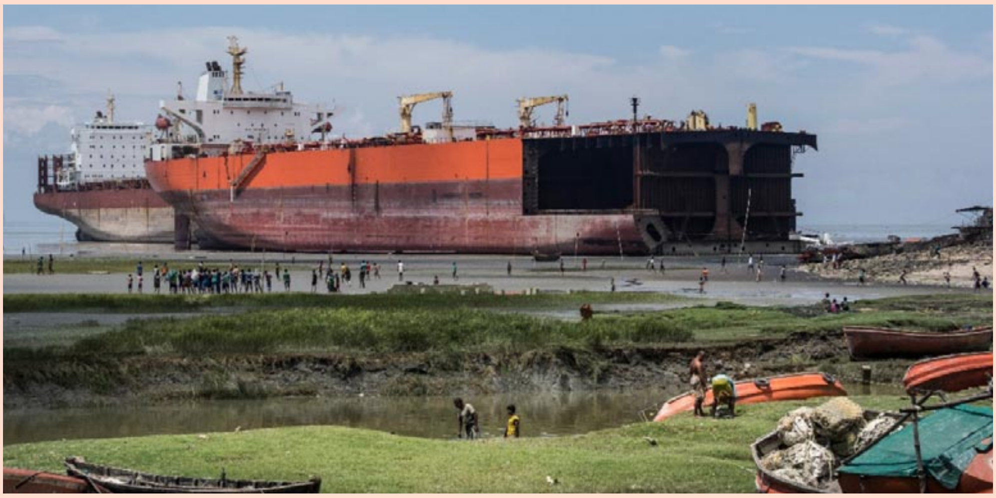

Photo by Reinhard Fasching for NGO Shipbreaking Platform

Over 70% of the world's ships are 'decommissioned' under rudimentary conditions on the beaches of Bangladesh and Pakistan at the end of their useful life – a practice known as 'beaching'. The human and environmental consequences of beaching are harsh: workers labour in unacceptable health and safety conditions in which they suffer injuries and diseases or even loss of life. At the same time, coastal ecosystems and local communities are affected by toxic spills and pollution.[5] Ship owners are able to avoid their responsibilities and externalise these human and environmental costs based on an easily circumventable legal framework for the decommissioning of ships.

UNEP Basel Convention [6]

- exporting-state jurisdiction
- adopted in 1989, entered into force in 1992
- controls transboundary movement of hazardous waste with a view to protecting lower- or middle-income countries via prior informed consent procedure
- Basel Ban Amendment [7] entered into force in 2019

Easy circumvention

- issue a false declaration of intent, such as 'further operational use' or 'repair work'

IMO Hong Kong Convention [8]

- flag-state jurisdiction
- adopted in 2009, enters into force June 2025
- aims to ensure that ships at the end of their operational lives are recycled safely
- sets low standards for ship recycling
- does not consider downstream waste management

Easy circumvention

- end-of-life sale of asset to cash buyer who sells on to blacklisted flag state to avoid more stringent regulations

Learning

- **The potential consequences of bad end-of-life management are significant for humans and the environment.**
- **Regulatory systems for end of life must be coordinated internationally to ensure they are robust and not circumventable.**

Based on a workshop presentation by Ingvild Jenssen from the NGO Shipbreaking Platform.

1.2. Identifying solutions

To start conversations on this topic, Engineering X convened a global, cross-sector workshop in London on 16–17 May 2024. Participants identified key challenges to ensuring a safe and sustainable end of life for offshore wind infrastructure using three focal areas: 'technology and infrastructure', 'circularity', and 'regulation'. They then looked across these focus areas to develop aims and starting points for action.

This report summarises the key findings and sets out priorities and recommendations identified by the workshop group. This work forms part of the wider Engineering X Safer End of Engineered Life programme's focus on enhancing safety in the decommissioning of offshore infrastructure and ships which began in 2019.

1.3. Workshop principles

To drive an inclusive conversation, develop holistic recommendations, and acknowledge wider impacts, the workshop was guided by principles considering (a) the **international context**, (b) a **systems approach**, and (c) **prioritising safety.**

While offshore wind decommissioning activity will initially be concentrated in Europe, where most of the older wind farms are currently installed, it is important to consider the international context and identify potential impacts globally, as well as the role of non-European stakeholders (see Spotlight 1.2, below). As seen with ship recycling and offshore oil and gas platforms (see Spotlight 1.1), unclear, unsafe, and polluting end-of-life practices are likely to affect parts of the world that are often less well equipped to manage them, and distant from the regions where the assets operated during their productive life.

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Spotlight 1.2 | The global dimension of safety at the end of life of offshore wind

Most offshore wind structures reaching their end of life in the near future are concentrated in Europe and so there is a tendency to consider end of life in a purely European context. The impact and appropriateness of end-of-life practices beyond the imminent wave of offshore wind decommissioning need to be considered though to ensure a globally responsible transition to green energy. Key considerations include:

Exporting safety risks: Following dismantling, decommissioned materials and components will need to be processed onshore. Responsibility for hard-to-recycle materials and components perceived as "waste" must not be passed on by European operators by simply selling them to regions with lower safety and environmental requirements for end-of-life processing.

Contextual differences: Safer end-of-life processes for offshore wind must include the perspectives of possible future offshore wind sites early in the conversation. Decommissioning practices developed in Europe will likely set the industry standard for offshore wind decommissioning more generally. As offshore wind energy continues to expand beyond Europe though, we must consider how the decommissioning process might vary based on context. For instance, geographic aspects, scale of farms or lack of pre-existing offshore infrastructure may all play a role.

Equitable use of resources: Offshore wind infrastructure is resource intensive, particularly for raw materials and rare metals. As many high-consuming countries are transitioning to renewable energy sources, there is a lack of consideration for the safe sourcing and fair distribution of these materials and resources globally (see Section 2.2).

Based on the Safer End of Life for Offshore Wind: Challenge Statement (Engineering X, 2024).

With this in mind, the workshop was designed and convened taking a systems approach. A 'systems approach' is a holistic and interdisciplinary way of considering and addressing complex problems. It requires viewing a challenge as a collection of interconnected and interdependent elements or people and emphasises the relationships and interactions between them. A true systems approach does not deliver solely technical solutions. It ensures the appropriate alignment of technology, processes, interactions, and policy to deliver innovative responses to today's most complex and pressing challenges.

End-of-life processes for offshore wind are complex and consist of many technical, socioeconomic, and environmental systems that are highly interconnected and interdependent on one another. Therefore, it is important to implement solutions that acknowledge those interconnections, uncertainty, and complexity. For the workshop, it meant bringing in a broad range of actors from across sectors and disciplines and to consider throughout who is missing from critical conversations and action.

Finally, running through all of this is the need to prioritise safety in the conversation. Given the scale and complexity of offshore wind infrastructure and the offshore wind sector, safety risks are potentially significant and inequitable and as such must be considered to ensure a just green transition (see Spotlight 1.2, above).

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1.4. Workshop participants

To initiate and promulgate this critical conversation, the workshop brought together 53 people from 14 countries across industry, research sectors, governments and non-governmental organisations (NGOs), and regulators.

Organisations represented included:

- Carbon Trust
- Crown Estate Scotland
- Decom Mission
- EDF Renewables
- Energy Institute
- Equinor
- G+ Global Offshore Wind Health and Safety Organisation
- Global Wind Energy Council (GWEC)
- Indian Register of Shipping
- Kingo Wind
- Lloyd's Register Foundation
- NGO Shipbreaking Platform
- Ocean Conservancy
- Offshore Renewable Energy (ORE) Catapult
- OWC
- RWE
- ScottishPower
- SDHernando Energy and Engineering Consultancy
- Siemens Gamesa
- State Secretariat of Energy and Economy of the Sea of Rio de Janeiro (SEENEMAR)
- The Crown Estate
- The University of Edinburgh
- TNO (Netherlands Organisation for Applied Scientific Research)
- Universiti Teknologi Malaysia
- University of Birmingham
- University of British Columbia
- University of Cambridge
- University of Leeds
- University of Southampton
- University of Strathclyde
- University of Warwick
- Vattenfall
- Velux Fonden
- Vestas
- Wood Thilsted

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2. Focus areas

Participants discussed the challenges and ways forward within three focus areas:

- Technology and infrastructure
- Circularity
- Regulation

An Advisory Group and other stakeholders selected these areas as being most relevant to building a safe, equitable and sustainable end-of-life system for offshore wind infrastructure.

2.1. Technology and infrastructure

Central to developing end-of-life approaches for a new sector is the question: "What technologies and infrastructure are needed for safe and sustainable end-of-life practices?"

While individual offshore wind farms have been decommissioned, these projects were smaller in scale and closer to shore than larger, newer wind farms.[9] There is insufficient experience of decommissioning the type of structures that will be reaching their end of life in large numbers over the coming years.

One participant group focused on questions concerning how to process individual components and materials long term, including for reuse, recycling, and reduction. A second group discussed the logistics, technologies, and infrastructure required for recovery, dismantling, and onshoring of equipment.

2.1.1. What is needed?

- **Standardised, modular structures and design** – so that logistical and technical maintenance and end-of-life processes can be streamlined and a supply chain built.
- **Development of material processing technologies** – including for blades, separating composite materials, recovery of rare earth materials, separating and recycling hose materials, and retaining the high-value materials (such as stainless steels or engineered bearing metals) separately from other, lower-value scrap.
- **Improved logistical processes** – specifically, in terms of heavy crane lifting, vessel availability and use, and port capacities.
- **More accurate and reliable collection mechanisms and availability of better data:**
  - data on components
  – manufacturing records and reliability data
  - occupational health and safety incidents.
- **Standardised, consistent training and skills for safe and circular decommissioning processes.**
- **Regulation and guidelines for end of life** – such as a consistent classification of materials to enable use of decommissioned materials in the manufacturing of new products for easy movement; clarity on removal requirements; inclusion of lifecycle analyses and environmental impact assessments that consider the full lifecycle, from cradle to cradle.
- **Collaboration between stakeholders** – in particular, exchanging knowledge and learning from each other on decommissioning processes; for example, in an international, noncompetitive knowledge-sharing space.

Technology and infrastructure

Key actors

- consumers and price regulators
- fishing industry
- international voice – emerging markets
- investors and financiers
- manufacturers
- regulators
- researchers
- search and rescue; first responders
- specialist and vessel equipment supply chains
- union and trade organisations

Missing perspectives

- environmental regulators
- health and safety organisations
- heavy lift vessel operators and port facilities
- International Maritime Organization
- port authorities

2.2. Circularity

While offshore wind is vital for achieving net zero and sustainability targets, it also requires a large amount of natural resources, such as low-carbon steel, concrete, and (near) critical materials – some of which are only available in limited quantities.[10] The beginnings of a race to secure those materials for offshore wind as well as other renewable energy technologies can already be seen among wealthier countries striving to meet their net zero goals. This means that many resources required for offshore wind will be less easily or not available at all for countries and regions that are just beginning development. Given the global dimension of climate change, reducing carbon emissions in one location at the expense of other parts of the world will continue to reinforce existing inequalities. We must find fairer solutions and develop renewable energy capacity across borders.

There are also issues concerning how these materials are extracted, which often happens under harmful conditions in parts of the world that do not benefit from their use and are already more likely to be exposed to the effects of climate change. For example, a large proportion of the global market for lithium (used in wind turbines, as well as for solar panels and in electric vehicles) is extracted from an area in the Andes shared by Chile, Argentina, and Bolivia;[11] the extraction affects the ecosystems, indigenous communities, and water supplies in the region.

Materials come at high human, environmental, and financial costs, but reducing the amount of materials – through reuse, replacement, and recycling across the lifecycle of a wind farm – can significantly reduce these costs. Circularity must be central.

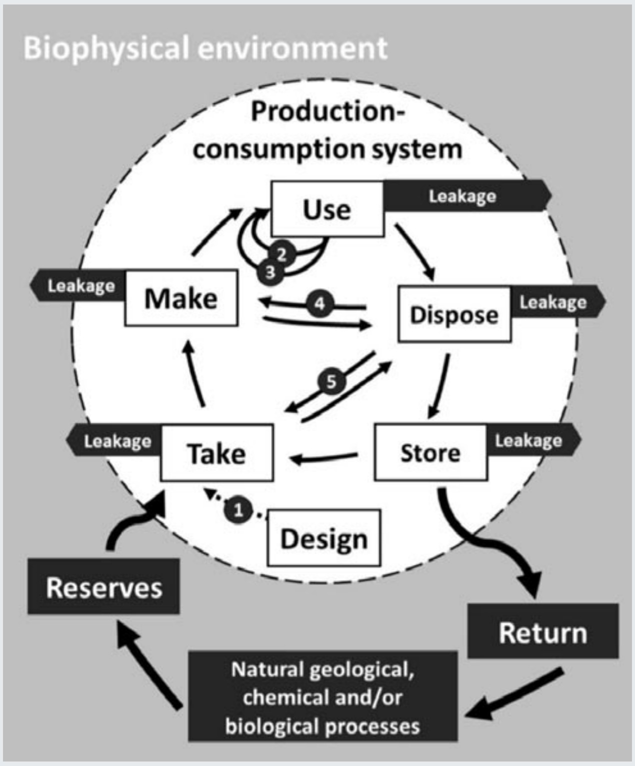
What is a 'circular economy'?

This report adopts a framework that integrates 'sustainable development' and 'circular economy' approaches (see also Figure 2.1).[12]

A 'sustainable circular society' is an equitable society that maintains environmental quality and economic prosperity for current and future generations, incorporating:

- **social and individual wellbeing** – creating conditions that offer equity in realising quality of life that, at a minimum, meets human rights standards for all
- **environmental quality** – using resources within planetary boundaries, enhancing natural capital **within and across generations**
- **economic prosperity** – organising collectively fair access to resources within and across generations to enable social and individual wellbeing and enhance environmental quality.

Fig. 2.1 | **Circular economy: integrated resource flow**



From Velenturf et al, 2019. Notes: Thick arrows are natural materials, thin arrows are industrial materials, dotted arrow is immaterial; (1) prevention by designing out all avoidable wastes, (2) shared consumption, (3) reuse and repair, (4) remanufacturing, (5) recycling)[13]

2.2.1. What is needed?

- **Changes in current mindsets to embed circularity, including:**
  - Understanding that the earth's resources are limited and thus growth cannot be infinite
  - Considering the circularity impact of changes to components resulting from technological improvements
  - Not assuming that end-of-life challenges can be 'exported'
  - Developing business models focused on more than just financial cost (for example, recycling only valuable materials such as metals but not plastics).
- **Engaging stakeholders across the supply chain, including manufacturers, developers, operators and end-of-life suppliers to prepare for future scale and volumes of decommissioning.**
- **Mapping, coordinating, and sharing learning from individual circularity initiatives across the system – for example, via an international working group convened by a neutral body.**
- **A reuse market for components. This requires:**
  - better and widely available data on assets and materials in terms of their (a) history and status, (b) availability, and (c) component location
  - design based on modularity and standardisation of models to allow for sector-wide efficient reuse and repair
  - a circular supply chain that enables effective monitoring, maintenance, repair, reuse, and recycling – current volumes are still small, but the sector needs to start planning and establishing an end-of-life supply chain now
  - training in circular economy and decommissioning practices for the workforce to ensure safety.
- **Regulation that enables circular approaches by:**
  - establishing ownership of the end-of-life process
  - equiring and incentivising circular and safe design solutions – for example, in the bidding process
  - securing implementation through accountability mechanisms.

Circularity

Key actors

- developers/operators
- industry bodies
- original equipment manufacturers (OEMs)
- policymakers
- researchers

Missing perspectives

- certification agencies for materials and components
- decommissioning facilities and people doing the decommissioning work on the ground
- local communities where materials are sourced as well as where recycling occurs
- OEMs
- port owners
- recycling and end-of-life suppliers

2.3. Regulation

Regulation can significantly set the tone and expectations for developing end of life in the sector. Regulation is a key requirement and enabler for better technology and infrastructure processes, and in embedding circularity within a sector and society.

As seen in other sectors, a lack of clear regulation – at national and international levels – can lead to significant challenges. Missing or insufficient decommissioning requirements for offshore oil and gas platforms in the North Sea have meant that decommissioning was substantially underbudgeted and the sector was largely unprepared. This led to health and safety issues in the early decommissioning stages. It also came at a high price for taxpayers; for example, in the UK, the total cost to the government of offshore oil and gas decommissioning due to tax relief is estimated at £24 billion.[14] Cost uncertainty was a challenge too, as it hindered the preparation of investment cases for timely supply chain development.

Spotlight 2.1 | Learning from oil and gas decommissioning

Strategy and planning are critical

- Scope, cost, and schedule – decommissioning is all cost and no revenue, so good planning is essential.
- Work closely with regulators on decommissioning programmes and plans.
- Identify and engage key stakeholders.
- Get early buy-in to your proposed removal method by providing the regulator with a professional comparative assessment.

Competition for resources in the future

- The offshore wind decommissioning sector needs to attract a workforce, ensure there is sufficient specific training available, and build on oil and gas decommissioning skills as a part of the green transition.

Based on a workshop presentation by Callum Falconer from Decom Mission

The decommissioning of ships offers an example of what can happen if national regulations are not aligned and international regulations have loopholes: more than 70% of the world's obsolete ships are taken apart in highly unregulated and unsafe conditions on beaches in India, Bangladesh, and Pakistan and international shipowners are easily able to circumvent responsibility (see Spotlight 1.1).[15]

These challenges in the decommissioning of ships – also increasingly seen with floating oil and gas platforms – demonstrate how important clear regulation at all levels is to embedding safe end-of-life approaches.

Two groups focused on regulatory frameworks. One discussed the mechanisms and processes required for transnational collaboration and communication for the development of end-of-life regulation. The other considered how regulation that enables circularity could be developed. The groups identified challenges in the sector that require regulatory clarity, as well as overarching issues with the process of creating regulation to ensure it is well informed and suitable.

2.3.1. What is needed?

- Regulatory clarity on a number of issues, including ownership across the lifecycle, as well as other requirements for cost, timelines, removal, material classification, health and safety, and environmental factors.
- Incentives to develop innovative and circular solutions.
- Project selection criteria beyond cost alone, such as circularity or safety.
- Context appropriate regulation.
- A well-informed regulator who can set out new regulation and assess cases on a contextual basis.
- More national coordination between agencies involved in the end-of-life process.
- An international guiding framework that:
  - can be implemented more locally
  - is clear but adaptable to contextual differences and technical advances.
- Effective implementation and accountability mechanisms.
- Regional and international collaboration to share best practice and align regulation, especially in neighbouring countries.

Regulation

Key actors

- developers as owners of the end-of-life process
- non-profit sector and lobbies to keep pushing different aspects
- policymakers and government regulators as coordinators of the process
- researchers to input latest research
- well-informed regulators

Missing perspectives

- biodiversity/nature component is missing or added on as a secondary consideration
- coastal and indigenous communities where the projects are situated
- future generations
- end-of-use operators offering reuse and refurbishment solutions
- environmental organisations
- ministries with relevant portfolios
- recycling industry
- research feeding into policymakers

3. Stakeholders

Throughout the workshop, a number of key stakeholders were identified across the focus areas as those who must urgently take action to ensure a safe and sustainable end of life for offshore wind infrastructure.

3.1. Key stakeholders

- **governments** – who set the overall direction towards safety and sustainability for the entire sector
- **regulators** – who develop well-informed, clear regulation internationally, regionally and nationally
- **offshore wind manufacturers, developers and operators** – who prepare the implementation of end-of-life processes
- **researchers** – who provide evidence to inform regulator and industry action
- **non-profit organisations** – who advocate for social and environmental responsibility

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3.2. Other stakeholders and missing perspectives

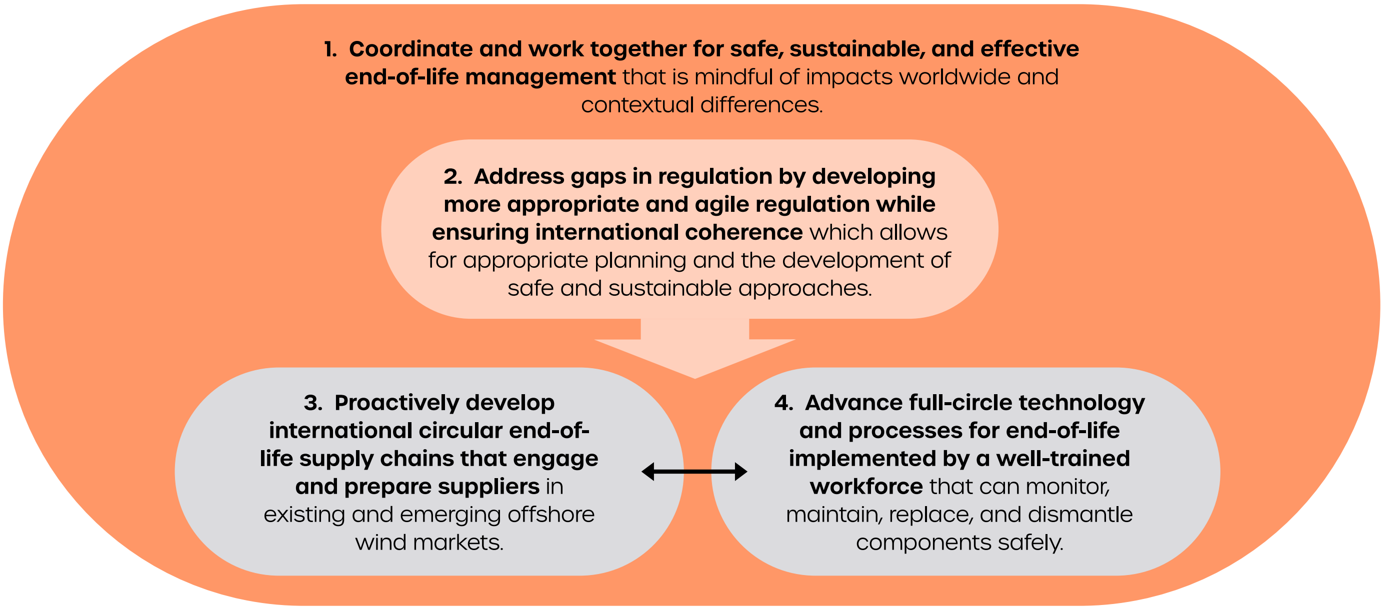
Beyond the key stakeholders who must push action forward, other groups that have a role to play in the end-of-life system were identified during the workshop. In particular, stakeholders who have not been a part of the conversation so far, or who have traditionally been left out in other sectors, must be included:

- **the end-of-life supply chain** – including recyclers, vessel operators, and ports, who must be informed of future volumes and type of materials to prepare
- **financial stakeholders** – such as shareholders, and international financial bodies providing loans, such as the International Finance Corporation and the World Bank, that can set incentives and put pressure on industry to prioritise safe and sustainable end-of-life approaches; similarly, insurance providers, who play an important role in life-extension projects and the reuse, repair, and refurbishment of components
- **communities affected by offshore wind installations** – who must be involved in end-of-life planning and whose interests should be considered as early as possible – including:
    - communities where component materials are sourced
    - adjacent communities to end-of-life processing, both offshore (fishing communities) and onshore (close to ports or recycling plants)
    - indigenous communities who have relationships with the land/ocean affected by offshore wind infrastructure.

4. Findings and recommendations

Ensuring safe and sustainable end of life of offshore wind infrastructure involves a complex system of factors and actors, with many of the requirements, challenges, and opportunities being closely linked and changes in one area requiring action in another. The workshop generated a huge volume of recommendations – highlighting the scale of action that is needed to tackle these challenges – around the themes of technology and infrastructure, circularity, and regulation. The full list is captured in Appendix A. Key findings are grouped here around four emerging categories, as illustrated in Figure 4.1.

Fig. 4.1 | Key findings from the workshop



A **regulatory framework** enables the building of **supply chains** as well as the development of **technical processes**, while activities must be **coordinated** across all three

A number of granular recommendations are collected under each of the key findings in the following sections, which are then synthesised into four priority recommendations from the workshop in Section 5 (see also Table 5.1) as a way forward for safer end-of-life for offshore wind infrastructure.

4.1. Coordinate and work together for safe, sustainable, and effective end-of-life management that is mindful of impacts worldwide and contextual differences

To tackle this complex challenge and make the most of the allied opportunities, activities must be coordinated across regions, sectors, and organisations. However, a lack of clarity regarding ownership of end-of-life processes has slowed learning, collaboration, and streamlining. To reach sufficient volumes and scales of decommissioning, cross-sector and interregional coordination is essential to attract investment for end-of-use infrastructure and equipment. Better coordination is also needed to improve processes for learning from experience and pilots, as well as to avoid duplication of efforts.

The following activities require independent coordination and collaboration:

- addressing gaps in regulation by developing more appropriate and agile regulation while ensuring international coherence which allows for appropriate planning and the development of safe and sustainable approaches (see section 4.2)

- proactively developing international circular end-of-life supply chains that engage and prepare suppliers in existing and emerging offshore wind markets (see section 4.3)
- advancing full-circle technology and processes for end of life implemented by a well-trained workforce that can monitor, maintain, replace, and dismantle components safely (see section 4.4).

Such coordination and collaboration is needed in relation to many stakeholders (see section 3 and Appendix A), but in particular regarding:

- the lifecycle of offshore wind infrastructure
- the supply chain
- geographical boundaries
- offshore wind markets of varying maturity levels
- relevant sectors, such as the onshore wind sector and any others requiring similar recycling capability.

4.1.1. Establish an international working group

This working group would take ownership of mapping and coordinating existing activities across the remaining three key finding categories: addressing gaps and developing appropriate and agile regulation, developing circular end-of-life supply chains that engage and prepare suppliers, and advancing full-circle technology and processes for end of life. It would be global and could be broken down by regions.

It would also facilitate learning by convening independent, noncompetitive sharing spaces and raise awareness for end-of-life issues where necessary. The working group could be located within an existing organisation with international recognition and connections in the sector, such as the Global Wind Energy Council (GWEC).

4.1.2. Develop benchmarks and a roadmap

Benchmarks are needed to ensure a high standard for end of life. The working group could develop these and coordinate an international roadmap to achieving them regionally and globally. This would be particularly helpful for coordination on the development of regulation and technology, but also for the development of supply chains nationally and internationally.

4.1.3. Raise awareness

Highlighting the importance of end-of-life issues will help to involve all required stakeholders in end-of-life activities. Securing buy-in from key actors is necessary for better collaboration and coordination, such as sharing learning from pilots, developing best practice, or preparing an end-of-life supply chain.

Key stakeholders with which to raise awareness include:

- **local, regional, national, and global governments** – to develop regulation
- **the full supply chain** – so that mid-lifecycle operators and developers can prepare for end of life, by identifying needs and establishing connections with end of life
- **international organisations** – such as GWEC, so that they can push end of life in international settings and emerging markets, as well as potentially coordinate activities
- **engineering workforce bodies** – to build skills and raise visibility of end of life
- **investor communities and financial services** – to understand the potential implications of a lack of end-of-life planning
- **educational institutions** – to incorporate awareness of circular economy and end-of-life design of engineering structures in the tertiary curriculum
- **local communities** – to highlight the importance and benefit to local supply chains of the recovery, reuse, and recycling of materials.

4.1.4. Establish and facilitate learning mechanisms

There is currently a lack of learning and knowledge exchange between different parts of the offshore wind lifecycle and supply chain. Mechanisms for better two-way communication between stakeholders is needed so that insights on what is working and what is not informs new design – for example, feeding insights from engineers on the ground back to OEMs and research.

4.1. Recommendations

to coordinate and work together for safe, sustainable, and effective end-of-life management that is mindful of impacts worldwide and contextual differences:

1. **Establish an international working group** for safe and sustainable end-of-life practices.
2. **Develop benchmarks and a roadmap** for coordination on development of regulation, technology, and supply chains.
3. **Raise awareness** across the sector of the importance of end-of-life issues to get all relevant stakeholders involved.
4. **Establish and facilitate learning mechanisms** across the supply chain.

4.2. Address gaps in regulation by developing more appropriate and agile regulation while ensuring international coherence which allows for appropriate planning and the development of safe and sustainable approaches

Another key finding concerned the lack of clear regulations, policies, and standards for all aspects of the end of life of offshore wind infrastructure.

Regulatory issues were discussed in two broad categories:

1. gaps in regulation that require clarity or improvement (see section 4.2.1, below)
2. overarching issues with the process of creating regulation to ensure it is well informed and suitable for the sector (see section 4.2.2.).

4.2.1. Gaps in regulation that require clarity or improvement

In the current system, there is no clearly assigned ownership of the end-of-life process and a lack of investment. This has inhibited development of end-of-life processes, despite the fast-growing sector and obvious future opportunities and challenges. Governments must urgently take initiative and explicitly include decommissioning in regulatory requirements and leasing agreements – beyond an acknowledgement or pro-forma requirement – to instigate processes.

4.2.1.1. Ownership

Clarifying ownership of the end of life of offshore wind infrastructure was raised by workshop participants as a significant issue. The uncertainty impacts the entire end-of-life supply chain and can lead to a lack of initiative or incentive to develop end-of-life methods.

Key questions in terms of ownership are who holds the ownership of the asset (for example, is it the state or is it privately owned) and, consequently, who is liable for decommissioning? A regulatory framework is needed to clarify ownership across the system and associated liability for decommissioning.

One option might be to apply a usage-based business model: could offshore wind move to a usage-based business model following the example of Rolls-Royce aircraft engines?[16] If OEMs were responsible for an asset for its entire lifecycle, including the end of life, this would incentivise design for life extension and end of life. OEMs already provide warranties that include maintenance and replacement, so there is opportunity to build out from the current system. Implementation questions arise, though, as this asks OEMs to take on the lifecycle risk. Consideration for how this might be managed – for example, through potential compensation across the supply chain for taking on the responsibility – is needed.

4.2.1.2. Incentives and accountability

Decommissioning is already a requirement, depending on the jurisdiction. Although safe and circular approaches could reduce costs and risks, they may require additional incentives to start off.

Guidance and initiatives from policymakers for safety and sustainability could increase interest and funding available for circular and end-of-life processes. Governments and leasing bodies could, for example, not award projects on cost alone but instead include non-price criteria:

- strengthening effectiveness of environmental impact assessments
- including lifecycle analyses in licensing [17]
- requiring sensitivity to local needs, especially in emerging markets to ensure projects are not detrimental to their most immediate context
- including circular design, reuse, and remanufacturing incentives
- including life extension and repowering incentives
- including sustainable sourcing of materials incentives

In one example of assessing non-price criteria in tenders and auctions, for the Dutch Ijmuiden Ver wind farms Alpha and Beta, tender criteria incorporated a circular economy section on circular design, including the use of alternative materials and critical/strategic raw materials, carbon footprint, and knowledge exchange.[18]

Moreover, business incentives could be created to boost activity and ensure stability for investment in the supply chain. These should be for safe and circular design, reuse, and remanufacture solutions. While there are already some innovation competitions and platforms, governments could increase this through competitions for solutions.

4.2.1.3. Costs and financial requirements

There is a poor understanding or avoidance of consideration of end of life and decommissioning costs in the current system. End of life is thus not adequately budgeted and planned for. Regulators need to set clear – and well-informed – financial requirements for early inclusion in budgets. Key considerations include:

- The question of ownership affects decommissioning costs: whose liability is the asset at the point of decommissioning and who bears its cost and risk?
- The cost is not meaningfully or accurately incorporated in the current context. Predicting costs is difficult because of inflation, market fluctuations (for example, vessel markets), and uncertainty over design lifespan. How can this be incorporated into requirements?
- Initial decommissioning projects have proven to be a lot more expensive than budgeted for, which results in safety risks and highlights the importance of appropriate budgeting.
- What mechanisms could be used to ensure the decommissioning costs can be covered long term despite uncertainty about exact costs and changes in ownership?
- Efforts to develop financial requirements should be coordinated across jurisdictions, to ensure requirements are harmonised. This is crucial to avoid countries with lower requirements becoming havens for developers and undermining the effectiveness of requirements.
- How can low-cost financing opportunities for offshore wind, especially in emerging markets, anticipate and include decommissioning costs?

4.2.1.4. Other regulatory gaps

- There is a lack of clear decommissioning timelines and expectations. This leads to difficulties in planning and appropriate supply chain development. Regulation should include expected timelines for removal, repowering, and life extension to allow time for preparation.
- There is a lack of regulation and requirements regarding what must be removed.
  - Developing this should include context-specific considerations; for example, on biodiversity – if the seabed was heavily trawled at the point of installation, should the requirements be different from those for a landscape with a different biodiversity load?
  - There is a lack of clarity on best practice for cables in the seabed. Key questions include: Does everything need to be recovered and is it possible to recover it? What are the risks to leaving in situ, from a circularity perspective and directly to other ocean users and the marine environment? What are the consequences for other land-based or marine ecosystems, which will be subject to more mining as a result?
- Current regulatory classifications of materials pose problems for the logistics of recycling. In particular, the classification of end-of-life materials and components as hazardous waste

hinders transboundary movement of materials for circularity and reuse, thereby disincentivising such practices.

- There is a lack of regulation banning landfilling composites. Some countries already ban landfilling of wind turbine blades; however, many do not. Industry itself is pushing on this front, and, recently, the European industry trade body, WindEurope, called for a Europe-wide ban.[19]

4.2. Recommendations

to address gaps in regulation by developing more appropriate and agile regulation while ensuring international coherence which allows for appropriate planning and the development of safe and sustainable approaches

4.2.1. Gaps in regulation that require clarity or improvement

Ownership:

5. Establish a guideline to specify which actors have which responsibilities at each point in the lifecycle of a wind turbine and wind farm, based on current legislation. Clarify ownership for all parts of the lifecycle, including the end-of-life process.

Incentives and accountability:

6. Assess what is realistically possible in terms of safety and sustainability, then set ambitions through regulation, accountability mechanisms, and incentives.
7. Create policy incentives for businesses at end of life to boost activity and ensure stability for investment in the supply chain.

Costs and financial requirements:

8. Consider the ownership of decommissioning costs and identify better mechanisms to ensure costs can be covered, to then develop guidance and requirements for decommissioning costs.
9. Connect regulatory incentivisation to project finance – for example, through environmental, social and governance (ESG) performance standards of lenders.

Other regulatory gaps:

10. Identify best practice and create regulation on biodiversity considerations, removal requirements, classification of end-of-use materials, banning the landfilling of composites.
11. Planning coordination: include offshore wind decommissioning in marine spatial planning (MSP).

4.2.2. Overarching issues with the process of creating regulation to ensure it is well informed and suitable for the sector – nationally

4.2.2.1. Developing context appropriate regulation at the national level

The lack of end-of-life regulatory experience in the offshore wind sector is a challenge, but also an opportunity to develop adaptive and thorough regulation. One key challenge in developing regulation is that the sector is so varied – differences in age, size, location, and so on mean that appropriate end-of-life processes have to look significantly different for different projects.

A goal-based approach to regulation at a national level would enable versatility to tailor decommissioning plans to different regions but also ensure that all decommissioning was underpinned by a common value set. This would enable clarity and planning assurance for industry while not prescribing blanket processes. A precondition for a goal-based approach to work, though, is a well-informed regulator who can develop and interpret such a framework and apply regulation appropriately to different projects.

4.2.2.2. Well-informed national regulators are key

Countries need confident regulators who are well informed on design policies and who can set out different options for different kinds of projects, ensuring that decommissioning plans are integrated appropriately into new projects. Upskilling regulators would enable them to make evidence-based decisions on a case-by-case basis with transparent reasoning for regulatory decisions. A process of information from fundamental research to inform regulators as well as assessments from independent researchers is needed.

4.2.2.3. Driving regulatory standards at the national level

The process of setting standards is complex because the end-of-life process is new and technically challenging. Regulators often have limited capacity and technical expertise, but regulatory standards are required urgently. It is likely that industry will push forward standard setting regardless and establish best practice if there is no formal guidance. This presents risks of industry bias towards considering costs over social and environmental factors. A neutral body is needed to drive the process. If regulators lack capacity currently, a cross-sector task force incorporating industry, research, and regulators led by an independent body is needed to set the process in motion.

4.2.2.4 National collaboration and coordination

There is currently a lack of coordination between national agencies and ministries involved in offshore wind project lifecycles. Addressing this on a country-by-country basis is necessary in order to be adaptable to the differing national combinations of ministries with responsibility for elements of the end-of-life process for offshore wind infrastructure.

Ministries must coordinate better in the design of regulations. Often, leases are granted by one agency while decommissioning plans are monitored and reviewed by another – however, from a regulatory point of view, these cannot by separated out.

Similarly, there is a lack of collaboration between oil and gas and offshore wind decommissioning bodies, as they often sit under different ministries, which means that experience from the oil and gas sector is not drawn on appropriately.

4.2.2.5. Sharing regulatory plans

Better information on regulation development plans is needed – as well as transparency on the considerations of impacts informing this development.

Constructing an overview of development plans, including a pathway towards regulation for industry that sets a timeline providing clarity on what will be expected at which point, would enable industry to plan early and develop relevant supply chain parts.

4.2. Recommendations

to address gaps in regulation by developing more appropriate and agile regulation while ensuring international coherence which allows for appropriate planning and the development of safe and sustainable approaches

4.2.2. Overarching issues with the process of creating regulation to ensure it is well informed and suitable for the sector – nationally

Developing context appropriate regulation at the national level:

12. Create a goal-based context-adaptive regulatory framework rather than one-size-fits-all removal requirements.

Well-informed national regulators are key:

13. Enhance regulator knowledge on the subject matter and establish an informing process from research and industry to regulators.

Driving regulatory standards at the national level:

14. Establish a task force between industry, research, and regulators to drive the development of regulatory standards.

National collaboration and coordination:

15. Enhance collaboration across national agencies who are involved in the offshore wind sector.

Sharing regulatory plans:

16. Regulators should create and share their plans for regulation and pathways for implementation to support industry preparation.

4.2.3. Overarching issues with the process of creating regulation to ensure it is well informed and suitable for the sector – internationally

4.2.3.1. Implementation and accountability

Offshore wind and its supply chains are international and so coordination to set international and regional standards for regulation is critical to avoid exporting risk to less well-regulated areas (see Spotlight 1.1 in the first section for a case study on shipping).

In addition to regulators, other actors could hold the sector accountable:

- financial accountability – is there a way to achieve accountability through financial incentives and subsidies?
- social accountability – public opinion can put strong pressure on the private sector, especially in offshore wind.

4.2.3.2. International versus national guidance

International guidelines do not necessarily result in regulatory changes in jurisdiction – as the example of shipbreaking, and the ease with which current international law can be evaded, shows (see Spotlight 1.1 in the first section). However, international guidelines are still necessary to ensure international coordination on minimum standards. These minimum standards can then be transferred into more specific, locally appropriate national laws.

Therefore, regulators need to set international standards inclusively so they can apply globally, including in emerging and future offshore wind markets. A key challenge, though, is that it is unclear which international body or bodies are best placed to set standards and regulation for offshore wind decommissioning.

4.2.3.3. International collaboration and coordination

Regulators must share good practice and information internationally. This would enable learning from one another, setting international regulatory standards, and thereby avoiding regulatory dissonance, vacuums, or havens.

Although there are international organisations working on wind, currently, none are focused on end of life. Coordination – in particular, regionally – is critical to establish streamlined regulation, so regional or international working groups including emerging and future offshore wind markets need to be developed.

Photo from iStock

4.2. Recommendations

to address gaps in regulation by developing more appropriate and agile regulation while ensuring international coherence which allows for appropriate planning and the development of safe and sustainable approaches

4.2.3. Overarching issues with the process of creating regulation to ensure it is well informed and suitable for the sector – Internationally

Implementation and accountability:

17. Develop accountability mechanisms to ensure consistent implementation of regulation across borders.
18. Develop social accountability mechanisms by engaging communities of interest/communities of place.
19. Develop financial accountability by influencing financial institutions.

International versus national guidance:

20. Identify the right international organisations that should take on responsibility for developing standards or guidelines at an international level, which can be specified into more local, context-specific regulation.

International collaboration and coordination:

21. Collaborate internationally to develop international regulatory standards – for example, through regional and international working groups.

4.3. Proactively develop international circular end-of-life supply chains that engage and prepare suppliers in existing and emerging offshore wind markets

The end-of-life supply chain must be developed to ensure the sector's growth can be sustained safely and sustainably for the entire lifecycle. Otherwise, the consequences could include bottlenecks, exporting the challenge of processing decommissioned components to regions even less well equipped for it, and wasting valuable resources.

4.3.1. Identify the best business approach

Options range from full integration of decommissioning into the developer, to contracting out the decommissioning to closely linked separate entities, all the way to separating the decommissioning entirely from the developer. Identifying the different models and establishing best practice is critical to ensure smooth coordination across suppliers.

4.3.2. Engage the end-of-life supply chain

The offshore wind industry as a whole and manufacturers, developers, and operators in particular must engage the potential end-of-life suppliers. Future demand must be communicated now, in order to plan ahead and begin to build the supply chain.

Specifically, the following stakeholders must be engaged:

- port authorities and owners – need to develop new ports as the current installation ports will be in full use for new offshore wind infrastructure, and thus will not be available for decommissioning projects
- vessel suppliers – need for dedicated ships that are designed for turbine decommissioning, and are not competing with installation vessels
- the wider end-of-life and recycling industry – existing decommissioning and waste recycling suppliers are not connected into the offshore wind world; the offshore wind sector needs to link in with them so they can prepare for the type and volume of materials that will need to be processed.

4.3.3. International coordination on supply chains

International coordination is necessary to provide certainty and create large enough markets for the establishment of regional supply chains. In many cases, individual countries, especially in emerging markets, will be too small to build all facilities – as learned from the Association of Southeast Asian Nations (ASEAN) oil and gas decommissioning cases (see Spotlight 4.1).

Spotlight 4.1 | Learning from oil and gas decommissioning

Key lessons from oil and gas decommissioning in the ASEAN

- **Shared resources:** Some countries do not have enough capacity to build individual decommissioning supply chains. Need a regional approach – for example, building a regional decommissioning yard.
- **Unified regulations:** There are no regional regulations specific to decommissioning. Need regional guidelines that are context specific.
- **Circularity:** Rigs to reef, reuse. Require guidelines – impact, benefits, transfer of ownership and liabilities.
- **Challenges:** Recycling yards readiness, issues of hazardous waste transboundary movement under the Basel Convention.[20]
- **Financial framework:** Cess fund, financial capabilities, future liability, residual risks.
- **Sharing platforms:** Need for a database of assets for reuse candidates, information sharing, best practices of decommissioning experiences.

Based on a workshop presentation by Professor Omar bin Yaakob from Universiti Teknologi Malaysia.

4.3.4. Build a reuse market for offshore wind

Circular practices require a sector-wide reuse market. A reuse market depends heavily on the availability of good monitoring and maintenance data, as well as clarity on warranties beyond initial ownership from OEMs.

Ideally, over time, the sector will adopt fully modular structures and design for the easy repair, reuse, and exchange of parts. The onshore wind sector is more advanced in terms of resale and reuse, so understanding the onshore system offers a good starting point.

Figure 4.2 and Figure 4.3 illustrate potential approaches for optimising the use of resources and their flows: the R-ladder in Figure 4.2 sets out the hierarchy of resource use in a circular economy; Figure 4.3 is a list of principles to design for the most ideal resource use ('R').

Photo by Rob Weddon on Unsplash

Fig. 4.2 | R-ladder chronicling the different stages of resource use and waste management in a circular economy according to R-strategy [21]

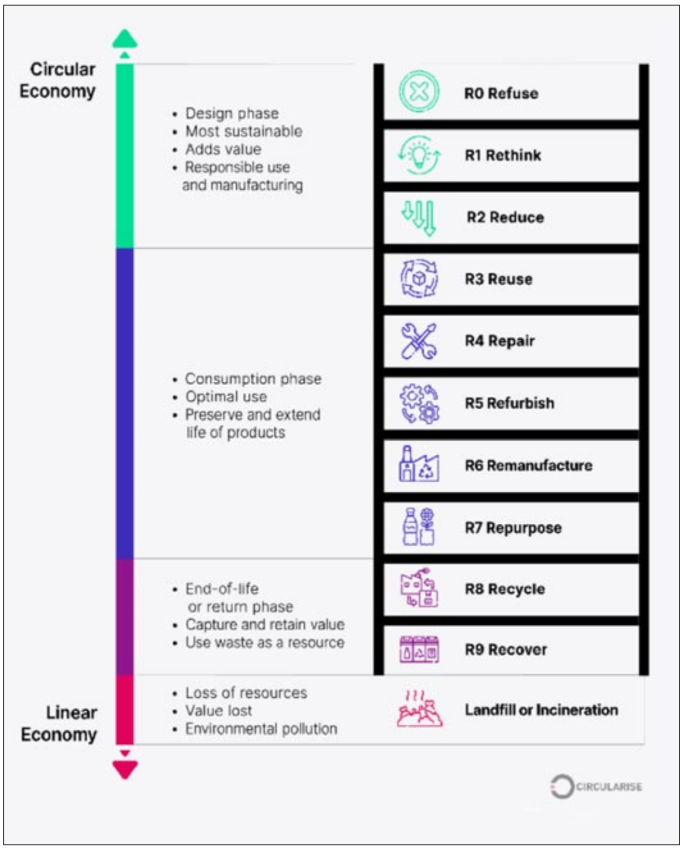


Fig. 4.3 | Principles for designing components, products, and infrastructure for the most efficient resource use [22]

R-strategies

- avoid hazardous and environmentally harmful materials
- prefer materials that can be reutilised easily
- allow for the use of remanufactured components
- design easily joining elements
- minimise variety of materials
- design for more easy transportation for assembly and pre-disassembly
- avoid materials and components incompatible with recycling processes in specific locations

4.3. Recommendations

to proactively develop international circular end-of-life supply chains that engage and prepare suppliers in existing and emerging offshore wind markets

22. **Identify the best business approach** for managing the decommissioning process.
23. **Engage the end-of-life supply chain** so it can prepare and build capacity.
24. **Coordinate efforts regionally and internationally** in establishing end-of-life supply chains.
25. **Build a reuse market** for offshore wind, learning from other sectors as well.

4.4. Advance full-circle technology and processes for end-of-life implemented by a well-trained workforce that can monitor, maintain, replace, and dismantle components safely

4.4.1. Current practices that make safe and sustainable end of life more difficult

4.4.1.1. Lack of interest in recycling and developing new recycling technologies

There is insufficient focus on recycling and developing new recycling technologies. Establishing economic mechanisms and policy measures to incentivise the development of creative and effective reuse and recycling approaches is needed.

4.4.1.2. Rapid evolution of technology

Efforts to improve technologies are important to improve efficiencies and processes. However, they can also be a barrier to designing for circularity because the original parts become redundant, rather than reusable. Careful thought is required on how to combine new and optimised technology with more standardisation for circularity.

4.4.1.3. Contextual differences

Contextual differences in infrastructure mean that logistical challenges and solutions may look very different in different cases: shallow versus deep waters, varying lifespan of different elements of a wind farm, varying locations. Flexible and multiple solution paths are needed to apply in different contexts.

Photo from iStock

4.4. Recommendations

to advance full-circle technology and processes for end-of-life implemented by a well-trained workforce that can monitor, maintain, replace, and dismantle components safely

4.4.1. Current practices that make safe and sustainable end-of-life more difficult

Lack of interest in recycling and developing new recycling technologies:

26. Raise awareness of the importance of and opportunities in circular practices to increase the development of better life extension, reuse and recycling technologies.

Rapid evolution of technology:

27. In the design and development stage, consider the impact of technological advances on the whole lifecycle and factor in circularity needs.

Contextual differences:

28. In planning, develop logistical solutions that are context adaptive.

4.4.2. End-of-life processes that require further development

4.4.2.1. Material processing approaches

Many of the materials used in wind turbines, particularly in the blades, can be difficult to separate and recycle. However, there are opportunities and first examples of innovative technologies.[23]

Continued development of processes for component and material reuse and recycling is critical to embed circularity and reduce the overall materials required. Some of the key processes required include foundation structure recovery, subsea cable recovery, and rare earth material recovery.

4.4.2.2. Logistical challenges

There are several key logistical challenges that require more attention, research, and development:

- Heavy crane lifting is a significant logistical challenge, with risks such as capsizing when pulling structures out of the seabed.
- There is a lack of availability of vessels and equipment overall, as well as a lack of appropriate vessels for different turbine sizes to work efficiently on decommissioning and not compete with installation.
- There is a lack of longer-term solutions for avoiding current bottlenecks – for example, to reduce vessel time required, could parts of the turbine (such as blades) be towed onshore for decommissioning?
- Opportunity to conduct further research into the technology challenges and into context-specific emerging markets.
- Move to zero carbon vessels.
- Minimise time offshore – reducing time spent offshore to ensure efficiency in maintenance and decommissioning.

4.4.2.3. Monitoring tools

Maintenance is essential for extended component use and good end-of-life decision-making – for example, to inform circular practices (such as those in the R-ladder; see Figure 4.2) and to enhance safety for workers involved in the end-of-life process. Maintenance relies on better monitoring and root-cause analysis to understand the assets and opportunities. Clear and meaningful warranties also play an important role, ensuring assets can be returned to the manufacturer to replace and repair.

4.4.2.4. Enabling reuse and life extension

Increasing data transparency regarding components and materials offers a significant opportunity to increase safe and circular practices. Data enhances the sector's ability to maintain, replace, reuse, recycle, and dispose of components effectively. Critical data includes:

- the history of all components and materials, including on the full use of each component as well as its maintenance history – current standard information only covers whether or not a part is working, which is not sufficient
- which assets are reaching their end of life when – and, thus, which parts may become available.

While some of this data is simply not available, much of it is and the missing element is sharing it across the supply chain. For example, operators may often not have the data stored by OEMs, or information operators hold from in-service monitoring is not available to other partners. Developing ways to store and share this information across the supply chain is critical. One potential method is 'material passports'. There are some examples of pilots, but there is no established process thus far.[24]

4.4.2.5. Increasing health and safety data to enable accident analysis and learning

While there is an existing platform for collecting health and safety data run by the G+ network,[25] overall, there is a lack of health and safety data on existing accidents available. Establishing and sharing a sector-wide accident log is needed, as well as thorough accident investigation for existing cases.

4.4.2.6. Training and skills

There is a lack of standardised, consistent training and skills development for decommissioning. Practical guidance and training for end of life and circularity are needed. Key challenges include:

- The technology is changing significantly and rapidly, from major components down to fittings and connections, and ancillary systems of hoses, pipes, and so on. This is especially true between manufacturing runs and different wind farms, but sometimes even within the same wind farm and thus part of the same manufacturing production run.
- Decommissioning is often not considered to be as attractive as working on new projects – how can the sector attract the workforce required to safely manage end of life?
- Skills and knowledge are not shared between actors involved in decommissioning: there is generally a lack of communication between different sectors (such as between academia and industry) and different stages of the lifecycle (such as between manufacturers and decommissioning providers).

4.4.2.7. Business opportunities

End of life holds many opportunities for local and global businesses across sectors and even the lifecycle. Some opportunities discussed during the workshop are outlined below.

Safe and circular business opportunities

- Develop higher-value recycling methods for turbine blades
- Develop higher-value recycling methods for materials
- Develop digital twins and monitoring tools
- Develop a system for enhanced data collection and sharing on components and materials to enable reuse and life extension
- Develop and establish use of a convenient platform for health and safety data collection to enable learning and analysis from past accidents
- Provide training in circular economy and decommissioning practices to existing offshore wind workforce, who are mostly focused on current construction and maintenance
- Provide stakeholder engagement training on specific areas of expertise, such as participation process management or communications
- Develop best practices for heavy crane lifting
- Develop alternative solutions to avoid current logistical bottlenecks for example on vessel use
- Develop context-specific logistical solutions for emerging offshore wind markets

4.4.2.8. Piloting

In order to test out and build the case for any new processes, pilots and feasibility studies are urgently needed. Learning from pilot projects and demonstrator sites is essential to make the case for safe and sustainable end-of-life business models: building case studies, concrete examples of successful and unsuccessful pilot projects, lessons learned.

While there is already a lot of activity in terms of piloting for end of life, this is mostly at the individual business level or through smaller industry programmes. Pilots are not at a large scale and activity is not coordinated or learning shared and available for the wider sector.

There is a need to:

- **map existing end-of-life activity**
- **coordinate and collaborate on activities to avoid duplication**
- **capture learning from activities**
- **share learning in an accessible, central place with an easy search function**
- **establish a learning culture**
- **design for decommissioning before the project start.**

Photo from iStock

Examples of projects focusing on offshore wind end of life

- ORE Catapult's Circular Economy for the Wind Sector (CEWS) joint industry programme
- EU-funded EoLO HUBS 'Wind turbine blades End of Life through Open HUBs for circular materials in sustainable business models' project
- International Energy Agency (IEA) Wind Technology Collaboration Programme (TCP) Task 45 – recycling wind turbine blades
- National Composites Centre's (with ORE Catapult, The Crown Estate, and RenewableUK) SusWIND programme – accelerating sustainable composite materials and technology for wind turbine blades
- European Metal Recycling's (EMR) Re-Rewind partnership with HyProMag, ORE Catapult, Magnomatics, and University of Birmingham, part funded by Innovate UK – establishing a circular supply chain for the rare earth magnets used in wind turbines
- The West Flanders Development Agency's (POM West-Vlaanderen) OWiDEX (Offshore Wind Decommissioning Expertise Center) project – centralising knowledge and fostering innovation in decommissioning offshore wind turbines in Belgium
- Blue Cluster's Circular Transition in Offshore Wind (CTO) project – increasing expertise in the field of circularity and sustainability assessments
- GROW partners' Hydraulic Pile Extraction Scale Tests (HyPE-ST) project – testing the removal of piles at the end of their operational life

4.4. Recommendations

to advance full-circle technology and processes for end-of-life implemented by a well-trained workforce that can monitor, maintain, replace, and dismantle components safely

4.4.2. End-of-life processes that require further development

Material processing approaches:

29. Develop higher-value recycling methods for turbine materials and other elements of offshore wind farms, especially foundation structure recovery, subsea cable recovery, and rare earth material recovery.
30. Design new infrastructure for circularity where possible, including to reduce, reuse, and repurpose components.

Logistical challenges:

31. Invest in developing context-adaptive key logistical practices and supply chains – especially regarding heavy crane lifting, vessel infrastructure and availability, and moving onshore where possible to minimise time offshore.

Monitoring tools:

32. Develop remote asset integrity monitoring tools.

Enabling reuse and life extension:

33. Industry to develop systems for enhanced data collection and – critically – sharing, to improve sustainability. Incentives from government could help move this forward quickly.[26]

Increasing health and safety data to enable accident analysis and learning:

34. Encourage and establish use of platforms for health and safety data collection for the decommissioning of offshore wind infrastructure such as the G+ database to ensure learning from past accidents.

Training and skills:

35. Train providers to develop standardised and consistent training for decommissioning.
36. Raise the profile of decommissioning roles and provide training in circular economy and decommissioning practices to existing offshore wind workforce, mostly focused on current construction and maintenance workforce.
37. Provide stakeholder engagement support on areas of expertise, such as participation process management or communications.

Business opportunities:

38. Develop safe and circular businesses.

Piloting:

39. Coordinate end-of-life pilot projects for cross-sector learning.

5. Priority recommendations

As evidenced in the key findings and wealth of recommendations showcased in the previous section, there is a lot to be done to move towards safe and sustainable end-of-life management for offshore wind infrastructure. To help navigate this, the below table summarises the four key findings, alongside priority recommendations assigned to each providing a starting point and suggestion of those actors in the sector who are well-placed to lead on each.

Table 5.1 | **Key findings and priority recommendations**

KEY FINDING	PRIORITY RECOMMENDATION	WHO SHOULD LEAD?
1 **Coordinate and work together for safe, sustainable, and effective end-of-life management** that is mindful of impacts worldwide and contextual differences.	**Launch a global, inclusive working group** – a neutral body to establish an inclusive, international working group that can raise awareness across the sector, convene stakeholders, set benchmarking targets, and coordinate activities across regulation, supply chains, and technological developments for safe and sustainable end-of-life processes for offshore wind.	• **A neutral body active in offshore wind, such as an intergovernmental body or an NGO**
2 **Address gaps in regulation by developing more appropriate and agile regulation while ensuring international coherence** which allows for appropriate planning and the development of safe and sustainable approaches.	**Develop international and national standards** – a neutral body to convene cross-sector actors to cocreate a framework that can be adopted by regulators. National regulators in countries with established or emerging offshore wind infrastructure will embed the framework in their respective national regulation. At the international level, the regulatory bodies responsible will be identified and the importance of end of life raised with them.	• **International regulatory bodies** • **National governments and regulatory bodies** • **Non-profit sector** • **Researchers** • **Trade bodies**
3 **Proactively develop international circular end-of-life supply chains that engage and prepare suppliers** in existing and emerging offshore wind markets.	**Collaboratively map and forecast end-of-life material flows** – industry and research to jointly map end-of-life materials. First, assess when and what minimum volumes are likely to emerge, in order to inform investment, scaling, and timelines. Then, reach out to end-of-life suppliers to prepare logistically and develop the skills and workforce needed (ports, vessels, and resource management sector).	• **Developers and operators** • **End-of-life supply chain** • **Researchers** • **Trade bodies**
4 **Advance full-circle technology and processes for end of life implemented by a well-trained workforce** that can monitor, maintain, replace, and dismantle components safely.	**Maximise learning by coordinating pilots and gaps** – cross-sector actors to build on initiatives to map existing technologies, approaches, and pilots, and then coordinate and share learning from piloting efforts. Meanwhile, develop and train the workforce for decommissioning processes.	• **Developers and operators** • **Non-profit sector** • **Researchers** • **Trade bodies**

6. Conclusion and afterword

Offshore wind infrastructure is essential in a world transitioning to green energy production. As global offshore wind capacity continues to increase, planning for decommissioning must be embedded into the sector. This will ensure the safe removal and transport of these immense offshore assets as well as the responsible management of the components and materials once brought to shore.

Other sectors have demonstrated that insufficient consideration of end-of-life processes can be extremely harmful to people and the environment. Safety challenges are often displaced to parts of the world distant from the beneficiaries of the asset and which are least able to manage them. We cannot repeat the same mistakes: now is the time to set up systems for a safe and sustainable approach to dealing with offshore wind infrastructure at the end of its design life.

This report has outlined the discussions and findings from an international, cross-sector workshop of key stakeholders, convened by Engineering X. The sheer volume of recommendations and drive for action displayed from participants across the industry underlines the scale and urgency of the challenge. We must now take action to establish the systems required – before the first big waves of commercial-scale decommissioning are due.

The key findings and priority recommendations for action shared in this report suggest a path forward. It calls on cross-sector partners to collaborate on this complex challenge. Actors and partnerships must take an inclusive approach, examining the problem in its global context, considering the consequences of inaction or bad practice internationally, and who's voices must be included. They must also take a systems approach, working in a holistic and interdisciplinary way, sensitive to the connections between actors and elements.

The scale and urgency of the challenge is evidently huge. However, the potential opportunities are also great: the offshore wind sector has an exciting and unique chance to learn from other sectors' good practice and mistakes – and to do things well from the start. Action is required now though, as the first commercial-scale decommissioning projects are fast approaching.

At Engineering X, we are ready to support stakeholders in this work. We will continue to convene key actors and to champion the unheard voices in the system in order to ensure that safety and sustainability are at the core of end-of-life approaches. We encourage others to consider their roles too – however large or small – in raising awareness of the challenge and implementing the recommendations for solutions.

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Engineering X Safer End of Engineered Life Offshore Wind Advisory Group Chair

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Advisory Group

Many thanks to our dedicated and thoughtful Advisory Group who were instrumental in shaping the workshop and this report.

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Presentations and speakers

Identifying the challenge

- **Introductory presentation: safer end of life for offshore wind infrastructure**
  Professor Susan Gourvenec FREng, University of Southampton
- **Technology and infrastructure for safety at end of life for offshore wind**
  Lorna Bennet, ORE Catapult
- **Circularity considerations for safety at end of life for offshore wind**
  Eve Andrews, The University of Edinburgh
- **Regulatory considerations for safety at end of life for offshore wind**
  Ingvild Jenssen, NGO Shipbreaking Platform
- **The global dimension of safety at end of life for offshore wind**
  Wangari Muchiri, GWEC

Learning from practice

- **Lessons from offshore oil and gas decommissioning in South East Asia**
  Professor Omar bin Yaakob, Universiti Teknologi Malaysia
- **Lessons learned from the decommissioning of oil and gas**
  Callum Falconer, Decom Mission
- **Examples of circularity**
  Dr Anne Velenturf, University of Leeds
- **Blade recycling**
  Dr Claire Barlow, University of Cambridge
- **Example of circular onshore decommissioning**
  Kasper Buhl Andersen, Kingo Wind
- **Blade recycling and community involvement**
  Alejandra Fabiola Herrera García; Rachel Ventura Loyola, Siemens Gamesa
- **Making the business case for life extension**
  Alastair Muir Wood, Wood Thilsted
- **Ocean renewable energy: scale, finance and biodiversity**
  Shamini Selvaratnam, Ocean Conservancy

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About us

Engineering X

This report was produced as part of the Engineering X Safer End of Engineered Life programme. Founded by the Royal Academy of Engineering and Lloyd's Register Foundation, Engineering X is an international collaboration that promotes the role of engineering in tackling safety and sustainability challenges by building collaborations across sectors and disciplines. We advocate for systems approaches and amplify unheard voices to ensure solutions are long-term and locally appropriate.

As one of Engineering X programmes Safer End of Engineered Life champions safety at the end of life and promotes circularity in engineered products and structures like offshore wind turbines and ships. Safer End of Engineered Life also leads international efforts on ending open burning of waste.

Royal Academy of Engineering

The Royal Academy of Engineering is a charity that harnesses the power of engineering to build a sustainable society and an inclusive economy that works for everyone. In collaboration with our Fellows and partners, we are growing talent and developing skills for the future, driving innovation and building global partnerships, and influencing policy and engaging the public. Together, we are working to tackle the greatest challenges of our age.

Lloyd's Register Foundation

Lloyd's Register Foundation is an independent global charity that supports research, innovation, and education to make the world a safer place. Our vision is to be known worldwide as a leading supporter of engineering-related research, training, and education that makes a real difference in improving the safety of the critical infrastructure on which modern society relies.

Join us

Working towards safety at the end of life of offshore wind will take an interdisciplinary community to consider and tackle it. If you are working in and around offshore wind, have experience or expertise in end-of-life management more generally, are from a region now expanding into offshore wind, or are simply interested in understanding more about this work, please join our LinkedIn group Engineering X Safer End of Life for Offshore Infrastructure and Ships Community of Practice or get in touch by emailing Ann-Sophie Freund, Programme Manager, Safer End of Engineered Life: ann-sophie.freund@raeng.org.uk.

We are particularly interested in hearing from:

- **health and safety focused organisations considering offshore wind**
- **international organisations pushing for a just transition to net zero**
- **offshore wind industry working on end of life within their companies**
- **regulators across the world who are developing end-of-life guidance**
- **academic representatives researching circular end-of-life technologies**
- **other members of civil society globally who are working to improve safety at end of life in offshore wind.**

Appendix A: Summary of recommendations across findings

Appendix A presents an overview of all recommendations put forward in the workshop and analysed in this report (see section 4).

#	RECOMMENDATIONS	STAKEHOLDERS	SHORT TERM	LONG TERM
4.1.	**Coordinate and work together for safe, sustainable, and effective end-of-life management that is mindful of impacts worldwide and contextual differences**			
	1 **Establish an international working group for safe and sustainable end-of-life practices that can support:** • the establishment of regulatory frameworks • the development of circular technical processes for end of life • building circular end-of-life supply chains	• A neutral body active in offshore wind, such as an intergovernmental body or NGO, for example, GWEC, IEA Wind, researchers	✓	
	2 **Develop benchmarks and a roadmap** for coordination on development of regulation, technology, and supply chains	• International working group		✓
	3 **Raise awareness across the sector** of the importance of end-of-life issues to get all relevant stakeholders involved	**Raising awareness:** • Non-profit sector • Researchers • Professional bodies • Regulators/policy **With:** • Educational institutions • Engineering workforce bodies • International organisations • Investors communities / financial services • Local, regional, national and global governments • Local communities • The full supply chain		✓
	4 **Establish and facilitate learning mechanisms** across the supply chain	• International working group		✓

#	RECOMMENDATIONS	STAKEHOLDERS	SHORT TERM	LONG TERM
4.2.	**Address gaps in regulation by developing more appropriate and agile regulation while ensuring international coherence which allows for appropriate planning and the development of safe and sustainable approaches** **4.2.1. Gaps in regulation that require clarity or improvement**			
	5 Ownership: establish a guideline to specify which actors have which responsibilities at each point in the lifecycle of a wind turbine and wind farm, based on current legislation. Clarify ownership for all parts of the lifecycle, including the end-of-life process	• Government agencies • Non-profit sector • Researchers	✓	
	6 Incentives and accountability: assess what is realistically possible in terms of safety and sustainability, then set ambitions through regulation, accountability mechanisms, and incentives	• Governments • Industry • Non-profit sector • Researchers • Co-produced with full end of use supply chain	✓	
	7 Incentives and accountability: create policy incentives for businesses at end of life to boost activity and ensure stability for investment in the supply chain	• Governments • Industry champions • Non-profit sector • Researchers • Co-produced with full end of use supply chain		✓
	8 Costs and financial requirements: consider the ownership of decommissioning costs and identify better mechanisms to ensure costs can be covered, to then develop guidance and requirements for decommissioning costs	• Governments • Industry and industry champions • Non-profit sector • Researchers • Co-produced with full end of use supply chain	✓	
	9 Costs and financial requirements: connect regulatory incentivisation to project finance – for example, through environmental, social and governance (ESG) performance standards of lenders	• Finance industry • Industry • Non-profit sector • Regulators • Researchers		✓
	10 Other regulatory gaps: identify best practice and create regulation on biodiversity considerations, removal requirements, classification of end-of-use materials, banning the landfilling of composites	• Industry • Non-profit sector • Regulators • Researchers		✓
	11 Other regulatory gaps: planning coordination: include offshore wind decommissioning in marine spatial planning (MSP)	• Industry / wind operators • National and international regulators		✓

#	RECOMMENDATIONS	STAKEHOLDERS	SHORT TERM	LONG TERM
	4.2.2. Overarching issues with the process of creating regulation to ensure it is well informed and suitable for the sector – nationally			
12	**Develop context-appropriate regulation at the national level:** create a goal-based context-adaptive regulatory framework rather than one-size-fits-all removal requirements	• National governments • Non-profit sector • Regulators • Researchers		✓
13	**Well-informed national regulators are key:** enhance regulator knowledge on the subject matter and establish an informing process from research and industry to regulators	• Industry – training workshops • Regulators • Researchers	✓	
14	**Driving regulatory standards at the national level:** establish a task force between industry, research, and regulators to drive the development of regulatory standards	• Industry • Non-profit sector • Regulators • Researchers	✓	
15	**National collaboration and coordination:** enhance collaboration across national agencies who are involved in the offshore wind sector	• Innovation bodies • National governments • Professional bodies • Regulators • Researchers	✓	
16	**Sharing regulatory plans:** egulators should create and share their plans for regulation and pathways for implementation to support industry preparation	• Industry • Professional bodies • Regulators • Researchers	✓	
	4.2.3. Overarching issues with the process of creating regulation to ensure it is well informed and suitable for the sector – Internationally			
17	**Implementation and accountability:** develop accountability mechanisms to ensure consistent implementation of regulation across borders	• Non-profit sector • Professional bodies • Regulators • Researchers		✓
18	**Implementation and accountability:** develop social accountability mechanisms by engaging communities of interest/communities of place	• Non-profit sector • Professional bodies • Wind industry		✓
19	**Implementation and accountability:** develop financial accountability by influencing financial institutions	• Lenders • International Finance Corporation • Shareholders • World Bank		✓
20	**International versus national guidance:** identify the right international organisations that should take on responsibility for developing standards or guidelines at an international level, which can be specified into more local, context-specific regulation	• Innovators • International regulatory and guiding bodies • Professional bodies • Researchers • Standards bodies		✓

#	RECOMMENDATIONS	STAKEHOLDERS	SHORT TERM	LONG TERM
	21 International collaboration and coordination: collaborate internationally to develop international regulatory standards – for example, through regional and international working groups	• International regulatory and guiding bodies • Professional bodies • National regulators • Non-profit sector • Researchers	✓	
4.3.	**Proactively develop international circular end-of-life supply chains that engage and prepare suppliers in existing and emerging offshore wind markets**			
	22 Identify the best business approach for managing the decommissioning process	• Decommissioning and removal sector • Developers • Regulators	✓	
	23 Engage the end-of-life supply chain so it can prepare and build capacity	• Decommissioning and removal sector • Developers • Government economic development teams • OEMs (feedback on design, use of reused parts / recycled materials) • Port authorities and owners • Regulators • Reuse / refurbish providers • Solution providers such as research centres and innovation bodies • Vessel suppliers • Waste management professional bodies • Wind operators	✓	
	24 Coordinate efforts regionally and internationally in establishing end-of-life supply chains	• Decommissioning and removal sector • Government economic development teams • Industry trade bodies • Reuse / refurbish providers • Waste management professional bodies • OEMs (feedback on design, use of reused parts / recycled materials) • Port authorities and owners • Regulators • Solution providers such as academia and innovation bodies • Wind operators	✓	

#	RECOMMENDATIONS	STAKEHOLDERS	SHORT TERM	LONG TERM
25	**Build a reuse market** for offshore wind, learning from other sectors as well	• Decommissioning and removal sector • Government economic development teams • Insurance providers • OEMs (feedback on design, use of reused parts / recycled materials) • Ports • Regulators • Resale contractors • Reuse / refurbish providers • Solution providers such as academia and innovation bodies • Waste management professional bodies • Wind operators	✓	
4.4.	**Advance full-circle technology and processes for end of life implemented by a well-trained workforce that can monitor, maintain, replace, and dismantle components safely** **4.4.1 Current practices that make safe and sustainable end of life more difficult**			
26	**Lack of interest in recycling and developing new recycling technologies:** raise awareness of the importance of and opportunities in circular practices to increase the development of better life extension, reuse and recycling technologies	• Governments • Industry • International working group • Non-profit sector • Research	✓	
27	**Rapid evolution of technology:** in the design and development stage, consider the impact of technological advances on the whole lifecycle and factor in circularity needs	• OEMs • Research	✓	
28	**Contextual differences:** in planning, develop logistical solutions that are context adaptive	• OEMs • Regulators, informed by industry • Research		✓
	4.4.2 End-of-life processes that require further development			
29	**Material processing approaches:** develop higher-value recycling methods for turbine materials and other elements of offshore wind farms, especially foundation structure recovery, subsea cable recovery, and rare earth material recovery	• Decommissioning and removal sector • Developers • End-use of recyclers • Innovators • Insurance providers • Regulators • Researchers • Waste management industry		✓

#	RECOMMENDATIONS	STAKEHOLDERS	SHORT TERM	LONG TERM
30	**Material processing approaches:** design new infrastructure for circularity where possible, including to reduce, reuse, and repurpose components	• Decommissioning and removal sector • Developers • Innovators • OEMs • Regulators • Researchers		✓
31	**Logistical challenges:** invest in developing context-adaptive key logistical practices and supply chains – especially regarding heavy crane lifting, vessel infrastructure and availability, and moving onshore where possible to minimise time offshore	• Communities • Economic development agencies • Port authorities and owners • The full end of use supply chain • Vessel owners and design engineers		✓
32	**Monitoring tools:** develop remote asset integrity monitoring tools	• Developers • Wind industry professional bodies • Researchers		✓
33	**Enabling reuse and life extension:** Industry to develop systems for enhanced data collection and – critically – sharing, to improve sustainability. Incentives from government could help move this forward quickly	• National governments • Researchers • Wind industry	✓	
34	**Increasing health and safety data to enable accident analysis and learning:** encourage and establish use of platforms for health and safety data collection for the decommissioning of offshore wind infrastructure such as the G+ database to ensure learning from past accidents	• Operators • Wind industry professional bodies	✓	
35	**Training and skills:** train providers to develop standardised and consistent training for decommissioning	• Businesses • Researchers • Wind industry professional bodies	✓	
36	**Training and skills:** raise the profile of decommissioning roles and provide training in circular economy and decommissioning practices to existing offshore wind workforce, mostly focused on current construction and maintenance workforce	• Businesses • Researchers • Wind industry professional bodies	✓	
37	**Training and skills:** provide stakeholder engagement support on areas of expertise such as participation process management or communications	• Businesses • Researchers • Wind industry professional bodies	✓	

#	RECOMMENDATIONS	STAKEHOLDERS	SHORT TERM	LONG TERM
38	**Business opportunities:** develop safe and circular businesses. Opportunities include: • higher-value recycling methods for turbine blades • higher-value recycling methods for materials • monitoring tools such as digital twins • a system for enhanced data collection and sharing on components and materials to enable reuse and life extension • a convenient platform for health and safety data collection to enable learning and analysis from past accidents • training in circular economy and decommissioning practices to existing offshore wind workforce, who are mostly focused on current construction and maintenance workforce • stakeholder engagement training on specific areas of expertise such as participation process management or communications • best practices for heavy crane lifting • alternative solutions to avoid current logistical bottlenecks for example on vessel use • context specific logistical solutions for emerging offshore wind markets	• Industry • Innovators • Researchers	✓	
39	**Piloting:** coordinate end-of-life pilot projects for cross-sector learning, through: • mapping existing end-of-life pilots • coordinating and collaborating on activities to avoid duplication • capturing learning from activities • sharing learning in an accessible, central place with an easy search function • establishing a learning culture • designing for decommissioning before project start	• Researchers • The full end of use supply chain • Wind industry professional bodies	✓	

Appendix B: References

1 Causes and effects of climate change, Climate Action, United Nations; Climate change, fact sheet, *World Health Organization*, 12 October 2023; IPCC 2023: summary for policymakers, *Climate change 2023: synthesis report. Contribution of Working Groups I, II and III to the sixth assessment report of the Intergovernmental Panel on Climate Change*, Core Writing Team, Hoesung Lee, and José Romero (eds.), IPCC, Geneva, Switzerland.

2 While turbines are designed for a specified design life, some are decommissioned earlier for performance or financial reasons, while others have a longer actual lifetime with life extension beyond the design life.

3 End-of-life planning in offshore wind, Offshore Renewable Energy Catapult, 2021.

4 The problem, *Our work*, NGO Shipbreaking Platform, 2019.

5 The problem, *Our work*, NGO Shipbreaking Platform, 2019.

6 Basel convention on the control of transboundary movements of hazardous wastes and their disposal, United Nations Environment Programme, UNEP, 1992.

7 The Basel convention ban amendment, United Nations Environment Programme, Basel Convention, 5 December 2019.

8 The Hong Kong international convention for the safe and environmentally sound recycling of ships, International Maritime Organization, IMO, 15 May 2009 (adoption).

9 58% (22) of the decommissioned projects have been individual offshore wind turbine demonstrators; 75% of decommissioning projects consisted of five turbines or less; and only three commercial offshore wind farms have been decommissioned globally (Sweden, seven turbines; Denmark, eleven turbines; Netherlands, twenty-eight turbines) (see 4C Offshore data base "Market Research and Intelligence for Offshore Renewable Energy", TGS, October 2024)

10 For a case study on offshore wind material recovery, see the National Engineering Policy Centre (NEPC) report Critical materials: demand-side resource efficiency measures for sustainability and resilience (NEPC, 2024, pages 55 and 65).

11 Critical materials: demand-side resource efficiency measures for sustainability and resilience, NEPC, 2024, pages 23–24.

12 See Principles for a sustainable circular economy, Sustainable Production and Consumption, volume 27, Anne P. M. Velenturf and Phil Purnell, 2021, pages 1437–1457; Circular economy and the matter of integrated resources, Science of the Total Environment, volume 689, Anne P. M. Velenturf, Sophie A. Archer, Helena I. Gomes, Beate Christgen, Alfonso J. Lag-Brotons, and Phil Purnell, 2019, pages 963–969.

13 Circular economy and the matter of integrated resources, Science of the Total Environment, volume 689, Anne P. M. Velenturf, Sophie A. Archer, Helena I. Gomes, Beate Christgen, Alfonso J. Lag-Brotons, and Phil Purnell, 2019, page 965.

14 Oil and gas in the UK – offshore decommissioning, HC 1870 Session 2017–2019, National Audit Office, 25 January 2019, page 4. See also Safety of offshore oil and gas operations: lessons from past accident analysis: ensuring EU hydrocarbon supply through better control of major hazards, JRC Scientific and Policy Reports, Michail Christou and Argyri Myrto Konstantinidou, Luxembourg, Publications Office of the European Union, 2012.

15 Dozens of UK-linked vessels scrapped on South Asian beaches, despite ban, *Unearthed*, Richa Syal, 18 December 2023; The problem, *Our work*, NGO Shipbreaking Platform, 2019.

16 Rent instead of buy: pay-per-part models in industrial service, *Dot Magazine*, February volume, Nils Klute, 2022.

17 There should be consideration of the full lifecycle and the broader impacts of decommissioning – decommissioning does not end when the structures are removed from the sea. Consideration must be given to the decommissioning of infrastructure once it is quayside and the downstream destination of its components.

18 Permits for wind farms at Ijmuiden Ver Alpha and Beta, Offshore wind energy, Netherlands Enterprise Agency, 15 November 2023.

19 Wind industry calls for Europe-wide ban on landfilling turbine blades, Newsroom, press release, WindEurope, 16 June 2021.

20 Basel convention on the control of transboundary movements of hazardous wastes and their disposal, United Nations Environment Programme, *UNEP*, 1992.

21 There are many variations of the R-ladder; this version is from Circularise: R-strategies for a circular economy, Circularise, Larae Malooly and Tian Daphne, 9 November 2023.

22 Adapted from R-strategies for a circular economy, *Circularise*, Larae Malooly and Tian Daphne, 9 November 2023, figure 1. See also Towards a circular maritime industry: Identifying strategy and technology solutions, *Journal of Cleaner Production*, volume 382, Dogancan Okumus, Sefer A. Gunbeyaz, Rafet Emek Kurt, and Osman Turan, 1 January 2023, article 134935; and Circular economy-increased value extraction from end of life marine assets, Circular Economy Network+ in Transportation Systems (CENTS), *Europe-Korea Conference on Science and Technology 2022: Pathways to Sustainability*, Sefer A. Gunbeyaz and Dogancan Okumus, July 2022.

23 See the NEPC report Critical materials: demand-side resource efficiency measures for sustainability and resilience (NEPC, 2024, pages 55 and 65) for a case study on offshore wind material recovery.

24 Some examples can be found in the materials mapping case study in Decommissioning case study: circular economy in the wind sector case study – summary, *ORE Catapult*, Vanessa Smithson-Paul, Lorna Bennet, and Orrin Fraser, 29 April 2024; and on the DecomBlades project website.

25 See G+ incident data report, *Energy Institute*, Global Offshore Wind Health and Safety Organisation, 2023.

26 There are examples of incentivising such practice from other sectors, such as the ship recycling Hong Kong Convention, which requires all shipbuilders to develop a 'ship construction file' (SCF) that contains the inventory of materials. The SCF then accompanies the ship throughout its life until its eventual dismantling in a recycling yard (see The Hong Kong International Convention for the Safe and Environmentally Sound Recycling of Ships, *SOLAS regulation II-1/3-10*, International Maritime Organization, 15 May 2009). There are also existing databases that could be modified to include offshore wind turbine data.

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