

Extending the Lifetime of Offshore Wind Turbines: Challenges and Opportunities

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Abstract: A significant number of first-generation offshore wind turbines (OWTs) have either reached or are approaching the end of their operational lifespan and need to be upgraded or replaced with more modern units. In response to this concern, governments, regulatory bodies and industries have initiated the development of effective end-of-life (EOL) management strategies for offshore wind infrastructure. *Lifetime extension* is a relatively new concept that has recently gained significant attention within the offshore wind energy community. Extending the service lifetime of OWTs can yield many benefits, such as reduced capital cost, increased return on investment (ROI), improved overall energy output, and reduced toxic gas emissions. Nevertheless, it is important to identify and prepare for the challenges that may limit the full exploitation of the potential for OWT lifetime extension projects. The objective of this paper is to present a detailed PESTLE analysis to evaluate the various political, economic, sociological, technological, legal, and environmental challenges that must be overcome to successfully implement lifetime extension projects in the offshore wind energy sector. We propose a decision framework for extending the lifetime of OWTs, involving the degradation mechanisms and failure modes of components, remaining useful life estimation processes, safety and structural integrity assessments, economic and environmental evaluations, and the selection of lifetime extension technologies among remanufacturing, retrofitting, and reconditioning. Finally, we outline some of the opportunities that lifetime extension can offer for the wind energy industry to foster a more circular and sustainable economy in the future.

Keywords: offshore wind turbine (OWT); end-of-life (EOL); lifetime extension; repowering; decommissioning; circular economy; PESTLE analysis



Citation: Shafiee, M. Extending the Lifetime of Offshore Wind Turbines: Challenges and Opportunities. *Energies* **2024**, *17*, 4191. <https://doi.org/10.3390/en17164191>

Academic Editor: Davide Astolfi

Received: 27 July 2024

Revised: 16 August 2024

Accepted: 19 August 2024

Published: 22 August 2024



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1. Introduction

Wind energy is one of the fastest-growing sustainable energy sources worldwide, recognized as the most cost-effective form of renewable energy generation [1]. As a sustainable solution, it also offers the benefits of reducing greenhouse gas (GHG) emissions and mitigating global warming, helping to support the achievement of net-zero goals by 2050 [2]. The Global Wind Energy Council (GWEC) reports that global wind energy capacity reached 1021 GW by the end of 2023, reflecting a compound annual growth rate (CAGR) of nearly 18% over the past two decades [3]. Many projections suggest that this upward trend will continue, driven by ongoing technological advancements, supportive policies, and the urgent need to transition to low-carbon energy sources.

Wind turbines are the primary technology used to harness wind power and generate green electricity. Wind turbine technology has evolved significantly over the past decades, with improvements in design, materials, and efficiency. The technology now comes in various design configurations (horizontal axis or vertical axis, single-rotor or multi-rotor), drivetrain concepts (geared or direct-drive systems), sizes (small: with a nominal power output of less than 50 kW, medium: with a nominal power output between 50 kW and 500 kW, and large: with a nominal power output above 500 kW), locations (onshore or offshore), type of offshore support structure (fixed-bottom: gravity-based structure, monopile,

tripod and jacket, or floating: spar-buoy, tension leg platform, and semi-submersible), and applications (residential use or commercial use) [4,5]. All these developments have made wind energy a more viable and cost-effective solution for renewable electricity generation.

A wind farm is a collection of wind turbines installed in a specific area and connected through a power substation. The substation is a crucial component of the wind farm infrastructure, acting as the central hub for managing and distributing the electricity generated by the wind turbines to homes and businesses. To support the development of a wind farm, substantial investment in infrastructure is required. This includes not only the wind turbines themselves but also the necessary supporting systems, including transportation networks, foundation installation, electrical infrastructure, cabling and transmission lines, monitoring systems and maintenance facilities [6]. The design lifetime of wind farms is typically between twenty to thirty years, during which they are expected to operate reliably and safely. A significant proportion of the wind farms that were built during the 1990s and early 2000s have reached, or are nearing, the end of their life expectancy. The Renewable Energy Foundation [7] published a wind energy dataset containing information on 282 wind turbines in the UK and 823 wind turbines in Denmark, with ages ranging from zero to nineteen years. Staffell and Green [8] reported that about 45 wind farms built in the UK in the 1990s were more than fifteen years old by the year 2014. Out of these 45 wind farms, 5 wind farms were repowered in their fifteenth year of operation, 5 wind farms operated for between sixteen and twenty years before being repowered, and 35 wind farms (i.e., 78%) were still operational. Ortegon et al. [9] reported that approximately 40,000 wind turbines will reach the end of their original design life between 2025 and 2030, necessitating urgent and effective actions to address the associated challenges. Ziegler et al. [10] reported that by 2016, the total number of onshore wind turbines exceeding 20 years of operational life was approximately 3400 in Germany, 1250 in Denmark, 500 in Spain, and 19 in the UK. They also provided evidence indicating that the number of wind farms reaching the end of their operational lifespan will continue to rise in the coming years.

The impending wave of aging wind farms poses significant challenges to the wind energy sector, including instability in power supply, fluctuations in electricity prices, environmental pollution, biodiversity loss, increased accident rates, and higher maintenance costs. Addressing these challenges is crucial for ensuring the long-term sustainability and reliability of wind energy. In response to this concern, governments, regulatory bodies, the wind energy industry, and other stakeholders have initiated the development of effective end-of-life (EOL) management strategies for wind farms and their supporting infrastructure. In principle, there are three strategies that can be adopted for the EOL management of wind farms. These strategies, as shown in Figure 1, include *lifetime extension*, *repowering*, and *decommissioning* [11]. Lifetime extension involves prolonging the service life of wind farms for some additional years beyond their original design life. Repowering involves upgrading or replacing old wind turbines with modern, higher-capacity, and more efficient models to improve the overall energy output of the wind farm [12]. Decommissioning is the final phase in the lifespan of a wind farm project, considered when other EOL strategies are not suitable [13,14]. During decommissioning, wind farm infrastructure is carefully dismantled, and wind turbines are systematically removed. References [15,16] offer further details on the EOL management strategies for wind farms and their practical implementation.

Among the various EOL management strategies, lifetime extension is considered a highly appealing option in the offshore wind energy sector. This approach can provide a wide range of benefits to wind energy investors, owners, asset managers, service providers, health and safety authorities, public policymakers, environment protection agencies, regulatory bodies, and others. A brief list of the benefits of extending the operational life of offshore wind turbines (OWTs) is provided below [17]:

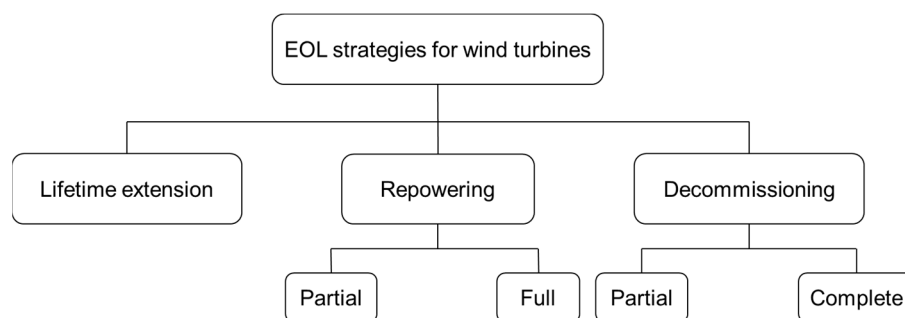


Figure 1. End-of-life (EOL) management strategies for wind turbines.

- *Economic benefits:* Lifetime extension saves capital expenditures (CapEx) needed for constructing new wind farms, mitigates financial risks compared to investing in greenfield projects, enhances return on investment (ROI), improves energy output, and ultimately lowers the levelized cost of electricity (LCoE).
- *Technical benefits:* Lifetime extension improves the operational condition of aging OWTs by conducting repairs on damaged parts, implementing software upgrades and adjustments, and updating safety systems and protocols to an acceptable level.
- *Social benefits:* Lifetime extension secures existing jobs while also potentially creating new job opportunities in the second-hand OWT sector (i.e., repair, refurbishment, and remanufacturing).
- *Environmental benefits:* Lifetime extension helps protect the marine ecosystem and preserve the natural environment by reducing pollutant emissions associated with constructing new wind farms. It also supports biodiversity and maintains ecological balance in marine environments by minimizing disturbances to marine habitats.
- *Legal benefits:* Lifetime extension provides legal certainty for investors and stakeholders by maintaining a stable operating framework and avoiding disruptions that could arise from the decommissioning and replacement of wind farm infrastructure.

Despite the benefits mentioned above, extending the lifetime of OWTs presents several challenges that must be effectively addressed to fully realize these advantages. The objective of this paper is to present a detailed assessment of the challenges that the offshore wind energy industry is likely to confront during lifetime extension projects. Various political, economic, sociological, technological, legal, and environmental challenges are identified and evaluated through a PESTLE analysis. This analytical tool is one of the most efficient and effective methods used by industries to assess factors that impact their operations and strategic decisions. Following this analysis, a decision framework is proposed for effectively extending the lifetime of OWTs. Our framework is a multifaceted approach that encompasses the degradation mechanisms and failure modes of OWT components, remaining useful life estimation processes, safety and structural integrity assessments, economic and environmental evaluations, and the selection of lifetime extension technologies. We then outline some of the opportunities that lifetime extension can offer for the wind energy industry to promote a more circular and sustainable economy in the future. Although the study primarily focuses on the wind energy sector, it also discusses relevant experiences of lifetime extension in other energy industries.

The rest of the paper is organized as follows: Section 2 analyzes the challenges the wind energy industry faces today in implementing lifetime extension projects. Section 3 shares the experiences and lessons that the wind energy industry can learn from other energy industries. Section 4 discusses the various steps involved in the lifetime extension process for OWT subsystems and components. Section 5 presents a decision framework for extending the lifetime of OWTs. Section 6 explores the opportunities that lifetime extension offers for creating a more sustainable and circular wind energy industry. Finally, the conclusions are provided in Section 7.

2. PESTLE Analysis for Lifetime Extension of OWTs

This section aims to analyze and evaluate the various challenges associated with OWT lifetime extension projects. First, an overview of the PESTLE technique is provided in Section 2.1, followed by a PESTLE analysis in Section 2.2.

2.1. PESTLE Background

PESTLE is an analytical tool that was first introduced in 1967 by Francis Aguilar, an American scholar specializing in strategic planning [18]. PESTLE stands for six factors. The letter ‘P’ denotes political factors. Such factors include regulatory policies, government stability, tax policies, and trade regulations that can impact the feasibility and execution of OWT lifetime extension projects. The letter ‘E’ represents economic factors. These factors include elements that can influence the cost, funding, and financial viability of OWT lifetime extension projects. The third letter, ‘S’, denotes social factors. Social factors include public attitudes towards prolonging the presence of OWTs in the marine environment and the availability of a skilled workforce. The fourth letter, ‘T’, denotes technological factors. These factors include technological advancements and innovations that can impact the feasibility and efficiency of OWT lifetime extension projects. The fifth letter, ‘L’, denotes legal aspects. The legal aspects determine the regulatory framework and compliance requirements that OWT lifetime extension projects must adhere to. The last letter, ‘E’, denotes environmental factors. These factors include the ecological and environmental impact of OWT lifetime extension projects, such as their effects on marine life, coastal ecosystems and climate change mitigation.

By systematically analyzing the six PESTLE factors, businesses can gain a comprehensive understanding of their external environment and make informed decisions. This model has been widely adopted by successful global corporations, such as Tesla and BMW, in their strategic planning process, business expansion decisions, workforce planning, product development, and marketing planning [19]. In the wind energy sector, the PESTLE tool has been employed for various applications, including wind farm development, power generation planning, and wind turbine technology selection [20–22]. However, this technique has received very little attention in the literature regarding EOL planning and decision-making. To the best of our knowledge, this study is the first to perform a PESTLE analysis aimed at better understanding the challenges and opportunities that lifetime extension may bring to the offshore wind energy sector.

To conduct a successful PESTLE analysis, it is necessary to collect up-to-date information from reliable sources to understand the current state of each factor. Therefore, the first step in the PESTLE analysis is to assemble a team of experts with extensive knowledge and experience in six areas, including political, economic, social, technological, legal, and environmental factors. For this study, six experts in the wind energy domain were interviewed, each specializing in one of the six areas. For instance, the technical expert was interviewed about the technological aspects of OWT lifetime extension. Similarly, the environmental expert was consulted about the environmental impacts of OWT lifetime extension, with a focus on greenhouse gas emissions and waste generation. The following section summarizes the findings of the PESTLE analysis for OWT lifetime extension.

2.2. PESTLE Analysis for OWT Lifetime Extension

2.2.1. Political Challenges

Political challenges related to the lifetime extension of OWTs include various factors. Currently, obtaining permits and licenses for the extended operation of OWTs involves navigating complex bureaucratic processes and ensuring compliance with updated environmental and safety standards. Continuous changes in government policies regarding wind energy have, in some cases, impacted the feasibility and approval processes for OWT lifetime extension projects. Moreover, since offshore wind projects often involve international cooperation and agreements, extending the lifespan of these projects may require careful geopolitical considerations. Shifts in public policy toward wind energy can

also influence financial incentives, subsidies, and support mechanisms that are crucial for extending the lifespan of OWTs. To address these political challenges, it is essential to foster collaboration among stakeholders, engage proactively with regulatory bodies, and adhere to evolving environmental and safety standards to ensure the sustainable extension of the OWT lifecycle.

2.2.2. Economic Challenges

Maintaining the integrity of existing OWTs and redeploying them for continuous operation with minimal modifications can result in significant cost savings for wind farm owners and other stakeholders in the wind energy sector. Economics is a primary driver for wind farm owners when deciding to extend the lifetime of OWTs. Like conventional energy industries, where lifetime extension decisions depend on production volume and cost, the key economic factor in the wind energy industry is the spot price of electricity. Some wind farm owners still earn profits from electricity tariffs through government subsidies. However, with the increasing number of zero-subsidy projects in the offshore wind energy sector, the future development of electricity prices remains uncertain. Momentum Energy Group reported that wind farms operating for more than 15 years would be more affected by lower electricity prices [23]. Therefore, changes in the current pricing regime of electricity would mean that wind farm owners must settle for competitive market prices. This uncertainty can potentially cause numerous economic challenges for lifetime extension projects in the offshore wind energy industry.

Settling for competitive market prices could reduce the profitability of wind farm projects and make extending the lifetime of existing OWTs less financially viable. In a research study, Abadie and Goicoechea [24] studied the economic benefits of lifetime extension for a wind farm in Spain, considering the seasonal evolution of future hourly electricity prices. They proposed models to estimate income gained under two scenarios: one for hourly electricity prices, incorporating seasonality, mean reversion, jumps, and non-working day effects, and another for the hourly capacity factor, also accounting for seasonality. The authors introduced “*re-blading*” as a strategy to extend the lifetime of OWTs.

2.2.3. Sociological Challenges

Currently, offshore wind farm owners are more inclined to decommission or repower old OWTs rather than extend their operational lifetime. This hesitation to extend operational lifetimes is partly due to a lack of understanding of the associated social benefits. A cultural breakthrough is essential for stakeholders in the offshore wind energy industry to fully understand and gain acceptance for extending the operational lifetime of existing OWTs. Achieving this requires comprehensive education and awareness efforts aimed at demonstrating the societal benefits of extending OWT lifetimes. Additionally, the wind energy industry, unlike conventional energy industries, lacks personnel with the requisite skills, experience, and knowledge to undertake lifetime extension projects. Efforts should be made to train personnel to enhance their understanding of lifetime extension practice.

2.2.4. Technological/Technical Challenges

The technological/technical challenges associated with the lifetime extension of OWTs include the degradation of structures and components, the lack of good quality data, appropriate tools to optimize maintenance activities, technology obsolescence, and proper procedures to help decision-makers select the most suitable lifetime extension technology for different components. These challenges are discussed in detail in the following sections.

Degradation of OWT Structures and Components

OWTs are exposed to various dynamic loads throughout their service lives, originating from sources such as wind and wave forces, ice impact, collisions, or earthquakes. These environmentally and operationally induced loads may cause degradation, which, if not controlled, can potentially lead to the collapse of the OWT. Therefore, assessing the

degradation levels of OWT structures and components using appropriate methodologies is essential for wind farm managers to determine asset conditions and associated failure risks. Typical physical degradation mechanisms that negatively impact the integrity of OWT installations include corrosion, fatigue, overload fracture, wear, tear, and scour. Additionally, components such as gearboxes, bearings, and bolts in mounted systems may suffer from fatigue-related damage over time. This damage can compromise the overall performance and safety of the OWTs, thereby affecting their remaining useful life (RUL). During the lifetime extension phase of operation, structural components of OWTs, such as towers and foundations, may experience increased degradation. This accelerated degradation can reduce the fatigue strength of OWT structures, leading to a higher failure rate, increased operation and maintenance (O&M) costs, and reduced safety during the extended operational period.

One of the challenges frequently reported in the literature is that fatigue calculations performed during the design phase of OWTs often rely on various assumptions and simplifications, leading to conservative estimates [25]. However, during the lifetime extension phase, the nature and severity of loading can vary significantly, necessitating adjustments to these initially conservative findings. Therefore, decision-makers are challenged to minimize these conservative outcomes to meet industry standards during the lifetime extension phase. To address this challenge, the offshore wind energy industry must enhance current fatigue analysis practices by adopting more rigorous, analytical, and computational approaches. This improvement is essential to accurately assess the fatigue life of OWTs under evolving operational conditions and ensure compliance with safety and performance requirements. In a research study, Nielsen et al. [26] highlighted that accurately predicting the residual fatigue life of OWT structures at the end of their original lifecycle is a significant technical challenge facing the offshore wind energy industry. To address this issue, they proposed using probabilistic and risk-based approaches to reassess the fatigue life of OWTs. By utilizing models similar to those used for calibrating partial safety factors in IEC 61400-1 [27], they discovered that probabilistic fatigue life assessments resulted in longer projected lifespans compared to deterministic assessment methods. Similarly, in another work, Nielsen and Sørensen [28] determined specific target reliability levels for the lifetime extension of OWTs, incorporating the economic consequences associated with the risk of structural failure. A target annual reliability index of approximately 3.1 was established for the lifetime extension of OWT structural components, which is 0.2 lower than the target reliability index of 3.3 used for designing new wind turbines [27].

Another significant technical challenge in the offshore wind energy industry is the continued reliance on visual inspection for assessing OWT degradation. This approach predominantly depends on the accumulated experience of engineers and inspectors, resulting in subjective assessments. Consequently, due to the inherent uncertainties associated with expert judgment, the effectiveness of visual inspection in accurately evaluating degradation levels is considered limited, particularly during the lifetime extension phase of operation. Expanding on this, advanced technologies such as non-destructive testing (NDT) methods and structural health monitoring (SHM) systems offer more precise and data-driven alternatives to traditional visual inspections. These technologies provide continuous and objective data on structural integrity, aiding in more informed decisions regarding the lifetime extension of OWTs.

Lack of Good Quality Data

Lifetime extension analysis of OWTs requires high-quality data from the design, manufacturing, construction, installation, and operation and maintenance (O&M) stages. The importance of good quality data in ensuring reliability and maintainability within the wind energy industry was discussed by Guo et al. [29] and Hameed et al. [30]. Igba et al. [31] pointed out that the wind energy industry continues to grapple with the challenge of collecting appropriate data, largely due to a significant number of wind farms still relying on offline methods for in-service data collection. Data gathered through these

offline methods are beset with issues such as measurement errors, potential falsification of records, and improper codification. For a deeper exploration of the challenges associated with manual data collection and codification in the wind energy industry, readers are encouraged to review the reference [32]. Igba et al. [33] highlighted that the limited maturity of fault diagnosis and prognosis technologies in OWTs inspection further hinders the acquisition of high-quality data. Martinez-Luengo et al. [34] noted that discrepancies in historical data, such as noisy or missing information, can significantly impact decisions regarding structural integrity and the extension of the lifetime of offshore wind turbines. Given these challenges, it is imperative for the offshore wind energy industry to intensify its efforts to establish a comprehensive database to support analyses for OWT lifetime extension projects. In recent years, some data sources, such as SPARTA [35], have become available to support lifetime extension decision-making for OWTs.

Lack of Appropriate Tools to Optimize Maintenance Activities

Maintenance activities play a key role in the successful implementation of lifetime extension projects in the offshore wind energy sector. Increasing the number of preventive maintenance (PM) actions during the lifetime extension phase of OWTs will enhance reliability by reducing the rate of deterioration. However, this increase in PM actions can lead to higher O&M costs. Therefore, it is crucial to develop efficient tools for planning OWT maintenance activities. These tools should be capable of flexibly incorporating weather dynamics, enabling accurate scheduling and execution of maintenance tasks even under variable and challenging environmental conditions [36]. By optimizing maintenance planning, the industry can balance the trade-off between improved reliability and the associated costs, ensuring sustainable and cost-effective lifetime extension of OWTs. A report published by Wind Energy Ireland [37] outlines the significance of conducting routine inspection and maintenance on OWTs for lifetime extension. The report emphasizes that maintenance activities, including lubrication, bolt tightening, and component replacements, are essential to maintaining the structural integrity and operational efficiency of OWTs during the extended lifetime. The report also highlights the importance of developing a robust maintenance strategy that incorporates predictive maintenance technologies, such as condition monitoring systems and data analytics, to optimize maintenance schedules during the OWT lifetime extension phase.

Technology Obsolescence

With advancements in design, materials, and digital signal processing, technology obsolescence has become a major concern in the offshore wind energy sector. As newer and more efficient OWT models are introduced, older turbines become less competitive and harder to maintain. This issue is particularly critical during the lifetime extension phase, where outdated components and systems may struggle to integrate with modern upgraded units. Additionally, older OWTs may lack compatibility with advanced monitoring and predictive maintenance tools that newer models offer, which can hinder effective management of turbine health and lead to increased risks of failure and higher maintenance costs. Upgrading control systems, sensors, and software can be expensive and technically challenging, especially for OWTs designed with now-outdated technology standards. These challenges present significant obstacles for wind farm owners seeking to extend the operational life of existing OWTs. To address technology obsolescence and minimize its impact during the lifetime extension phase, the wind energy sector must develop standardized protocols for integrating new technologies with older systems. By implementing robust obsolescence management strategies from the design stages of OWTs, the industry can ensure that lifetime extension projects remain viable and cost-effective. Ortegon et al. [38] investigated the impact of technological evolution on the remanufacturing of wind turbines as a strategy to extend their lifetime. Using a system dynamics approach, they modeled the interactions between maintenance activities, reliability, and technological obsolescence.

Their analysis concluded that technological obsolescence would increase the overall cost of lifetime extension projects.

Selection of the Most Suitable Lifetime Extension Technology

Based on the outcomes of lifetime extension assessments, wind farm owners should select the most suitable technology for extending the life of each OWT component. Making such a critical decision involves a trade-off between conflicting criteria such as improved performance, increased costs, and other considerations. This indicates that selecting the most suitable lifetime extension technology among different options (remanufacturing, retrofitting, reconditioning, etc.) is a challenging task. Multi-criteria decision analysis (MCDA) and cost–benefit analysis (CBA) techniques can be useful in handling such cases effectively [39]. However, these techniques require extensive data collection and processing. Due to the lack of knowledge and previous experience regarding lifetime extension in the offshore wind energy industry, uncertainties are involved in the decision-making process. Thus, stakeholders must develop tools and models capable of handling uncertainties in the OWT lifetime extension decision-making process.

2.2.5. Legal Challenges

The availability of regulations, standards, and guidance documents is crucial for the implementation of OWT lifetime extension projects. These resources assure wind farm managers that extending the operational lifetime of OWTs will not introduce additional risks regarding health, safety, and environmental issues. For example, in the offshore oil and gas industry, the NORSOK U-009 [40] and NORSOK Y-002 [41] standards have been developed to support lifetime extension assessments for subsea systems and transportation infrastructure, respectively. The ISO/TS 12747 standard [42] also provides guidance on assessing the feasibility of extending the service life of pipeline systems beyond their specified design life. Lifetime extension standards and requirements in the wind energy industry are still evolving and tend to be prescriptive in nature. Currently, four standards—DNVGL-ST-0262 [43], DNVGL-SE-0263 [44], IEC/TS 61400-28 [45], and IEA Wind TCP Task 42 [46]—provide general technical requirements and guidance for the lifetime extension analysis of wind turbines. A major drawback of these standards is that they use uniform procedures to assess all control and protection systems, as well as load-transferring components of wind turbines, without accounting for their unique failure modes and operational conditions [47]. This generic approach may not adequately address the specific needs and challenges of the environments in which OWTs operate. Therefore, there is a need for more tailored standards and assessment procedures that consider the unique conditions and requirements of both onshore and offshore settings.

2.2.6. Environmental/Ecological Challenges

Lifetime extension of OWTs offers many environmental and ecological benefits, including reduced natural resource use, decreased consumption of raw materials, and lower energy usage with associated carbon savings. However, an OWT lifetime extension still has some negative environmental consequences, which could be a source of concern to the public. One of the environmental challenges is the noise generated during the implementation of lifetime extension technologies onsite. This noise can disturb marine and bird life, as well as nearby human communities [48]. Additionally, extended use of existing infrastructure can add to visual clutter, especially in coastal areas where the presence of OWTs is already a contentious issue. Other potential environmental-ecological impacts include the risk of oil and chemical spills from maintenance activities, the disturbance of seabed habitats during structural reinforcements, and the possible increased risk of collisions with marine vessels due to prolonged turbine presence [49].

The next section reviews experiences and lessons that the wind energy industry can learn from other energy sectors.

3. Experiences and Lessons Learned from Conventional Energy Industries

To successfully undertake lifetime extension projects in the offshore wind energy industry, it is crucial to learn from the best practices and experiences of other conventional energy industries that have implemented similar programs. Extensive research on lifetime extension has been conducted in the nuclear power and offshore oil and gas industries. In contrast, the wind energy industry is relatively new to this topic. The following subsections summarize experiences from the nuclear power and offshore oil and gas sectors and explore how these can address gaps in the wind energy industry.

3.1. Nuclear Power Industry

A significant number of nuclear power plants will reach the end of their operating lives in the coming years. These plants are usually designed for a technical life of 40 years, which may be extended by an additional 10 to 20 years [50]. To ensure the safe operation of critical equipment during the extended lifetime, the nuclear power industry follows several processes to meet regulatory requirements. Lifetime extension management in this industry focuses on maintaining the availability of essential safety functions throughout the plant's extended life. Recognizing the potential dangers of aging on plant safety, the industry has developed a comprehensive framework for lifetime extension analysis. The following studies on life extension have been conducted in the nuclear power industry:

Bhartee and Hart [51] proposed a methodology to support the lifetime extension of low- and medium-voltage equipment in the nuclear power industry. Stevens and Ranganath [52] used data from online fatigue monitoring systems as a technical basis for the lifetime extension analysis of boiling water reactor (BWR) components in nuclear power plants. Shah and MacDonald [53] discussed the issue of aging degradation and lifetime extension of light water reactor (LWR) components in nuclear power plants. Saldanha and Frutuoso e Melo [54] proposed a generalized non-homogeneous Poisson process (NHPP) model to predict the rate of occurrence of failure (ROCOF) for water pumps in a nuclear power plant, aiding in informed decision-making regarding their lifetime extension. Asmolov et al. [55] reported the outcomes of extending the service life of the Novovoronezh nuclear power plant beyond 45 years. Trampus [56] provided examples from the Paks nuclear power plant in Hungary, highlighting the substantial role and importance of non-destructive evaluation (NDE) in ensuring the long-term integrity of nuclear components. These examples included ultrasonic and eddy current examinations of critical areas and sub-components of the reactor pressure vessel, reactor internals, the steam generator, and various pipeline systems. Kim et al. [57] conducted an analysis of cost savings achieved by extending the lifetime of nuclear power plants in the United States. They estimated that extending the lifetime of nuclear power plants from 40 years to 60 and 100 years would result in cost savings of \$330 billion and \$500 billion, respectively. In a recent study, Woo [58] proposed a methodology based on system dynamics and Monte Carlo simulations to support the lifetime extension of nuclear power plants. In another more recent study, Dimova [59] adopted a five-step approach for the evaluation of the lifetime extension of nuclear power plant components. The five steps included: (i) classifying critical equipment; (ii) identifying the dominant degradation mechanisms of the equipment; (iii) determining the effects of equipment degradation on nuclear power plant integrity; (iv) identifying methods to control the degradation effects; and (v) developing methodologies to evaluate the efficacy of the control measures.

3.2. Offshore Oil and Gas Industry

There has been a steady growth in the number of offshore oil and gas installations reaching the end of their original design life. Stacey et al. [60] and Stacey [61] reported that over 50% of the fixed installations in the UK sector of the North Sea have exceeded their original design life. Examples of lifetime extension projects executed in the offshore oil and gas industry include Ekofisk (from 2005 to 2015), Asgard C (from 2005 to 2018), Ula (from 2005 to 2028), Statfjord A (from 2007 to 2028), Valhall QP (from 2007 to 2010), Valhall PCP

and DP (from 2007 to 2015), Hod (from 2008 to 2028), Norpipe oil (from 2008 to 2028), and Veslefrikk A and B (from 2009 to 2020) [62]. Other studies conducted on lifetime extension of offshore oil and gas assets are summarized below.

Jansen and Van [63] and Rincón et al. [64] proposed risk-based methodologies for lifetime extension of oil and gas pipelines. Hudson [65] discussed how companies can optimize the use of their topside facilities, time, and resources during the lifetime extension period of operation. Saunders and Sullivan [66] discussed various requirements, methods, and technologies developed for the lifetime extension of flexible pipes in the oil and gas industry. Vaidya and Rausand [67] discussed various requirements, including degradation modeling and uncertain environmental and operational conditions, for decision-making on lifetime extension in the subsea oil and gas industry. Brandt and Mohd Sarif [68] developed an integrated technical and economic technique to support lifetime extension of topside facilities in the oil and gas industry. Tveit et al. [69] discussed the innovations that could be used by companies to resolve the technical challenges of extending the RUL of subsea separators and pumps. Ramírez and Utne [70] proposed a dynamic Bayesian network model for assessing the technical feasibility of extending the lifetime of a firewater pump system in an oil and gas facility.

Shafiee et al. [71] developed a lifetime extension assessment framework that incorporates both equipment health and economic value factors. They applied this model to support the extension of water deluge systems in offshore oil installations. Animah and Shafiee [72] provided guidelines for oil and gas operators to meet lifetime extension requirements and optimize costs. The framework included modules for condition assessment, RUL prediction, and lifetime extension decision-making. Its benefits were demonstrated through a case study of a three-phase separator system on a West African oil platform. Ferreira et al. [73] provided guidelines for lifetime extension process management in the Brazilian oil and gas industry. Shafiee and Animah [74] proposed a model for evaluating risks and prioritizing mitigation strategies for subsea facilities operating in high-pressure/high-temperature (HPHT) environments over their extended lifetime. To illustrate the model, a case study of subsea manifolds and flowlines was provided, with results evaluated and discussed. Oubella [75] proposed a systematic approach for the lifetime extension assessment of the pressure vessels and piping of an old offshore oil and gas platform constructed in the mid-1980s. Ferreira et al. [76] discussed strategies for evaluating and managing asset obsolescence during the lifetime extension of oil and gas facilities. They proposed a framework with six stages for managing obsolescence and validated it with a case study from the Brazilian oil and gas industry.

Table 1 summarizes the lessons learned from the nuclear power and offshore oil and gas industries. These insights can be applied to the wind energy sector to guide lifetime extension practices. A comprehensive feasibility assessment framework that integrates technical, economic, environmental, social, and political factors is crucial for making informed decisions on OWT lifetime extension. Key data, including test reports, degradation and condition monitoring, maintenance records, and design information, are essential for a thorough lifetime extension analysis. Probabilistic Safety Assessment (PSA) tools can help identify which OWT components are suitable for lifetime extension. Additionally, developing reliable models to predict component degradation, estimate RUL, and mitigate risks will significantly benefit the wind energy industry. Such models will improve the ability to forecast failures, optimize maintenance schedules, and ensure the safe and cost-effective operation of OWTs throughout their extended lifespan.

Table 1. A summary of the lessons learned from lifetime extension in the nuclear power and offshore oil and gas industries.

	Nuclear Power Industry	Offshore Oil & Gas Industry	Current Practices in Wind Energy	Recommendations for Wind Energy
Lifetime extension standards	There is no universally accepted standard for lifetime extension; however, the periodic safety review (PSR) remains the primary regulatory process for authorizing such projects.	There are several standards for authorizing lifetime extension of subsea structures and pipeline systems: NORSOK U-009 [40], NORSOK Y-002 [41], ISO/TS 12747 [42].	Several recent standards provide general principles, technical requirements, and guidance for certifying the lifetime extension of wind turbines: DNVGL-ST-0262 [43], DNVGL-SE-0263 [44], IEC/TS 61400-28 [45], IEA Wind TCP Task 42 [46].	There is a pressing need to develop a ‘unified’ standard for the lifetime extension of OWTs. This standard should include guidelines that address structural integrity, operational efficiency, environmental impact, and economic viability throughout the wind farm lifecycle.
Lifetime extension methodologies	They often use comprehensive and structured technical assessment frameworks.	They usually apply methodological techno-economic feasibility assessment frameworks.	There is no comprehensive and structured approach for lifetime extension feasibility assessments.	There is a need for a ‘holistic’ approach that integrates technical, economic, environmental, social, and political aspects in the certification of lifetime extension for OWTs.
Lifetime extension monitoring	PSA tools are widely used to screen, prioritize, and monitor critical safety elements within a nuclear power plant.	Generic industrial tools are used for screening and prioritizing critical components for lifetime extension in subsea systems. Additionally, PSA tools are gradually being used.	There is currently no established approach in the wind energy sector for prioritizing and monitoring critical wind turbine components for lifetime extension.	There is a need to develop a ‘systematic’ decision-making approach that incorporates PSA tools to screen, prioritize, and monitor critical components within an offshore wind farm.
Lifetime extension risk assessment	Probabilistic risk assessment tools are widely used to estimate the consequences of system failure during lifetime extension.	Probabilistic risk assessment tools are often used to estimate the consequences of system failure during lifetime extension.	Probabilistic risk assessment tools are gradually being used to extend the lifetime of wind turbine components.	A more ‘thorough’ risk assessment methodology incorporating all aspects is needed for OWTs during the lifetime extension phase of operation.
Lifetime extension strategy selection	There are well-established approaches, such as MCDM, LCA, and BCA, for selecting a suitable lifetime extension strategy.	There are well-established approaches, such as MCDM, LCA, and BCA, for selecting a suitable lifetime extension strategy.	Currently, the selection of a lifetime extension strategy in the wind energy sector is predominantly based on expert opinion.	There is a need for a ‘structured’ framework to evaluate various factors, ensuring a more balanced assessment of lifetime extension strategies.

4. Lifetime Extension Process for OWTs

In this section, we discuss life estimation processes, aging failure modes, and effective strategies to support informed decision-making for the lifetime extension of OWT subsystems and components.

OWTs consist of various subsystems and components, each with unique characteristics and potential failure modes. Understanding these mechanisms and assessing the health of components is crucial for developing effective strategies to extend their operational life. Figure 2 illustrates the categorization of OWT subsystems and components addressed in this study. As depicted, OWTs are categorized into four subsystems: electrical subsystems, mechanical subsystems, power control subsystems, and structural components. By analyzing each subsystem and component in detail, we can develop targeted strategies

tailored to the lifetime extension of each individual part. This holistic approach ensures that lifetime extension decisions are well-informed, balanced, and aligned with several key objectives in the wind energy industry, including energy efficiency, safety standards, and cost-effectiveness.

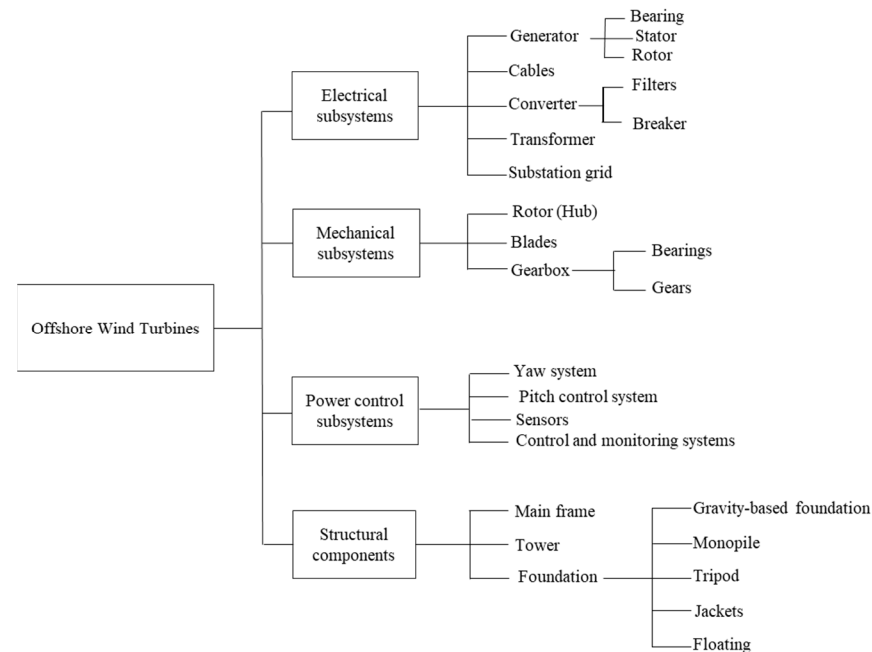


Figure 2. OWT subsystems and components.

4.1. Lifetime Estimation Process and Aging Failure Mode Analysis

During the planning and design phases of offshore wind farms, failure modes are exhaustively identified, with particular emphasis on critical areas to mitigate risks in the installation and operation of OWTs. Shafiee and Dinmohammadi [77] indicated that risk analysis tools such as Fault Tree Analysis (FTA), Failure Mode, Effects, and Criticality Analysis (FMECA), and Design of Experiments (DOE) are used for identifying failure modes during the design phase of OWTs. While these tools may be effective in the design phase, their application is limited during the lifetime extension phase of operation. For effective and efficient lifetime extension decision-making, it is essential to focus on the failure modes that are most likely to impact operations during the extended lifetime. Moreover, the environmental and operational conditions must be taken into consideration to identify potential failure modes and calculate the RUL. Since these conditions can change by the end of the original design life, RUL estimations must be updated with new data to ensure confidence in lifetime extension decisions. In cases where good quality data is not readily available, decision-makers can rely on alternative methods such as expert judgment or using data from similar OWT types as a guide.

In what follows, the lifetime estimation processes and key aging failure modes corresponding to each subsystem and component of the OWT system are analyzed.

4.1.1. Electrical Subsystems

The failure of electrical subsystems during the lifetime extension phase of OWT operations can lead to significant consequences. Beyond economic impacts for wind farm owners, such failures can result in potential fire outbreaks. Additionally, the failure of electrical subsystems could lead to oil leakages, raising serious environmental concerns. It is reported that failures of electrical subsystems or components of OWTs can also pose health and safety risks for personnel working onsite [78]. Therefore, it is crucial to analyze aging failure modes for each electrical subsystem and component of OWTs and employ appropriate lifetime estimation approaches to mitigate these risks.

Generator

The generator is one of the high-risk subsystems of OWTs. In the offshore wind energy industry, two common generator systems are used: synchronous generators with permanent magnet coils installed on the rotor and double-fed induction generators. The lifetime estimation procedure for generator systems must ensure that the reliability and functionality of critical components such as bearings, stators, and rotors have not degraded over time. This is achieved through regular inspection and maintenance of these components throughout the original design life of the OWT. Consequently, the RUL of a generator can be estimated by statistically analyzing inspection and maintenance records. This assessment helps determine whether the generator can continue to maintain electrical contact safely and effectively for power generation throughout the lifetime extension phase of operation. Popa et al. [79] indicated that for induction generators, bearings account for almost 40% of failures, followed by stator failures at 38% and rotor failures at 10%. Luengo and Kolios [80] identified that potential failure modes associated with induction generators used in OWTs include opening or shorting of inter-turn failures at the stator or rotor winding circuits, abnormal connections in stator windings, dynamic eccentricity, broken rotor bars, cracked end-rings, and static and dynamic air-gap eccentricities. However, not all of these failure modes occur with the same frequency during the extended lifetime. The potential aging failure modes of OWT generators during the lifetime extension phase could primarily involve issues such as cracks in rotor bars or the total breakage of rotor bars due to higher stresses. These specific failure modes are critical considerations for ensuring the continued safe and reliable operation of the generator beyond its original design life.

Cables

Cables play a critical role in delivering power generated by OWTs to substations and serving as export lines to transmit electricity from substations to the grid. Various types of cables are used in the wind energy industry, including power transmission and distribution cables, control cables, electronic cables, data transmission cables, and fiber optic cables. For offshore wind energy applications, submarine cables connect offshore wind farms to offshore transformer substations, which then link to the onshore grid. Submarine cables are susceptible to age-related degradation, such as water treeing and deterioration of polymeric materials. Water treeing occurs when cable dielectric material is attacked by water, moisture, or vapor. Aging of insulation material refers to the gradual loss of dielectric strength due to factors like high temperatures, cyclic thermal, electric, and mechanical stresses, as well as environmental effects. These aging failure modes can compromise cable properties and lead to complete cable failure during the extended lifetime. Therefore, thorough assessment and testing are essential to ensure the continued reliability and safety of cables in offshore wind energy applications. Currently, various diagnostic testing methods are employed to predict the RUL of submarine cables [81]. These tests include:

- *Low-voltage time domain reflectometry test*: This test measures the true length of the cable, identifies splice locations, and assesses the condition of the concentric neutral.
- *Leakage current measurements at direct voltages or below the peak operating voltage*: This test aims to detect cables that may be affected by water treeing.
- *Partial discharge measurements*: This test is used to detect potential difference (PD) sites using time domain reflectometry.
- *Breakdown voltage test*: This test uses a cos-rectangular or sine wave test supply to locate breakdown sites in buried cables for recovery and examination.

Converter, Filters and Circuit Breakers

The power converter plays a crucial role as the interface between the generator and the power grid. Depending on its location, the converter must meet operational requirements for both the generator side and the grid side. As converters age, their condition gradually deteriorates, increasing the risk of failure towards the end of their original design life. To assess the RUL of converters, maintenance and operational data must be analyzed using

appropriate statistical methods to identify potential trends. Converters and filters are susceptible to electrical faults such as converter burnout and capacitor fires [82]. Circuit breakers, on the other hand, are prone to wear and tear over time. Therefore, conducting root cause analysis on a case-by-case basis is recommended for the lifetime assessment of converters. This approach helps identify specific issues affecting converter reliability and informs decisions on maintenance strategies and potential upgrades to ensure continued safe and efficient operation.

Transformer

Dry, non-flammable, and moisture-proof transformers installed in the nacelle platform or inside the tower dominate offshore wind farm applications. These transformers have a compact design, are vibration-resistant, and offer the highest reliability and efficiency. Their robust construction makes them well-suited for the harsh marine environment, where moisture and salt can pose significant challenges to electrical equipment. For extended lifetime operations, it is crucial to assess the condition of transformers using appropriate techniques. These include partial discharge tests, insulation resistance tests, and visual inspections for locating bent connecting rods between taps and other connections. The condition of the insulating system is the key life expectancy indicator for all transformers. Over time, the structural strength and properties of dry transformer insulating materials degrade due to factors such as thermal cycling, electrical stresses, and environmental exposure. This degradation impacts their performance and reliability, potentially leading to increased failure rates if not properly managed.

Substations

Wind farm substations are built to receive power generated by the OWTs through cables. A typical wind farm substation consists of medium voltage systems, high voltage systems, capacitor banks, control, protection and metering systems, communication systems, and fire and intruder protection systems. Common aging failure modes, such as corrosion, wear, tear, and obsolescence, often occur in electrical systems and may apply to the systems mentioned above. To assess the health status and estimate the RUL of the different systems in a power substation for lifetime extension, a combination of visual inspection, statistical methods, and laboratory testing is recommended.

4.1.2. Mechanical Subsystems

Rotor (hub)

The rotor of a wind turbine connects the blades to the main shaft and the rest of the drivetrain system. It is typically made of welded steel or cast metal. During the design phase, various load models and baseline analyses are conducted. To estimate the RUL of an OWT hub, these models and analyses must be revalidated using updated historical data from the OWT's original design life. This data may include inspection, maintenance, failure probability, and condition monitoring records. If loading models and design analyses are unavailable, lifetime estimation information can be obtained through expert elicitation. Despite the hub's critical function, aging failure information is rare. However, if failures occur, they can cause significant damage to the OWT, potentially leading to its decommissioning before the end of its life. Potential aging failure modes to consider during the extended life of rotor operations include broken or loose-mounted bolts, corrosion fatigue of the hub structure, and degraded materials.

Blades

Wind turbine blades are the most challenging components to recycle due to their large size, complex structure, and the materials used in their construction. The blades are typically made from composite materials, such as fiberglass-reinforced epoxy or carbon fiber, which are difficult to break down and separate into reusable components [83]. Most

OWT blades currently end up in landfills or are incinerated. Therefore, finding efficient methods for extending the operational lifetime of OWT blades is crucial.

During the operational life of OWTs, blades are susceptible to various defects and failures. Common blade defects and aging failure modes include cracks and delamination of the composite material due to fatigue. Leading-edge erosion, caused by impact fatigue from collisions with rain droplets, hailstones, or other airborne particles, is also a significant issue for OWT blades. Blade failures can have significant economic consequences for wind farm owners due to extended turbine downtime. Additionally, such failures can pose health and safety risks, including potential injuries to the public. Therefore, ensuring the structural integrity of blades is essential for extending the operational lifetime of OWTs. Verifying the reliability of blades is crucial to achieving this lifetime extension. This verification ensures that the blades can withstand specific site operational conditions, comply with relevant safety standards, and avoid failures that could result in turbine downtime.

Assessing the condition of blades for lifetime extension should include analyzing past operational and maintenance records to identify any damage incurred during the original design life and determine if this damage could affect the blades' structural integrity during the extended operational phase. If high-quality data and design load models from the blades' design stages are available, the remaining fatigue life of the blades can be estimated. In a study, Zhang et al. [84] analyzed the forces acting on OWT blades in different environmental conditions and determined the relationship between the blades' damage value and their remaining fatigue life. Bech et al. [85] studied the impact of leading-edge erosion on the lifetime extension of OWT blades. They discovered that reducing the tip speed of the blades during extreme precipitation events could significantly extend the service life of the leading edges from just a few years to the entire operational lifecycle of the OWT. Saathoff and Rosemeier [86] proposed an analysis method based on residual stresses to assess the lifetime extension of a 1.5 MW wind turbine. They applied this method to blade bolts and compared the results with those obtained using damage-equivalent load calculations. More recently, Su and Kam [87] proposed a set of analytical methods to verify the reliability of composite wind turbine blades after material aging due to external environmental factors. They found that the blade's reliability did not exceed 98% after 20 years. Therefore, it is crucial to enhance the blade structure to maintain high reliability throughout the extended lifetime.

Gearbox

The gearbox is one of the most critical subsystems of OWTs. Although it is designed to last for 20 years, it often begins to fail within seven years. Common aging failure modes of a gearbox include damage to gear teeth and bearings through cracks. Other aging failure modes, such as pitting and wear, can also occur during the lifetime extension phase of operation. Gearbox failures are often linked to failures in the bearings. The lifetime estimation of an OWT gearbox should be based on the analysis of condition monitoring data obtained during the original design life. Additionally, lubricating oil analysis can help asset managers determine if the oil contains contaminants such as sand, rust, grinding dust, chips, splatter, and debris caused by wear and machining. These contaminants can lead to gearbox failure through the pitting of bearing rollers. Therefore, using new lubricants with improved properties could potentially reduce the damage and prolong the OWT gearbox's lifetime. In a research study, Qiu et al. [88] used ten minutes' average wind speed of Supervisory Control and Data Acquisition (SCADA) data to estimate the remaining fatigue life of a wind turbine's gear component under external and internal loadings. Junior et al. [89] proposed a damage mechanics model based on finite element analysis (FEA) to estimate the RUL of wind turbine gearboxes under severe service conditions, such as angular misalignment and lack of lubrication. Olave et al. [90] provided a case study on the lifetime extension of OWT pitch bearing and gearbox components. They concluded that reducing noise emissions is an important requirement that needs to be considered for the lifetime extension of gearboxes. Bill and Bill [91] developed an innovative particle-based

surface treatment technology to extend the lifetime of wind turbine gears and bearings. Testing this technology on a grease-lubricated main bearing in a 1.5 MW wind turbine, they observed significantly lower surface roughness, which ensured better load distribution, lower local pressure, and reduced tribological stresses. Simulation results also indicated that the probability of bearing failure significantly decreases, leading to a lifetime extension of up to 17.3 years.

4.1.3. Power Control Systems

Pitch Control System

Regarding safety, the pitch control system is among the most critical components of wind turbines. This system measures, monitors, and controls the working angle of the rotor blades. The pitch control system consists of electrical components (pitch motor) and mechanical components (pitch bearing and gears). Therefore, the lifetime estimation methods discussed for electrical and mechanical systems are applicable here as well. Common aging failure modes for the pitch control system at the end of its original design life include cracked motor shafts, fractured gear teeth, and cracked bearings. These potential failures highlight the importance of thorough inspections and maintenance to ensure the continued safe operation of the pitch control system.

Yaw System

The yaw system consists of active components such as the yaw drive and brakes, as well as interfacing components like the yaw mesh, yaw bearing, and yaw brake disc. These components are designed to last for the entire operational lifetime of OWTs. However, they may suffer damage from various failure modes, such as cracks in the yaw drive shaft, damaged gear teeth, pitting of the yaw bearing, and worn-out brake discs. Lifetime estimation of the yaw system must be based on its functionality and the wear and tear of its parts.

Sensors

Sensors play a critical role in improving the condition and performance of OWTs. The data provided by sensors can be extremely valuable for wind farm operators, helping them maximize energy output, minimize maintenance costs, and extend the operational lifetime of their turbines. Sensors provide data about vibration levels, temperature, pressure, operational loads, misalignments, and other critical parameters. This data helps identify potential issues before they become serious problems, optimize maintenance schedules, and assess the overall health of the OWTs. Using this data, wind farm managers can make informed decisions about necessary repairs, adjustments, or upgrades, ultimately enhancing the reliability and safety of OWTs during their extended operational life. Loraux and Brühwiler [92] discussed how sensor data—including acceleration information, strain measurements, and temperature readings—could be analyzed to assess the remaining fatigue life of OWT components. In another work, Ziegler et al. [93] used load monitoring data in the form of strain measurements to calculate the RUL and decide on the lifetime extension of an 8MW OWT monopile structure.

Given that OWT sensors operate in environments with harsh conditions and potential sources of interference, they may fail or provide incorrect readings. Sensor failures or erroneous data can lead to inaccurate assessments of turbine health, increased risk of undetected defects, and, ultimately, higher maintenance costs and reduced potential for lifetime extension. Therefore, the suitability of sensors for the continuous operation of OWTs beyond their original design life must be thoroughly evaluated. Lifetime assessment of sensors can be achieved by benchmarking their data and analysis against data from similar sensors operating in comparable environments to identify potential gaps.

Control and Monitoring Systems

Control and monitoring systems are prone to aging-related faults and may become outdated. Upgrading control and monitoring systems is crucial for the lifetime extension of OWTs. Implementing advanced control strategies can significantly reduce structural fatigue loading and enhance the overall reliability of the OWT, ensuring efficient operation beyond the original design life. Vali et al. [94] studied the impact of an active power control strategy on the lifetime extension of a highly loaded OWT. They showed that the structural fatigue loading of the OWT could be significantly reduced while maintaining wind farm power production. In another work, Njiri et al. [95] proposed an online damage evaluation model integrated with a variable gain multiple-input multiple-output (MIMO) control strategy to extend the lifetime of OWTs. Their results showed that the proposed prognostic-based control strategy achieved a good balance between structural load reduction and extending the RUL without causing any significant reduction in power production.

4.1.4. Structural Components

Main Frame

The main frame is a complex rigid steel casting/weldment structure located between the nacelle and the yaw bearing. It supports mountings such as gearbox, generator, and brake and is responsible for maintaining their proper alignment. Predicting the RUL of the main frame requires a deep understanding of the principles of fatigue crack growth (FCG), including crack initiation, crack propagation, and rupture in welded and bolted joints. Fatigue crack failure, due to the combination of large and unstable crack propagation caused by extreme loading, is the main aging failure mode of the main frame structure. Like the tower and foundation, failure of the main frame during the lifetime extension phase of operation can result in significant economic loss and potential injury to technicians.

Tower and Foundation

Tower and foundation are among the most critical components of OWTs because their failure can result in the total collapse of the entire system. Fatigue cracks are the most common aging failure modes experienced by OWT towers and foundations. Additionally, OWT foundations suffer from scouring—a phenomenon where soil is eroded around the foundation by water currents—and corrosion. The life assessment of OWT tower and foundation structures can be conducted using either deterministic or probabilistic models. While conventional S-N curves are commonly used during the design phase to estimate the fatigue life of OWT structural components, they may be less suitable for the lifetime extension phase. The S-N fatigue damage assessment provides only a rough estimate of fatigue life and lacks a detailed view of the actual damage. In contrast, the fracture mechanics approach, which utilizes damage accumulation models like Fatigue Crack Growth (FCG), offers a more precise analysis by calculating and quantifying crack growth over time under cyclic stress. The FCG method has several advantages over the S-N approach, including its suitability for non-linear damage analysis. Additionally, it supports the scheduling of inspection, repair, and maintenance activities during the lifetime extension phase based on detailed damage information.

Recently, numerous studies have advocated for the use of FEA and fracture mechanics approaches to estimate the remaining fatigue life of OWT structural components for lifetime extension. Ziegler and Muskulus [96] analyzed the suitability of numerical fatigue assessment methods for extending the lifetime of a 5 MW OWT monopile foundation. They calculated the residual fatigue lifetime of the monopile under various environmental, structural, and operational conditions. Rubert [97], in his PhD thesis, presented a methodology for monitoring residual stresses in OWT foundation structures using optical sensor networks. This approach aims to minimize conservative design assumptions and support decision-making for OWT lifetime extension. Kazemi Amiri et al. [98] proposed an aeroelastic FEA model to assess the remaining fatigue life of OWT tower structures, accounting for stress concentration around the tower door and site-wide variations in wind characteristics.

Grieve et al. [99] proposed an aeroelastic model to estimate the operational loads on OWT tower structures using actual SCADA data and then compared these results to design loads. They utilized fatigue damage accumulation information to identify tower structures with the greatest potential for lifetime extension across a large wind farm. Mitchell et al. [100] proposed a probabilistic Bayesian network (BN) methodology and trained the algorithm with inputs from design codes and standards to recalculate the fatigue life of an OWT steel tower structure. The study concluded that applying the same partial safety factors in the fatigue reassessment as those used in the original design would result in overly conservative fatigue life estimations.

Geotechnical considerations play an important role in the lifetime extension of OWT foundations. The OWT foundations must withstand various environmental forces, including waves, currents, and wind loads, which can lead to significant stress and potential degradation over time. Moreover, the type of seabed soil and its properties, such as density, shear strength, and compressibility, are crucial factors that affect the performance and longevity of the OWT foundations. To effectively manage these issues during the lifetime extension phase, detailed geotechnical surveys and assessments are necessary. These should include the evaluation of current soil conditions, the extent of scouring, and the degree of corrosion or other degradation in the foundation material. Advanced geotechnical models and simulation tools can be employed to predict future changes in the soil-structure interaction and to design appropriate mitigation measures, such as scour protection systems or foundation reinforcement techniques. For further reading on the geotechnical considerations in assessing the lifetime extension of OWT foundations, readers can refer to reference [101].

4.2. Lifetime Extension Strategies for OWTs

Several strategies can be applied to extend the lifetime of OWTs, including retrofitting, reconditioning, remanufacturing, reusing, and reclaiming. The following subsections provide brief discussions of these key strategies.

4.2.1. Retrofitting

Retrofitting is a lifetime extension strategy aimed at enhancing the efficiency, capacity, and reliability of OWTs by integrating new systems and technologies. This approach not only addresses obsolescence issues but also improves the overall performance and reliability of the turbines. By upgrading outdated components, wind farm operators can significantly extend the operational lifetime of their OWTs, improve energy production efficiency, and reduce maintenance costs. The major retrofitting activities for OWTs include installing new components such as low voltage full power converters, upgrading control systems, and reconditioning the generator to facilitate variable speed operation. This approach enables old fixed-speed OWTs to operate at variable speeds during the lifetime extension phase of operation. Countries like the UK, Germany, Denmark, and the Netherlands are pioneers in the retrofitting of wind turbines. These nations have implemented retrofitting strategies to optimize the performance of aging wind turbines, aligning with advancements in technology and industry standards.

4.2.2. Reconditioning

Reconditioning is the process of restoring old OWTs to a satisfactory functional condition, albeit with performance outputs that may be lower than those specified by the Original Equipment Manufacturers (OEMs). This process involves thorough inspections, repairs, and replacements of worn-out or outdated components to ensure OWTs continue to operate efficiently. OWT subsystems that can be easily assembled and disassembled, such as gearboxes, generators, and control systems, are ideal candidates for reconditioning. These components can be restored to their original factory condition during the lifetime extension phase of operation, providing a cost-effective alternative to complete replacement.

By adopting reconditioning practices, wind farm operators can ensure their OWTs continue to generate power efficiently even as they age, thus maximizing their investment.

4.2.3. Remanufacturing

A remanufactured OWT is an old system that has been restored to OEM functional specifications by replacing all key components with high-quality parts. The warranty for a remanufactured OWT is equivalent to that of a new system. Remanufacturing OWTs offers several advantages, including cost and workload reduction and retained profit through lower production costs. Additionally, remanufacturing OWT components uses less material and energy, leading to significant carbon savings compared to manufacturing new OWTs. Remanufacturing has received increasing attention in recent years within the wind energy industry. Ortegón et al. [102] introduced remanufacturing as an attractive lifetime extension strategy for wind turbines. In another study, Dahane et al. [103] adopted a multi-agent approach to evaluate how remanufacturing old gearboxes can contribute to extending the operational life of OWTs.

4.2.4. Reusing

Reusing is a lifetime extension strategy that involves relocating old OWTs to a different site once they reach the end of their original design life without making modifications to their components. For instance, some components such as blades, generators, transformers, towers, and gearboxes are often reused by wind farm owners in regions with growing energy needs. This practice not only reduces costs but also promotes resource efficiency and sustainability by extending the functional life of OWT components [104]. Reusing can involve either full reuse of the entire OWT or partial reuse of specific components. Reports indicate that the costs associated with this approach are lower compared to reconditioning, remanufacturing, and retrofitting strategies [105].

4.2.5. Reclaiming

Reclaiming is a strategy that involves recovering, repurposing, or recycling components and materials from decommissioned OWTs. In this strategy, key OWT components, including blades, gearboxes, generators, transformers, and structural elements, are inspected and assessed for their condition. Usable materials such as metals (steel, aluminum, and copper) are recovered. Some components or materials may be directly reused in other turbines or repurposed for different industries or applications. For instance, composite materials from blades can be utilized in the construction industry [106]. In some cases, energy recovery methods are employed to extract and utilize the residual energy content from certain materials, contributing to overall energy efficiency. Reclaiming not only helps manage waste and conserve resources but also reduces the environmental footprint associated with OWTs. It supports a circular economy by ensuring that valuable materials and components are recovered, repurposed, or recycled, thereby extending their lifecycle and reducing the need for new manufacturing. This approach enhances the sustainability of offshore wind energy projects by minimizing waste, conserving resources, and lowering the demand for new raw materials.

Table 2 shows a summary of the life estimation processes, aging failure modes, and suitable lifetime extension strategies for OWT subsystems and components.

Table 2. A summary of life estimation processes, failure modes, and lifetime extension strategies for OWT subsystems and components.

Subsystem/Component	Life Estimation Process	Dominant Failure Modes	Potential Mitigation Actions	Lifetime Extension Strategy
Generator	Lifetime estimation often relies on statistical analysis of historical inspection and maintenance data.	Crack in rotor bar and breakage of rotor bar.	Regular inspection and maintenance.	Reconditioning, remanufacturing, and reuse.
Cables	Lifetime estimation often relies on low voltage time domain reflectometry tests, leakage current measurements, partial discharge measurements, and breakdown voltage tests.	Water treeing and aging insulation material.	Through diligent design and proper material selection.	Reuse, reclaiming.
Converter, filters and circuit breakers	Lifetime estimation often relies on statistical analysis of historical inspection and maintenance data.	Electrical faults, capacitor fire, wear and tear.	Inspecting capacitors for potential damage and breakers for signs of wear and tear.	Retrofitting, reuse.
Transformer	Lifetime estimation often relies on partial discharge tests, insulation resistance tests and visual inspections.	Degrading insulating material properties, contaminated oil.	Inspecting for partial discharge, dust accumulation in cooling channels, and checking for bent connection rods between taps and other connections, along with regular oil testing for contaminants.	Retrofitting, reuse.
Substation grid	Lifetime estimation often relies on statistical analysis of visual inspection data and laboratory testing.	Corrosion, wear, tear and obsolescence.	Regular inspection, maintenance and testing of various systems for possible defects.	Retrofitting, reconditioning.
Rotor (Hub)	Lifetime estimation often relies on revisiting design phase load models and analyses, incorporating updated information.	Broken and/or loosely mounted bolts, corrosion fatigue of hub structure and material degradation.	Visual inspection for cracks and corrosion on the hub, supplemented by non-destructive testing (NDT) if necessary.	Reconditioning, remanufacturing.
Blades	The remaining fatigue life of the blades can be estimated using design phase load models updated with current information.	Cracks and delamination of the composite blades as a result of fatigue, leading-edge erosion.	Visual inspection and repair, supplemented by sensor monitoring, as an alternative solution.	Retrofitting, reuse, and reclaiming.
Gearbox	Lifetime estimation often relies on analyzing condition monitoring data obtained from sensors and inspections.	Damage to gear tooth and bearing through cracks.	Regular inspection for damaged parts for replacement.	Reconditioning, remanufacturing and reuse

Table 2. Cont.

Subsystem/Component	Life Estimation Process	Dominant Failure Modes	Potential Mitigation Actions	Lifetime Extension Strategy
Pitch control system	Lifetime estimation often relies on statistical analysis of historical inspection and maintenance data.	Cracked motor shaft, fractured gear teeth and cracked bearings.	Regular inspection and maintenance.	Reconditioning, remanufacturing, and reuse
Yaw system	Lifetime estimation of the yaw system is based on its functionality and the wear and tear of its parts. Assessment for functionality.	Crack in yaw drive shaft, damaged gear teeth, pitting of yaw bearing and worn out brake disc.	Regular inspection and maintenance.	Reconditioning, remanufacturing, and reuse
Sensors	Lifetime assessment of sensors is based on benchmarking their data against data from similar sensors	Sensors may fail or provide incorrect readings due to poor calibration.	Regular inspection for dust, dirt and moisture.	Retrofitting
Control and monitoring systems	Lifetime estimation of the control and monitoring software is based on expert judgment.	Aging-related faults, obsolescence	Regular update	Retrofitting
Main frame	The remaining fatigue life of the main frame can be estimated using crack growth models.	Fatigue crack.	Regular inspection and maintenance.	Reuse, reclaiming
Tower	The remaining fatigue life of the tower can be estimated using either S-N curves or crack growth models.	Fatigue crack.	Regular inspection and maintenance.	Reuse, reclaiming
Foundation	The remaining fatigue life of the foundation structures can be estimated using either S-N curves or crack growth models.	Fatigue crack, corrosion, and scour.	Regular inspection and maintenance.	Reuse, reclaiming

5. Lifetime Extension Decision-Making for OWTs

This section introduces a cross-disciplinary approach to assist the offshore wind energy industry in making informed decisions about extending the lifetime of OWTs. As shown in Figure 3, this approach combines inputs from technical safety, economic, environmental, and regulatory perspectives into a unified framework. It ensures that the return on investment (ROI) is optimized while also addressing crucial safety considerations during the lifetime extension phase of OWTs. The key tasks for each stage of the proposed approach are detailed in the following subsections.

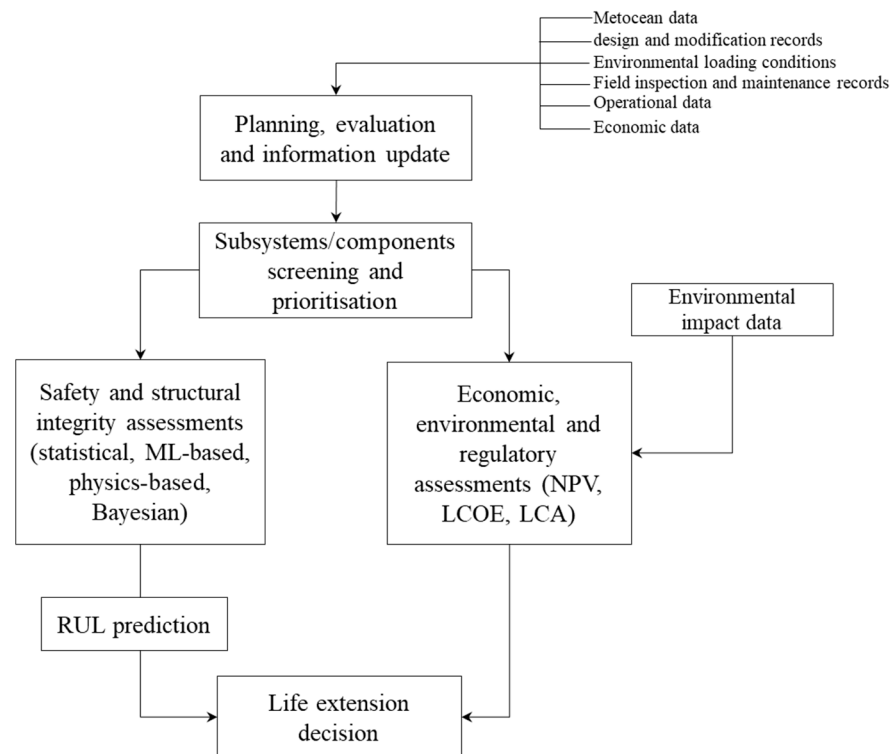


Figure 3. Lifetime extension decision-making for OWTs.

5.1. Planning, Evaluation and Information Update

Extending the operational life of OWTs beyond their original design life requires more comprehensive and detailed information than what was used during the design phase. To accurately assess the health status of OWT components and plan effectively for lifetime extension, it is crucial to update existing records with data collected throughout the wind farm's operational life. This includes metocean data, design and modification records, environmental loading conditions, field inspection and maintenance records, sensor data from monitoring devices, operational data, and economic data. Table 3 summarizes the different types of data needed to support decision-making for extending the operational life of OWTs.

Table 3. Summary of the various types of data required for analyzing the lifetime extension of OWTs.

Type of Data	Required Information	Source of Data
Metocean data (post design and installation)	Wind speed Wind direction Wave conditions Current Sea conditions Atmospheric conditions	Sensors such as anemometers, Light Detection and Ranging (LIDAR) systems
Design and modification records	OWT design criteria Design specifications for various OWT components CAD drawings Design life models Material specifications Engineering modifications Design regulations, standards and guidelines	Designers, OEMs, design codes, bill of materials, standard documents

Table 3. Cont.

Type of Data	Required Information	Source of Data
Environmental loading data	Vibration Sea loading Seismic effects	Sensors such as accelerometers, strain gauges, motion sensors
Field inspection and maintenance data	Reliability levels Maintenance data Conditioning monitoring data	SCADA, maintenance records, condition monitoring systems
Operational data	Turbine's availability Electricity production Turbine's capacity factor	SCADA, operational data
Economic data	Cost of modification Cost of installation Cost of operations and maintenance Taxes Revenue accruing from sale of electricity Delayed decommission cost	Suppliers, maintenance providers, electricity market, Trade tariffs

5.2. Subsystems/Components Screening and Prioritisation

As OWTs consist of numerous subsystems and components, assessing and upgrading all parts of an OWT in a wind farm for lifetime extension is expensive, laborious, and challenging. Therefore, technical, financial, and material resources must be allocated to components whose failure could result in loss of life, significant property damage, environmental damage, or extended downtimes. Analytical tools such as Cause-Consequence Analysis (CCA), checklist analysis, Event Tree Analysis (ETA), Fault Tree Analysis (FTA), HAZard and OPERability analysis (HAZOP), Failure Mode and Effects Analysis (FMEA), and what-if analysis are suitable for screening and prioritizing critical components of OWTs for lifetime extension analysis.

The use of artificial intelligence (AI) and machine learning (ML) algorithms for identifying OWT components suitable for lifetime extension has gained significant momentum in recent years. Some of the key ML techniques employed in this context include [107]:

Classification: This technique is used to categorize OWT components based on their condition and predict whether they are suitable for lifetime extension. By training models on historical data, classification algorithms can effectively distinguish between healthy and deteriorating components.

Clustering: This technique groups similar components or operational conditions together, enabling the identification of patterns and common factors that may affect the lifetime of OWT components. This can help to understand the underlying reasons for component failures and optimize maintenance schedules.

Regression: This technique is used to predict the RUL of components based on various operational and environmental factors. By modeling the relationship between these factors and the degradation of components, regression algorithms can provide accurate estimates of OWT reliability.

Time series analysis: This technique involves analyzing temporal data to understand trends, seasonal effects, and long-term patterns in the performance and condition of OWT components. Time series analysis can help to forecast future maintenance needs and plan for lifetime extension activities.

Yeter et al. [108] reviewed the use of big data analytics, advanced signal processing techniques, and supervised and unsupervised machine learning methods in the risk-informed lifetime extension management of OWT support structures. In another study, Yeter et al. [109] used an unsupervised k-means clustering algorithm to identify and evaluate fixed-bottom OWTs across a wind farm for the purpose of lifetime extension. This study combined structural integrity assessment, considering corrosion crack growth,

with economic analysis, accounting for the likelihood of estimated returns, to analyze the feasibility of OWT lifetime extension.

5.3. Safety and Structural Integrity Assessments

This stage of the decision model focuses on safety and technical integrity issues related to the lifetime extension of OWTs. The objective is to develop a component-level model that analyzes the degradation of OWT components and evaluates their safety and performance during the extended operational phase. Tartt et al. [110] provided a comprehensive review of the lifetime extension practices for OWT drivetrain components. In real-world applications, OWT components often suffer from multiple failure mechanisms associated with a particular aging failure mode. Therefore, it is essential to identify all failure mechanisms linked to a given failure mode and analyze the safety based on all these factors. The safety assessment and structural integrity analysis models can be either deterministic or probabilistic. Deterministic approaches focus on identifying various aging failure modes and their underlying causes. On the other hand, probabilistic approaches estimate the RUL of components or systems, incorporating the inherent uncertainties in material properties, operational conditions, and environmental factors. Probabilistic models offer a more comprehensive risk assessment by quantifying the likelihood of different failure scenarios, thus enabling more informed decision-making regarding lifetime extension. Various probabilistic models can be applied to estimate the RUL of OWT components, including:

Statistical models: These models use historical data to predict future performance and estimate the likelihood of failure during the OWT lifetime extension phase.

ML-based models: ML models analyze large datasets to identify patterns and predict degradation trends during the OWT lifetime extension phase.

Physics-based models: These models use physical laws and principles to simulate the behavior and degradation of OWT components over an extended lifetime.

Bayesian models: Bayesian approaches combine prior knowledge with new data to update the RUL estimates of OWT components. To review the state-of-the-art Bayesian models in wind energy, readers can refer to reference [111].

In addition to operational conditions, environmental conditions play a crucial role in the RUL assessment of OWTs. To calculate loads and stresses during the lifetime extension period, it is essential to gather comprehensive environmental condition data, including average wind speeds, turbulence intensities, and extreme wind events [112]. If complete data for the entire period is not available, long-term extrapolation may be performed using other relevant data sets to ensure accurate assessments. Guo et al. [113] provided a case study on predicting the RUL of OWTs in a wind farm in South China to aid in the development of lifetime extension or decommissioning strategies. They gathered the environment data of the OWT met mast and estimated the fatigue loads on the OWT based on both the design load conditions and site-specific load conditions.

Additionally, in the case of a wind farm, *wake effects* must be considered in the structural integrity assessment of OWTs. Wake effects, caused by the turbulence generated by upstream turbines, can significantly impact the loading conditions on downstream turbines, leading to increased fatigue and potential degradation of components. Properly accounting for both environmental and operational factors is vital for effective lifetime extension strategies. In a research study, He et al. [114] studied the effects of various wake conditions, including both full wakes and partial wakes, on the remaining fatigue life of OWTs.

5.4. Economic, Environmental and Regulatory Assessments

Although technical assessment is a critical requirement for lifetime extension certification, the economic, environmental, and regulatory impacts of OWT lifetime extension projects must not be ignored. The economic assessment accounts for the total investment cost required to implement the OWT lifetime extension project. To evaluate the economic

viability of OWT lifetime extension projects, the net-present value (NPV) approach is often used. NPV calculations consider the projected costs and benefits over the extended operational period, discounting future cash flows to their present value. This method helps determine whether the expected returns justify the investment in extending the OWT's lifetime. A major indicator for the economic viability of OWT lifetime extension projects is the levelized cost of electricity (LCOE). The LCOE represents the average cost per unit of electricity generated over the lifetime of the OWT, including all capital, operational, and maintenance costs. By calculating the LCOE, wind farm managers can assess whether extending the OWT's lifetime will result in cost-competitive electricity production compared to alternative EOL strategies such as repowering or decommissioning.

In a research study, Rubert et al. [115] analyzed the LCOE for a wind farm consisting of six 900 kW wind turbines operating beyond their design lifetime to support economic lifetime extension decision-making. Their results indicated that extending the lifetime of the wind turbines could reduce the LCOE by 4.9% for a 5-year extension, 7.7% for a 10-year extension, and 9.3% for a 15-year extension. In two other research studies, Yeter and Garbatov [116] and Yeter et al. [117] utilized Markowitz's modern portfolio theory, adapted from finance, to assess the economic added value of extending the lifetime of OWTs by evaluating the increased returns from the overall wind farm assets and the reduced risks associated with continued operation. They developed a multi-dimensional optimization model, incorporating a detailed structural integrity analysis, free cash flow analysis, probability of project failure, and both local and global economic constraints to manage the lifetime extension process for OWTs.

In addition to economic factors, the environmental impact of extending the operational lifetime of OWTs must be carefully considered. This assessment should include evaluating the potential benefits associated with reduced resource consumption and waste generation compared to alternative EOL strategies such as repowering or decommissioning. Extending the operational lifetime of OWTs can reduce the overall environmental footprint associated with the manufacturing and installation of new turbines. However, it is also crucial to evaluate any potential negative impacts of prolonging the OWTs' presence in the marine environment. This includes assessing how the extended operation may affect local ecosystems, such as marine wildlife and habitats. Environmental assessments should also explore potential issues such as changes in marine biodiversity, effects on fish populations, and alterations to seabed conditions caused by the ongoing presence of the OWTs. For this purpose, Life Cycle Assessment (LCA) methods can be particularly useful. LCA provides a comprehensive evaluation of the environmental impacts associated with all stages of the OWTs' lifecycle, from construction and installation through to operation, maintenance, and lifetime extension. By employing LCA, wind farm managers can make more informed decisions about whether to extend the operational lifetime of OWTs or pursue alternative EOL strategies.

Regulatory considerations are equally important. Extending the lifetime of OWTs may require compliance with updated standards and regulations, which could involve modifications to existing infrastructure or additional inspections and certifications. It is crucial to stay informed about regulatory changes and ensure that all aspects of the OWT lifetime extension project adhere to current legal requirements. By incorporating the economic, environmental, and regulatory factors into the OWT lifetime extension decision-making process, the offshore wind energy industry can develop more robust and sustainable solutions.

5.5. Life Extension Decision Making

This stage involves making lifetime extension decisions for future operations based on the safety and technical life assessments as well as the outcomes of the economic, environmental, and regulatory analyses. The decision may include decommissioning the entire wind farm, repowering the OWTs, or remanufacturing and retrofitting the OWTs for safe and continuous operation. Choosing among these options involves a complex evaluation

process that considers various factors. The use of MCDM methods can be particularly beneficial in this context. MCDM is a powerful tool that allows decision-makers to evaluate various options by considering multiple criteria simultaneously, which is particularly useful in complex and multifaceted decision-making processes. MCDM techniques help wind farm managers systematically compare different EOL strategies by assessing them against a set of predefined criteria. Boyd et al. [118] provided a comprehensive set of criteria worth considering when deciding the most suitable solution for extending the lifetime of OWTs. These criteria include economic factors (such as costs and financial returns), technical considerations (such as the condition and performance of wind turbines), environmental impacts (such as carbon footprint and ecological effects), and regulatory compliance.

Another tool that can be highly beneficial for the lifetime extension of OWTs is a Decision Support System (DSS). A DSS is an advanced, multifaceted tool designed to aid wind farm managers in evaluating and selecting the most effective strategies for extending the operational lifetime of OWTs. This system integrates a diverse array of data sources, analytical techniques, and decision-making frameworks to provide a holistic approach to managing the complexities involved in OWT lifetime extension decision-making. One of the key advantages of a DSS is its ability to evaluate different scenarios and strategies under varying conditions. For instance, it can simulate the impact of different maintenance schedules, upgrades, or environmental conditions on the OWT's performance and lifetime. Recently, some DSS tools have been developed to enhance the EOL management of OWTs. These tools aim to address the complex challenges associated with decommissioning, re-powering, or lifetime extension of OWTs, providing valuable support for making informed and strategic decisions. As an example, DecomTools [119] is an initiative under the Interreg North Sea Region Programme that focuses on developing and implementing tools and strategies for the decommissioning of OWTs.

6. Opportunities

The lifetime extension of OWTs presents several business and research opportunities in the wind energy industry. This section briefly discusses these opportunities, highlighting how extending the operational lifetime of OWTs can benefit the industry.

6.1. Business Opportunities

The business opportunities of lifetime extension for OWTs are diverse and significant, offering various avenues for growth and innovation within the wind energy industry. Some of these opportunities are reviewed below:

Lifetime extension consultancy: Consultants can support the wind energy industry by developing comprehensive lifetime extension plans, including cost-benefit analyses, risk assessments, and tailored maintenance schedules.

Technological innovations: Companies can invest in the development of innovative technologies for the lifetime extension of OWTs. For example, advanced materials that enhance the durability and performance of OWT components can significantly extend their operational life.

Retrofitting and remanufacturing services: Businesses can specialize in retrofitting and remanufacturing older OWTs with new, more efficient components, such as advanced blades, gearboxes, and control systems.

Decommissioning and recycling services: Businesses can offer phased decommissioning services that allow for the systematic replacement of OWTs while maximizing the use of existing assets. Businesses can also develop specialized recycling services for OWT components, focusing on environmentally friendly disposal and repurposing of materials.

Predictive maintenance services: Companies can offer advanced predictive maintenance services, using data analytics and AI to predict and prevent failures, ensuring OWTs remain operational for longer periods.

Safety audits: Businesses can provide detailed assessments of OWT safety and structural integrity, advising on whether lifetime extension is safe and feasible.

Environmental and sustainability audits: Companies can offer services to audit and enhance the environmental conditions and sustainability practices associated with the lifetime extension of OWTs.

Legal services: Helping offshore wind farms navigate and comply with evolving regulations related to the extended operation of OWTs can be a valuable service.

Financial and insurance services: Financial institutions can create investment opportunities that fund OWT lifetime extension projects, offering attractive returns based on the extended revenue generation from older OWTs. Additionally, insurance companies can develop extended warranty contracts specifically tailored to cover the risks associated with operating OWTs beyond their design lifetime.

Training development: Companies can develop training program for technicians and engineers to improve the skills required for remanufacturing and retrofitting OWTs.

Certification services: Offering certification services for professionals in remanufacturing and retrofitting OWTs can create a niche market.

6.2. Research Opportunities

Lifetime extension of OWTs offers numerous research and development (R&D) opportunities in the wind energy industry. These opportunities focus on enhancing the reliability, durability, and safety of OWT components, as well as improving the overall energy efficiency of wind farms. Some important R&D opportunities include:

Collaboration with universities and research institutions: Businesses can partner with universities and research institutions to innovate and develop new technologies that support OWT lifetime extension. Conducting pilot projects to test and validate new lifetime extension technologies and methodologies can provide a competitive edge.

Advanced composite materials and new coatings: New composite materials can be developed for OWT blades and other components to enhance resistance to fatigue, corrosion, and environmental wear. Additionally, advanced coatings that protect against harsh marine environments can be researched to reduce corrosion and extend the lifespan of metallic and composite OWT components.

Structural Health Monitoring: New sensors can be developed for real-time monitoring of OWT components, including strain gauges, vibration sensors, and acoustic emission sensors. Efficient algorithms and user-friendly software are also needed to analyze the data collected from these sensors, predict potential failures, and optimize maintenance schedules during the extended lifetime.

Condition assessment technologies: Advanced NDT methods, such as ultrasonic testing, thermography, and radiography, can be developed to detect internal defects and assess the structural integrity of OWTs at the end of their design life. Additionally, the use of drones equipped with high-resolution cameras and sensors will enhance the efficiency and safety of inspecting OWT blades and towers.

Automated repair techniques: Automated systems can be developed for onsite repairs and upgrades, such as automated blade repair technologies. Additionally, robotic systems capable of performing maintenance tasks on OWTs at the end of their design life will reduce the need for human intervention and enhance safety.

Optimized energy production: New methods can be developed to improve the efficiency of older OWTs, such as optimizing blade aerodynamics or updating control systems to enhance energy capture. Additionally, advanced load management systems can be designed to reduce wear and tear on components, thereby improving the overall lifespan and performance of the OWTs.

Lifetime extension technologies: New technologies and methodologies can be developed for retrofitting and remanufacturing various OWT components.

Analytical tools: Predictive models can be developed to assess future performance and degradation of OWT components based on historical data and real-time monitoring. Additionally, simulation tools will be valuable for modeling and predicting the impacts of various operational and environmental factors on OWT lifetime. Combining both

deterministic and probabilistic approaches can lead to a robust and holistic assessment of safety and structural integrity, ensuring optimal performance and reliability during the extended operational phase.

Regulatory frameworks: New frameworks and standards can be designed to support the safe and efficient extension of OWT lifespans while ensuring compliance with evolving regulations.

The above-listed business and research opportunities not only contribute to extending the operational lifetime of OWTs but also drive innovation in the wind energy industry, improving sustainability, efficiency, and safety across the sector.

7. Conclusions

The high initial capital cost of constructing new offshore wind farms, compared to the ongoing operation and maintenance (O&M) expenses, has created significant interest in extending the operational licenses of OWTs beyond their original design life of 20–30 years. To secure these extensions, wind farm owners must demonstrate that their assets can maintain safety and structural integrity throughout the extended operational period. However, extending the operational lifetime of OWTs presents a variety of challenges that must be carefully addressed. To effectively manage these challenges, the wind energy industry can draw valuable lessons from other sectors with extensive experience in lifetime extension. This paper presented insights gained from these industries and explored how these lessons can be applied to the wind energy sector's lifetime extension efforts. Additionally, it outlined the specific challenges that the wind energy industry is likely to face during the lifetime extension phase.

The paper delved into the processes of lifetime estimation, the various aging failure modes, and the appropriate strategies for extending the life of different OWT subsystems and components. Based on the challenges identified, a decision-making framework was proposed to support the lifetime extension of OWTs. This framework serves as a crucial tool for evaluating and qualifying OWT subsystems and components for extended operations. It incorporates safety and structural health assessments, as well as economic, environmental, and regulatory considerations. Furthermore, the paper identified opportunities that lifetime extension efforts can leverage to enhance the reliability, durability, and safety of OWT systems while also improving the overall energy efficiency of wind farms. From a technical standpoint, there is significant potential for technological innovation and enhancement. Economically and socially, expanding the OWT remanufacturing market could create new job opportunities. Finally, the paper emphasized the importance of continued research into lifetime extension within the wind energy industry to deepen the knowledge base of stakeholders and drive further advancements in the field. Addressing the challenges associated with extending the lifetime of OWTs requires a coordinated and comprehensive approach involving collaboration among various stakeholders, including engineers, researchers, policymakers, and industry leaders. Effective communication with stakeholders and transparent decision-making processes are essential to ensuring that efforts are well-integrated, efficient, and widely supported.

Funding: This research received no external funding.

Conflicts of Interest: The author declares no conflict of interest.

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