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Research article

Investigating pathways to improve the circular economy adoption for near-end-of-life offshore wind farms

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A R T I C L E I N F O

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A B S T R A C T

Offshore wind (OW) power has expanded rapidly, playing a vital role in climate change mitigation. As first-generation OW farms approach their end-of-life (EOL), sustainable EOL management becomes essential. The circular economy (CE) offers a promising solution, yet its adoption within the OW industry remains limited. This study investigates the factors influencing CE adoption and explores ways to address them, guided by the question: what factors are hindering the adoption of CE strategies to sustainably manage near EOL OW farms, and what are the pathways to overcome them? Based on 21 semi-structured interviews across seven OW industry segments, the study reveals that while various economic, environmental, institutional, regulatory, and market drivers support CE adoption, numerous similar barriers, including technological barriers, impede its implementation. It reports that some barriers are more central than others, and addressing these can help resolve others. It also notes thatvaguely defined drivers that outline what needs to happen, rather than suggesting specific actions, tend to be less effective, and they require enabling support to enhance their impact. Addressing barriers, on the other hand, clearly requires enabling support. Our study finds that three types of enabling measures are necessary to support inadequately defined drivers and overcome barriers: industry-specific, market-specific, and regulatory measures. It is noteworthy that although the development of such measures is aimed at tackling central barriers, they also address non-central barriers. Finally, we argue that the systemic application of these measures can accelerate CE adoption for near EOL OW farms. A notable contribution of this study is its comprehensive analysis of drivers and barriers and the development of enabling measures, which enhances existing literature and offers policy and practical recommendations for OW stakeholders aiming to enhance CE adoption.

1. Introduction

Growth in the deployment of renewable energy sources is considered essential to meet the Intergovernmental Panel on Climate Change (IPCC)'s target of limiting global warming to 1.5 °C above pre-industrial levels (IPCC, 2022; World Economic Forum, 2023). The offshore wind (OW) industry is considered central to meeting this goal because of its unprecedented growth in recent years. Since commissioning the world's first OW farm, Vindeby, in 1991, there has been enormous growth in the deployment of OW farms. In 2023, 75 GW of OW was in operation, and another 410 GW is expected to be added by the end of 2033 (GWEC, 2024). This rapid expansion is largely driven by economic and environmental incentives. However, while addressing climate challenges through increased deployment, there is a concern that we may replace one set of environmental challenges with another, specifically related to resource usage. As some of the first-generation OW farms approach their end-of-life (EOL), concerns about sustainable decommissioning practices are growing. It is anticipated that 3.5 GW of global OW capacity will reach EOL by 2035 (Spyroudi, 2021), yet there is no concrete plan for sustainable decommissioning in place. Addressing this issue is crucial to maintaining the credibility of the OW industry.

To sustainably manage the wind turbine (WT) waste stream, the wind industry is currently looking at several circular economy (CE) pathways; however, despite having theoretically promising solutions to the EOL problem, the actual implementation of CE towards near EOL OW farms seems to be limited. To complicate this even further, the matured CE strategies are only available in certain geographies, there is no uniformity in the regulation to manage EOL waste, and the incentives to promote CE adoption in the wind industry towards near EOL wind farms are non-existent or very limited (Velenturf, 2021; Gode et al.,

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2024). This study aims to explore the reasons behind this limited adoption of CE and suggest pathways to accelerate its adoption for the sustainable decommissioning of near EOL OW farms. The research question asks: what factors are hindering the adoption of CE strategies to sustainably manage the near EOL OW farms, and what are the pathways to overcome them?

To answer this question, we conducted 21 semi-structured interviews with actors from seven segments of the OW industry from 2022 to 2024. The interview guides were periodically updated based on the empirical observations from the interview data and grey literature such as industrial reports, industrial conference proceedings and theoretical findings from peer-reviewed journal articles.

This is the first study we are aware of that systematically analyses the drivers and barriers to CE adoption and proposes pathways for accelerating it in the management of near EOL OW farms. Our research identified several types of drivers – economic, environmental, institutional, regulatory and market exists for the adoption of CE in the OW industry. However, it also found that an even greater number of barriers impede CE development. Industry practitioners are actively working to overcome these barriers by developing pathways to accelerate CE adoption. However, they are either unaware of or have not fully considered all potential pathways that could improve CE adoption. Our study bridges this gap by demonstrating how various enabling measures can address these barriers, thereby facilitating the acceleration of CE adoption.

2. Theoretical background

2.1. Concept of circular economy

The concept of CE is evolving. A recently published study documented that there exist at least 221 definitions of CE (Kirchherr et al., 2023). While the variety of definitions reflects the broad scope of sustainability (Nagatsu et al., 2020; Caradonna, 2014) and the evolution of the CE (Kirchherr et al., 2023), it is crucial that these definitions do not overly emphasise specific aspects of circularity, such as recycling, reuse, or related economic gains (Kirchherr et al., 2017, 2023). Instead, they should also consider the connections to sustainable development and supply chain reconfiguration that are often needed for the effective implementation of CE (Kirchherr et al., 2017, 2023). For this article, we will adopt the CE definition proposed by the EU Parliament, which states CE as "a model of production and consumption, which involves sharing, leasing, reusing, repairing, refurbishing and recycling existing materials and products as long as possible" (European Parliament, 2021). We have chosen this definition as we believe it encompasses the essential aspects of CE that are included in this article.

2.2. Adoption of circular economy

Adopting CE is considered an attractive venture by organisations, society and governments due to the numerous benefits it offers, often referred to as drivers. CE adoption provides an opportunity to extend product lifecycles and retain materials within the economy at the component's EOL, thereby contributing to value creation (European Parliament, 2021). In practice, CE adoption can help improve resource management, reduce raw material usage, reduce the generation of waste and improve long-term revenue generation, thereby offering significant economic and environmental benefits (Velenturf et al., 2019; Govindan et al., 2018).

Various studies have looked at the drivers to the adoption of CE from different perspectives that fall broadly into two categories – regional and sectoral. From a regional perspective, a recently conducted study in Australia about its CE transition found that sustainable waste management to reduce waste generation and improve waste handling efficiency and sustainable resource use during the usage cycle were the key drivers to adopt CE (Melles, 2023). Another study examining circular economy adoption in China, the US, and Europe identified several regulatory drivers: laws on responsible product lifecycle management and cleaner production initiatives in China, state-level e-waste management laws for electric products and recycling legislation in the US, and a landfill ban on organic waste in Europe (Ranta et al., 2018). Additionally, the study found normative drivers, such as products retaining their value for longer periods, supporting reuse initiatives in China. Cultural cognitive drivers also play a role, such as the high support for source separation activities in European nations, which aids recycling initiatives. In China, recyclables are often seen as valuable rather than waste.

A variety of studies have investigated the drivers for CE adoption from a sectoral perspective. For instance, a study conducted about drivers and barriers in a CE within the built environment and found that sectoral drivers such as increase in R&D and innovation capabilities of the sector, imposing standards and assurance schemes that enable reuse of structural materials and use of recycled material, development of reverse logistics infrastructure to create material storage facilities and market place and upcycling initiatives can improve CE adoption in the sector (Hart et al., 2019). Research conducted in Pakistan's automobile industry found that the economic gains, the potential to reduce costs by reducing raw material use and end-of-life waste, and the global call for sustainable development were the top three drivers for managers to adopt CE initiatives (Agyemang et al., 2019). A study conducted in the circular building sector found that the focus of embedding circularity in the design process allowed architects to explore new products and materials, design strategies and new business models (Kanters, 2020).

However, despite the presence of a variety of drivers, several studies show that the current state of CE adoption is very limited. The Circularity Gap Report published by Circle Economy found that, despite the rise in popularity over the last five years, the actual global circularity is on the decline, with the share of secondary material used in the economy reducing from 9.1 % in 2018 to 7.2 % in 2023 (Circle Economy, 2024). The consumption of materials is also continuously increasing; from 2018 to 2023, we have consumed over 500 gigatonnes of material, which is 28 % of all the material consumed since 1900.

Similar to the drivers, there exist numerous studies that have looked at barriers to CE adoption from regional and sectoral perspectives. For example, a study conducted in Australia about its transition to CE found that recycling, despite its lower sustainable potential, is often considered a necessary strategy in the short term; however, there is a lack of clarity about its mid and long-term success due to the resistance of businesses, government and society to make the necessary adjustments in the economy to incorporate recycling initiatives (Melles, 2023). A cross-regional study on CE adoption in China, the US and Europe found that CE adoption is limited due to the presence of numerous environmental barriers, such as low-level regulation and enforcement, lack of supporting laws and incentives, and low-level separation of materials for recycling (Ranta et al., 2018). The same study also found several institutional barriers, such as inconsistent regulation and enforcement, lack of support for other CE strategies apart from recycling, tendency of customers to prefer new products and lack of interest in developing reuse and reduce activities (Ranta et al., 2018). A study on the barriers to CE in the European Union found that cultural barriers, such as hesitant company culture, lack of consumer awareness, and dependency on linear economy solutions, along with market barriers, such as low virgin material prices and high upfront investment, were key barriers to CE adoption in the EU. Furthermore, the study emphasises that there exists a chain reaction between these barriers that influence other cultural, regulatory, market and technological barriers, highlighting the need for system-level change necessary to provide a solution to these barriers (Kirchherr et al., 2018).

From a sectoral perspective, a recently conducted study in the building sector found that CE adoption is limited due to the presence of conservative practices in the sector, interdependency of the building sector on other sectors such as the financial sector, lack of innovation, lack of flexibility in regulations and building codes to allow CE practices, mismatch between material supply and demand, lack of knowledge and experience about material reuse and material harvesting, lack of standards for use of materials and tools, and expensive labour (Kanters, 2020). A study conducted on CE adoption in the agri-food supply chain found key barriers to be a lack of standards to measure the effectiveness of proposed rules, low short-term economic and financial benefits associated with implementing CE initiatives, and maintaining the quality of often short-lasting food commodities (Mehmood et al., 2021). A study published on Pakistan's automobile industry found that a lack of awareness about CE as a concept, short-term high financial costs required to invest in CE initiatives, organisational restructuring, and the lack of expertise needed to derive value from waste materials were the most pressing barriers (Agyemang et al., 2019).

Despite the numerous drivers for CE adoption, several barriers continue to limit its implementation, and these barriers are idiosyncratic to various regions and sectors. However, there is limited knowledge about circularity adoption in born-sustainable industries, which are designed from the outset to address sustainability challenges (Dicuonzo et al., 2020; Ostermann et al., 2021). Born-sustainable industries, such as OW, are significantly material-intensive. To avoid replacing one environmental challenge with another, i.e., solving the climate crisis while creating resource challenges, CE adoption in such industries requires urgent attention and credible consideration.

2.3. Context of the offshore wind industry

The discussion of CE in the OW industry gained momentum when Bloomberg Green reported on WT blades awaiting landfilling at Casper Regional Landfill in Wyoming in 2020 (Bloomberg, 2020). Currently, 85–90 % of a WT's mass is considered recyclable (Woo et al., 2022; Topham et al., 2019; ETIPWind, 2020). However, components like blades and nacelle covers pose recycling challenges due to their composite material composition, making it hard to segregate individual components. That is why a majority of recently conducted studies focus on developing CE strategies to manage blade waste (Gode et al., 2024; Bloomberg, 2020; Beauson et al., 2022; Kramer et al., 2023; Deeney et al., 2025). Adopting CE in OW practices offers several benefits beyond recycling blades, such as reducing raw material and energy usage - dematerialisation (Velenturf, 2021; Mendoza et al., 2022), designing more durable components, and extending component lifetimes through modularisation, repair, maintenance, remanufacturing, reuse, and refurbishing strategies (Velenturf, 2021; Gode et al., 2024; Mendoza et al., 2022). CE also allows materials to remain in the lifecycle through repurposing – manufacturing alternate components using wind farm infrastructure, e.g. bridges, playgrounds and furniture (Velenturf, 2021; Gode et al., 2024; Topham et al., 2019), upcycling (e.g., recycling glass fibres from old blades to make new ones) (Deeney et al., 2025; Menéndez, 2021; GE, 2022) or downcycling (e.g., making tabletops from shredded blades) (Fonte et al., 2021) – both of which are part of component recycling.

Despite these benefits, CE adoption in the OW industry is limited (Velenturf, 2021; Gode et al., 2024; Jensen et al., 2020). Contributing factors include a lack of uniform regulation and incentives, a lack of economic viability of CE strategies, underdeveloped CE strategies, and a lack of decommissioning experience (Gode et al., 2024; U.S. Chamber of Commerce, 2024). Studies also highlight low material recovery rates at EOL, discrepancies in actual recycling rates (Demuytere et al., 2024), a lack of financial incentives, and insufficient information about blades that hinder the development of EOL strategies, such as repurposing and recycling (Deeney et al., 2025). Studies conducted on onshore wind farms where CE is currently more actively investigated found that the development of circular EOL strategies is hindered by insufficient feedstock volumes, inadequate supporting infrastructure, lack of incentives and policy support to promote CE initiatives, stakeholder unfamiliarity with sustainable EOL pathways, quality losses during manufacturing second-life products, and lack of data for accurate lifecycle analysis (Woo et al., 2022).

Recent studies have suggested pathways to overcome the limited adoption of CE in the wind industry. For example, a study conducted on circular EOL management of onshore wind farms recommended the importance of industry-wide collaboration, product and process standardisation, accurate estimation of EOL volumes, and supporting incentives and regulations to improve future CE adoption (Woo et al., 2022). Another study on circular EOL scenarios for WT blades suggests developing alternative payment structures for blade OEMs to encourage durable blade production, sharing information to support second-hand markets to develop repurposing and recycling initiatives, and creating financial incentives like compliance bonds to reward sustainable EOL processing for blade owners (Deeney et al., 2025). A recent report by the World Economic Forum emphasised that enhancing circularity in the renewable sectors, such as wind and solar PV, requires a shift in organisational mindset, digital transformation, technological and market advancements, and the development of collaborative ecosystems (World Economic Forum, 2025). Importantly, these efforts should not be limited to any single phase of the lifecycle, but must be applied across all stages to ensure a truly circular approach. In addition, there are some industrial collaborations happening as well, such as the development of a blade material passport to help scale recycling and repurposing initiatives (DecomBlades, n.d.), Re-Wind project to develop repurposing solutions for wind turbine blades (Nagle et al., 2022), and the Circular Wind Knowledge Hub to develop decommissioning and recycling technologies for WT blades (EOLO Hubs, 2025).

However, these initiatives often target onshore wind farms, which have different scales and infrastructure compared to OW farms. Contrary to onshore wind farms, where decommissioning has already started on a commercial scale, the decommissioning of OW farms will only begin at the end of this decade. A study on challenges in offshore wind decommissioning predicted that around 1800 offshore WT will decommission in this decade in Europe (Topham et al., 2019). However, this number will increase to 20,000 WTs from OW in the next decade. Given the growing scale and size of the OW farms, this represents a key challenge, one that needs to be considered a priority. Moreover, the CE initiatives that are developing are focused on specific components like WT blades or specific CE strategies like recycling. This results in a lack of comprehensive pathways for other circular EOL alternatives. Our study aims to bridge this gap by mapping drivers and barriers to CE adoption across seven segments of the OW value chain, providing a thorough analysis and suggesting pathways to overcome the hindrances to CE adoption.

2.4. Analytical framework

The identified studies revealed a complex dynamic interplay between barriers and drivers influencing the adoption of CE practices. In the majority of cases, barriers tend to outweigh the drivers, explaining the limited adoption of CE practices (Ranta et al., 2018; Hart et al., 2019; Agyemang et al., 2019; Kanters, 2020). However, the interaction between drivers and barriers can be even more intricate. Analysing this interaction is crucial, as it can provide valuable insights to improve CE adoption from a systemic perspective.

One study about drivers and barriers to CE adoption in the built environment reported that barriers and drivers can sometimes be mirror images, where the absence of a driver itself creates a barrier (Hart et al., 2019). It also reported that not all drivers are equally effective; their impact on improving CE adoption sometimes depends on the presence of enabling support (measures), which are often unspecified, and clarity in their implementation. Vaguely defined drivers that merely outline what needs to happen, rather than suggesting specific actions to improve CE adoption, tend to be less effective (Hart et al., 2019).

Enabling measures also play a critical role in overcoming barriers. Government involvement, for example, has been identified as a key enabler that can overcome a range of barriers and facilitate the adoption of CE (Govindan et al., 2018). The same study emphasised that regulators should not only be aware of the problem, but solving it needs to be on their policy development agenda. Moreover, it also highlighted that the regulations developed by the government should be feasible to follow; otherwise, they can hinder organisations from adopting CE practices. However, regulatory enabling measures alone are not sufficient; institutional support is also required to improve CE adoption (Ranta et al., 2018). Such measures should reduce the amount of products and materials used in a system and promote reuse initiatives. Similarly, research on CE barriers in the EU found that, beyond government action, a broader cultural shift is required to improve the adoption of CE (Kirchherr et al., 2018). This includes overcoming hesitant company culture to invest in CE initiatives, increasing consumer awareness and interest about CE, and moving away from established linear economy models (Kirchherr et al., 2018). Such measures should also target raising awareness about CE and developing reliable performance indicators to measure circularity (Govindan et al., 2018).

To support systemic CE adoption, it is essential that the development of enabling measures target a wide range of CE strategies, rather than focusing on a single strategy (Fig. 1). A cross-regional study on drivers and barriers to CE implementation in China, the US, and Europe found that although there is substantial support for recycling initiatives, support for higher-order sustainability strategies, such as material reuse, is significantly lacking (Ranta et al., 2018). A study conducted on CE development in OW found similar results, where higher-order sustainability strategies such as repurposing, lifetime extension, modularisation, reuse, remanufacturing, and refurbishing are considerably less researched than recycling (Gode et al., 2024). This imbalance can create a systemic ripple effect that can hinder CE adoption. Therefore, a coherent approach needs to be developed to integrate various enabling measures that target a broad spectrum of CE strategies mentioned in Fig. 1.

Fig. 1 presents the analytical framework developed in this study, illustrating the dynamic interplay between drivers and barriers to CE adoption. The bi-directional arrows between the drivers and barriers boxes reflect their interdependence—drivers can mitigate barriers, while weak or absent drivers and unresolved barriers hinder CE implementation. The dotted arrow from drivers to enabling measures suggests that drivers may sometimes need external support to be effective. In contrast, the solid arrow from barriers to enabling measures highlights that overcoming barriers requires strong, targeted support. Without the development of such measures, CE efforts may fail, leading organisations back to linear models. Enabling measures thus play a dual role: enhancing drivers and resolving barriers. Moreover, it is crucial that the development of such measures should support the development of a broad range of CE strategies to foster holistic and systemic CE adoption.

3. Methodology

To address the research question, a qualitative design with semi-structured interviews was selected. This is considered a good fit for explorative research in emerging contexts such as CE within the OW industry, as it offers intimate, open-ended insights by engaging directly with practitioners (Plakoyiannaki et al., 2019).

For the case study, 21 semi-structured interviews were conducted across seven segments of the OW value chain, covering design and manufacturing, operation and maintenance, and end-of-life stages, thereby capturing the entire picture of circularity in the OW value chain. Table 1 summarises the types of organisations and venues where interview participants were recruited. Given the emerging nature of this industry, identifying expert practitioners was challenging. To address this, one of the authors attended several relevant industry events, including

Table 1
Interview participants' details.

Organisation type	How and where participants were recruited
OEM1	Wind Europe
OEM2	Through reference (2 participants)
OEM3	Wind Europe (Included a follow-up interview)
OEM4	Wind Europe
WO1	Wind Europe
WO2	Through reference
WO3	Wind Europe (Included a follow-up interview)
CE1 DO2	Wind Europe
CE2	Through reference
CE3	Through reference
CE4	Wind Europe
RMS	Through reference
DO1	Wind Europe
URC1	Sustainable Blade Recycling Conference
URC2	Sustainable Blade Recycling Conference
URC3 PA1	CE Symposium
URC4	Sustainable Blade Recycling Conference
URC5	Wind Europe, Sustainable Blade Recycling Conference, CE Symposium
PA2	Wind Europe

RMS Raw material suppliers.
OEM Original Equipment Manufacturers.
WO Wind Farm Owners/Wind farm operators.
DO Decommissioning operators.
CE CE operators.
PA Policy advisors.
URC University or research centers.

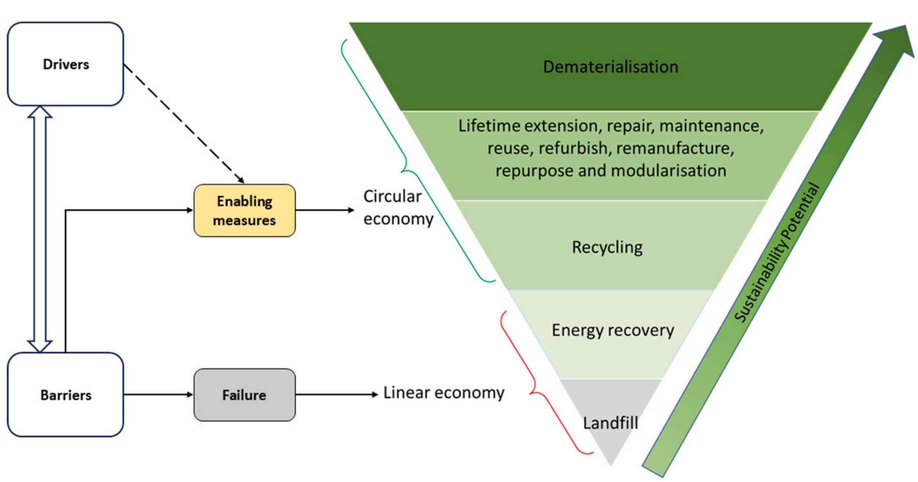

Fig. 1. Complex interactions between drivers, barriers and enabling measures (adapted from (Velenturf, 2021; Gode et al., 2024; Jensen et al., 2020)).

Wind Europe Annual Events (2022, 2023), the 4th Symposium on CE and Sustainability (2022), and the International Conference on Sustainable Wind Turbine Blades (2022). This led to the recruitment of 14 individuals, with an additional 6 respondents identified through the network of already chosen interviewees. Some actors were involved in multiple businesses within the value chain, as indicated in Table 1.

The interview participants came from four segments: executive positions, sustainability leadership, product and project development, and academic research, as illustrated in Fig. 2. They represented eight countries, with most from Denmark (10), followed by Germany (2), the Netherlands (2), and the UK (2), who are also the global leaders in OW development, and one participant from Belgium, Norway, Poland and Portugal. For confidentiality reasons, specific roles and countries were not identified individually. Some participants belonged to global conglomerates operating in multiple countries and continents, so the interviewees were chosen for their expertise in circularity across their firm's entire OW portfolio rather than solely from their country of residence.

The interview guide was tailored for each interviewee and their activities related to CE in the OW industry. Despite this, all interview guides revolved around five common themes: understanding the adoption and transition of CE within the organisation, CE strategies being considered or implemented, measurement of CE strategies and collaboration within the value chain actors, drivers and barriers to CE adoption, and future plans to accelerate CE adoption. The interviews were conducted on Microsoft Teams from late 2022 to early 2024, and they typically lasted from 30 min to 1 h, with an average meeting time of 49 min. The content of the interview guides was also periodically updated based on the empirical observations from interviews and conference proceedings, literature review, and grey literature, including LinkedIn posts by industry experts and industrial reports.

The interviews focused on two areas: understanding the current state of CE adoption for near EOL OW farms and circular planning of planned future OW farms. This article focuses on the data analysis related to the first area: understanding CE adoption for near EOL OW farms.

The interviews were coded using NVivo. The transcripts were coded using both primary and secondary codes. In the primary codes, the interview data was divided into smaller segments according to the interview themes. The identified primary codes were drivers and barriers to CE adoption and enabling measures to accelerate CE adoption. In the secondary codes, the relationship between first-order codes and the data was further analysed to identify sub-categories (Saldaña, 2013). This can include, for example, sub-categories related to barriers such as regulatory, economic, technological barriers, etc. The primary and secondary coding categories identified during the data analysis can be seen in Table 2,Table 3 and Table 4.

To ensure the scientific rigour and transparency of the analysis, we have included which interviewees highlighted selected drivers, barriers, and enabling measures in Table 2, Table 3 and Table 4, indicating the variety of segments and interviewees mentioning a specific category.

The findings from the interview analysis were periodically validated by discussing them during subsequent interviews and updating the interview guide. At the end of data collection, the analysed results were presented to experts at three international conferences related to CE and the wind industry.

4. Findings

4.1. Drivers to adopt CE in the offshore wind industry

To address the RQ and understand the current state of CE adoption, we first mapped the drivers. This step is crucial as it reveals the motivations of organisations implementing CE in their portfolio. By understanding these motivations, we can effectively identify and address the factors hindering CE adoption. These drivers can be categorised into five broad categories: economic, environmental, institutional, regulatory, and market drivers. Table 2 demonstrates these drivers with the help of some illustrative codes.

Our study highlights various **economic drivers** that motivate organisations to pursue CE strategies. Interview participants noted that integrating CE into business models provides a competitive advantage and economic gains by reducing raw material needs and minimising manufacturing waste. Lifetime extension, a highly sustainable circular strategy, is prioritised due to energy security concerns from the Ukraine war, high energy prices, and supply chain issues related to rare earth elements (REEs) (Commission et al., 2023; Alves Dias et al., 2020; Smith et al., 2022; Månberger et al., 2019). Significant economic benefits arise from recycling metals like copper, steel and aluminium, a practice that has been ongoing since the wind industry's inception.

Regarding **environmental drivers**, interview participants indicated that they pursue CE in their organisations to reduce raw material usage and promote sustainable resource use, conserving resources for future generations. This approach also helps lower emissions from raw material extraction and processing. Additionally, most participants noted that

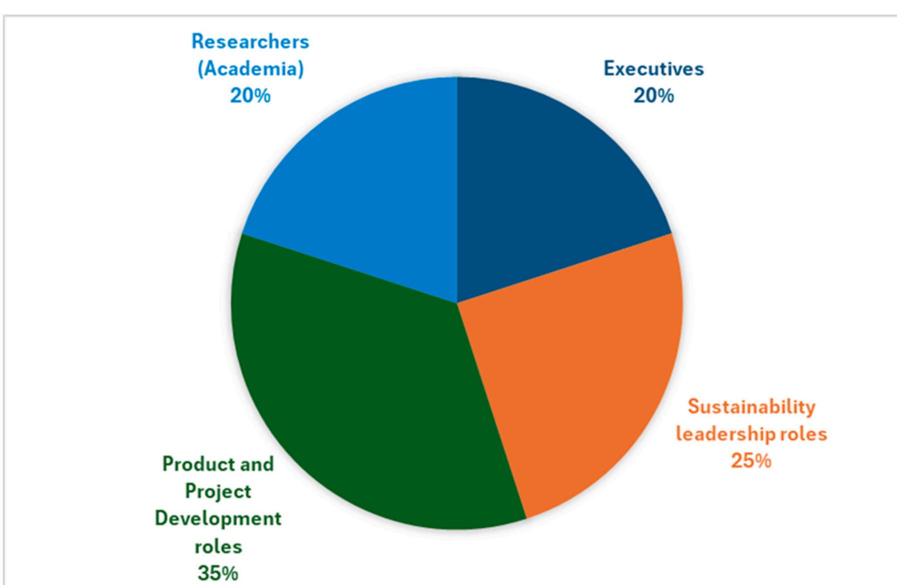

Fig. 2. Indicative work positions of interview participants.

Table 2
Drivers to circular economy adoption in the offshore wind industry with illustrative quotes.

Drivers	Description & mentions	Illustrative quotes
Economic	Business benefits of CE (CE1 DO2, URC4, WO2, WO3)	There is actually a business incentive now for us to also look at circularity, not only from a brand perspective but also from a business perspective. **(WO2)**
	Raw material and waste reduction in manufacturing (OEM3, WO2)	Back then, we were part of the Z corporation, which always had a strong focus on substances entering into the material system, waste reduction and so on. **(OEM3)**
	High energy costs (URC1)	Because the energy prices increased, we did a lifetime extension. And that was because of the war. **(URC1)**
	Revenue generation from recycling (DO1, PA2)	We already have a clear value chain established since the beginning…. All steels, ferrous and non-ferrous metals, are recycled. **(DO1)** The other way is that they are just going to focus on the rare earth elements because they have the highest value. **(PA2)**
Environmental	Sustainable use of resources (CE2, CE4, DO1, OEM3, URC3 PA1, WO3)	What happens to all of these materials? How are they going to be recycled? How are they going to be used? And if we don't recycle and reuse all the materials that we're decommissioning, then where on earth are we going to get all of the materials we need to meet the future demands of the sector? **(URC3 PA1)**
	Reduction of emissions (CE4)	When you use raw material … when you use rare earths, you have a carbon footprint that's not very nice. So, you cannot waste these materials. **(CE4)**
	Avoid landfilling of materials (CE2, CE4, DO1, PA2, URC3 PA1)	The big trigger for us to work on circular economy, to start working on this, was really the news that broke a few years ago with a very notable Bloomberg article about challenges related to decommissioning of wind farms in the US. **(PA2)**
Institutional	Landfill ban as an internal driver (DO1, OEM4, PA2, WO2)	I think de facto it is happening in Europe because the big energy utilities they're not landfilling anymore and go for instance cement coprocessing instead. **(PA2)**
	Creating industrial value chain collaborations (OEM1, OEM4, URC1, WO3)	For OEMs, I think we should not be competing on waste generation or end-of-life…. If we don't get into solutions to this mutual problem, then we might be irrelevant as an industry at a certain stage. **(OEM1)**
	Sustainabilty is a stakeholder requirement (WO2, WO3)	We need to work towards a circular business to secure the future of the next generation. From a business perspective, we also see that this is required from our stakeholders. **(WO3)**
Regulatory	Landfill ban (OEM1, OEM4, PA2)	But some countries have already introduced a landfill ban. Countries like Finland, Austria, the Netherlands, and Germany, as far as I remember. They have introduced the landfill ban for composite waste and blades already. **(OEM4)**
	Government incentives for setting up CE facilities (PA2, URC3 PA1)	One good example is the Spanish government, which used part of its recovery and resilience funds for investments in manufacturing facilities that specialise in dealing with the recycling of decommissioned wind turbine blades. There's a dedicated pot of money for that. **(PA2)**
Market	Creation of alternate supporting industries (CE1 DO2, CE2)	Our goal was to be first, to make noise around this installation that is really the first product [first commercial product of its kind] made from the blade in the world. **(CE1 DO2)**

avoiding the landfilling of wind turbine blades and manufacturing waste was a primary motivation for adopting CE in their organisations.

When it comes to **institutional drivers**, many companies are actively researching ways to incorporate more circularity into their businesses and have formed several collaborative initiatives with other value chain actors. Some such notable initiatives are mentioned earlier in subsection 2.3. Increasing stakeholder pressure to enhance sustainability in their operation is another driver for wind organisations to pursue CE practices. Most members of the wind industry trade organisation, WindEurope, back its call for a landfill ban and have implemented their own internal bans within their organisations.

Regarding **regulatory drivers**, landfill ban is already implemented in several EU countries, with more European countries working on similar regulations (WindEurope, 2021). The European Critical Raw Materials Act, which promotes sustainable use and material security of REEs (European Council, 2023) and the Spanish government's incentive for WT blade recycling (MITECO, 2022; Invest in Spain, 2022) are examples of more such initiatives.

All these drivers collectively influence the creation of markets, i.e. **market drivers** in supporting industries. For instance, three of the interviewed actors work in the repurposing sector, where they transform wind turbine blades into structural components such as furniture, bridges, etc.

4.2. Barriers to adopt CE in the offshore wind industry

Despite various drivers, the adoption of the CE in the OW industry remains limited. We analysed empirical data to identify factors affecting CE adoption, categorising them into economic, environmental, institutional, regulatory, market, and technological barriers. The table below highlights these barriers with illustrative quotes. Notably, some barriers were identified as more central to limiting CE adoption, either emphasised by participants as key barriers or frequently reported in interviews. These central barriers are highlighted in green in Table 3.

Our analysis highlights two central **economic barriers**: high upfront costs for scaling technologies and the difficulty of creating a viable business case. Many interview participants noted that uncertainty in predicting WT waste volumes complicates business case formation, making it difficult to attract investors. Large utilities, such as OEMs and wind farm owners, have the capacity to fund some initiatives but are waiting to identify those with the best business potential, as these facilities often require substantial short-term investments.

Environmental barriers were not frequently mentioned, but earlier studies identified one such barrier, leading us to categorise it as a central barrier. One actor highlighted the lack of accurate circularity measuring indicators, which could result in discrepancies in measuring circularity, such as the recycling rate (Demuytere et al., 2024). Two participants

Table 3
Barriers to circular economy adoption in the offshore wind industry with illustrative quotes.

Barriers	Description & mentions	Illustrative quotes
Economic	Difficulty in creating a business case (CE3, OEM2, PA2, URC1, URC2, WO2, WO3)	If you go to the banks and say, hey, I have this idea of recycling blades, and they're going to go, yeah, but what's your business? What's your business model? It's difficult, so this financial support is going to be essential as well. **(PA2)** And then it's still also a bit unclear where the funding should come from, who should make the investments. **(URC2)**
	High upfront costs (CE2, CE3, DO2, OEM3, PA2, URC2)	Because a lot of the solutions that we could think about to increase circularity will have a cost in the short term, at least. So that means that somebody needs to be willing to pay something up front. **(OEM3)**
	Inaccurate decommissioning cost estimates (URC5, WO1)	We analysed all decommissioning plans, and we found that they were of really poor quality. They did not include certain economic approaches, and their financial estimates were way out. They were so far out that we alerted the government about it. All of the decommissioning plans had to be revised as a result of that. **(URC5)**
Environmental	Tracking actual circularity rate (URC1)	The other thing is that from an environmental point of view, we have no idea where we are. And then, of course, how circular. **(URC1)**
	Only marginal benefits above linear solutions (URC3 PA1, URC4)	The problem with cement co-processing is that it's only slightly better than incineration. You're burning most of the material, and you are disposing of the remaining fibres and leftovers in cement, where it's just kind of captured forever. So, it's better than landfill. It's better than incineration, but only slightly. **(URC4)**
Institutional	Uncertainty regarding waste handling (OEM4)	Legislation and what you think is toxic will vary from country to country ... the same material in one country can be regarded as hazardous waste, and the same material in another country can be regarded as a material that you can recycle and is non-hazardous. **(OEM4)**
	Pushing suppliers for co-location (OEM1)	It has to be on selected topics, right? For instance, it's not realistic to co-locate a glass manufacturer because their furnaces have a capacity of 10-20 thousand tons a year. They will never be locating to our plants. However, carbon pultrusion [carbon fibre polymer manufacturing] production suppliers, whose production capacity is much lower and targeted for specific applications, would be a good example of those who could co-locate. There would be significant merit in doing so. Therefore, it would be on select suppliers and select topics. **(OEM1)**
	Complexity in data sharing (CE1 DO2, CE2, OEM2, OEM4, URC3 PA1)	25 years ago, there were about 20, 30 companies designing and building wind turbines. And now we've got like four. So, we've got at least 15 companies that have been acquired or gone out of business. Trying to work out what's actually installed and where has been a real headache. **(URC3 PA1)**
	Lack of experience in EOL management (OEM3, URC1, URC3 PA1, URC5, WO3, CE2, CE3)	I think it's because it's new; nobody has done this before, so it's novelty, I would say. There's nobody who has put these together yet. There are some unknowns that need to be explored, and it's just easier to overcome those unknowns if you can see that this will be a profitable business. **(OEM3)** At the moment, we cannot foresee if we will have a wind farm coming up in five years, and we have no clue who will then be the right actor. **(WO3)**
Regulatory	Heterogenous regulations (CE2, OEM1, OEM3, OEM4)	One of the big blocking stones here [recycling] is that there's very different legislation in different countries. **(OEM1)** You will always have to tap into the local legislation and local value chains for materials. And of course, that will be different from country to country and region to region. **(OEM4)**
	Geopolitical tensions (CE4, OEM4, URC1, WO2)	If China stops exporting rare earths and permanent magnets. If they don't supply us with these materials, all our technology stops working. You cannot make cell phones; you cannot make wind turbines. It's a serious geopolitical problem. **(CE4)**

	Lack of landfill ban (CE3, OEM3, PA2, URC2, URC4, WO3)	I think legislation is important because if you can still landfill, if you can still send to cement incineration and are not aiming for ... a much more sustainable route, then this process [recycling] will be a bit more expensive. **(CE3)** We also see that it would be needed, and that is something we try to trigger by the WindEurope Sustainability Working Group. ... it would be good if there is a regulation that landfilling is not allowed. **(WO3)**
	Lack of waste codes for composite (PA2, URC1, URC2, URC4, URC5, WO2)	Having a waste code that is the same for all blades, even though blades are maybe not using exactly the same material, but it would make the waste stream more apparent, more traceable. **(URC1)**
	Lack of incentives to support CE initiatives (OEM3, URC2. URC3 PA1, WO3)	In the Netherlands, we have this national waste plan, and it states that composite materials have to be processed by a certified company, and you can choose whichever you like. But if the processing fee for your material exceeds a certain limit, then you are still allowed to go for incineration. So that kind of kills everything. **(URC2)** If there's no regulation demanding recyclability, there's no incentive apart from ethics and good morale. **(OEM3)**
Market	Uncertainty in volumes (CE1 DO2, CE3, CE4, DO1, OEM1, OEM2, OEM3, PA2. URC1, URC2, URC3 PA1, URC4, URC5, WO3)	We need to be more certain about the quantities of input material. And that is very difficult. A lot of different forecasts, a lot of different opinions.... How much will end up in our facility? **(CE3)** And then, secondly, there is still the problem about volume, because you can only structure these value chains if you have continuous business. **(OEM3)**
	Lack of standardisation (DO1, URC1, URC2, URC4)	Definitely the non-standards about the different size and the resin. We have actually said to the OEMs that they should at least have a uniform [resin]. Having one resin type would make it much easier to recycle because otherwise you need to take into account that you need to have three different technologies and after processing, they might need three different off-takers. **(DO1)**
	Lack of scalability (CE1 DO2, CE2, OEM1, OEM2, OEM4, PA2, URC1, URC4, URC5, WO2)	There are a lot of small companies using the elements of the blades in repurposing applications. But scaling-wise, it's nothing compared to how many blades you have out there in the market. **(OEM1)** The other limitation is scale. How many benches can you make and sell? We're still talking just a few 10,000 tons of end-of-life material, but that will increase to very significant volumes of 60,000 tons per year of blade material that will come to the end of life. You cannot turn all that into benches. **(PA2)**
Technological	Lack of reliable measuring indicators (OEM2, URC1)	I think there's a lot of speculation, like, this is more sustainable than that. But based on what? I haven't seen the analysis. **(OEM2)** I mean, in the Danish state recyclability criteria, the criteria were that it had to be at least TRL [Technology Readiness Level] six. But what is the TRL six exactly? That was a bit fluffy. **(URC1)**
	Lack of scalable technologies (CE3, OEM1, RMS, URC2, URC4, URC5)	For fibreglass composite materials or glass fibre composites, there isn't really a good process that is able to recapture the materials at value, at scale. **(URC2)** For blade recycling, the pyrolysis and so forth, is just not sustainable and commercially viable. This is a challenge that needs to be resolved, and there's a lot of investment going into that. **(URC5)**
	Process efficiency and material losses (CE1 DO2, CE3, PA2, URC1, URC2, URC5)	When you look at the shape of turbine blades, then there's only so many structures that you can cut out of it.... I think that you'll always have offcuts, and there will always be big chunks that are going to be left over. **(URC5)** The big challenge so far has been that the recycling process involves some degradation, particularly on the fibres. And because we use the highest ends of the glass fibres, with the highest tensile strength flexibility ratio. Any degradation on that makes our blades less performant. **(PA2)**

Table 4
Enabling measures to accelerate circular economy adoption for existing offshore wind farms with illustrative quotes.

Enabling measures	Description & mentions	Illustrative quotes	CE strategies that can be targeted
Industry-specific	Developing material passports (OEM2, OEM4, URC1, URC4, WO3)	We've introduced a material passport for blades…. It contains the level of information that we've seen that recycling companies are interested in. Where's the carbon, where's the metals, so they can process accordingly. So, a high-level diagram of the blade structure. And then high-level material categories, approximately how much glass, resin, metals, and other materials. **(OEM2)**	Repurposing and recycling
	Keep parts as parts (URC5, WO1, WO2)	The UK has hardly any manufacturing capacity for wind …. We're very reliant on imports. I think for the UK, the absolute best thing to do at this stage is to keep components as components. Strategically, because if you want to keep your wind farms operational, then you're going to need these components. And if you can't buy them, and if you can't manufacture them, then you need to keep the ones that you currently have. **(URC5)**	Reuse, refurbishing, remanufacturing and modularisation
	Create a circular hub for material collection (CE1 DO2, CE2)	I would like to be part of such a circular wind hub, and we have been in conversations about that … Where the blades are already stored, because we want to minimise transport as much as possible. **(CE2)**	Reuse, refurbishing, remanufacturing, repurposing and modularisation
	Sending waste back to suppliers for reusing or recycling (OEM1, OEM2)	I think it would be more [logical] to prevent the waste, and then if there is some waste, then we can send it to our supplier, and they can use it back into their production process or they can find other off-takers of that material. **(OEM2)**	Reuse and recycling
	Create an inventory of repaired, refurbished and remanufactured parts (OEM3, URC3 PA1)	Company X has its entire business model built around repair and refurbish, and they've got like a one in, one out. If you send a pitch gear to them for repair, they've probably already got one in stock because they've repaired it for somebody else and they'll send it straight back out. It's like a two-day turnaround, so much faster than waiting for replacements from an OEM. **(URC3 PA1)**	Repairing, refurbishing and remanufacturing
Regulatory	Incentivising CE solutions (OEM3, WO3)	We need to put monetary value on circularity some way or the other, whether it will be in auction schemes or what it is that I don't know. But it needs to have a higher value. **(OEM3)**	Lifetime extension, reuse, refurbishing, remanufacturing, repurposing, modularisation and recycling
	Developing designated waste codes for wind turbine material (OEM1, PA2, URC1, WO2)	I do think that when Europe is working on some kind of new waste coding system, that will make it easier to actually transport a blade from country A to B for recycling. And the problem is that it's a composite material, so there's no one waste code. Apparently, that's what makes the whole thing so bureaucratically difficult. **(WO2)**	Repurposing and recycling
	Enforce a landfill ban (PA2, WO2)	WindEurope has long said that it wants the EU to ban all landfilling of blades by 2025. I think basically everybody agrees that that should be a law. So let's see. It's most likely going to be implemented. **(WO2)**	Lifetime extension, reusing, refurbishing, remanufacturing, repurposing, modularisation and recycling
Market-specific	Finding alternate applications for the waste input (CE1 DO2, OEM1, OEM2, RMS, WO2)	We see waste as a resource. So what is leftover from our process should be raw materials that could be used by others, and we are actually doing that a lot. **(OEM1)**	Repurposing and recycling
	Creation of local market and supporting	Currently, I would say it's a practical approach. Within the long run, we	Reuse, refurbishing, remanufacturing, repurposing,

(*continued on next page*)

Table 4 (*continued*)

Enabling measures	Description & mentions	Illustrative quotes	CE strategies that can be targeted
	industries (CE2, OEM1, WO2)	hopefully can be more and more precise in saying, OK, if we have blades from around Hamburg, we will try to repurpose them in and around Hamburg…. But we need more proof of concept to be able to deal with it like that. **(CE2)**	modularisation and recycling
	Finding market requirements before taking the waste input (CE1 DO2, CE2, OEM4)	You know, if we've got a lot of orders for furniture, even the blade construction, let's say, is so good that it can be used as a footbridge. But nobody wants to buy a footbridge. But there are a lot of customers for the furniture. Then we recycle for this application. **(CE1 DO2)**	Repurposing and recycling
	Creating a market within the same company (URC2)	Company Y does a lot of repurposing of stuff for other companies. They always try to bring the stuff back to the same company, because there's sort of this connection already. Indeed, like wind companies, they have a connection to the wind turbine blades, so they are likely to accept it. And it creates a market in itself. **(URC2)**	Repurposing
	Materials-driven design (CE1 DO2, CE2)	With material-driven design, we mean that we look at specific blade types. So we would treat V44 or V80 differently. Because of the size, the shape, if there's space to stand inside, you can make a product where this function is happening. If the size doesn't allow for that, we're not going to try to make the blade bigger to accommodate that. Then we will do something else. So the material is leading in what it can become. **(CE2)**	Repurposing and recycling

observed that some circular technologies are only marginally better than linear technologies, offering insufficient incentives for value chain actors to invest in and develop these technologies.

Two **institutional barriers** were frequently mentioned by various business segment actors: the complexity of data sharing and the lack of knowledge or experience in EOL management. The complexity of data sharing was often linked to wind turbine blade data, which is crucial for recycling and repurposing companies. We encountered differing opinions on this issue from CE operators, OEMs, and researchers. CE operators in the repurposing sector expressed a strong desire for more detailed drawings of wind turbine blades to better understand their structural properties and composition, facilitating necessary cuts. On the other hand, OEMs, which manufacture these blades, claim that they are already providing blade material passports containing this data, which should assist repurposing businesses. They suggested that if specific data is unavailable, businesses could refer to the material passports of similar blades for approximations. A researcher pointed out that many earlier wind turbine blade OEMs were acquired by current OEMs, and during these takeovers, crucial design data was either lost or made unavailable, hindering the deployment of material passports. This may explain why the industry is rolling out blade material passports at a slow pace. Additionally, various URCs, OEMs, CEs, PA and WOs noted that the industry's limited experience in EOL management is a barrier to CE adoption, as few wind farms have been decommissioned to provide the necessary insights.

Regulatory barriers were frequently cited as key obstacles to accelerating CE adoption within the OW industry. Several OEMs and CE operators emphasised that differing regulations for handling EOL waste and CE goods across European countries make it challenging to transport waste for processing. Several actors, including WO, researchers and PAs, pointed out that the EU currently lacks a waste code for composite materials, hindering their cross-border transportation for further processing. Furthermore, many actors, including CE operators, OEMs, WOs, and researchers, emphasised the need for a Europe-wide landfill ban and economic incentives to create a viable business case for CE initiatives.

Our analysis found three central **market barriers**: uncertainty of volumes, lack of standardisation, and scalability issues. Uncertainty in volumes was the most frequently mentioned barrier cited by a variety of different segments. High energy costs have led operators to run turbines longer than expected, creating uncertainty, which complicates business cases for recycling and repurposing. While this is positive from a sustainability perspective, it creates challenges for operating these businesses. Several researchers and a decommissioning operator identified the lack of standards as another key market barrier. The presence of various blade designs and resin types makes it challenging for recycling companies to produce uniform-quality end products and for repurposing companies to mass-produce goods. Scalability is also a critical barrier. Several participants expressed concerns about the ability to scale the repurposing of WT blades into structural components such as bike sheds, playgrounds, and bridges and about the traceability of the material once WT blades are repurposed. Despite being more sustainable than recycling, repurposing companies struggle with scalability due to non-standardised WT components received for processing. The state of the wind turbine components further affects the scalability of the repurposing applications.

There are various **technological barriers**, including a lack of reliable technology maturity assessment indicators, scalable technologies, and issues with quality and material losses. Our findings suggest that the latter two are the key barriers. Several interview participants noted that there are very few scalable technologies available, and they are often limited to certain markets. These technologies frequently struggle to maintain uniform product quality due to factors such as material losses during wind turbine operation, inefficiencies in the chosen processing methods, and non-uniform input materials, such as variations in wind turbine blade size or design.

4.3. Enabling measures to accelerate CE adoption of existing offshore wind farms

CE practitioners recognise the limited adoption of CE practices in the offshore wind industry and are working to develop solutions. However, our findings show that many practitioners are either unaware of or have not considered various existing pathways that could accelerate CE adoption and effectively manage end-of-life waste. To address this, we provide in Table 4 a comprehensive list of enabling measures to overcome the identified barriers & support drivers categorised into three groups: industry-specific measures, regulatory measures, and market-specific measures. In Table 4, there is also a column that shows which CE strategies the various enabling measures are targeting, from recycling to higher-level strategies such as lifetime extension, as outlined in Fig. 1.

4.3.1. Industry-specific measures

Industry-specific measures focus on practical measures that organisations can implement to improve CE adoption. One such measure is the development of material passports for wind turbine blades. These documents provide detailed information about the materials used in the blades, including their approximate weight and location. This information includes materials such as glass fibre, balsa wood, metals like aluminium, copper, steel, and types of resin (DecomBlades, n.d.). Despite being considered a promising solution, the deployment of blade material passports has been rather slow. Some interview participants pointed out that this is due to past business mergers, during which crucial data regarding old wind turbine blades was lost or not made available. Others suggested that making minor tweaks in the design of blade material passports, such as adding lines on the blade structure to indicate where to cut the material, would greatly enhance usability for a variety of CE businesses, such as recycling and repurposing companies. Another approach suggested was to keep parts as parts, i.e., storing components until a feasible end-of-life solution is found. This strategy is particularly relevant in regions like the UK, where manufacturing capacity is limited, making it essential to preserve existing components for future use. Additionally, creating circular hubs for material collection can minimise transport emissions, provide storage and inventory facilities for small CE businesses, and also streamline downstream material handling processes.

Sending manufacturing waste back to suppliers is another solution, where suppliers can reuse and recycle it for manufacturing processes, thereby reducing raw material use, or they can send it to off-takers to repurpose it for another application. Creating an inventory of repaired, remanufactured, and refurbished components has significant potential to reduce the downtime of wind turbine operations and can also reduce the demand for new components, yielding significant economic incentives.

4.3.2. Regulatory measures

Regulatory measures are often cited as key enablers in overcoming barriers to CE. One such measure is incentivising CE solutions by assigning monetary value to circularity, potentially through auction schemes or other financial mechanisms. One interview participant mentioned that the Spanish government provides fiscal incentives for businesses to recycle wind turbine blades (MITECO, 2022; Invest in Spain, 2022). Other governments could develop similar initiatives to promote local circular value chains, enhancing circularity in the offshore wind sector. Additionally, the EU is providing financial incentives and funding to businesses that are promoting sustainability and material security to REEs, under the Critical Raw Materials Act (European Council, 2023). One of the interviewed startups reported that they are receiving funding from the EU as part of this scheme.

Developing a designated waste code on the EU level for wind turbine composite materials is another solution that can significantly improve CE adoption. A dedicated waste code would incentivise clean waste segregation, making it easier to transport wind turbine waste across borders for further CE processes such as recycling and repurposing.

At least four European countries, Austria, Finland, Germany and the Netherlands, have a landfill ban in place for the WT composites (WindEurope, 2021). However, most interview participants mentioned that having a Europe-wide landfill ban would ensure that no landfilling occurs in Europe, thereby enabling the creation of business cases and markets for CE businesses.

4.3.3. Market-specific measures

Market-specific measures address the economic and market deployability challenges associated with CE strategies. One practical approach is to find alternative applications for waste inputs or recycled waste fractions. For example, companies repurpose production waste from the wind industry in other industries, such as using it as filler in concrete and cement manufacturing. Creating local markets and supporting industries working with reuse, refurbishing, remanufacturing, modularisation, repurposing, and recycling can improve CE adoption by reducing transportation needs, related emissions and foster growth of such businesses.

Understanding market requirements before accepting waste inputs ensures that repurposed wind farm components and recycled materials meet the demand for specific products, such as sustainable furniture. Additionally, creating markets within the same company, where CE-processed components and materials that are repurposed and recycled to be used internally, can strengthen the connection between production and downstream CE processes.

Finally, adopting materials-driven design principles, where the characteristics of specific wind turbine parts or blade types guide their downstream processing, such as repurposing blades into playgrounds or furniture and recycling WT material to create applications in wind or alternate industry, can optimise the use of materials and support the development of innovative CE solutions.

5. Discussion

This study has identified a variety of economic, environmental, institutional, regulatory, and market drivers that make CE adoption an attractive business opportunity for various OW value chain actors. We observed that some of these drivers are similar to those that have been identified in section 2.2 as key drivers to adopt CE. For instance, sustainable waste management, reduction in waste generation, sustainable and reduced use of raw materials, and reduction of emissions by cleaner production initiatives are also found in earlier studies (Melles, 2023; Ranta et al., 2018; Agyemang et al., 2019).

Our analysis of barriers also revealed similar findings, with the identified barriers aligning with those documented in existing literature. For instance, several studies in different sectors and regions have pointed out that regulatory barriers, such as a lack of incentives and inconsistent regulation, affect the adoption of CE practices (Ranta et al., 2018; Kirchherr et al., 2018; Mehmood et al., 2021), including in the wind industry (Gode et al., 2024; Woo et al., 2022; Deeney et al., 2025). The high upfront cost required to develop CE initiatives has also been documented earlier (Agyemang et al., 2019; Kirchherr et al., 2018; Mehmood et al., 2021). Several previously reported wind and non-wind industry studies have pointed out that a lack of experience in the responsible handling of materials creates an obstruction for the adoption of CE (Gode et al., 2024; Agyemang et al., 2019; Kanters, 2020; Mehmood et al., 2021; Woo et al., 2022). In addition, other studies have also identified the lack of standardisation (Kanters, 2020; Kirchherr et al., 2018), inadequate supporting infrastructure and quality and material losses associated with CE strategies (Woo et al., 2022), which hinders its adoption.

The barriers and drivers' categories identified in CE adoption within the OW industry are of a similar nature (Table 2, Table 3 & Fig. 3), with a notable addition of technological barriers – indicating technical hurdles

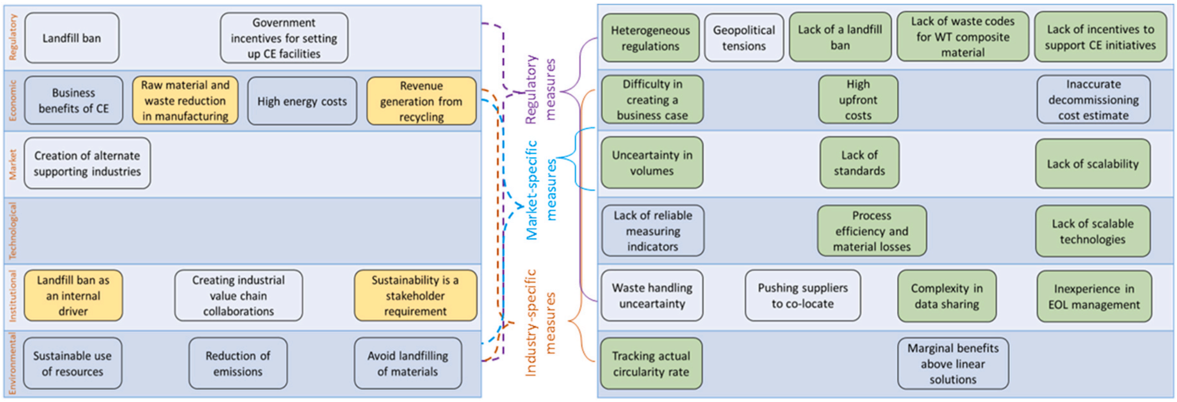

Fig. 3. The use of enabling measures in enhancing the effects of drivers (left) and addressing barriers (right) to the adoption of circular economy for near-end-of-life offshore wind farms. The dotted path connecting drivers and enabling measures indicates that not all CE drivers require enabling support, whereas the solid path connecting barriers and enabling measures suggests that addressing barriers always needs enabling support.

that OW organisations face in adopting CE strategies. We also observed that despite the similar nature, the number of barriers is quite significant compared to the drivers, indicating the overwhelming nature of barriers that is limiting CE adoption in the OW sector, similar to the observation in the analytical framework in section 2.4.

Our findings also demonstrate interactions between drivers and barriers, as illustrated in the analytical framework (Fig. 1). Despite strong economic drivers, such as business benefits, raw material savings, and waste reduction, many CE initiatives in the OW sector struggle to establish a viable business case. This is primarily due to barriers like uncertainty in EOL volumes, lack of investor support, and the high upfront costs required to scale operations. Despite the presence of strong institutional drivers to create industrial collaborations to boost CE adoption, its effects remain limited due to the presence of institutional barriers such as complexity in data sharing and a lack of experience in EOL management. The landfill ban, a necessary regulatory driver, only exists in a few European countries. Similarly, incentive schemes are also heterogeneous and unevenly distributed in various regions. This lack of regulatory consistency and supportive incentives can derail the momentum needed to accelerate CE adoption. Some CE businesses in the value chain are highly motivated to invest in higher-order sustainability strategies, such as repurposing – making structural components from WT materials. However, due to factors like the uncertainty in EOL volumes, the lack of standardisation in manufacturing OW components, and insufficient means to scale their products, these businesses find it difficult to establish a strong business case.

Although the complex interaction of various drivers and barriers to CE adoption explains why it is limited, it does not necessarily demonstrate how to overcome it. Our study has bridged this gap by systematically exploring ways to enhance drivers and address barriers by suggesting various pathways through industry-specific, regulatory, and market-specific measures.

Earlier studies have suggested pathways to overcome the lack of CE adoption (Woo et al., 2022; Deeney et al., 2025), and there are some industry-wide collaborations happening as well (DecomBlades, n.d.; Nagle et al., 2022; EOLO Hubs, 2025). However, these studies are targeting a particular CE strategy or component of WT, or they are developed for onshore wind farms, which have different scales, infrastructure, and EOL predictions than OW farms.

The majority of CE practitioners in our study are aware of the non-adoption problem, but are either unaware of or have not considered all the pathways that can improve CE adoption for near EOL OW farms. To address this, we systematically used the enabling measures provided in the interviews to enhance the implementation of drivers and address the central barriers limiting CE adoption in the OW industry by suggesting various pathways through regulatory, industry-specific, and market-specific measures.

Regulatory measures are the cornerstone for addressing the limited adoption of CE practices in the OW industry. Our study finds that regionally harmonised regulatory measures like landfill bans, waste codes, and CE incentives improve the economic feasibility of CE strategies, thereby offering business benefits for firms to invest in CE strategies. It also promotes sustainable use of resources, supports the development of CE businesses and alternative dependent industries and promotes the creation of new circular value chain collaborations, thereby reinforcing a range of economic, environmental, institutional, regulatory and market drivers. The regulatory measures also address a variety of central barriers. Developing homogeneous EU-wide incentives for CE adoption, such as the European Critical Raw Materials Act (European Council, 2023), the Spanish government's incentive for WT recycling (MITECO, 2022; Invest in Spain, 2022), EU-wide landfill ban on WT components (WindEurope, 2021), and creating waste codes for WT composites can help overcome various central regulatory, economic, market, technological and institutional barriers. If these measures are co-developed, they would prevent the landfilling of WT components in Europe, facilitate the cross-border trade of EOL waste, and incentivise the development of innovative, local, and regional CE solutions. This would then reduce upfront investment costs, make it easier to attract investors, and thereby improve the scalability of CE processes by carrying out necessary pilots. Such regulations could also incentivise CE businesses to form meaningful partnerships with the relevant upstream actors in the value chain, such as wind farm owners. This would lead to more accurate predictions of WT waste coming to these businesses, helping them to form a stronger business case. Additionally, it would also enhance the innovation capabilities of the sector, improve the development and scaling of more innovative CE solutions and foster the growth of small-scale yet highly innovative CE businesses.

Industry-specific measures such as returning waste to suppliers, developing material passports, maintaining inventories of old, repaired, refurbished, and remanufactured parts, and establishing circular hubs support environmental drivers such as sustainable resource use and related emissions. These measures can reduce demand for raw materials needed to produce new components and extend the usage cycle of parts, thereby also supporting wind farm lifetime extension driven by high energy costs (an economic driver). These measures foster circular innovation, enable the creation of new CE businesses and industries (market driver), and promote collaboration within value chains (institutional driver). The development of industry-specific measures also helps to address a range of central barriers. Industry-specific measures, such as developing and releasing blade material passports with suggested design improvements, can significantly benefit CE businesses. These passports would help businesses better understand WT blade drawings, including the structural properties and material locations. This understanding would enable them to create byproducts with minimal waste. Additionally, it would facilitate the design of technologies to standardise byproduct manufacturing, avoid quality and material losses, and help scale product design, thereby forming a solid business case. Keeping an inventory of parts as it is or as repaired, refurbished and remanufactured parts is beneficial for wind farm owners and CE actors who are involved in such businesses. Component reuse, refurbishment, and remanufacturing are significantly better than WT recycling (Velenturf, 2021; Gode et al., 2024; Jensen et al., 2020), as they delay EOL management, allowing components to serve their intended function for a longer time. This reduces the demand and associated manufacturing cost of new components and decreases material extraction and the associated carbon footprint. Using component swaps with reused, remanufactured, or refurbished components further reduces the downtime of WT operations. Therefore, CE businesses that are involved in these strategies have great potential to form a stronger business case, and such businesses will often thrive in markets such as the UK, where they have limited manufacturing capacity. Creating a circular hub for the storage of WT components would also help dependent CE businesses to reduce uncertainty in volumes and reduce the cost of storage and transportation. As an indirect effect, these savings could be used to improve the scalability and efficiency of their products. Furthermore, research institutions can collaborate with industry practitioners to design novel methods and tools to accurately estimate the circularity of various EOL processes. This collaboration would help industrial stakeholders calculate the sustainability of these processes before scaling up.

Market-specific measures primarily focus on driving business development for firms engaged in CE initiatives. Measures such as identifying alternative applications for waste, creating internal markets, and implementing materials-driven support facilitate the development of businesses in alternative industries, such as repurposing wind turbine blades into furniture, bridges, and other products—thus supporting market drivers. The creation of local markets and supporting industries further strengthens the scaling and development of local CE businesses, thus supporting economic drivers. These efforts also support environmental drivers, such as reducing transportation emissions and promoting sustainable material use. By finding new applications for wind turbine waste, these measures help avoid landfilling. Since these strategies centre on business development, they also foster the creation of new industrial value chain collaborations, which is an institutional driver. Initiatives like Re-Wind (Nagle et al., 2022) and DecomBlades (DecomBlades, n.d.) exemplify how cross-sector partnerships can accelerate CE transition. However, contrary to regulatory and industry-specific measures, which address a range of barriers, market-specific measures solely focus on addressing market barriers, as illustrated on the right side of Fig. 3. For example, analysing market requirements before taking the EOL waste and selling it locally can reduce transportation costs and enable standardisation and scaling of processes and products, further lowering the manufacturing cost of byproducts. For instance, sustainable furniture made from WT blades can be sold locally to meet local demands for furniture or skis made from recycled WT blades can be sold to Nordic countries (Vattenfall, 2025). CE businesses can also sell these goods to their upstream partners, such as wind farm owners or OEMs, thereby enhancing their sustainability and brand value. Upstream businesses, such as OEMs and raw material suppliers, can reuse or recycle their manufacturing waste. They can either use it again in their manufacturing operations or resell it to another customer, thereby improving their revenue stream, reducing waste fractions, and minimising the associated environmental footprint. Material-driven design enables the standardisation and scaling of CE processes. For example, if recycling or repurposing businesses are aware of the shape, size, material composition, and quantity of WT blades coming for processing, they can adjust their manufacturing processes accordingly. This allows them to design standardised byproducts at scale with uniform quality and low material losses, ultimately reducing the manufacturing costs of the byproducts.

Some businesses, such as raw material suppliers, OEMs and recycling companies, have long pursued strategies such as reducing raw material use, decreasing manufacturing waste and generating revenue from recycling, even before the formal development of CE in the OW industry. These practices provide immediate economic benefits to the involved firms, as well as improve resource efficiency. In contrast, other firms adopt CE strategies due to strong institutional drivers, such as respecting WindEurope's call for a landfill ban or because stakeholder demand greater sustainability in the firm's operation. In both cases, the involved firms do not rely on external enabling support, which indicates the defined nature of these drivers. This observation aligns with the analytical framework, which suggests that not all drivers depend on enabling measures for their adoption. Thus, enabling measures supporting the enhancement of drivers are indicated by a dotted line in Figs. 3 and 1, whereas the drivers that do not require this support are highlighted in pale orange in Fig. 3. Firms reporting these drivers are likely intrinsically motivated to pursue CE, as these strategies not only provide economic and environmental benefits but also enhance their sustainability branding.

In Fig. 3, the green highlighted boxes represent the central barriers hindering CE adoption for near EOL OW farms. As mentioned earlier in section 4.2, we consider these barriers central because they were either emphasised by participants as hindering factors or documented across various interviews and types of actors.

While enabling measures primarily target central barriers, their adoption also helps resolve non-central ones (represented as uncoloured boxes on the right in Fig. 3), as well as support vaguely defined CE drivers (represented as uncoloured boxes on the left in Fig. 3). For example, regulatory measures do not only target economic barriers, such as the high upfront costs of expanding CE infrastructure, but may also reinforce economic drivers, such as the business case formation for CE firms pursuing strategies like recycling, reuse, and repurposing. Region-wide regulations and incentives, like the Critical Raw Materials Act (European Council, 2023) and economic support for scaling reuse and recycling businesses can ease geopolitical tensions in materials trade like REE (Månberger et al., 2019). Similarly, EU-wide landfill bans, composite waste codes, and strong incentives for CE businesses reduce uncertainty in waste handling and support the scaling of innovative CE strategies such as reuse, remanufacturing, and repurposing. This motivates WOs to shift their asset management from lower-order to higher-order, more sustainable circular practices as illustrated in Fig. 1. Policymakers can further support such initiatives by mandating regular periodic updates from WOs' decommissioning cost estimates. Industry actors also play a vital role in addressing non-central barriers, such as developing circularity indicators and encouraging supplier co-location. Nevertheless, strong regulatory and economic incentives are essential to make these efforts viable. That said, efforts to develop enabling measures might not be straightforward; there may be trade-offs. For instance, the deployment of blade material passports (DecomBlades, n.d.) might be slow due to bureaucratic challenges involved in sharing sensitive data about blade design, as well as past business reacquisitions where small wind turbine blade OEMs were bought by larger OEMs, during which design data was either lost or became unavailable, as mentioned in Section 4.2. Similarly, the current lack of decommissioning volumes (Gode et al., 2024; Woo et al., 2022; U.S. Chamber of Commerce, 2024) and fluctuations in EOL volume predictions caused by geopolitical issues such as the Ukraine war can hinder the scaling and business development of CE strategies. However, despite these trade-offs, development of enabling measures is essential to boost circularity in the OW value chain, as it can foster competition based on circularity performance and encourage actors such as WOs and OEMs to demand supplier co-location where feasible.

The development of various enabling measures also supports a broad range of CE strategies. This observation aligns well with the analytical framework, which highlights the role of enabling measures in promoting systemic CE adoption. It is worth noting, however, that dematerialisation, the most sustainable CE strategy, as illustrated in Fig. 1, was not considered in this study. This is because our research focuses on CE development for OW farms approaching EOL, whereas dematerialisation is primarily relevant during the manufacturing of new components and therefore does not apply to existing wind farms.

6. Conclusion

The interaction between drivers, barriers, and enabling measures in CE adoption within the OW industry mirrors the pattern outlined in the analytical framework. Our findings show that although a range of drivers exists, their impact is often undermined by corresponding barriers. The majority of barriers, in comparison to drivers, indicate that they are the key hindering block to CE adoption. Moreover, some barriers were identified as more central than others and addressing these could help mitigate the non-central barriers.

We also found that the development of enabling measures is crucial to accelerate CE adoption in the OW industry. From the analysis of interview data, three types of enabling measures emerged: industry-specific, regulatory, and market-specific measures. These measures play a dual role: enhancing the development of inadequately defined drivers and addressing both central and non-central barriers. Furthermore, the development of enabling measures analysed in the study was found to target a range of CE strategies, from low to higher-order sustainable CE strategies, demonstrating their role in improving systemic adoption of CE.

Our study contributes to the existing literature by systematically categorising the drivers and barriers for CE adoption in the OW sector. By comparing the identified drivers and barriers with those in existing literature, the relevance of our findings is validated, highlighting common issues faced by various sectors in adopting CE. It further advances the literature by illustrating the complex interplay between drivers and barriers, and by demonstrating how enabling measures can strengthen vaguely defined drivers, address both central and non-central barriers, and support the development of diverse CE strategies. In doing so, the study reinforces the analytical framework and its emphasis on systemic improvement in CE adoption.

The proposed enabling measures provide a practical roadmap for OW value chain actors to accelerate sustainable circularity. It does so by bridging the gap between theory and practice by providing actionable strategies for CE practitioners and policymakers to develop innovative CE solutions and enhance adoption.

6.1. *Implications for policymakers*

Policymakers play a vital role in driving sector-wide circularity and the development of regulatory measures. Given their influence over the OW value chain, they should prioritise the development of harmonised, region-wide regulations, such as landfill bans and composite waste codes for WT materials. These measures must remain feasible, as overly rigid policies risk discouraging organisations from systematic CE adoption (Govindan et al., 2018). Moreover, it is equally important to incentivise a broad range of CE strategies through financial support for recycling, repurposing, refurbishing, remanufacturing, and material recovery. Existing examples, like Spain's economic incentives for blade recycling (MITECO, 2022; Invest in Spain, 2022) and the EU's support for REE recovery (European Council, 2023), show how consistent legislation and funding can help CE firms build viable business cases, scale operations, and overcome high upfront costs.

6.2. *Implications for industry actors*

CE practitioners like OEMs and WOs play a crucial role in developing industry and market-specific circular measures. Their influential position in the value chain allows them to foster cross-sectoral collaboration and share best practices to help scale CE businesses. For instance, they can develop more such collaborations, like the development of blade material passports (DecomBlades, n.d.) and repurposing WT materials for infrastructure like bridges, playgrounds, and furniture (Velenturf, 2021; Gode et al., 2024; Topham et al., 2019). In markets such as the UK, where manufacturing capacity is limited, these actors can establish material hubs and inventories of decommissioned parts; such inventories are particularly useful for emerging remanufacturing, refurbishing, repurposing, and recycling businesses. Reusing decommissioned components as part replacements cuts WT downtime. CE businesses, such as recycling and repurposing, should adopt market measures such as materials-driven design and identifying local market needs while manufacturing CE processed goods, as this supports a reduction in raw materials demand and sustainable use of resources.

6.3. *Future research*

While this study offers a foundational understanding of the drivers, barriers, and enabling measures for CE adoption in the OW industry, several avenues for future research remain underexplored. Due to the current lack of data on OW decommissioning, testing the validity of our findings, as well as challenges and limitations in implementing enabling measures, proves to be difficult. It is also possible that the findings obtained in the study may differ when the decommissioning starts on a commercial scale, possibly revealing different barriers, drivers and enabling measures. Additionally, measures such as developing uniform composite waste codes and economic incentives for CE strategies might disproportionately accelerate the development of certain CE strategies and impact the business growth of others, which may also influence the survival of involved CE businesses. We emphasise the need for further research in this area. Future research could investigate the adoption of CE practices when first-generation commercial OW farms begin decommissioning by conducting longitudinal case studies. Additionally, future studies should focus on developing and testing standardisation protocols and circularity measurement indicators, as these are vital for enabling circularity through benchmarking and comparing various CE strategies and technologies. We also recommend future studies to look into newly developed concepts, such as the deployment of Siemens Gamesa's recyclable blades in the Sofia Offshore Wind farm (World Economic Forum, 2025; RWE, 2025). These blades are reported to be a major breakthrough in circularity in the sector as they incorporate an advanced resin system that makes it possible to separate materials at EOL, thereby facilitating CE strategies such as material reuse and recycling. Future studies should investigate the commercial viability of this case when these blades approach EOL. Finally, since our empirical data is obtained from within Europe, there is a risk that not all drivers, barriers, and enabling measures are captured. Future research should validate these findings through comparative studies across mature and emerging European and non-European markets. For instance, a recently published report by the World Economic Forum cited that China is becoming a leader in renewable sectors such as wind and solar energy, and it is estimated that around 35 million tons of these assets will decommission by 2030, underscoring the urgent necessity to investigate CE adoption in China (World Economic Forum, 2025). Similarly, the U. S. Chamber of Commerce noted that a major share of solar and wind assets will decommission in the US by 2040 (U.S. Chamber of Commerce, 2024). However, since this is relatively far into the future, future studies can investigate the commercial feasibility of several CE EOL alternatives before scaling relevant CE strategies.

CRediT authorship contribution statement

Pankaj Ravindra Gode: Writing – original draft, Visualization, Methodology, Formal analysis, Conceptualization. **Øyvind Bjørgum:** Writing – review & editing, Supervision, Conceptualization.

Declaration of generative AI and AI-assisted technologies in the writing process

During the preparation of this work, the authors used Microsoft Copilot and Grammarly to improve the readability of the article. After using this tool/service, the authors reviewed and edited the content as needed and take full responsibility for the content of the article.

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Declaration of competing interest

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Data availability

Original data is unavailable due to privacy and ethical restrictions.

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