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Review

A Framework and Baseline for the Integration of a Sustainable Circular Economy in Offshore Wind

Anne P. M. Velenturf

School of Civil Engineering, University of Leeds, Leeds LS2 9JT, UK; A.Velenturf@leeds.ac.uk

Abstract: Circular economy and renewable energy infrastructure such as offshore wind farms are often assumed to be developed in synergy as part of sustainable transitions. Offshore wind is among the preferred technologies for low-carbon energy. Deployment is forecast to accelerate over ten times faster than onshore wind between 2021 and 2025, while the first generation of offshore wind turbines is about to be decommissioned. However, the growing scale of offshore wind brings new sustainability challenges. Many of the challenges are circular economy-related, such as increasing resource exploitation and competition and underdeveloped end-of-use solutions for decommissioned components and materials. However, circular economy is not yet commonly and systematically applied to offshore wind. Circular economy is a whole system approach aiming to make better use of products, components and materials throughout their consecutive lifecycles. The purpose of this study is to enable the integration of a sustainable circular economy into the design, development, operation and end-of-use management of offshore wind infrastructure. This will require a holistic overview of potential circular economy strategies that apply to offshore wind, because focus on no, or a subset of, circular solutions would open the sector to the risk of unintended consequences, such as replacing carbon impacts with water pollution, and short-term private cost savings with long-term bills for taxpayers. This study starts with a systematic review of circular economy and wind literature as a basis for the coproduction of a framework to embed a sustainable circular economy throughout the lifecycle of offshore wind energy infrastructure, resulting in eighteen strategies: design for circular economy, data and information, recertification, dematerialisation, waste prevention, modularisation, maintenance and repair, reuse and repurpose, refurbish and remanufacturing, lifetime extension, repowering, decommissioning, site recovery, disassembly, recycling, energy recovery, landfill and re-mining. An initial baseline review for each strategy is included. The application and transferability of the framework to other energy sectors, such as oil and gas and onshore wind, are discussed. This article concludes with an agenda for research and innovation and actions to take by industry and government.

Keywords: circular economy; resource and waste management; resource efficiency; wind energy; sustainable development; low-carbon infrastructure; renewable energy; energy transition

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1. Introduction

Low-carbon infrastructure and technologies such as wind, solar and electric vehicles are important in the mitigation of climate change and to keep global temperature rises below two degrees Celsius [1]. This article focuses on offshore wind because of its fast growth, while the first generation of turbines is about to be decommissioned. Offshore wind has rapidly developed into a preferred technology due to the large potential capacity, reducing costs and high social acceptance. While offshore wind is still dwarfed by onshore wind in terms of installed capacity—4.8% of the global wind capacity was offshore by 2020—it is forecast to accelerate more than ten times faster in terms of growth rates in the period 2021–2025 [2]. The levelised cost of energy for offshore wind are expected to fall at more than twice the speed (55%) than onshore wind (25%) between 2018 and 2030 [3].

The growing scale, however, also brings new sustainability challenges. Building offshore wind infrastructure will require vast amounts of additional foundation materials, such as steel, copper, concrete and glass fibre, as well as critical materials, such as neodymium and dysprosium [4]. Bigger offshore wind turbines may use more materials per unit of power generated than their smaller predecessors [5]. The freshwater and terrestrial ecotoxicity and human toxicity potentials are the largest adverse impacts from offshore wind, caused by material extraction and component manufacturing [6]. The recycling of offshore wind turbine materials is often depicted as the main strategy to limit future impacts, but research suggests that there is a far greater potential to reduce environmental impacts through improved component durability [7]. It is a challenging balance to strike, though, to design an infrastructure that is durable yet that can be disassembled to enable reuse and recycling [8]. Moreover, the sustainable decommissioning solutions that are required to enable component reuse and high-quality recycling are underdeveloped [9]. These sustainability challenges are related to circular economy and, as this article will substantiate with a review in Section 2, they are not effectively addressed, because circular economy strategies are not commonly and systematically applied to offshore wind.

Circular economy can be understood as the better alternative to the current linear take–make–use–dispose economy. Circular economy contributes to sustainability by minimising natural resource extraction and waste while optimising environmental, social, technical and economic values throughout the lifecycles of materials, components and products [10]. Circular economy brings together an eclectic mix of ideas, such as cleaner production [11–13], industrial ecology [14–18], resource efficiency [19–21], cradle-to-cradle [22,23], regenerative design [24], products-as-service [25–28], natural capital [29–32], zero waste [33–36] and more (further insights in, e.g., [37–39]). Generally speaking, circular economy strategies encompass (1) a narrowing of resource flows in the economy, e.g., by optimising designs using less materials; (2) a slowing of resource flows, e.g., by repairing and reusing products to keep them in use for longer; (3) a closing of resource flows by recycling materials; and (4) integrating resource flows back into natural biogeochemical cycles at the end of their consecutive uses [40,41]. Circular economy is committed to renewable resources, including energy supplies through renewable energy solutions (see, e.g., [42–44]).

The purpose of this article is to enable the integration of a sustainable circular economy into the design, development, operation and end-of-use management of offshore wind infrastructure. Systematically integrating circular economy will require a holistic overview of the potential strategies that apply to offshore wind. Focus on no, or a subset of, circular economy strategies would open the sector to the risk of unintended consequences—for example, growing offshore wind without circular economy considerations could reduce carbon impacts but would likely cause trade-offs with clean water and nature conservation, a focus on recycling could lead to more pollution and costs in comparison to durable designs [45] and the race to reduce costs for the private sector to grow offshore wind in the near-term can lead to higher decommissioning costs that may, moreover, have to be paid by the public later on [8,46]. Only four publications include initial circular economy frameworks for wind energy [8,47–49]. This article will evidence that none of these articles meet the full breadth of strategies demanded in offshore wind. Moreover, none fully explain what the circular economy strategies mean for offshore wind, leading to confusion and suboptimal solutions developed in the sector, such as a widespread misconception that circular economy is an end-of-pipe strategy to increase recycling.

The objective of the presented research is to develop a novel framework for a sustainable circular economy in offshore wind through a combination of literature reviews and stakeholder coproduction. Section 2 will systematically review circular economy and wind literature, evidencing that circular economy is not structurally applied to offshore wind and that a holistic framework is lacking, and will explain why such a framework is necessary to effectively address circular economy-related sustainability challenges and opportunities in the offshore wind sector. Section 3 will detail the literature review and stakeholder coproduction process through which the framework was developed. Section 4 will present the framework of circular strategies covering the materials, components and infrastructure for offshore wind at all lifecycle stages, briefly comprising: design for circular economy, data and information, recertification, dematerialisation, waste prevention, modularisation, maintenance and repair, reuse and repurpose, refurbish and remanufacturing, lifetime extension, repowering, decommissioning, site recovery, disassembly, recycling, energy recovery, landfill and re-mining. This study thereby also makes an original contribution to the circular economy literature, which is generally product-centric and not focused on a whole infrastructure. Section 4 will also include a baseline review to gauge where major research efforts are required. Section 5 will discuss the application of the framework and the transferability to other energy sectors, and will conclude the article with an agenda for research and innovation and actions for industry and government, including the need for cross-sectoral learning with onshore wind in particular; the development of data systems for the economic, technical, social and environmental values of material, products and component flows into, through and out of offshore wind; better tools for holistic sustainability assessments; insights into the capabilities of related sectors that are essential in supporting circular economy in offshore wind; and context-sensitive decision support tools to optimise whole lifecycle scenarios for offshore wind.

2. Background: Circular Economy and Offshore Wind

Circular economy has been defined in hundreds of different ways [50], the only common denominator being the aspiration to make better use of materials, components and products when compared to a linear economy. It has been argued that the purpose of a circular economy is to organise resources to maintain or enhance social well-being and environmental quality for current and future generations, recognising economic prosperity as a boundary condition for sustainable development [10].

Circular economy has gained momentum in industry, government and academia because of its ability to reduce environmental impacts while opening new business opportunities, which can create jobs and other social benefits. Evidence suggests that it is impossible to reach climate targets without realising a sustainable circular economy [51,52]. Environmental benefits stretch further than carbon emission reductions alone, given that a broad spectrum of absolute environmental improvements are increasingly targeted (e.g., [45,53]). However, arguably, it has been the envisaged economic benefits that have made circular economy attractive for governments and businesses [54], with forecasts of $25 trillion in new business opportunities globally by 2050 [55] and a potential eight million jobs created in the EU by 2030 (calculated based on [56]).

2.1. Current Circular Economy Literature on Wind Energy

This section will show that circular economy strategies are not commonly and explicitly applied to offshore wind, with a systematic review of the scientific literature on circular economy and (offshore) wind that demonstrates the novelty and demand for a circular economy framework for offshore wind. While Liu et al. [57] optimistically stated that "wind power is following the path of sustainable development and circular economy" in 2010, a Scopus search on "circular economy" and "offshore wind" more than ten years later (2 June 2021) returned only six publications—all from the last three years [8,48,58–61]. Pego [58] discusses that renewable energy is a key part of a circular economy, noting that—according to experts on energy and marine spatial planning at the European Commission—the end-of-use management of wind infrastructure is a "fragile point" in the environmental performance.

Jensen [48] argues that 70–80% of the environmental impact of turbine manufacturing originates from material extraction and processing. Stamford and Azapagic [6] concur, highlighting the importance to maximise resource productivity with measures throughout the lifecycle of a wind farm [8]. While there is a consensus that 80–90% of materials (by weight) in a turbine could theoretically be recycled, empirical evidence that this is indeed happening is thin [48]. Moreover, recycling ranks relatively low in the hierarchy of circular economy strategies, because (a) other strategies such as repair, reuse and remanufacturing generally have a better sustainability potential, and (b) recycling can be energy- and water-intensive while being associated with losses in the material quality and volumes that then have to be substituted in subsequent production cycles [41,62,63]. The largest concerns exist around the recycling of blades due to a lack of commercially available sustainable solutions to recover the composites of which blades are made [59,64].

Overall, the analysis by Jensen et al. [8] shows that offshore wind farms are not generally developed with a circular economy in mind and fail to take a long-term and joined-up perspective regarding resource extraction, use and end-of-use management. Moreover, decommissioning plans are found to be vague with regard to resource management methods and do not provide evidence that materials can and will be sustainably recovered [8], converse to the consensus articulated by Jensen [48] and industry reports (e.g., [65]). Developing and commercialising solutions for end-of-use can be challenging due to limited insights into the resource stocks and flows in offshore wind [66]. The approach of Chen et al. [60] can more accurately estimate the volumes of materials used for foundations in varying water depths. More of such solutions are in demand to better gauge the challenges ahead in terms of the quantities, qualities and timings of resource and waste flows. Here, digital technologies play a crucial role [61].

A broader Scopus search for literature on the interface of the subjects of "circular economy" and "wind" (3 June 2021) returned 91 publications, of which 39 hold direct importance and 27 are peripherally relevant—66 in total (Figure 1). About a third of the 66 titles broadly discuss: the role of wind and other renewable energy technologies to power a sustainable and circular economy [57,58,67–77], or battery storage (e.g., [72,78]) and the potential for integration with a hydrogen economy to avoid a loss of generated wind power (e.g., [79]), using hydrogen subsequently in methanol production [80–82]. Schoden et al. [83] present a project to raise public awareness about the need for a circular economy for wind turbines.

The majority of publications are focused on material recycling and recovery: (a) in general [7,48,84], (b) of blade materials [47,85–96] or (c) of critical raw materials [97–105]. Joining up the start and the end of low-carbon infrastructure supply chains, resource security concerns [102,106,107], design for recycling [108,109] and supply chain security and development [95,103] are covered. Solutions that go beyond material recovery are emerging with publications on lifetime extension [110,111], eco-design [7], reuse and repurposing [83,93,112,113] and remanufacturing [114]—terminology explained in Section 4 (S4).

Data systems that offer insight into the quantities and qualities of resource stocks and flows are essential to enable decision-making for the uptake of more circular economy practices [66] and policies and regulations [115]. Initial signs of the development of such systems can be derived from articles on the Internet of Things [61,116], indicators [117] and material stocks and waste flows [8,49,59,60,89,94]. Mathews and Huang [118] compare the uptake of renewable energy in China within a global context. Lesniewska [119] discusses EU policy and regulation for a circular economy in solar and wind sectors, and Kopnina [120] talks about renewable energy policy options, comparing reformative energy efficiency measures with more transformative circular economy and cradle-to-cradle approaches.

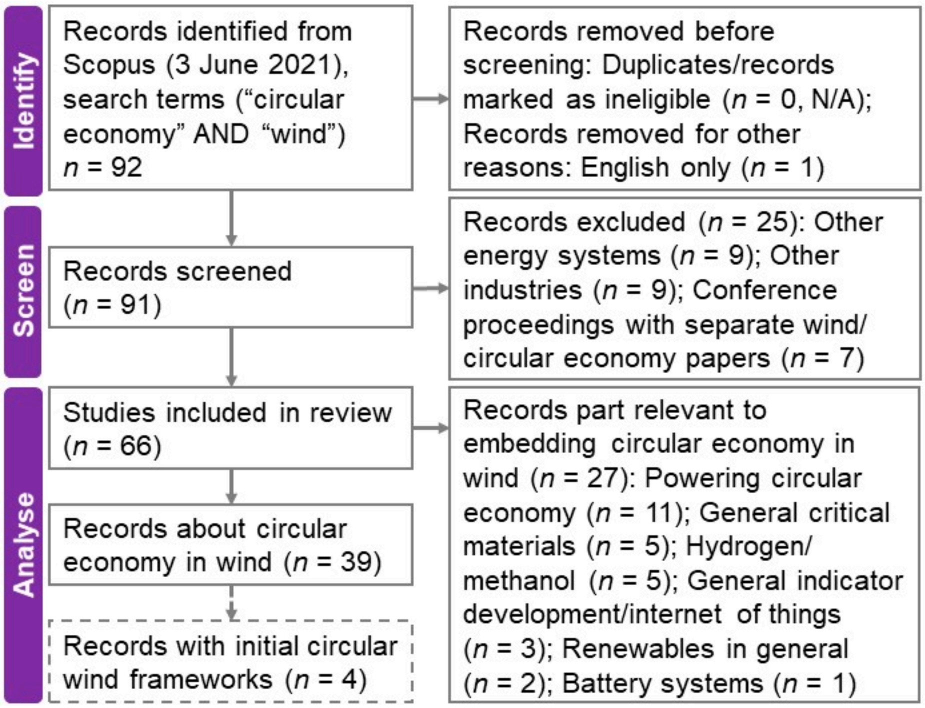

Figure 1. Systematic review of scientific publications on circular economy and wind energy based on the PRISMA guidelines [121].

Four publications include initial circular economy frameworks for the wind sector [8,47–49]. Jensen and Skelton [47] position the current end-of-use solutions for turbine blades within the context of a circular economy diagram, visually similar to the Ellen MacArthur's "butterfly diagram" (an overview and critical review in [41]). The applicability of the framework to other wind turbine components and the whole infrastructure are not part of the study. Conversely, Jensen [48] does discuss recycling solutions for most components. While recycling is placed within the broader context of circular economy—covering longer usage enabled by service and maintenance, reusing products and components and refurbishing/remanufacturing—the estimated relative environmental performance of recycling compared to these circular economy strategies is not discussed. Moreover, this is a single-criterion assessment using energy expenditure as a proxy for environmental performance, missing out on broader environmental factors (e.g., eco/human toxicity) and excluding social and economic factors. In other words, this study does not take a whole system perspective, as would be expected within circular economy. Jensen et al. [8] argue that such limited whole lifecycle and whole system perspectives with regard to resources is pervasive across low-carbon infrastructure sectors. In response, they propose a rudimentary framework for a sustainable circular economy in offshore wind. Similarly, Delaney et al. [49] take the waste hierarchy as a starting point and connect other circular economy practices to it, such as lifetime extension and repair. The frameworks do not explain in detail what each circular economy strategy includes. The latter frameworks indicate that, in offshore wind, there is demand for circular economy strategies that operate at the level of whole infrastructure (e.g., whole turbines and wind farms), while existing circular economy frameworks are generally focused on the product level (also see, e.g., [122,123]). These frameworks will be summarised in Section 3 to start developing a circular economy framework that meets the full breadth of demands in offshore wind with greater clarity.

2.2. Circular Economy-Related Challenges and Opportunities in Offshore Wind

Circular economy involves wide-ranging system changes, but at its basis it is about resource and waste management. A literature review and expert survey in 2020 on sustainable development challenges and opportunities for offshore wind revealed a number that are circular economy-related [124]:

Fossil fuels: Moving away from using non-renewable resources such as fossil fuels that contribute to global warming is an opportunity [6,125,126]. Nevertheless, reliance on fossil-based materials (e.g., resins) and processes (requiring high temperatures) and the importance of reducing whole lifecycle greenhouse gas emissions remain challenges [124,127–129].

Energy use: While offshore wind power generation can be sustainable, its usage is not necessarily so, and in many countries the per capita energy use has to decrease following the energy hierarchy, a trend already underway with the global energy demand declining 5% in 2020 [130].

Resource exploitation: The demand for resources for renewable infrastructure is rising steeply [8], raising challenges for environmental sustainability—e.g., due to potential high impacts of resource extraction and processing [6,131]—and social sustainability—e.g., due to slave and child labour and the displacement of indigenous people [124,132]. Conversely, opportunities include developing more equitable ownership and business models.

Resource competition for materials is increasing across renewables sectors, especially materials for grid development and for batteries for electric vehicles and large-scale energy storage [8,133,134]. Geopolitical dynamics for resource access have been visible for decades, for example, in export restrictions and/or tariffs applied by China on rare earth materials required by industries in Japan, the EU and the US (e.g., [135]) and limiting the manufacturing capacity in India by subjecting raw materials to higher import duties than components. This constrains the capability of countries to break into new global markets for offshore wind, take advantage of opportunities for local industrial development and job creation, and create a ripple effect in which the growing local manufacturing capacity drives further offshore wind deployment [127].

Material innovation solving resource security and sustainability challenges [134,136], including: (a) lifetime extension and component durability, e.g., better blade coatings and materials (e.g., [137]) and lighter materials reducing structural loads [138]; (b) more resilient materials for the marine environment with less pollution potential through harmful leakage into the sea; (c) alternatives to fossil-based materials, e.g., replacing resins in blades and SF6 in switchgear; (d) components and materials to disassemble and recycle easily [8]; (e) alternatives for critical raw materials. However, early warning signs were raised that ongoing cost reductions start to limit funds for industry innovation.

Durability and lifetime extension are crucial for increasing the resource productivity of materials, e.g., extending the component lifetime from 20 to 30 years can increase the resource productivity by 50% and significantly reduce the relative environmental impacts of resource extraction and processing. This requires understanding the state of individual components and whole offshore wind structures throughout their lifecycle, and operations and maintenance (O&M) with the help of robotics and remote monitoring can improve insights, especially when combined with better data systems to capture, share and use data across the supply chain, which may be constrained by proprietary systems [66,134,136]. Better insights into material stocks and flows are also important for decision-making for business models, policies and investments into circular economy solutions [66], with data on the volumes, material properties and associated environmental, social and economic values of products, components and materials [139]. Supply chains are considered complex, because stakeholders can play multiple roles across projects (e.g., OEMs—Original Equipment Manufacturers—can also own wind farms or function as operations and maintenance providers) [140], and because market conditions and contractual terms can strongly vary, especially at end-of-use [141].

End-of-use management: Growing concerns around resource access and the social and environmental impacts require sustainable solutions for end-of-use management. The impact of material usage in offshore wind is relatively high compared to other power technologies in terms of potential water, human and ecotoxicity and tend to be justified by the assumption that materials can be recycled [6,127,141]. However, the issues around end-of-use management and recycling are prevalent [8,66], particularly regarding blade waste from replacements and decommissioning operations due to the lack of sustainable and commercially viable recycling solutions [8,59]. This is exacerbated by long-running circular economy challenges with regards to finding end users for recycled materials, relatively low costs of virgin materials and low costs of less-sustainable solutions [59]. Supply chains for offshore wind decommissioning, associated infrastructure and end-of-use management are still to be developed [9,66].

Sustainable decommissioning: Offshore wind end-of-use management and decommissioning experiences are limited [141]. While decommissioning is often only considered as an afterthought [141], it could be eased proactively with "design for decommissioning", for example, designing sites upfront to enable a retrofit with bigger turbines at the end-of-use. Working in marine conditions poses challenges due to the logistics and diverse weather conditions [141,142]. Future (de)commissioning could be eased by floating wind farms where some operations can occur closer to shore. The lack of specific and suitable regulations for offshore wind increases the uncertainty in decommissioning processes and allows for inadequate plans to be articulated, with offshore wind infrastructure being constructed without plans for the recovery of materials and/or obligations to develop such solutions when they are absent at the point of construction [8,141]. The lack of proactive planning can affect the decommissioning costs, with offshore wind decommissioning costs four-to-ten times higher than expected, while financial securities are not keeping up sufficiently [8,46,141,143]. These issues were previously experienced by other sectors, e.g., North Sea oil and gas, with a high potential for cross-sectoral learning regarding cost management, decommissioning technologies and reusing infrastructure from other sectors.

3. Methods

3.1. Developing the Framework

In August 2020 a draft framework of circular economy strategies for offshore wind was developed through a systematic review of the scientific literature on wind energy that included overviews of circular economy strategies (S2.1). The three articles that included initial frameworks and were available at the time [8,47,48] were used as a starting point (Table 1). The identified strategies contained duplications around processes describing the recovery of materials. These were recycling, recovery and conversion, which describe processes that, under the legal terms of the waste hierarchy, would all be considered recycling and, therefore, were consolidated into one strategy. Resize/reshape describes a process that, in circular economy, is commonly called "repurpose" and was reworded as such.

Table 1. Initial circular economy framework for offshore wind based on the scientific literature [8,47,48]. Grey cells indicate the initial frameworks that named the circular economy strategies. "N/A" indicates that descriptions of named strategies were missing in the publication(s).

Circular Economy Strategy	Strategy Description	Jensen and Skelton 2018	Jensen 2019	Jensen et al. 2020
Design for circularity	Balancing durability, reparability, disassembly and recyclability at design stage			
Service, maintenance	N/A			
Repair	N/A			
Reuse, redistribution	Reuse of the whole blade in its current structure; of products and components			

Repurpose; Resize/reshape	Standardized and custom-made parts made from the blade and used for secondary applications
Remanufacture/refurbish	N/A
Recycling; Recovery; Conversion	Recycled material used in secondary applications as aggregates. Waste management processes to extract fibres and resin to retain best possible quality. Converting the composite material into new materials for other purposes
Energy recovery	N/A
Landfill/controlled storage	N/A
Lifetime extension	Extending the life of a whole wind farm
Site replanting	Replanting sites with similar turbines
Site repowering	Replacing turbines with larger models
Decommissioning/site restoration	Remove turbines and restore site to conditions similar to before the development

The circular economy strategies from Table 1 were discussed in a workshop with the Offshore Renewable Energy Catapult in August 2020 (a UK government-funded leading technology innovation and research centre for offshore renewable energy) to brainstorm about how circular economy terminology intersects with language in offshore wind (overview of the results in Table 2). In parallel, an initial exploration of the scientific literature on the individual circular economy strategies and offshore wind was carried out. This led to adaptations of the terminology used in the framework. Dematerialisation and waste prevention came up in the review and were discussed in the workshop, and are clearly reflected as important in circular economy literature and the waste hierarchy. These strategies were, hence, added to the framework. The groupings of the strategies reuse, refurbish, upgrade and remanufacture were altered, respectively, based on the processes described. The difference between reuse and repurpose became fuzzy in discussions and, with the difference appearing minimal, were merged into reuse. Re-mining was added to express the potential to recover resources from landfilled wastes for use in low-carbon infrastructure. Replanting was dropped, because the term is not commonly used. Disassembly was added due to the importance for enabling component reuse, recycling, etc. The discussion with the Offshore Renewable Energy Catapult offered a vital source of alternative keywords that were used as search terms for further exploration of the literature. The interactions also underlined the diverse interpretations of circular economy terminology and the value of offering a framework with clear descriptions to enable the effective integration of circular economy within the offshore wind industry.

Table 2. Results from the workshop with the Offshore Renewable Energy Catapult in August 2020.

Circular Economy Strategy	Alternative Terminology Raised in Workshop
Design for circular economy/circularity	Ecoselector, Product environmental design Holistic lifetime design, Integrated design
Repair, Maintenance	O&M (operations and maintenance), Inspection, Service, PPM/planned preventative maintenance, Condition based maintenance Scheduled and unscheduled Troubleshooting (or T/S) Component replacement/exchange, Retrofit Jacked-up events, Event of crane demand
Reuse, Repurpose	Refurbished Breaking (e.g., breaking up, breaking for parts), Salvage Second-hand, Used

Refurbish, Remanufacturing	Upgrade, Overhaul Refurb Recon/reconditioned Parts
Recycling	Scrap (in relation to metal) Diversion (from landfill)
Energy recovery	Waste to heat, Waste to energy, Energy from waste, Incineration, Burning, Pyrolysis, gasification, etc.
Landfill, Controlled storage	Burial, Burying Re-mining
Lifetime extension	Asset life management, Asset life extension Fatigue life extension, End of life extension Remaining life; Residual strength determination; Digital twin Leading edge protection, Cathodic protection, Corrosion prevention End of life
Replanting	Not commonly used. If used, means process similar to repowering.
Repowering	Full/partial repowering End of life extension
Decommissioning	Removal/Asset removal; Extraction Dismantling End of life
Site restoration	Site recovery, Artificial reefs, Habitat restoration, Aftercare Foundation cutting, Monopile extraction Remediation
Other terms from open discussion	Waste reduction, Waste prevention Lifecycle management Lean manufacturing, Dematerialisation Overhaul Rebuild Reprocess Re-energise

The draft framework was communicated with the waste, resources and offshore wind sectors in the period September–December 2020 via blogposts [144,145], presentations, podcasts and interviews at industry events inviting expert feedback [146–150]. Feedback included clarification questions and suggestions regarding individual strategies, suggestions for additional strategies (modularisation and recertification, and making the difference between reuse and repurpose explicit) and to complement and ease the legibility of the accompanying diagram, and questions about how to use the framework (subsequently covered in the discussion of this article).

The framework went through a third and final step of stakeholder input at a business workshop in January 2021 [151]. The workshop was attended by 112 participants from industry (49%), government (10%), research, development and innovation organisations (36%), and other organisations (5%) in various offshore wind and related sectors in the supply chain, including, for example, the wind, removal services, and resources and waste sectors. The participants were missing a number of strategies from the presentation of the framework, including: Coprocessing (covered under recycling/energy recovery); Lifetime extension through derating (specification under lifetime extension); Degrowth (economic model rather than a circular economy strategy); and Information strategies (added to the strategies as a key enabler).

3.2. Reviews to Define and Take a Baseline of the Identified Strategies

Each of the identified circular economy strategies were defined for the purpose of generating clarity in their application. Interactions with practitioners (see S3.1) displayed confusion about the meaning of circular economy strategies. While presenting the broad diversity of perspectives on each strategy could be seen as more objective, it can also feed further—counterproductive—confusion. Hence a strategic choice was made to select circular economy literature to define strategies based on the consensus that they derived from a diversity of perspectives reviewed and/or their apparent thought leadership based on novelty (for newer strategies) and the number of citations (for more established strategies).

Subsequently, an initial baseline review was carried out on research on each circular economy strategy within the subject area of offshore wind, consisting of three steps (Table 3): (a) searching for the key term(s) named in circular economy for offshore wind framework, (b) searching for the associated terms as identified in Table 2 and (c) searching for key term(s) in the broader wind energy literature. The first step of the reviews was systematic for nearly all the strategies, except for repair and maintenance, data and information and circular design, because these represented large and fuzzy bodies of the literature with thousands of publications that could not be covered within the time available for this project. Each strategy would deserve a further in-depth review in their own right, but that went beyond the purpose of this baseline review, which was to gauge the current expertise in offshore wind to inform an agenda for research and practice in the—new to offshore wind—subject area of circular economy.

Table 3. Literature searches for keywords in the publication title, abstract or keywords on Scopus (last repeated on 5 and 6 June 2021, unless specified otherwise) for three consecutive searches on (a) circular economy strategies in offshore wind, (b) associated terms in offshore wind based on Table 2 and (c) circular economy strategies in wind energy in general.

Circular Economy Strategy		Search Terms
1. Dematerialise	a	((“offshore wind” OR off-shore wind”) AND (dematerial* OR de-material*))
	b	((“offshore wind” OR off-shore wind”) AND (“lean manufacturing”))
	c	((“wind”) AND (dematerial* OR de-material*))
2. Prevent waste	a	• ((“offshore wind” OR “off-shore wind”) AND (“waste prevention” OR “prevent waste”)) • ((“offshore wind” OR “off-shore wind”) AND (“industrial symbiosis”))
	b	((“offshore wind” OR “off-shore wind”) AND (“waste reduction” OR “reduce waste”))
	c	• ((“wind”) AND (“waste prevention” OR “prevent waste”)) • ((“wind”) AND (“industrial symbiosis”))
3. Maintain and repair	a	• ((“offshore wind” OR “off-shore wind”) AND repair*) • ((“offshore wind” OR “off-shore wind”) AND “maintenance”)
	b	• ((“offshore wind” OR “off-shore wind”) AND (inspection)) • ((“offshore wind” OR “off-shore wind”) AND (service)) • ((“offshore wind” OR “off-shore wind”) AND (O&M)) • ((“offshore wind” OR “off-shore wind”) AND (retrofit)) • ((“offshore wind” OR “off-shore wind”) AND (“trouble shooting”)) • ((“offshore wind” OR “off-shore wind”) AND (“component replacement” OR “component exchange”)) • ((“offshore wind” OR “off-shore wind”) AND (“jacked-up event”))
	c	• (“wind” AND repair*) • (“wind” AND “maintenance”)
4. Reuse and repurpose	a	• ((“offshore wind” OR “off-shore wind”) AND (“reuse” OR “re-use” OR reus*)) • ((“offshore wind” OR “off-shore wind”) AND (“repurpose” OR “re-purpose” OR repurpos*))
	b	• ((“offshore wind” OR “off-shore wind”) AND (“used” AND “parts”)

		• ((“offshore wind” OR “off-shore wind”) AND (“breaking” AND “parts”)
	c	• ((“wind”) AND (“reuse” OR “re-use” OR reus*)) • ((“wind”) AND (“repurpose” OR “re-purpose” OR repurpos*))
5. Lifetime extension	a	((“offshore wind” OR “off-shore wind”) AND (“lifetime extension”))
	b	• ((“offshore wind” OR “off-shore wind”) AND (“asset life”)) • ((“offshore wind” OR “off-shore wind”) AND (“fatigue life”)) • ((“offshore wind” OR “off-shore wind”) AND (“end of life extension”)) • ((“offshore wind” OR “off-shore wind”) AND (“remaining life”)) • ((“offshore wind” OR “off-shore wind”) AND (“residual strength”)) • ((“offshore wind” OR “off-shore wind”) AND (“digital twin”)) • ((“offshore wind” OR “off-shore wind”) AND (“derating”))
	c	• ((“wind”) AND (“lifetime extension”)) • ((“wind”) AND (“fatigue life”))
6. Repower	a	((“offshore wind” OR “off-shore wind”) AND (“re-power*” OR repower*))
	b	• ((“offshore wind” OR “off-shore wind”) AND (“replanting”)) • ((“offshore wind” OR “off-shore wind”) AND (“end of life extension”))
	c	((“wind”) AND (“re-power*” OR repower*))
7. Refurbish and remanufacture	a	• ((“offshore wind” OR “off-shore wind”) AND (“refurbish*” OR “re-furbish*”)) • ((“offshore wind” OR “off-shore wind”) AND (“remanufactur*” OR “re-manufactur*”))
	b	• ((“offshore wind” OR “off-shore wind”) AND (“upgrade”)) • ((“offshore wind” OR “off-shore wind”) AND (“overhaul”)) • ((“offshore wind” OR “off-shore wind”) AND (“recondition”)) • ((“offshore wind” OR “off-shore wind”) AND (“parts”))
	c	• ((“wind”) AND (“refurbish*” OR “re-furbish*”)) • ((“wind”) AND (“remanufacture*” OR “re-manufactur*”))
8. Recertify	a	((“offshore wind” OR “off-shore wind”) AND (“recertify*” OR “re-certif*))
	b	((“offshore wind” OR “off-shore wind”) AND (certify*))
	c	• ((“wind”) AND (“recertif*” OR “re-certif*)) • ((“wind”) AND (certif*))
9. Disassemble	a	((“offshore wind” OR “off-shore wind”) AND (disassembl*))
	b	N/A
	c	((“wind”) AND (disassembl*))
10. Modularisation	a	• ((“offshore wind” OR “off-shore wind”) AND (modular*)) • ((“offshore wind” OR “off-shore wind”) AND (“modularisation” OR “modular design”))
	b	N/A
	c	• ((“wind”) AND (modular*)) • ((“wind”) AND (“modularisation” OR “modular design”))
11. Decommission	a	((“offshore wind” OR “off-shore wind”) AND (decommission*))
	b	• ((“offshore wind” OR “off-shore wind”) AND (“asset removal”)) • ((“offshore wind” OR “off-shore wind”) AND (“removal”)) • ((“offshore wind” OR “off-shore wind”) AND (dismantl*)) • ((“offshore wind” OR “off-shore wind”) AND (extraction))
	c	((“wind”) AND (decommission*))
12. Restore site	a	• ((“offshore wind” OR “off-shore wind”) AND (“site recovery” OR “recover site”)) • ((“offshore wind” OR “off-shore wind”) AND (“site restoration” OR “restore site”))
	b	• ((“offshore wind” OR “off-shore wind”) AND (“artificial reefs”)) • ((“offshore wind” OR “off-shore wind”) AND (“habitat restoration”)) • ((“offshore wind” OR “off-shore wind”) AND (“aftercare”)) • ((“offshore wind” OR “off-shore wind”) AND (“foundation cutting”)) • ((“offshore wind” OR “off-shore wind”) AND (“monopile extraction”))

	c	• ((“wind”) AND (“site recovery” OR “recover site”)) • ((“wind”) AND (“site restoration” OR “restore site”))
13. Recycle	a	((“offshore wind” OR “off-shore wind”) AND (recycl*))
	b	• ((“offshore wind” OR “off-shore wind”) AND (“scrap”)) • On 30 December 2020: ((recycle*) AND “steel”)) • On 30 December 2020: ((recycle*) AND “concrete”) • ((recycle*) AND “glass fibre reinforced composite”) • ((recycle*) AND “critical materials”)
	c	((“wind”) AND (recycl*))
14. Recover energy	a	((“offshore wind” OR “off-shore wind”) AND (“energy recovery”))
	b	• ((“offshore wind” OR “off-shore wind”) AND (“energy-from-waste”)) • ((“offshore wind” OR “off-shore wind”) AND (“waste-to-heat”)) • ((“offshore wind” OR “off-shore wind”) AND (“incineration” OR “burning”)) • ((“offshore wind” OR “off-shore wind”) AND (“pyrolysis”)) • ((“offshore wind” OR “off-shore wind”) AND (“gasification”)) • ((“offshore wind” OR “off-shore wind”) AND (“solvolysis”)) • ((“offshore wind” OR “off-shore wind”) AND (“thermal treatment”))
	c	((“wind”) AND (“energy recovery”))
15. Landfill	a	((“offshore wind” OR “off-shore wind”) AND (“landfill*”))
	b	• ((“offshore wind” OR “off-shore wind”) AND (“controlled storage”)) • ((“offshore wind” OR “off-shore wind”) AND (“burial” OR “burying”))
	c	((“wind”) AND (“landfill*”))
16. Re-mine	a	((“offshore wind” OR “off-shore wind”) AND (“re-mine”))
	b	((“offshore wind” OR “off-shore wind”) AND (“urban mining”))
	c	((“wind”) AND (“re-mine”))
17. Data and information	a	((“offshore wind” OR “off-shore wind”) AND (“data system” AND “information”))
	b	• ((“offshore wind” OR “off-shore wind”) AND (“data” AND “lifecycle”)) • ((“offshore wind” OR “off-shore wind”) AND (“sustainability assessment”)) • ((“offshore wind” OR “off-shore wind”) AND (“sustainability” AND “indicators”)) • ((“offshore wind” OR “off-shore wind”) AND (“data standards”)) • ((“offshore wind” OR “off-shore wind”) AND (“data sharing”))
	c	((“wind”) AND (“data system” AND “information”))
18. Design for circularity	a	((“offshore wind” OR “off-shore wind”) AND (“design*”) AND (“circular economy”))
	b	• ((“offshore wind” OR “off-shore wind”) AND (“ecoselector”) • ((“offshore wind” OR “off-shore wind”) AND (“product environmental design”) • ((“offshore wind” OR “off-shore wind”) AND (“holistic” AND “design”) • ((“offshore wind” OR “off-shore wind”) AND (“integrated design”)
	c	((“wind”) AND (“design*”) AND (“circular economy”))

4. Results: Circular Economy Framework for Offshore Wind

The finalised framework includes eighteen circular economy strategies (Figure 2) organised by their application to materials, components and whole infrastructure, and by strategy type, i.e., narrowing, slowing, closing and integrating resource flows (as introduced in S1) throughout the lifecycle of offshore wind infrastructure from design to end-of-use and beyond. The definitions of each strategy and the relations between the strategies will be discussed hereafter, followed by baseline reviews to identify major knowledge gaps. The application of the framework within offshore wind and the transferability to other sectors will be covered in S5.

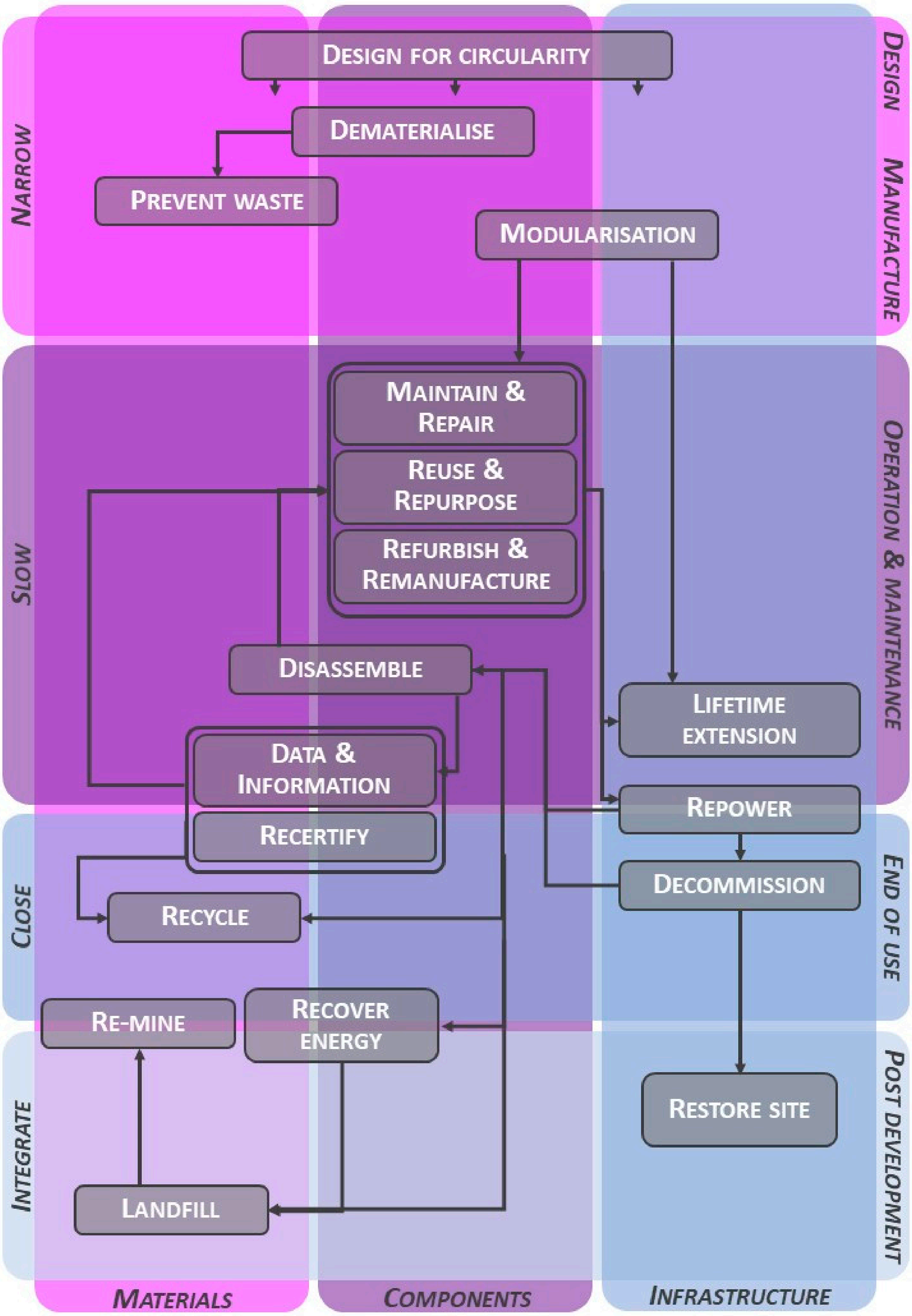

Figure 2. Circular economy strategies for offshore wind organised by their application to materials, components and whole infrastructure (columns), the narrowing, slowing and closing of resource flows and their integration into the environment (rows, left side), throughout the offshore wind infrastructure lifecycle, from design to the end-of-use and beyond (rows, right side). Arrows indicate that one strategy enables another—for example, disassembly enables remanufacturing, and maintenance and repair enable lifetime extension.

4.1. Dematerialisation

Dematerialisation is about reducing resource use. It is one of the most effective approaches to reduce costs and environmental impacts. At a whole system level, dematerialisation is an essential part of achieving a sustainable circular economy. Circulating resources within society, through whichever circular economy strategy, generally costs energy, water and the addition of new materials [41,62,63]. Maintaining the current levels of material use is unlikely to become sustainable, and therefore the total volumes of materials within the economies of developed countries must be reduced [152–154].

Dematerialisation for offshore wind includes the exploration of reduced resource use through, for example, shape optimisation and alternative materials. While Bakker et al. [155] implies that designing products with less materials is common practice because it reduces costs, Andrews [156] argues that such a circular economy strategy is not normally part of designers' mindsets. Moreover, there may be a trade-off between dematerialisation and designing for reliability [40] due to high safety margins in high-risk sectors. Additionally, reduced resource use could affect component durability, thereby introducing a potential trade-off with, for example, component reuse (S4.4) and lifetime extension (S4.5).

There are currently no scientific articles published on dematerialisation in offshore wind (search in Table 3 and results in Figure 3). A deeper search covering wind energy in general revealed ten publications on dematerialisation, but only one appears relevant to wind power based upon scanning the abstracts [157] while the others cover the dematerialisation of society in more general terms (e.g., [118]). The accompanying term "lean manufacturing" (search in Table 3) also did not recover further publications on offshore wind. Dematerialisation may be more prevalent under the banner of various design terms (S4.18).

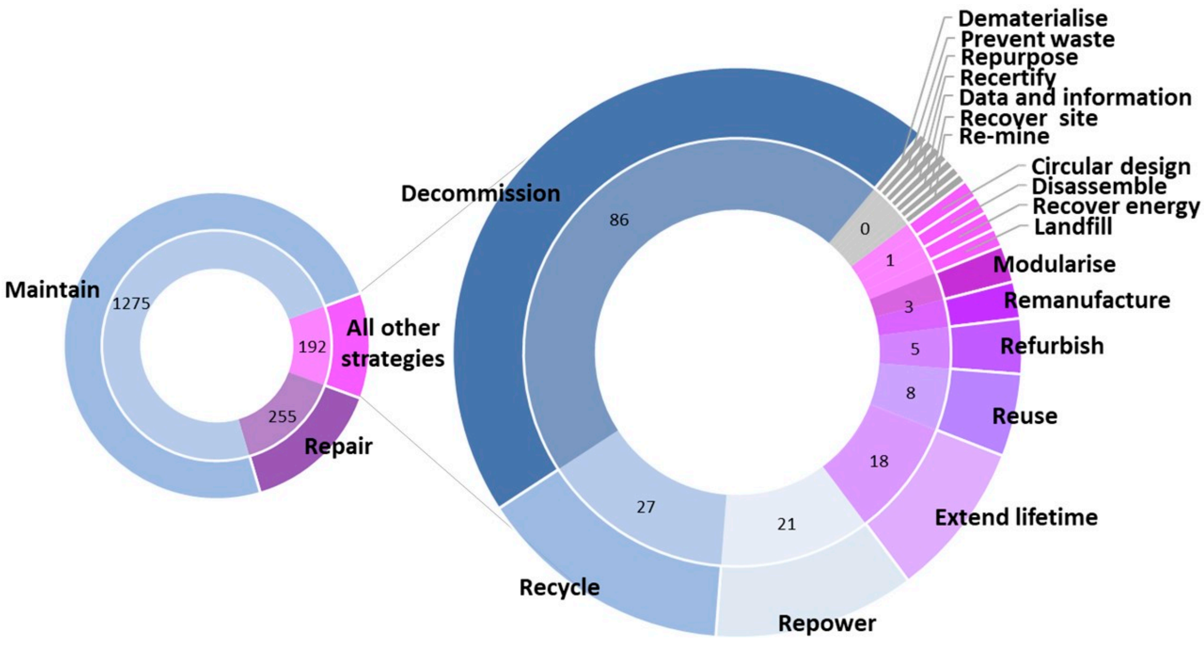

Figure 3. Overview of the number of scientific publications on circular economy strategies in offshore wind (based on Scopus searches on 5 and 6 June 2021).

4.2. Waste Prevention

The reduction of resource use is often conflated with a reduction of waste [123], because the latter is expected to logically be prevented by the use of less and less hazardous materials while using materials for longer [158]. Herein, however, waste prevention is included as a separate strategy to enable a more transparent application. Preventing waste is about eliminating waste from production rather than having to deal with waste once it has emerged [123,159].

Wastes can be proactively designed out, or they can be put to valuable use through industrial symbiosis (e.g., [160]). Industrial symbiosis can be described as "the establishment of close working agreements between normally unrelated companies that lead to resource efficiency. Working agreements include, among other, the direct reuse of one company's waste stream as another's raw material, the innovative reprocessing of problematic by-products and the sharing of underutilised power, water and/or steam" [161].

Waste prevention, industrial symbiosis and recycling can be confusing to distinguish. Waste prevention and industrial symbiosis are proactive and positioned at the design and manufacturing stages, while recycling is generally positioned at the end-of-use of products and components (S4.13). Waste prevention should not be confused with the use of recycled materials. By definition, if a recyclate exists, then it has been a waste, and the waste was not prevented from emerging in the first place, which is the purpose of waste prevention.

No publications on offshore wind and waste prevention or industrial symbiosis were identified (search in Table 3 and results in Figure 3). A broader search on wind and waste prevention reveals five publications, none of which are about waste prevention in the manufacturing of wind infrastructure components. Scopus holds eight publications on wind and industrial symbiosis, one of which is somewhat relevant. Huang et al. [84] present a wind and solar infrastructure design using renewable wood and recycled metals. There may be more relevant publications, because industrial symbiosis is linked to the development of multifunctional systems that avoid underutilisation of the infrastructure, combining, for example, offshore wind with desalination (e.g., [162]) and integrating wind into optimised energy systems (e.g., [163]). Alternative searches on "waste reduction" or "reduce waste" (Table 3) return one article that is not about waste prevention but, rather, about the repurposing of oil and gas infrastructure [164].

4.3. Repair and Maintenance

Repair and maintenance are strategies to increase the duration over which a component—and, thereby, a whole infrastructure (S4.5)—is in operation. Maintenance and repairs can be preventative, planned or ad hoc in response to faults [123]. Maintenance has been described as "the performance of inspection and/or servicing tasks at regular intervals, to retain a product's functional capabilities and/or cosmetic condition" [165]. This can involve repair, which has been defined as "restoring a product to a sound/good condition after decay or damage. After repair, the product is expected to be in a usable state, but assurances of performance are generally limited to the repaired part" [40]. During repair and maintenance, it is important to avoid introducing measures that impede other circular economy strategies, such as disassembly (S4.9), reuse (S4.4) and remanufacturing (S4.7).

Maintenance and repair are often, in part, combined and confused with refurbishment and upgrading [123,165]. Refurbishment has more similarities to remanufacturing and will be covered there (S4.7). Upgrading—described as "the process of enhancing, relative to the original design specifications" [165]—would arguably be more at par with refurbishing if it constitutes an improvement in functionality, while cosmetic changes could be a part of maintenance and repair.

Repair and maintenance are normal practices in offshore wind, as reflected in the literature with 254 publications on repair and 1274 on maintenance (search in Table 3 and results in Figure 3), the former being almost a complete subset of maintenance. An outward exploration suggests a focus on various parts of the wind infrastructure, costs and risk, and strategies/planning to deliver maintenance and repairs. Alternative searches (Table 3) related to repair and maintenance practices returning significant numbers of results include inspections (247 publications), service (634), O&M (operations and maintenance) (238) and retrofit (20). A deeper review can determine the alignment of current offshore wind repair and maintenance practices with circular economy, and articulate whether any improvements are possible.

4.4. Component Reuse and Repurposing

Component reuse constitutes operations through which products or components that are not waste are used again for the same function and may involve "checking, cleaning, repairing, refurbishing, whole items or spare parts" to prepare for reuse [158,165,166]. Reuse can be enhanced by durable designs (S4.18) and maintenance and repair (S4.3) for lifetime extension (S4.5) (Figure 2), and it slows down the speed of material flows from production and use to recycling [40]. If a component or product is used for another function, then it would be considered repurposing. For example, using a turbine blade as a blade again would be reuse, whereas using (a section of) a blade to construct a bridge would constitute repurposing (see, e.g., [47,113,167,168]).

Research on reuse is still emerging, with eight of the 32 results from the literature search (Table 3) indeed covering publications on the reuse of offshore wind turbine components (e.g., [43,169–171]) (Figure 3). Various publications explore the reuse of oil and gas platforms for offshore wind (e.g., [172–176]). Some articles write about the reuse of materials, which technically is recycling (S4.13). Filtering through the 372 publications on used parts and the eleven on breaking parts may render additional relevant publications. There are only two publications on repurposing (search in Table 3), neither of which are about the repurposing of offshore wind components (Figure 3). There is potential for knowledge exchange with onshore wind where component reuse and repurposing are already more common practice.

4.5. Lifetime Extension

Wind farms currently have a designed service life of 20–25 years, when operators have to decide whether to extend the lifetime of assets or to repower (S4.6) or decommission (S4.11) the site [177,178]. These strategies operate at the whole infrastructure level and thereby differ from the most common circular economy strategies, which are generally product-centric (see, e.g., [50,123]).

Lifetime extension means that assets are kept in use beyond the designed service life. Decisions for end-of-use scenarios are formed by a range of technical, economic, environmental and governance aspects, influenced by a range of stakeholders [178,179]. The technical aspects include "an exhaustive failure mode identification" for the whole lifecycle of the wind farm [178]. While lifetime extension can increase the return on investments and reduce the levelized cost of electricity, any wins may be cancelled out by higher operation and maintenance costs [178]. From a resource productivity perspective, extending the lifetime of wind farm assets is generally beneficial.

Lifetime extension is likely to include more repairs and maintenance (S4.3) and possibly the reuse of components (S4.4) that may have been refurbished, upgraded or remanufactured (S4.7). The line between lifetime extension and repowering (S4.6) is not clearly defined but, through stakeholder discussions, it appears that lifetime extension does not involve the large-scale replacement of components, whereas repowering does.

The scientific literature harbours sixteen publications on offshore wind and lifetime extension (search in Table 3), all of which appear relevant upon scanning the abstracts (Figure 3). The articles primarily discuss structural health monitoring and fatigue assessments [180–193], data systems [194] and decision-making to either extend the lifetime, repower or decommission [195], aligning well with alternative circular economy terminologies suggested during the Offshore Renewable Energy Catapult workshop (Table 2), such as "digital twin" and "residual strength determination". Alternative searches (Table 3) rendering significant results are "fatigue life" (190 publications) and "remaining life" (17), suggesting that these are more common terms than "lifetime extension" within the offshore wind community. An initial exploration suggests that the terms are related but not synonymous, with fatigue and remaining life investigating the durability aspects, though not for lifetime extension in particular (e.g., [196–198]). The term "derating" also returned ten search results. A broader search on wind energy returned 62 publications on lifetime extension and 1213 on fatigue life, and these results may hold relevant insights that can be transferred to the marine environment.

4.6. Repowering

Repowering has been described as: "A way of extending wind farm's service life by replacing either wind turbine components or existing wind turbines with new, more powerful machines. There are two main types, partial and full repowering" [179]. Partial repowering involves the lifetime extension of some components—e.g., foundations and towers—while others get replaced—e.g., generators, drive trains and blades [178,179,199]. Full repowering involves the replacement of the whole turbine [179]. In all cases, a part of the wind farm infrastructure is reused, such as the subsea cables [178].

The ability to reuse the infrastructure depends on repowering with smaller, similar or larger turbines. Smaller turbines can be attractive if there are concerns about the structural strength of the foundations—which may not be able to carry a similar or larger turbine for a required period—while postponing the decommissioning costs [200]. More common, however, is the repowering with larger turbines, especially in locations with a high wind resource [179].

Repowering decisions are made with regard to the whole wind farm and not at the individual component level. Similar to lifetime extension, it can make use of repaired, reused, refurbished, upgraded and/or remanufactured components, depending on the repowering strategy. Alternatively, components can be sent for repurposing in other sectors or join the recycling and disposal stream.

Repowering is still an emerging subject in offshore wind literature, with the literature searches (Table 3) returning 56 publications, of which 21 bear direct or some relevance (Figure 3). Most articles speak about decision-making approaches literally [179,195] or subjects in relation to decision-making, such as optimisation strategies [201], environmental impacts [202] and techno-economic/cost assessments [178,199,203–205]. Others focus more on lifetime extension [200,206] and decommissioning [177]. "Replanting" (discussed in [8]) and "end-of-life extensions" (Table 3) did not find resonance in the offshore wind literature. There were 280 publications on wind and repowering on Scopus with the potential to transfer expertise from onshore to offshore wind, as the repowering of onshore wind farms is already more widespread (see, e.g., [207–216]).

4.7. Refurbish and Remanufacture

Refurbishing and remanufacturing are similar, but the former is less rigorous in nature. Refurbishing has been described as "the overall structure of a large multi-component product remains intact, while many components are replaced or repaired, resulting in an overall 'upgrade' of the product" [123]. Products and components can be designed to accommodate upgrades in the future (S4.18) and have been described as "the ability of a product to continue being useful under changing conditions by improving the quality, value, and effectiveness or performance" [40].

Remanufacturing is a process in which components and products are sorted, selected, disassembled, cleaned, inspected and repaired or replaced before being reassembled and tested to function as good as new or better [217,218]. Arguably, remanufacturing has to follow a standardised industrial process that is "fully documented" and "capable to fulfil the requirements established by the remanufacturer" (internationally agreed remanufacturing definition from September 2016 [219]).

Remanufacturing is considered more sustainable than manufacturing due to its reduced energy and material requirements, which can be calculated into the price, generally making remanufactured products and components more affordable to customers and profitable for a remanufacturing business [220]. There are benefits for remanufacturers to adopt product–service systems (see, e.g., [221]), i.e., selling the function that a component fulfils while the (re)manufacturer keeps ownership of the asset, because it reduces the risk in terms of the timing, quantity and quality of the components returned for remanufacturing, with the economic and environmental benefits rippling through to clients and Original Equipment Manufacturers [222].

Refurbishing [199,223–226] and remanufacturing [8,227,228] are emerging subjects within the offshore wind literature, with only a handful of publications coming forward (Figure 3). Alternative searches (Table 3) that return results include "upgrade" (32 publications)—regularly used, for example, for upgrades to transmission systems (e.g., [229–231])—and "overhaul" (four publications), while "parts" attracted over a thousand search results, reflecting the generality of the term. There are substantially more publications on wind energy and refurbish (175 publications) and remanufacturing (44,), which may render useful insights for applications in offshore wind.

Refurbishing and remanufacturing are considered closely alongside disassembly (S4.9)—a necessary step ahead of remanufacturing and, indeed, other circular economy practices such as repair (S4.3), reuse (S4.4) and recycling (S4.13)—Figure 2.

4.8. Recertification

The importance of the reliability of materials and components was raised in conversations with offshore wind experts, and this is also a known challenge in other energy sectors, such as oil and gas. Recertification has been proposed in circular economy as a possible enabler for various strategies (e.g., [27,232,233]), giving quality assurances about the processes followed, and the quality of reused, repurposed, refurbished and/or remanufactured components (S4.4 and S4.7) and recovered materials (S4.13 and S4.16). Although recertification is neither without challenges nor a silver bullet to all barriers (e.g., [234–236]), it can pre-empt barriers to the uptake of circular economy strategies in offshore wind. Recertification is also important in creating a level playing field internationally, to avoid dynamics such as those observed in metal recycling with illegal exports and rogue operators that undercut quality undertakings and introduce high price dynamics that constrain investment [232]. Recertification is closely related to reliability testing [27], a concept that finds resonance within the offshore wind literature (e.g., [237,238]).

Searching for publications on recertification in offshore wind (Table 3) rendered no results (Figure 3), but a search for certification returned twelve publications (e.g., [239–241]). For wind energy in general, there were nine articles mentioning recertification, none of which look particularly relevant with regard to the considerations outlined above, and over a thousand publications about certification.

4.9. Disassembly

Disassembly plays a key part in the repair (S4.3), reuse (S4.4), remanufacturing (S4.7) and recycling (S4.13) of components, and all can benefit from the consideration of disassembly at the component design stage (S4.18) [242]. Disassembly is a highly specialised activity [243] which can benefit from and generate detailed data on the resource volumes and qualitative characteristics (covered in S4.17) necessary to enable a circular economy for low-carbon infrastructure [66].

Disassembly is also intricately linked to decisions about the end-of-use strategy [244], and the demand for saving components to reuse, remanufacture, etc. for usage in lifetime extension (S4.5) or repowering (S4.6). Decisions on end-of-use can be made before, during and after disassembly, deciding whether a (part of a) component can be repaired, reused or remanufactured or should be sent to recycling or disposal [244]. Components can be fully or partially disassembled, but generally they are fully taken apart because the value of recovered parts outweighs the disassembly cost, and it is usually more time-efficient [243,244].

Disassembly is also important for high-value recycling, as it enables the better segregation and recovery of material streams with less contamination when compared to, for example, the crushing and milling of whole components or structures [245]. Here, too, design for disassembly can help to enable the closing of resource flows (S4.18).

Disassembly is not widely investigated in offshore wind research, with only two publications emerging [246] (Figure 3). There is a high potential for knowledge exchange across the wind sector, with 99 search results on disassembly.

4.10. Modularisation

Disassembly (S4.9) to enable repairs (S4.3), reuse (S4.4) and remanufacturing (S4.7) can be eased by the modular design of components (Figure 2). Modular design enables the decoupling of the component lifetime from the lifecycle of a wind turbine (thereby enabling lifetime extension, S4.5), avoiding the wastage of the remaining lifetime of components that are still safely operational [247]. Modular design includes the avoidance of irreversibly joining together different materials and components, especially when they have different forecast lifetimes, a preference for using common modules that can be reused and that are easy to repair and upgrade, the ease of quality assurance and, possibly, the inclusion of quality monitoring devices [247–250].

Modularisation and modular design are known strategies within offshore wind but, so far, have not been considered within the context of a circular economy (Figure 3). Scopus did reveal six publications on modularisation or modular designs, half of which appeared to hold relevance [251–253], though there were 189 search results for wind modularisation in general. A deeper search better demonstrated the relevance to circular economy, covering subjects such as easing repair and operations and maintenance [253,254], adaptability of components [255], improving quality and performance [252,256], reducing costs [257] and enabling the manufacturing and transport of very large components [258].

4.11. Decommissioning

Decommissioning has been described as "de-energising and removing wind farm infrastructure", in which de-energising involves the disconnecting of the wind turbines and/or whole farm from power transmission [259]. The standardisation of decommissioning is expected to be limited due to the technical diversity of offshore wind farms, weather conditions and site-specific conditions [199]. Smith and Lamont [260] defined three stages in decommissioning processes consisting of the "preliminary work to develop detailed plans and permits; then an operational phase to remove the turbines and their foundations, and to address other offshore structures and cables; and finally a monitoring phase".

Experience with offshore wind decommissioning is limited and lacks clear practical guidelines [177,260]. It is often depicted as reverse engineering requiring similar techniques, equipment and skills [199]; however, early signals suggest that the process is more complex, especially with the aim of maximising resource productivity [8,66]. Perspectives on the end-of-use management of decommissioned components are often limited to "waste treatments" that are "divided into recycling, landfilling, and incineration" [178], leaving the broader set of economically, socially and environmentally more valuable circular economy strategies such as reuse (S4.4) and remanufacturing (S4.7) out of sight. This is not aided by underdeveloped regulations [177] that, moreover, fail to take a proactive approach to salvage components before the formal seize of operations, and lump component reuse and material recycling into one category [8].

Jensen et al. [8] argue for a proactive approach, taking a whole system perspective to design offshore wind farms with decommissioning in mind. Similarly, Smith and Lamont [260] argue for the design of large components that can be broken into parts. Early experiences suggest that downsizing large components into smaller parts that can be processed further is challenging. Such design considerations must be made while being mindful of the interface between decommissioning, disassembly, and the potential to maximise the value generated from components and materials using the full spectrum of circular economy strategies (Figure 2).

The decommissioning of offshore wind farms can be partial or in full. Partial decommissioning involves the dismantling of the components except for those that have a longer designed service life, such as foundations and inter-arrays and export cables [199], combined with repowering (S4.7). Full decommissioning involves, in principle, the removal of all infrastructure, the objective of which is, arguably, "to return the site to its condition before project deployment as far as possible" (S4.12) [199].

Offshore wind decommissioning is a growing subject area, with 112 publications (search in Table 3), of which 86 hold direct or some relevance to offshore wind (Figure 3). Subjects covered include estimating the scale of the decommissioning challenges (aided by articles such as [60,261,262]); cost models and decommissioning scenarios (e.g., [171,200,204,263–273]); decommissioning processes; challenges and solutions [8,141,177,274,275]; vessels and port facilities (e.g., [276]); end-of-use scenarios (e.g., [195,277,278]); risk, durability and the remaining life estimates (e.g., [279–281]); alternative joints to ease decommissioning [282]; environmental impacts (e.g., [283–286]); and calls for better policy, guidelines and certification (e.g., [8,287–289]). Alternative searches (Table 3) to explore further include removal (72 publications), extraction (187) and dismantling (21). Trawling through the 355 search results on decommissioning and wind energy in general may also return useful further insights for offshore wind.

4.12. Site Recovery

Returning sites to a similar state as before wind farm development is inherently integrated with decommissioning (S4.11). In principle, in the North Sea, full decommissioning and site recovery is obligatory under international agreements. However, given that offshore wind farms tend to have been developed in locations with high wind resources, full decommissioning and site recovery may not be a strategy often taken within the next few decades. So far, sites were fully decommissioned due to seabed instability or being demonstration/research projects [260], or due to being located closer to shore with limitations for upscaling through repowering (S4.6).

Similar to debates in oil and gas with regard to rigs-to-reefs (e.g., [290–292]), in offshore wind, there is a discussion about whether the complete removal of concrete structures is the best environmental option due to the potential to function as artificial reefs [199,293,294]. In the recovery of sites, as in every step of the wind farm lifecycle, consideration should be given to other users of the marine space, such as nature conservation, fishing, shipping and defence [124,134].

Within the offshore wind literature, no articles surfaced on site recovery or site restoration (search in Table 3 and results in Figure 3). Habitat restoration returned two publications [295,296]. Artificial reefs as an alternative search (Table 3) had 52 search results worth investigating further.

4.13. Recycle Materials

The recycling of materials is not clearly defined in the waste hierarchy, being described as "any operation the principal result of which is waste serving a useful purpose by replacing other materials which would otherwise have been used to fulfil a particular function, or waste being prepared to fulfil that function, in the plant or in the wider economy" [297]. DEFRA [158] described it as "turning waste into a new substance or product", displaying ambiguity about what constitutes recycling: just the collection and preparation of wastes into materials that can re-enter production, or must it be followed by reprocessing into new products? Den Hollander et al. [165] argued that "the recycling process involves the dismantling and disintegration of a product and its constituent components and the subsequent reprocessing of the product's materials". Recycled materials are also known as secondary resources, differing from primary resources that were sourced directly from the natural environment. Recycling is the only circular economy strategy that is truly about "closing loops" of material flows within the economy [40]. Recycling is often confused with reuse—implying the reuse of materials—and it is therefore distinguished herein by material recycling and component reuse (S4.4).

There are 42 publications on offshore wind and recycling (search in Table 3), 27 of which look relevant (Figure 3). Many studies present lifecycle assessments, emphasising how recycling can reduce the environmental impacts of offshore wind [298–304]. Others discuss the selecting of recyclable materials [287] and the use of recyclates [43,305,306]. Further articles offer insight into recycling processes, technologies and the costs and value of recycling [5,48,59,307]. More knowledge about the recycling of wind turbine components could be found by broadening the scope to wind energy in general (1675 search results) and by focusing on specific components and materials. Note, for example, the growing body of literature on blade recycling, which remains problematic (see, e.g., [308,309] and publications with recent cross-sectoral reviews of relevant composite recycling technologies, e.g., [8,64,310]). Regarding the materials in general, there are more than 8,000 publications on steel recycling, over 12,000 on concrete recycling (but do note that the recycling of concrete from the marine environment differs from the terrestrial environment), 65 on glass fibre reinforced composite recycling and 151 on the recycling of critical materials.

4.14. Energy Recovery

Energy "recovery" refers to the recovery of the energetic input invested into the preparation of materials, components and products. Recovery is often confusingly used for both the recovery of materials (technically recycling, S4.13) and energy [123,311]. Energy recovery can include the capturing of heat, gas, power or a combination of these, generally from thermal treatments of wastes but, also, biological treatments [312]. DEFRA [158] captures energy recovery under the broader banner of "other recovery", including "anaerobic digestion, incineration with energy recovery, gasification and pyrolysis which produce energy (fuels, heat and power) and materials from waste". Thermal energy recovery processes are commonly described as energy-from-waste and considered a less preferable strategy within a circular economy due to the loss of the quantities and qualities of materials. Incineration without energy recovery is considered disposal, similar to landfilling [158]. It is possible to recover some materials from energy-from-waste ashes.

There are thirteen publications mentioning energy recovery and offshore wind (search in Table 3), only one of which discussed energy recovery in the context of offshore wind end-of-use management [8] (Figure 3). Three further publications on energy-from-waste (alterative search Table 3) do not discuss the processing of wind turbine components. A similar fate goes to the affiliated terms such as incineration, burning, gasification and thermal treatment. More relevant results may emerge in the 318 search results when broadening to wind in general (e.g., [310,313,314]).

4.15. Landfill and Controlled Storage

Landfills are used for disposing solid wastes. Landfills can be "open or uncontrolled dumps" with "immediate risks to human health and the environment" [315]. However, in developed countries, landfills are, generally speaking, engineered sites in which solid wastes are placed and compacted into defined cells, in lined systems to prevent leachate (a liquid of water that has been in contact with waste) from polluting the surrounding water sources, that are regularly covered with soil during the filling operations to prevent fires and air pollution, and capped once the landfill cell is full [315]. Landfills are increasingly integrated with materials and energy recovery systems. Landfill gas—primarily methane—can be captured and converted into heat or power. Resources can be recovered with the use of bio-related technologies that enable re-mining (S4.16) [316,317].

There are seven articles on Scopus on offshore wind and landfills (search in Table 3), of which only one article holds some relevance [318] (Figure 3). Additional and alternative searches (Table 3) such as controlled storage and burial/burying did not deliver relevant results. A broader search for wind and the landfilling of waste may offer starting points leading to further insights (e.g., [49,94,319,320]).

4.16. Re-Mine

Re-mining is the recovery of materials from "Anthropogenic Ores": the industrial, municipal, metallurgical and mining wastes that people have entrusted into geological storage [317]. Landfill/urban/secondary mining is receiving growing attention [316,317]. This is, in part, due to the need to clear away legacy wastes and mitigate risks due to landfill degradation, environmental change, pressure on land availability and resource scarcity. Landfills contain considerable resource stocks of materials that are essential for low-carbon infrastructure [321]. Elements such as copper (e.g., for cables), cobalt (e.g., for generators) and vanadium (e.g., in alloy steel for towers) can be re-mined from landfills [316]. Moreover, "landfills" can be engineered specifically for the recovery of target materials [317,322]. While landfilling and mining tend to fall outside of the scope of circular economy thinking, there is much to win from applying circular economy approaches in these sectors due to the high volumes of waste involved and the presence of increasingly scarce materials for low-carbon infrastructure [41,42]. The recovery of valuable yet potentially harmful substances from landfills is also important to enable the safe reintegration of organic and inorganic resources into natural biogeochemical cycles [41].

Re-mining is a new concept to offshore wind with no publications yet (Figure 3), and one publication when searching for wind in general which was unfortunately not relevant. Urban mining is more commonly used, with three relevant articles for the wind sector [323–325] and much more potential when searching at the material level of urban mining (e.g., copper, rare earth elements, etc.).

4.17. Data and Information

Insights into the volumes, qualitative technical characteristics and associated environmental, social and economic values are crucial in enabling a more circular economy, because such information is necessary for decision-making by governmental bodies, as well as companies, with regard to the uptake of circular economy practices (see, e.g., [139,326]). A company will want to ensure that sufficient volumes of materials are available before committing to specific designs, such as using electromagnetics instead of permanent magnet solutions to alleviate the competition for critical materials [327]. Governments will want to manage geopolitical dynamics around accessing critical materials necessary for low-carbon transitions. Manufacturers need to have assurances about the component and material qualities to enable reuse (S4.4), remanufacturing (S4.7), recycling (S4.13), etc. based on accurate information that can be verified and certified (S4.8).

There are many sides to developing data and information strategies to enable circular practices in offshore wind. These include, but are not limited to: the design and management of data systems themselves; the provision, linking, storing, converting and sharing of datasets; standards to guide all aspects of data collection, sharing, etc.; a relevant set of indicators about which the data will be collected; and sensors and other measuring equipment and infrastructure to collect data. Chen et al. [60] offer a recent overview of research on waste generation forecasts, primary and secondary material flows, and component stocks. Lifecycle assessments are common practice within offshore wind, meeting a part of the demand for data and information to enable decision-making about circular practices.

Literature searches (Table 3) have demonstrated that research on the various aspects of data and information systems are underway in offshore wind, but it is not immediately clear that an integrated holistic system, as described above, is available or under development (Figure 3). Zhao et al. [328] propose the combining of SCADA (Supervisory Control and Data Acquisition) and CMS (Condition Monitoring System) models to assess drivetrain degradation, and Cheng et al. [329] develop a multi-model industrial big data benchmark involving the bill of materials for wind infrastructure, which may form a stepping stone towards an integrated holistic data system for the diverse values of materials, products and components.

Alternative searches (Table 3) return 60 publications on lifecycle and data, confirming the regular use of lifecycle assessments. Sustainability assessments only return eleven search results, implying this may be a less common practice in the sector. Nevertheless, sustainability and indicators show some relevant results (e.g., [330,331]). Nothing has been published in the scientific literature on data standards in offshore wind, although this could easily have been captured under an alternative search term. Data sharing has been raised (e.g., [332,333]). The progress made for this circular economy strategy is very fuzzy to assess, with many aspects of data and information systems that need to be brought together deserving a deeper review, which would likely result in a more positive assessment of the state of play in offshore wind (Figure 3).

4.18. Design for Circularity

The art of designing for circularity is to design products, components and whole infrastructure in such a way that it maximises the sustainability potential of a circular economy with a balanced mix of the strategies included above (S4.1–S4.17, Figure 2). The design for a circular economy has to be proactive, as Andrews [156] said: "Designers cannot wait for the development of a remanufacturing, reuse and/or recycling infrastructure and other alternative business models, however, before they start to design for the Circular Economy; they must anticipate and prepare for the alternative economy particularly where there is a long product lead time from initial concept to shop floor". Indeed, it is important to consider circular economy early on in the design process, "because once product specifications are being made, only minor changes are usually possible" [40]. None of the circular economy strategies should be considered in isolation, enabling strategies to narrow, slow, close and integrate resource flows [40,41,155,334,335] throughout the lifecycle of materials, products, components and infrastructure (Figure 2).

Design for circularity differs from eco-design. Eco-design is described as a practice to make the current poor environmental performance of products and components less bad throughout their lifecycles [165,336], i.e., incrementally improving the existing situation. Although design for circular economy takes a similar whole lifecycle perspective, it arguably differs by starting from the perspective of an ideal vision and taking a backcasting approach to design products and components in a radically more environmentally benign way [165,337]. It has been demonstrated, however, that there are circular economists that take a reformative view (staying close to the status quo, arguably staying closer to eco-design practices), while others are more transformative in their ideas (radically changing the current practices) [123].

There are more than 5,000 publications on Scopus (search in Table 3) about offshore wind and design and, after narrowing the search results to "circular economy", only one covers designing offshore wind with a circular economy in mind [8] (Figure 3). An alternative search on holistic design (Table 3) returns relevant search results, for example, in terms of the potential to reduce material use, i.e., dematerialisation (S4.1) (e.g., [338–340]) and the incorporation of a broader set of whole system sustainability considerations (e.g., [341–344]). The alternative "integrated design" is more about the approach towards testing whole units of wind infrastructure as one system (e.g., [345]). A closer inspection of this large body of literature on offshore wind design is necessary to determine the current alignment with circular economy principles and to identify more targeted opportunities for improvement.

5. Discussion: Application and Transferability of the Framework

5.1. How to Use the Framework

Circular economy is a whole system and whole lifecycle approach and therefore all strategies are important to consider in conjunction with each other (Figure 2). In principle, the strategies at the top of Figure 2 have a greater sustainability potential than the strategies nearer to the bottom. For example, decisions made at the design stage will greatly affect the potential for component reuse, lifetime extension, the repowering of whole sites, etc. There may be trade-offs between durability—with strategies such as maintenance and repair, reuse and repurposing and lifetime extension—and recyclability. Strategies focusing on durability generally have a higher potential to increase resource productivity and to reduce environmental impacts, but in the long term, resource security may be best served with access to high-quality recycled materials. At this point, it is not clear yet whether these strategies can work in synergy or whether trade-offs should be anticipated for some or all of the components in offshore wind. The steel in towers, for example, is not a particular concern with regard to resource security, and the design for durability—by adding more concrete to the tower—can substantially increase the longevity and has a far greater potential for reducing environmental impacts than steel recycling alone [7]. Conversely, neodymium used in permanent magnet generators is a critical material due to geopolitically motivated resource access risks, and long-term access may depend on high-quality recycling but, currently, the recycling rates are very low, and the potential use of recyclate in offshore wind also appears limited [97]. Finally, the application of the framework is pragmatic. For example, it is too late for strategies such as design for circularity for turbines that are already in the water, but for wind farms early in the development phase this is still a possibility.

It would be unrealistic to act as if the offshore wind sector is starting from a blank canvas. This sector is in the process of moving from industrial exploration to exploitation with the dominating three-blade rotor design, with strong growth ambitions that, as introduced in S2.2., raise a number of circular economy-related sustainability challenges and opportunities. Figure 4 depicts the top three circular economy strategies to help getting to grips with each of the sustainability challenges, but further circular economy strategies may apply as well. Speaking through each of the challenges:

In an effort to **reduce fossil fuel reliance**, the primary aim should be to design out fossil-based materials, but, if impossible, the usage should be minimised and, given the reliance on a non-renewable resource, ensuring recyclability should then take priority. There is an interdependence between the challenge of designing out fossil-based materials and the opportunity of material innovation (discussed next).

Growing resource exploitation, **resource competition** and **material innovation** are clustered together, because they form closely related challenges and opportunities. Resource exploitation and competition imply that it may become more difficult to access sufficient volumes of resources in a sustainable manner to meet the sector’s growth ambitions, and, in response, solutions are being sought via material innovation. In the short term, the challenge could be met by minimising the volumes of materials that are difficult to obtain and to search for alternative sources of increasingly critical raw materials, such as re-mining landfills. In the medium-term, alternative materials may become available for the design and manufacturing of components. For long-term resource security, it is important to design for recyclability and to improve the usage of recycled materials—such as recovered rare earth elements—in offshore wind component manufacturing, which may be aided by recertifying the secondary resources supported by transparent data and information systems about resource stocks and flows.

The **durability and lifetime extension** of the existing stock of offshore wind infrastructure is best aided by maintenance and repair to keep all the components in a good state, thereby enabling safe lifetime extension of the infrastructure. As argued in S2.2, this could be supported by remote monitoring, digital twin models and data systems. Lifetime extension may increase the potential for direct component reuse within the offshore wind sector, with greater environmental benefits when compared to repowering with new and larger components. At a whole system level, however, this strategy would have to be weighed against the environmental benefits of the growing renewable energy capacity through repowering.

End-of-use management and **sustainable decommissioning** are clustered, because they are closely related. Decommissioning and disassembly should be done in such a way that the components can either be reused, repurposed, refurbished, remanufactured or taken apart further to enable material segregation followed by high-quality recycling. The recertification of components and materials can help in creating new markets, unlocking investment into sustainable end-of-use supply chains, backed up by data and information systems through which the availability of volumes of materials and their technical characteristics can be assured. Experiences with end-of-use management should feed back into the design stage to grow the expertise in design for circularity, including the design for sustainable decommissioning and end-of-use management.

The framework is not the answer to all sustainability challenges and opportunities as indicated by the energy use challenge not being connected to a particular circular economy strategy. **Reducing energy use** falls outside the scope of the design, development, operating and end-of-use management of offshore wind infrastructure for which the circular economy framework was developed. Nevertheless, it is an important challenge to become involved in as part of the broader low-carbon and sustainable transition, for example, via the delivery of corporate social responsibility policies.

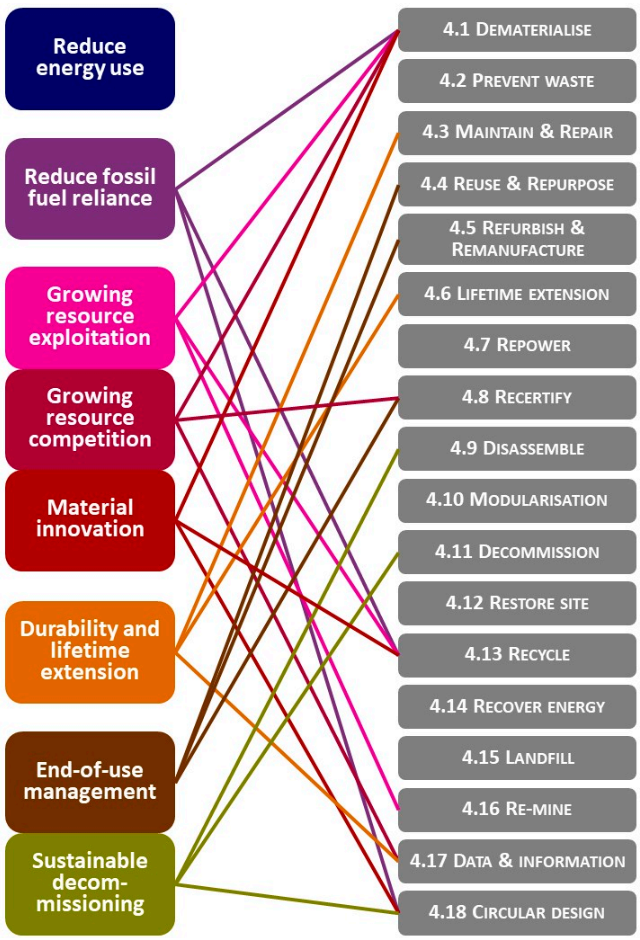

Figure 4. Top three circular economy strategies (on the right, as introduced in Section 4) in response to circular economy-related sustainability challenges and opportunities (on the left, as introduced in Section 2.2).

5.2. Transferability to Other Sectors

5.2.1. Circular Economy Frameworks across Energy Industries

This section will discuss that circular economy is an emerging subject in the scientific literature on energy infrastructure, and the presented framework could add value more broadly beyond offshore wind. A Scopus search on 7 June 2021 revealed just six publications mentioning energy infrastructure and circular economy in their article title, abstract or keywords [9,247,346–349]: Moore et al. [348] analyse how electric vehicle batteries could have a second life as emergency back-up power storage, while Fogarassy et al. [347] explore the circularity of solar power infrastructure for large-scale events, and Mignacca et al. [247] focus primarily on the modularisation of oil and gas infrastructure to enable a more circular economy. Overarching studies cover the circularity of China's infrastructure [346] and how circular economy can function as a positive driver to increase project performance in energy infrastructure decommissioning [9]. Kouloumpis and Yan [349] present and pilot a tool for the participatory lifecycle assessment of small island energy scenarios. Given that none of these publications include a comprehensive circular economy framework, the framework presented herein could potentially also add value to other energy sectors.

Investigating the presence of circular economy frameworks in specific energy sectors offers further insights. Niccolini, et al. [350] recognise circular economy as a means to reduce costs throughout oil and gas infrastructure project lifecycles. No articles were identified that systematically apply circular economy to the management of nuclear energy infrastructure. In low-carbon infrastructure, circular economy represents a new subject area with three articles currently published, all taking a holistic perspective on interconnected infrastructure systems [8,351,352]. Frameworks for circular economy and renewable energy are more common, with Scopus returning 62 publications. However, only six articles carry a potential relevance upon scanning the titles and abstracts [353–358]. Klemeš et al. [355] offer an overview of circular economy and sustainability in the context of energy systems, covering resource recovery, sustainability indicators, air pollution, and energy system optimisation for cooling, heating and power generation. Abokersh et al. [358] develop a set of Sustainable Circular System Design indicators, including a product Material Circularity Index and an Environmental Sustainability and Circularity indicator, for the sustainability assessment of geothermal storage in a circular economy context. Taking a transition perspective, Kylili et al. [357] share a holistic approach for sustainable renewable energy developments, including circular economy approaches in the form of lifecycle assessments and more sustainable management of waste biomass. Salim et al. [353] propose a framework of barriers, drivers and enablers for the solar PV sector to transition towards greater circularity, and Chen and Kim [354] compare the circular economy and energy transition contexts and argue for the non-energy use of fuels as a bridge to integrate them better. Searching for circular economy frameworks in photovoltaic systems specifically reveals the article by Contreras-Lisperguer, et al. [359], developing a model to forecast material flows in support of the recycling of solar technologies.

Aguilar Esteva et al. [356] propose a circular economy framework closely resembling the style of the framework presented herein, though for automobiles and at the product level, which excludes the necessary infrastructure level strategies for circularity in offshore wind. Similar strategies for the material and product levels are included, covering three lifecycle stages: materials and manufacturing (material sourcing, product design, automotive manufacturing and supply chain logistics); use (fuel economy, fuel type and powertrain, servicing incl. refuelling, cleaning, maintenance, repair and remanufacturing) and end-of-life (dismantling, remanufacturing, parts reuse and material recycling). Strategies such as material sourcing, logistics and powertrain design could be interesting to bottom out more for offshore wind as well.

5.2.2. Application of Offshore Wind Circular Economy Framework in Other Sectors

The circular economy framework can be applied to other sectors, but the emphasis of strategies may differ due to their industrial lifecycle stage—i.e., whether a sector is generally exploring or exploiting practices—within the energy transition. Exploration involves radical innovation and a searching for the reason, or function, for an industry to exist, while exploitation involves incremental innovation and a focus on the efficiency of delivery of an industry's function [360–363]. For example, given the steady growth and stabilising practices, fixed bottom offshore wind with the domineering three-blade rotor design could be seen as entering exploitation. Circular economy strategies for offshore wind are the most likely to offer opportunities for transferability to oil and gas due to the infrastructure located in the marine environment, and to onshore wind due to the technological similarities.

Onshore wind has been in exploitation for longer and, reaching end-of-use of the first generation of onshore wind farms in many locations, may be entering a mild exploration phase to reinvent itself as a more multifaceted industry combining additional functions on wind farms such as energy storage—some have suggested this could be another circular economy strategy titled "retasking" (term coined at EoLIS 2020). With regulatory uncertainty regarding repowering currently hanging over onshore wind, lifetime extension is often preferred as a strategy.

Oil and gas should, arguably, be in a deeper exploration phase [364], having to reinvent itself as a more general energy sector for companies to survive. Although the energy transition is gaining momentum, new oil and gas infrastructure is still being commissioned. These should be designed with the energy transition in mind, to enable oil and gas infrastructure repurposing for—and integrating with—sustainable energy systems, for example, using infrastructure for blue and green hydrogen, carbon capture and storage and offshore wind (as suggested by stakeholders, see [365]). In other words, in the case of oil and gas, the lifetime extension of infrastructure for the purpose of extracting fossil fuels should not be strived for, and instead the repurposing of components and whole sites should take centre stage.

The framework could also be applied to other energy sectors, such as biogas, solar energy and energy storage. These types of infrastructure are generally more distributed than wind energy, and this can have implications for the feasibility of circular economy strategies such as maintenance and repair, reuse and remanufacturing—depending on the local skills availability and logistics. Conversely, smaller units of operation, such as solar panels and batteries, may be easier to replace than the large components used in onshore and offshore wind, which could benefit the uptake of circular economy strategies.

Lastly, circular economy requires a cross-sectoral perspective, recognising that the potential for one sector to become more circular is dependent on actions in other sectors. For example, the potential for circular economy in offshore wind could be strengthened by sustainable recycling solutions implemented by the resources, steel and composites sectors. The oil and gas sector explored the potential to repurpose infrastructure for offshore wind (e.g., [366,367]). Offshore wind, in turn, could possibly increase the circularity in onshore wind by reusing decommissioned components for the repowering of onshore wind farms. There are many more of such potential solutions, opening opportunities for sustainability and for new business activities.

6. Conclusions and Future Perspectives

In this article, a whole system and whole lifecycle framework was proposed for the integration of a sustainable circular economy into the offshore wind sector, thereby also making an original contribution to the circular economy literature by defining infrastructure level strategies (S4). Circular economy-related sustainability challenges and opportunities (S2.2) can only be addressed effectively with a holistic approach, such as enabled by the framework, to avoid trade-offs and make the most of synergies (S5.1). Moreover, there is a high potential to transfer the framework to other energy sectors and to identify cross-sectoral synergies as well (S5.2).

The next steps in the development and uptake of circular economy in offshore wind must include a deeper baseline assessment of the current practices via literature reviews and roundtable discussions with industry practitioners on the various circular economy strategies, including knowledge exchange with onshore wind. Such discussions will also be informative to gain insights into the barriers and enablers for a more circular economy in offshore wind. Figure 3 suggests that the majority of circular economy strategies are deeply under-researched in offshore wind and, if an in-depth baseline assessment indeed confirms this is the case, this opens a high demand for fundamental and applied research.

A more thorough baseline review will also provide the foundations for the coproduction of circular economy whole lifecycle scenarios. Such scenarios should then be subjected to the holistic sustainability assessments of social, environmental and economic costs and benefits throughout the offshore wind infrastructure lifecycle (e.g., [368]). Sustainability assessments tend to be data hungry, highlighting the need for the development of data systems and collaborative arrangements to share data on resource stocks and flows into, through and out of the offshore wind sector, which will also give better insight into the scale of challenges and opportunities in terms of the volumes and qualities of components and materials.

Circular economy scenarios for offshore wind are inherently linked to their capability in related sectors (S5.2.2). For example, the ability to decommission components in one piece, to enable reuse, repurposing, refurbishing and remanufacturing, depends on the capabilities in the decommissioning and removal sector as well as port facilities; remanufacturing depends on the capabilities of Original Equipment Manufacturers and/or specialist remanufacturing businesses; and recycling depends on the capabilities in the resources sector as well as the resources demand in manufacturing sectors. Developing a circular economy in offshore wind will therefore require a multisector perspective and approach, with business opportunities emerging within and outside of the offshore wind sector. This can open chances to grow or develop local supply chains, often subject to political debate, while reducing the risk for offshore wind, e.g., in terms of sourcing materials to sustain growth ambitions and finding markets for recyclates.

Regional and national capabilities with regard to the various circular economy strategies will influence the feasibility of whole lifecycle scenarios. For example, if the capacity for operations and maintenance is low, then a heavy reliance on maintenance and repair could not be recommended; conversely, when the decommissioning, disassembly and/or recycling capabilities are underdeveloped, then an initial heavier focus on maintenance and repair to increase the chances for lifetime extension would offer the best chance to grow circularity in the short term. The offshore wind sector needs a decision support tool for whole lifecycle scenarios to help determine which strategies are best under which conditions. The conditions may vary across countries due to the differences in legal obligations, and a decision support tool must be coproduced with government and industry representatives.

Finally, the proposed circular economy framework can increase the sustainability of the management of offshore wind infrastructure but, as pointed out in S5.1, it is not a silver bullet to all sustainability challenges and opportunities. The integration of the offshore wind sector into discussions on low-carbon and sustainable transitions will require a broader engagement and partnerships beyond the material aspects of growing offshore wind.

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