Operations and Maintenance of Floating Wind: A Holistic Approach Review, Modelling, and Opportunistic Maintenance Strategies

Jade McMorland

A thesis submitted for the degree of Doctor of Philosophy

Wind and Marine Energy Systems Centre for Doctoral Training Department of Electronic and Electrical Engineering

University of Strathclyde

2024

This thesis is the result of the author's original research. It has been composed by the author and has not been previously submitted for examination which has led to the award of a degree.

Signed: Jade McMorland

Date: August 2024

Abstract

Climate change is a pressing global issue caused by increasing greenhouse gas emissions, primarily from the burning of fossil fuels for energy generation. The deployment of renewable generation is essential to mitigate climate change as it offers a sustainable and clean alternative energy. Following the success of bottom fixed wind, developers are looking to deeper waters to expand current development.

This thesis delves into the complexities and challenges associated with the operation and maintenance of floating offshore wind farms. The research explores the unique hurdles presented by harnessing wind energy in deeper waters, such as increased distance to shore and uncharted areas. Floating wind sites also introduce specific operational challenges due to the motion of the turbine which has a significant impact on the way in which offshore sites are both operated and maintained.

This work consists of three distinct parts: identifying challenges, quantifying their impact, and proposing potential mitigating strategies. Through analysis and modelling of operational expenditure, the study identifies key challenges faced during the maintenance of floating wind farms, with a focus on technology-specific issues arising from turbine motion.

Based on a review of current technology, future markets of deployment, and current operational challenges: location, scale, design convergence and turbine motion are identified as the key areas which are set to have a significant impact on the operation of future floating offshore sites.

After identifying the challenges, their impact on the operational phase of the project is quantified. Through the use of offshore wind key performance indicators, the accessibility and total operational expenditure are determined for floating wind against an equivalent bottom fixed wind site. This then has a potentially significant impact on lost revenue which increases total cost. The increase in lost revenue is a result of reduced access due to additional restrictions placed on accessible conditions during specific turbine motion.

Additionally, the thesis quantifies the operational impact of these challenges and explores potential maintenance strategies to reduce OPEX, including the concept of opportunistic maintenance. The study introduces the OM+ framework, which identifies market-based opportunities for maintenance, aiming to enhance cost-effectiveness and efficiency.

The thesis concludes with a comprehensive summary of the research findings and recommendations for future work, contributing to a sustainable and reliable renewable energy solution for the global energy landscape.

Dedication

This thesis is dedicated to the **McMorlands**. None of you will ever read this, but all of you made it possible - “You raise me up to walk on stormy seas”.

Acknowledgements

A Special thank you goes to my supervisors for their support and guidance over the past four years, Dr Maurizio Collu, Dr David McMillan, Dr Andrea Coraddu, and Dr James Carroll. I express gratitude to Maurizio for letting me explore all avenues, and "reigning" my ideas in when needed. Thanks to David for supervising my first ever research project which led me to become enchanted by both research and offshore wind O&M. Thanks to Andrea and James for always sharing ideas, your contributions have been invaluable.

I would like to acknowledge EPSEC for funding the work completed within this thesis through the Wind and Marine Energy Systems Centre for Doctoral Training (EP/S023801/1,). I am extremely thankful to everyone involved in the running of the CDT, in particular Drew Smith and Lynn O'Brien, for their help especially.

Thanks to everyone I've had the pleasure of collaborating over the past 4 years, especially Peter Jamieson and Sally Lockwood.

Thanks to my wonderful CDT support system: Victoria, Laurie, Euan, Rui, Callum, and the wider CDT community. Thank you for sharing the ups and (more importantly) the downs. I already miss seeing you all every day.

Thanks to my mum and dad for always encouraging me, both throughout this and in everything else.

Finally, thanks to my (almost) husband, David. Thank you for everything, always.

Contents

Table of Figures

Table of Tables

Abbreviations

AHTS	Anchor Handling Tug Supply
BFW	Bottom Fixed Wind
CapEx	Capital Expenditure
CBM	Condition-Based Maintenance
CfD	Contract for Difference
CM	corrective maintenance
CoE	Cost of Energy
CTV	Crew Transfer Vessel
DecEx	Decommissioning Expenditure
DLC	Design Load Case
FID	Financial Investment Decision
FOW	Floating Offshore Wind
HLV	Heavy Lift Vessel
Hs	Significant Wave Height
JUV	Jack Up Vessel
KPI	Key Performance Indicator
LCoE	Levelized Cost of Energy
MCR	Major Component Replacement
O&M	Operation and Maintenance
OM	Opportunistic Maintenance
OpEx	Operational Expenditure
PM	Preventive Maintenance
PrM	Predictive Maintenance
RAO	Response Amplitude Operator
RUL	Remaining useful life
SFV	Specialist Field Vessel
SOV	Service Operations Vessel
T2S	Tow to Shore
TBA	Time Based Accessibility
TLP	Tension Leg Platform
Tp	Peak Wave Period
TRL	Technology Readiness Level
TT	Travel Time
TTR	Time to repair
WACC	Weighted Average Cost of Capital
WI	Workability Index
WW	Weather Window
WW_L	Available Weather Window at any given time
WW_R	Required Weather Window

Chapter 1 : Thesis Introduction

This Chapter introduces the research topic and motivation as well as an overview of the thesis structure and details of each chapter.

The deployment of floating offshore wind (FOW) introduces several technical challenges throughout the whole project lifecycle from design to decommissioning. This thesis aims to identify operational challenges, quantify their impact, and explore potential mitigating strategies to reduce operational expenditure (OpEx), and the overall cost of energy to contribute towards a generation mix of clean, secure, and affordable energy. An overview of this Chapter is provided in Figure 1.1.

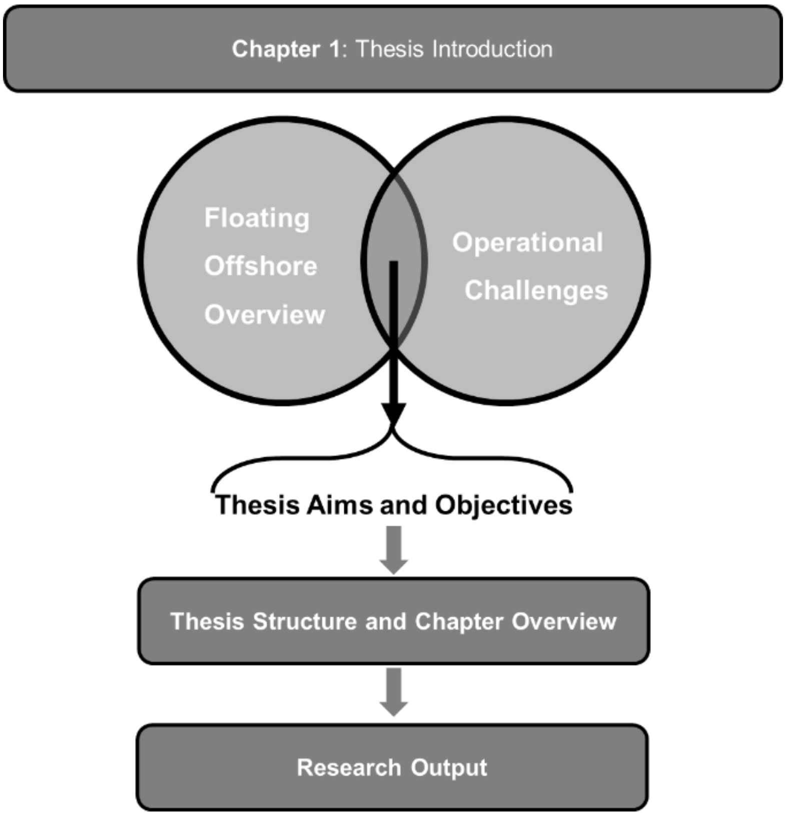


Figure 1.1 Chapter 1 overview and summary

1.1. Background

The past decade has seen an uptake of renewables due to the commitment of the EU to global climate action under the Paris Agreement [1]. The UK government set its own target with a commitment to Net-Zero by 2050 [2], and the Scottish Government set an even more ambitious deadline of 2045 [3]. One of the driving forces behind these targets is the success of offshore wind within UK waters. The UK's offshore wind capacity has more than quadrupled from 2010 to 2020 (5.4 GW - 29.1GW) [4]. The advancement of offshore wind is much greater than previously imagined, with the UK government awarding 5.5 GW of new offshore wind in the 2019 Contract for Difference (CfD) auction at a record low delivery price of £39.65/MWh (in 2012 prices) – below the current wholesale market price for electricity and thus ensuring offshore wind within the UK can be delivered unsubsidised. The technology continues to see cost reduction, with the 2022 CfD auction seeing a secured strike price of £37.35/MWh for future bottom fixed wind (BFW) developments.

Recent auctions such allocation Round 5 have highlighted the strain on price reduction, where 3.7 GWs of renewables were granted. Among the 95 newly approved projects are those focused on onshore wind, solar power, and tidal energy, with no allocation for offshore wind [5]. The challenges faced by projects in this round are, in part, attributed to the worldwide increase in inflation, and its repercussions on supply chains. Similar outcomes have been observed in other countries such as Germany and Spain [6] [7].

However, the offshore wind industry faces a new set of challenges. Water depth and increasing distances to shore add an additional complexity to current operational sites which have proven to be not only economically viable but also profitable. Therefore, extensive work is required to maintain the energy trilemma of secure, green, and affordable energy.

Due to the deployment of BFW, many of the remaining offshore sites are now within depths unsuitable for BFW (>60m), making FOW one of the only viable options. However, the industry lacks experience with FOW technology, with only 73MW operational installed capacity globally (2020). It is estimated that up to 70 GW of FOW could be operational by 2040 [5]. Recent estimates of FOW global capacity have been accelerated by the recent results of floating wind leasing rounds in the US, Asia, and the UK. The historic ScotWind leasing round (2022), saw almost 30 GW of offshore wind capacity being granted, split amongst 20 projects, of which 14 will include floating wind [6].

Floating support structures for offshore wind turbines enable the utilization of previously untapped offshore wind resources, as approximately 60% to 80% of ocean areas are inaccessible to bottom-fixed structures limited to shallow water depths of up to 60 m [7]. With significant advancements in technology readiness over the past decade, floating offshore wind technology is maturing, as indicated by WindEurope's floating offshore wind vision statement [8]. Extensive research studies, projects, and prototype developments have contributed to the emergence of numerous technology concepts and planned future developments [9].

1.2. Operation and Maintenance Challenges

O&M for offshore wind refers to the ongoing activities and tasks required to operate and manage offshore wind farms, including the monitoring, control, and optimization of wind turbine performance, as well as maintenance activities such as inspections, repairs, and component replacements to ensure the reliable, efficient, and safe operation of the wind farm over its lifespan. These efforts aim to maximize energy production, minimize downtime, and ensure the safety and longevity of the offshore wind infrastructure.

Floating wind will allow areas with previously untapped resource to be utilised in the fight against climate change. FOW has the advantage of being able to learn from the growth of BFW technology. With technology and supply chain development there is a clear and credible trajectory to delivering commercial FOW sites [10]. However, the introduction of FOW into the offshore energy mix also introduces additional challenges. The water depth at floating wind sites exceeds the limits of conventional vessels for major component replacement (MCR) [11], and therefore alternative methods, such as tow to shore (T2S) , must be explored [12]. The motion of the turbine will impact all aspects of O&M, from major component replacement to minor/major repairs and scheduled maintenance activities. Due to the platform's motion, access and the availability of safe working conditions on the structure are expected to be reduced [13] [14] [15]. In addition to these FOW technology-specific challenges, logistical problems, such as the increase in the distance to the shore and the harsher environment, are key areas of concern from an O&M perspective.

O&M can account for up to a third of the total cost of energy (CoE) for a BFW site [16], making it a key area for cost reduction. However, based on the challenges highlighted above, early estimates show that the OpEx contribution to total CoE for FOW is expected to be up to 40% [17].

Due to the risk involved with the development of new technology, it is important for cost-effective and accurate OpEx predictions. Understanding OpEx and understanding the operational requirements for the successful operation of FOW is crucial for driving the economic viability and long-term success of FOW farms.

The primary aims of this thesis are to investigate and address the operational and maintenance challenges specific to floating offshore wind farms.

1.3. Aims and Objectives

Floating offshore wind is a relatively new and rapidly evolving technology. Understanding its operational and maintenance aspects is crucial for maximizing its potential as a renewable energy source and addressing the unique challenges it presents. O&M directly impact the sustainability and reliability of floating wind farms. Effective maintenance strategies can ensure consistent energy production and prolonged lifespan, contributing to a more stable and sustainable energy generation system. With the increasing interest and investment in floating offshore wind projects, the industry is seeking innovative solutions for efficient and cost-effective maintenance practices.

This thesis aims to offer valuable insights and practical recommendations for industry and policymakers.

To achieve the primary aim of understanding the potential OpEx implications of a FOW site and methods for mitigation, the thesis has the following three key objectives:

1) To **review the current challenges** associated with floating offshore wind technology and identify the key areas which will have a direct impact on OpEx

2) Model and quantify the impact of FOW-specific challenges on offshore wind operational key performance indicators (KPIs) such as accessibility and OpEx

3) Highlight potential **mitigation strategies** to reduce OpEx for floating wind, through a review of maintenance strategies and case studies illustrating potential savings.

1.4. Thesis Structure

This thesis consists of seven chapters, including this introductory chapter. Each chapter contains an introductory abstract with a graphical overview of the contents. The thesis structure and the link between Chapters are outlined in Figure 1.2.

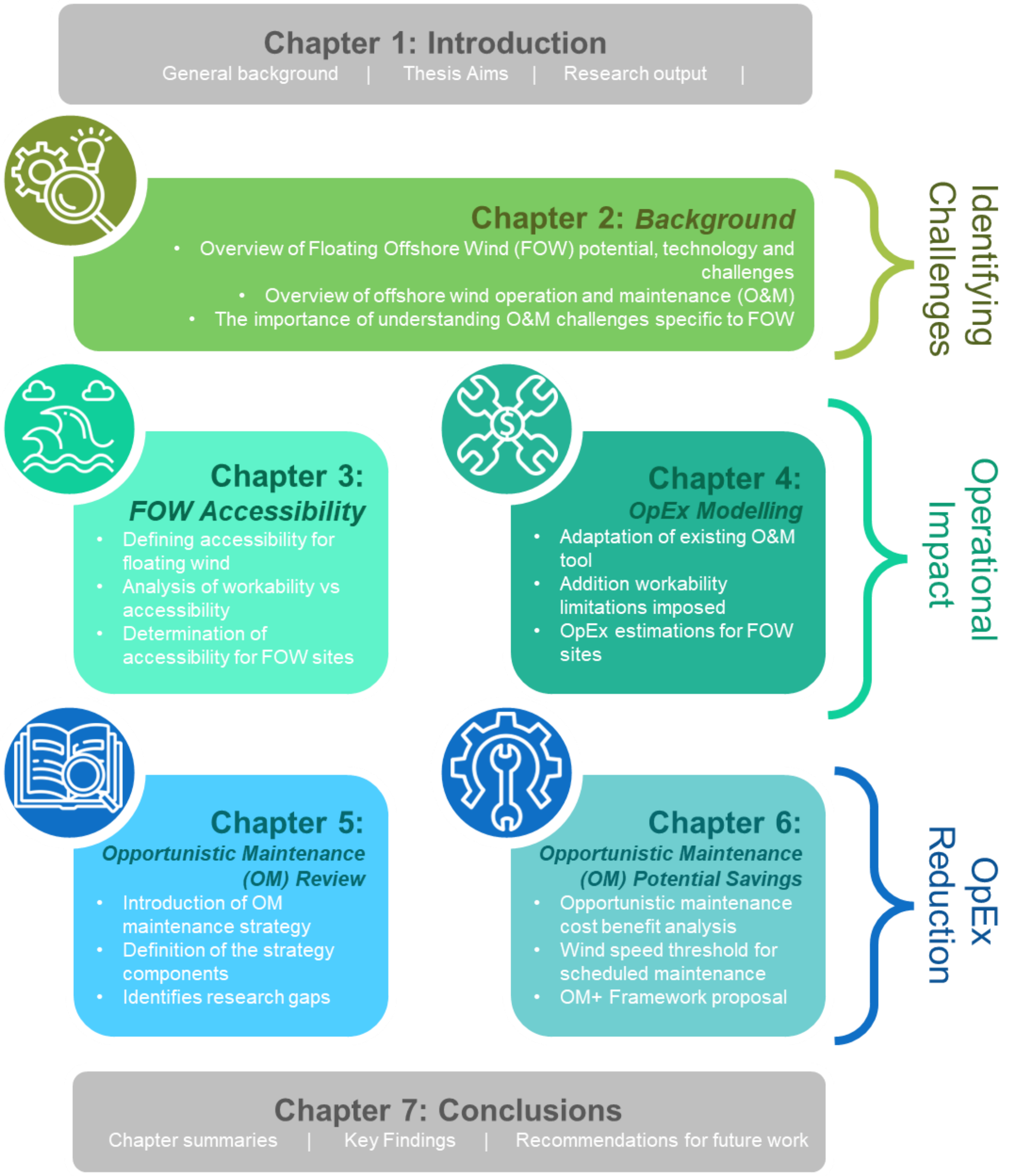


Figure 1.2. Thesis Structure and overview

Chapter 2 of the thesis delves into the complexities surrounding floating wind technology and investigates the challenges it presents. The chapter starts by exploring the unique hurdles associated with harnessing wind energy in deeper waters, highlighting factors like increased distance to shore and exploring uncharted areas. Subsequently, the focus shifts to OpEx modelling for offshore wind, analysing the costs involved in running and maintaining floating wind farms. Through detailed research and analysis, the chapter identifies the key challenges faced during the operation and maintenance of floating offshore wind farms, with a particular emphasis on addressing the technology-specific issues arising from the motion of the turbines. By examining these challenges, the chapter aims to contribute to a comprehensive understanding of the feasibility and sustainability of floating wind as a viable renewable energy solution.

Chapters 3 and 4 aim to quantify the operational impact of the challenges identified in Chapter 2. In Chapter 3, the thesis concentrates on the critical challenges posed by the distance to shore, water depth, and turbine motion in the context of floating offshore wind farms. The chapter introduces the concept of workability, emphasizing its importance in ensuring a safe and efficient operating environment. To assess the impact of accessibility on technicians' safety and the overall maintenance process, the chapter develops an accessibility and weather window model. By analysing these factors, the chapter aims to provide valuable insights into optimizing operational procedures and enhancing safety measures, ultimately contributing to the effective management and maintenance of floating wind farms.

Chapter 4 aims to quantify the outcomes from Chapter 3 by assessing their implications on OpEx in the context of FOW. The main emphasis lies in exploring the impact of additional weather limitations, identified as significant challenges in the previous chapter. The chapter starts with a comprehensive literature review, examining existing OpEx models for FOW, and subsequently adapts the Strathclyde-OW O&M model [19] specifically for daily maintenance operations in floating wind farms. By utilizing this adapted model, the chapter aims to provide a robust framework for estimating operational costs, considering the influence of weather constraints, and enhancing the understanding of financial implications.

Chapters 5 and 6 explore potential maintenance strategies to reduce OpEx for future FOW developments. Previous chapters illustrate the requirement for cost-effective and flexible maintenance strategies to reduce OpEx. In Chapter 5, the thesis presents a comprehensive literature review focusing on the concept of opportunistic maintenance, OM. This review delves into the advantages and limitations of adopting opportunistic maintenance strategies, particularly in the context of floating offshore wind farms. The chapter explores how OM can offer benefits such as reduced operational costs, increased equipment reliability, and minimized downtime. Simultaneously, it critically analyses potential drawbacks and challenges associated with this approach. The review further evaluates the suitability of opportunistic maintenance for floating offshore wind.

In Chapter 6, the thesis offers context for the potential advantages of implementing an opportunistic maintenance strategy. The chapter begins by conducting a cost-benefit analysis, bridging the gap in the existing literature regarding the implications of spending additional time at sea for maintenance operations. It specifically examines the impact of introducing wind speed thresholds for scheduled maintenance, aiming to optimize maintenance scheduling while considering site accessibility due to weather. The chapter introduces the OM+ framework, which identifies market-based opportunities for maintenance, seeking to enhance cost-effectiveness and overall efficiency in maintenance activities. To demonstrate the potential effectiveness of the opportunistic approach, the chapter presents a detailed curtailment case study, highlighting the potential benefits of turning market constraints into maintenance opportunities and why FOW specifically would benefit from such a strategy.

Each Chapter contains a conclusion section which summarises the chapter output and makes recommendations for future work. In Chapter 7, the thesis provides a comprehensive summary of the key findings and contributions from each previous chapter. It highlights how each chapter addressed the initial aims and objectives set out at the beginning of the research, underscoring their collective impact on advancing the understanding of FOW maintenance challenges. Building upon these insights, the chapter concludes by presenting recommendations for future research, identifying areas where further investigation and development are needed.

1.5. Research Output and Novel Contribution

As part of the PhD, a number of publications have been generated. A list of the PhD research outputs relevant to this thesis, their contribution to knowledge and the thesis Chapter which they have contributed to within this work are detailed in Table 1.1.

.

Table 1.1. PhD publication contribution to knowledge

Publication	Chapter	Contribution to Knowledge
Accepted Journals		
McMorland, J., Collu, M., McMillan, D. and Carroll, J., 2022. Operation and maintenance for floating wind turbines: A review. Renewable and Sustainable Energy Reviews, 163, p.112499.	2, 4	• Overview of existing FOW O&M research • Highlighting research gaps including ○ Inclusion of workability limits ○ The requirement for more relevant case studies (location, scale, etc)
McMorland, J., Flannigan, C., Carroll, J., Collu, M., McMillan, D., Leithead, W. and Coraddu, A., 2022. A review of operations and maintenance modelling with considerations for novel wind turbine concepts. Renewable and Sustainable Energy Reviews, 165, p.112581.	2, 4	• Overview of state-of-the-art offshore wind research • Highlighting future market challenges including scale of development
McMorland, J., Collu, M., McMillan, D., Carroll, J. and Coraddu, A., 2023. Opportunistic Maintenance for Offshore Wind: A Review and Proposal of Future Framework. Renewable and Sustainable Energy Reviews, 184, p113571.	5, 6	• Overview of OM within an offshore wind context • Highlights literature gaps such as: ○ Lack of consideration of additional time at sea required. • Proposal of future framework to tackle future market conditions/concerns

Submitted Journals		
McMorland, J., Collu, M., McMillan, D., Carroll, J. and Corradu, A, 2023. The Impact of Limiting Sea States on Floating Offshore Wind Operation and Maintenance. Applied Oceans Research, [under review]	3, 4	• Identifying the impact of turbine motion on technicians' safety and the overall maintenance process • Development of weather window model with workability consideration • Adaptation of existing OpEx tool to quantify workability limits on OpEx. • Quantifying the impact of workability on project financing
Russel, A., **McMorland, J.,** Collu, M., McDonald, A., Thies, P., Keane, A., McMillan, D., Carroll, J. and Coraddu, A, The impact of LIDAR-assisted control on floating offshore wind operational expenditure. Applied Oceans Research, [under review]	4	• OpEx modelling for future FOW sites. • Highlights potential cost reduction in OpEx due to LIDAR controls resulting in reduced failure rates
McMorland, J., Kampolis, G., Carroll, J., Collu, M., McMillan, D., Hart, E. and Coraddu, A, 2023. Effective Use of Limited Access: A ScotWind Offshore Wind Case Study. Applied Oceans Research, [pending submission]	3, 6	• Development of weather window model • Introduced concept of "missed opportunities" within weather windows. • cost-benefit analysis, bridging the gap in the existing literature regarding the implications of spending additional time at sea for maintenance operations
Conference Papers		

Saeed, K., **McMorland, J.,** Collu, M., Coraddu, A., Carroll, J. and McMillan, D., 2022, November. Adaptations of offshore wind operation and maintenance models for floating wind. In Journal of Physics: Conference Series (Vol. 2362, No. 1, p. 012036). IOP Publishing.	3, 4	• development of waiting time weather window model • highlighting the importance of false inputs on accessibility requirements and predictions
Joseph, A., Gray, A**., McMorland, J**., Berkley, A. 2023.Weather Window Analysis for Offshore Renewable Energy Assets using Machine Learning Methodologies. EERA DeepWind, Trondheim. [under review]	3	• development of novel weather window model to predict weather window length and accessibility based on basic site inputs of average wave height, distance to shore and water depth
Academic Posters		
McMorland, J., Collu, M., McMillan, D., Carroll, J. and Coraddu, A. 2023., Turning Market Constraints into Offshore Wind Maintenance Opportunities. EPC	5, 6	• Identification of market constraints as opportunities of “free downtime” to perform maintenance actions. • Utilising downtime to increase uptime
McMorland, J., Collu, M., McMillan, D., Carroll, J. and Coraddu, A., 2022. Opportunistic maintenance for ScotWind Sites. Supergen ORE, Oxford.	5, 6	• Presents the concept of maintenance “missed opportunities” by analysing weather window length of ScotWind sites. • Weather window profiles across all ScotWind sites would allow for an OM strategy

McMorland, J., Collu, M., McMillan, D., Carroll, J. and Coraddu, A., 2022. A New Proposed Framework for Opportunistic Maintenance for Offshore Wind (OM+). WindEurope 2022, Bilbao.	5, 6	• Identification of maintenance opportunities of internal, external, or market-based • Proposal of future framework highlighting the current gap of "market-based maintenance"
McMorland, J.; Impact of Health and Safety on Offshore Wind Operations and Available Resource. 2021. Wind Europe Technology Workshop, Italy.	2, 3	• Overview of impact of health and safety limitations on offshore wind O&M operations including ○ Place of safety thresholds ○ Helicopter weather thresholds
McMorland, J., McMillan, D. and Carroll J. 2019. The Disruptive Potential for Service Operations Vessels (SOV) to Drastically Reduce Access-Based Operational Costs for Offshore Wind. WindEurope 2019, Copenhagen	3, 4	• Travel time is the main factor for determining most cost-effective vessel strategy.

The research presents several novel contributions aiming to advance the understanding of the challenges faced when operating and maintaining FOW sites. Firstly, the thesis explores the complexities and challenges specific to floating wind technology, considering factors like increased distance to shore and uncharted areas. This thesis provides better definition of existing challenges, as well as identification of new ones, based on a comprehensive literature review. By providing examination of these hurdles, the thesis fills a crucial knowledge gap and offers valuable insights into the feasibility and sustainability of floating wind as a viable renewable energy solution. While several reviews have been conducted on FOW future development, there has been limited work dedicated to the O&M phase of the project lifecycle. By analysing the potential challenges associated with the technology, this work aims to identify those which are expected to have the highest impact on O&M procedures.

Secondly this work aims to quantify and model the impact of these challenges highlighted through key performance indicators (KPIs) used within industry to assess the operational viability of future developments. While there has been work discussing the operational strategy and feasibility of future FOW farms, the focus area has been on the use of a tow to shore strategy, or alternative major component replacement techniques. As major repairs make up the minority of offshore wind failures [18], this work focuses on day-to-day maintenance actions. The operational impact of the challenges highlighted in the first section are quantified both in terms of accessibility and in terms of financial indicators such as OpEx.

Finally, based on the findings, opportunistic maintenance (OM), is introduced as a potential mitigating strategy to reduce OpEx. The work surrounding the development of OM simulations for offshore wind has grown significantly in recent years, however, there are several gaps within the literature. As of yet, this maintenance strategy has not yet been applied to a FOW scenario. This maintenance strategy has potential synergy with FOW due to the need to aim to reduce technician exposure to motion throughout the whole maintenance campaign.

The novel findings and methodologies presented in the thesis aim to contribute to FOW research and provide valuable guidance for industry stakeholders and policymakers. By defining the challenges, their impact, and potential strategies for cost saving, it is hoped that this research will highlight the importance of understanding, and giving high consideration, to the operational phase of future FOW projects, throughout the whole project lifecycle.

1.5.1. Other Research

Due to the scope of this thesis and the focus on floating wind maintenance operations, additional research outputs have been included as part of this thesis. A full list of additional research outputs and details of conference presentations completed throughout the period of PhD research are fully provided in *Appendix A.*

1.6. Chapter References

[1] J. Blau, “The Paris Agreement: Climate Change, Solidarity, and Human Rights,” Springer, 2017.

[2] Department for Energy Security and Net Zero and Department for Business, Energy and Industrial Strategy, “Energy White Paper: Powering Our Net Zero Future,” HM Government, 2020.

[3] Scottish Government, “Update to the Climate Change Plan 2018 - 2032: Securing a Green Recovery on the Path to Net Zero,” Scottish Government, 2020.

[4] Global Wind Council, “Global Offshore Wind: Annual Market Report 2020,” Global Offshore Wind Report, 2020.

[5] The Carbon Trust, “Phase II Report,” Floating Wind Joint Industry Project, 2020.

[6] Cown Estate Scotland, “ScotWind: List of Successful Partners,” Technical Report, 2022.

[7] R. James and M. Ros, “Floating Offshre Wind: Market and Technology Review,,” Carbon Trust, UK, 2015.

[8] WindEurope, “Floating Offshore Wind Vision Statement,” WindEurope, Brussels, 2017.

[9] Q FWE, “Floating Wind Project Maps,” Quest Floating Wind Energy, 2020. [Online]. Available: https://questfwe.com/map-download-contact-form/. [Accessed 6 February 2023].

[10] S. Bradley, “Floating Wind Technology,” Energy Technologies Insitute, 2015.

[11] D. Ahn, S. Shin, S. Kim, H. Kharoufi and H. Kim, “Comparative evaluation of different offshore wind turbine installation vessels for Korean west-south wind farm,” *International Journal of Naval Architecture and Ocean Engineering,* vol. 9, no. 1, pp. 45-54, 2017.

[12] I. Bayati, “Challenges and opportunities of major maintenance for floating offshore,” World Forum Offshore Wind, 2021.

[13] B. Jenkins, A. Prothero, M. Collu, J. Carroll, D. McMillan and A. McDonald, “Limiting wave conditions for the safe maintenance of floating wind turbines,” in *Journal of Physics: Conference Series (Vol. 2018, No. 1, p. 012023)*.

[14] S. Butterfield, W. Musial, J. Jonkman and P. Sclavounos, “Engineering Challenges for Floating Offshore Wind Turbines,” National Renewable Energy Lab (NREL), Golden, 2007.

[15] M. Martini, R. Guache, I. Losada-Campa and L. IJ, “The Impact of Downtime Over the Long-Term Energy Yield of a Floating Wind Farm,” *Renewable Energy,* vol. 117, pp. 1-11, 2018.

[16] Y. Feng, P. Tavner and H. Long, “Early experiences with UK round 1 offshore wind farms,” in *Institution of Civil Engineers - Energy*, 2010.

[17] BVG Associates, “Guide to Floating Offshore Wind - Floating Wind Lifecycle Overview,” 2023. [Online]. Available: https://guidetofloatingoffshorewind.com/floating-wind-lifecycle-overview/. [Accessed 10 June 2023].

[18] J. Carroll, A. McDonald and D. McMillan, “Failure rate, repair time and unscheduled O&M cost analysis of offshore wind turbines,” *Wind Energy,* vol. 19, no. 6, pp. 1107-1119, 2016.

[19] I. Dinwoodie, F. Quail and D. McMillan, “Analysis of offshore wind turbine operation and maintenance using a novel time domain meteo-ocean modelling approach,” in *Turbo Expo: Power for Land, Sea and Air, American Society of Mechanical Engineers,* 2012.

Chapter 2 : Identifying the Challenges of Operating and Maintaining a Floating Offshore Wind Farm

To determine the operational impact of future floating wind sites, the technology-specific challenges must first be identified.

This chapter aims to provide an overview of FOW technology, exploring the potential challenges associated with both operating and maintaining these future offshore sites. The first part examines the intricacies of FOW technology, providing an overview of the main design concepts, and future markets, where deployment can access the resource of previously untapped regions. An overview of O&M practices is also presented, providing insight into the modelling of OpEx. Drawing parallels with the unique demands of the floating systems, this chapter investigated the specific challenges faced during the O&M phase of floating projects, emphasising critical factors such as location selection, turbine scale/capacity, design consensus, and the operational impact of the dynamic motion-induced complexities inherent in floating structures. This chapter aims to provide context to the subsequent work and identify the existing gaps within the literature. An overview of the chapter contents is provided in Figure 2.1.

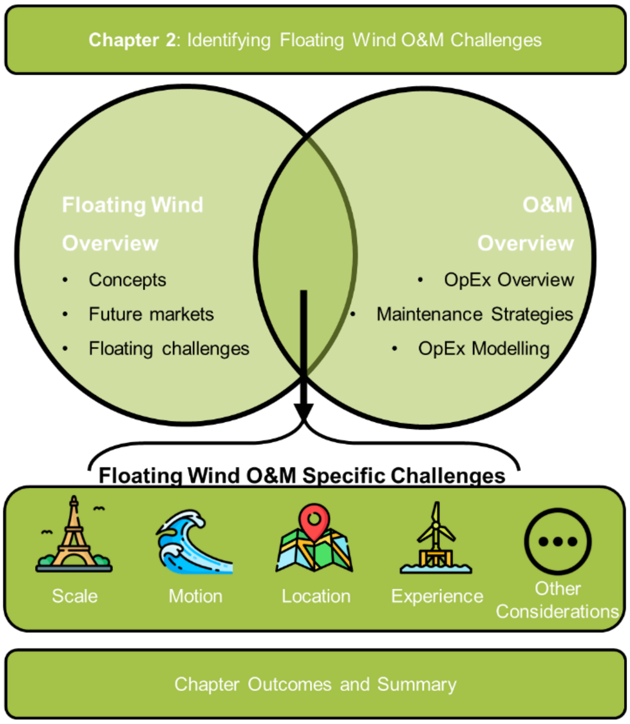


Figure 2.1. Chapter 2 Overview and Summary

2.1. Background

As offshore wind farms move into deeper waters, the use of floating wind turbines to utilise the resource is one of the only feasible solutions. FOW was first proposed by Heronemus in 1972 [1], however, since then there has yet to be large-scale deployment of the technology or a standardised design.

FOW is a promising technology aiming to harness wind energy in deep water environments. At present, BFW has been limited to shallow water depths, limiting the potential of the offshore wind industry. FOW turbines are designed to float on the water surface, allowing access to vast untapped wind resources in deeper seas.

FOW holds great potential for meeting increasing energy demands, reducing greenhouse gas emissions, and accelerating the transition towards a sustainable and clean energy future. The growth of the technology is expected to be rapid with a predicted 70 GW installed capacity globally by 2040 [2]. As the distance from shore increases, the average wind speed also increases allowing a potential for increased energy yield and capacity factors. Floating turbines can also unlock previously untapped shallow water locations which could not support fixed turbines due to the seabed materials. Globally, around 80% of the offshore wind resource is located in waters exceeding 60 meters in depth [3], beyond the current limits for bottom-fixed installation, revealing a huge potential market for the technology.

2.1.1. FOW Concepts

The selected FOW platform design has not been standardised, allowing for several innovative designs created each with its own set of advantages and disadvantages. At present, there are four main categories of floating platforms: spar, semi-submersible (semi-sub), barge, and tension leg platform (TLP). An example of these designs is provided in Figure 2.2.

There are three main stabilising mechanisms used: ballast, mooring line, and buoyancy.

Spar is ballast stabilised. These platforms are vertical structures resembling buoys with a large cylindrical hull. The design gains its stability from having the centre of gravity lower than the centre of buoyancy. These designs have a large draft and are anchored to the seabed. The design has the advantage of simple design and fabrication. However, the large draft can introduce significant challenges during the transportation, and installation phases. This design is typically constrained to deployment in waters exceeding 100 m depth [5].

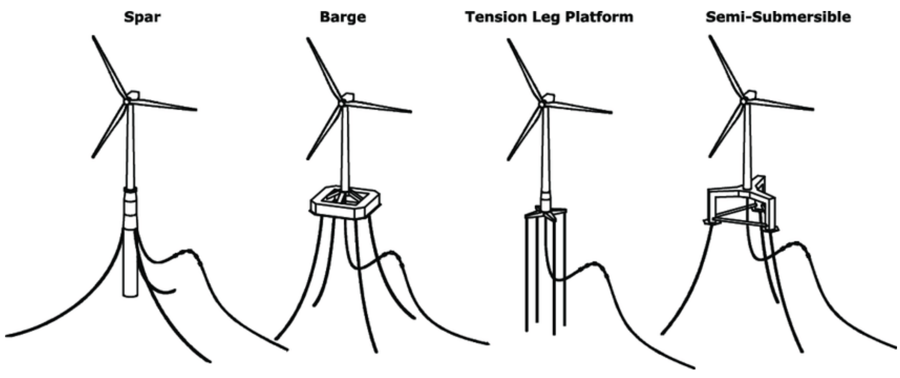


Figure 2.2. Example of FOW platform substructure designs [4]**.**

TLPs consist of semi-submerged buoyant structures which are anchored to the seabed using long tethers, known as tension legs, to anchor the platform to the seabed [5]. This design is mooring line stabilised which minimizes vertical motion and enhances stability by generating the restoring moment when the structure is inclined. However, while the shallow draft allows for a smaller and lighter structure, there in an increase in stresses on the anchor system.

The semi-sub designs are large, buoyant structures held in place with mooring lines. The buoyancy stabilised design typically consists of three columns placed on the edge of a triangle using distributed buoyancy, taking advantage of weighted water plane area for a righting moment [6]. These designs have the advantage of good stability, making them suitable for harsher environments [5]

Finally, barge platforms are flat-bottomed vessels that float on the water's surface, also utilising buoyancy for stability. The required pitch–roll restoring moment for stabilization is achieved from a large water-plane area [6]. A summary of the platform types and their characteristics is given in Table 2.1.

Table 2.1 Overview of the four key offshore wind platform types

	Spar	TLP	Semi-Submersible	Barge
Stability	Ballast	Mooring line	Buoyancy	Buoyancy
Advantages	• Simple design allows for ease of manufacture. • Excellent stability	• Onshore assembly • Excellent stability • Low structural mass	• Can operate in shallow waters. • Amendable for tow to shore maintenance	• Can operate in shallow waters. • Amendable for tow to shore maintenance
Challenges	• Constrained to deep water locations	• High loads on the mooring and anchoring system	• High structural mass to provide sufficient buoyancy and stability	• Sensitivity to large-wave-induced motions

Table 2.2 Overview of operational floating projects

Name	Location	Capacity (MW)	Platform Design	Water Depth (m)
Hywind Scotland	Scotland	30	Spar	95 - 130
WindFloat Atlantic	Portugal	25	Semi-sub	100
Kincardine	Scotland	50	Semi-sub	60 - 80

Each platform design suitability for specific site use is dependent on several factors including depth, soil conditions, and the size of the wind turbine. The site-dependent suitability of the substructure is evident in the types of platforms currently used within operational and demonstration sites. A summary of the site, selected substructure, and water depth for currently (2022) operating FOW farms is provided in Table 2.2.

As of 2023, there are only two operational commercial floating wind farms, both located in Scotland. Hywind is the first prototype wind farm using spar platforms; it is in the North Sea, off the Scottish coast, featuring five turbines with a total installed power of 30MW [7].Kincardine FOW farm, became operational in 2021, making it the current largest FOW farm globally. This site consists of six semi-subs. Kincardine is also the first FOW to complete a tow to shore operation in the summer of 2022 where one of the turbines was successfully towed to Rotterdam for maintenance operations [8].

WindFloat is a single semi-submersible platform (semi-sub) prototype, located in the Atlantic Ocean off the Portuguese coast [9]

2.1.2. Future Markets

In addition to the currently operational sites detailed in Table 2.1, there are several new sites being explored in new markets globally. The development of FOW technology allows for previous untapped regions to be exploited, opening markets in the US, Asia, and throughout Europe. However, within the existing literature on FOW modelling, all case studies are based in European waters. Brons-Illing [10] and Rinaldi et al. [11] model sites in the North Sea (German Bright and Westermost Rough), which has been identified as a key area of development for FOW sites in the future. The remaining literature is focused on Northern Europe with Castro-Santos et al. [12] focusing on Portugal and Castro-Santos et al 2020b [13], looking at the Cantabric region within Spanish waters. [14 – 19] also use European-based sites, ignoring future development such as the US, Asia, Europe and specifically, Scotland.

Europe is currently the leader in the industry with three-quarters of the planned developments being in European waters. The first operational site was launched in 2017 with Equinor’s Hywind Scotland project. Ideol quickly followed with their installation in France with the Floatgen demonstrator the following year. FOW allows previously unreachable resource to be utilised.

The European energy market has set the target of offshore wind making up 25% of the total electricity mix by 2050. WindEurope analysed the potential for floating offshore wind sites in the Northern Seas, the Atlantic and the Mediterranean and calculates that 330MW of floating offshore wind can be installed by 2022 and up to 7 GW by 2030. To reach the EU expansion targets, 150 GW of floating turbines could be spinning in Europe by 2050 [20]. This would mean that by 2050, up to a third of all offshore wind installations could be floating. The utilisation of floating wind allows new locations within Europe to be unlocked such as France, Norway, Portugal, and Spain by using floating turbines in a shallow water environment (approx. 30m). Previously, these locations could not effectively benefit from fixed turbines despite the 30 m water depth due to the geotechnics making fixed bottom turbines unviable. France, Spain, Portugal, Ireland, and the UK have been identified as the key European markets. Their use case for floating comprises of their large, deep territorial waters, significant wind resources offshore, high population and industrial activity near the coastline.

However, despite funding challenges, FOW has the advantage of being able to learn from the previous success of BFW farms, both within the UK and globally. There is evidence to suggest that the learning curve for floating wind will be significantly steeper than that of bottom-fixed offshore wind. Statoil claims to have brought down its costs by 80% since it first trialled the Hywind Demo off Karmøy, south Norway, in 2009 [21]. The group is also on the record as claiming costs for its future projects could realistically be reduced by a further 40%-50% [21]. The success of Hywind has exceeded expectations with the latest reports of a 57% capacity factor across the site, setting new industry records. The success of the project has led other developers to become involved in FOW.

Hywind Scotland has the advantage of being supported under the UK Renewable Obligation Centre (ROC) subsidy scheme at a pledged price of £160/MWh [22]. The ROC scheme has since finished in the UK making it harder for small-scale demonstrator projects to receive funding. A lack of funding has already been the downfall of less-established developers, such as Dounreay Tri, which was planning to launch a floating farm off the Scottish coast later this year. The group went into administration in July 2017.

ScotWind Overview

The UK Government has committed to a legally binding target of Net-Zero by 2050. The Committee on Climate Change (CCC), estimate this will require a quadrupling of low-carbon electricity capacity [23]. This would entail levels of offshore wind deployment of around 75GW by 2050 significantly beyond the existing total UK pipeline of 38.5GW. The

UK government has set a new target of 5 GW floating wind capacity by 2030 and will invest 160 million pounds in UK offshore wind ports and infrastructure to achieve its target of 40 GW of offshore wind by 2030 [24].

Round 4 of the UK Contract for Difference (CfD) auctions saw FOW being able to bid for contracts for the first time with TwinHub Floating Offshore Wind Project, which was successfully awarded [25]. Recent restructuring of the scheme has seen offshore wind moved to its own pot (Pot 3) and floating wind added to Pot 2 along with other less-established technologies such as tidal stream.

Crown Estate Scotland launched the first cycle of ScotWind Leasing seabed leases in Scottish waters in over a decade. The aim of this leasing round was to deliver another 8-10GW of offshore wind which will see the Scottish capacity target increase to 17-19GW, the bulk of which should be delivered by 2030-32. The 2022 ScotWind leasing results have greatly accelerated this target by awarding 11 floating projects with a capacity of ~18 GW, and a total capacity of almost 30 GW awarded. This highlights the pace at which the FOWT industry is growing, and in which Scotland is positioned to be an early leader.

However, this historic auction has highlighted key challenges associated with the technology. These remote islands surrounding mainland Scotland rely heavily on ferry services for commuting and resources. There is a potential that this may limit operational limits, port availability, and vessel travel path. However, this is not a universal issue and is handled on a case-by-case basis.

Ports and additional infrastructure will significantly influence the maintenance strategy for FOWTs, particularly for major component replacement. For a tow to shore (T2S) strategy to be viable, the port should have sufficient depth, capacity, and facilities to accommodate these large assets. In addition to this, weather conditions at site must be monitored. Major component repair/replacement at shore will require sufficient high tide and low wind speeds. As the turbine (or repair vessel) moves from deep (on-site) to shallow waters (at port), there can be a significant change in wave [26], and other weather, conditions along the travel path, which could result in a failed transfer.

These sites selected in the ScotWind leasing have the existing challenges of bottom-fixed operation, in addition to increased distance to shore, expected challenging met-ocean conditions and limited existing infrastructure. In addition, the additional complexities of FOWT operation need to be explored. While the existing literature explores deep water sites far from shore, the scale of the modelled capacity is much smaller than the predicted future sites.

International Markets

There are several net-zero ambitions out with Europe within global markets. Chinese President Xi Jinping committed to carbon neutrality before 2060. The Asian region is predicted to see up to US 250 billion dollars of new investment flow into utility scale renewable energy projects by 2025 [27]. Much like Europe, the floating wind industry is still in its infancy with floating offshore wind accounting for just 6% capacity of the 26 GW of new offshore capacity expected in the current decade in the Asia Pacific excluding China [28]. New markets such as Japan, South Korea, and Taiwan are set to benefit from the new technology. South Korea has installed only 132.5 MW of offshore wind capacity currently. It has several floating offshore wind projects in development [29].

The US is also set to take advantage of floating wind. It is expected that floating installations in the US will be focused on the west coast due to the water depth. California and Hawaii already have plans for floating farms in place with Oregon and Washington expected to follow. Worldwide, offshore wind resource has been shown to be extremely abundant, with the U.S. energy potential ranked second only to China [30]. The Biden administration has recently announced a new programme of support for offshore wind across the US including the commitment to offshore wind RD funding through the National Offshore Wind Consortium, access to $3 billion in Debt Capital to Support Offshore Wind Industry through the Department of Energy Loan Programs Office and establishing a target of employing tens of thousands of workers to deploy 30 Gigawatts (30,000 megawatts) of Offshore Wind by 2030 [31].

2.1.3. Floating Wind Challenges

Despite the lack of commercial sites operating, several literature reviews on the technology have been carried out. At present, efforts have been focused on the optimisation of the sub-structure and the advantages and disadvantages of existing technologies. Based on the current academic literature, spar, TLP, and semisubmersible (semi-sub) support structures are the most advanced technologies. The details of existing review papers, the types of structures considered, the focus area of the review, and details of any O&M considerations are provided in Table 2.3.

Most of the FOW reviews conducted thus far provide recommendations/details of O&M requirements for the technology, as shown in Table 2.3. It is agreed in the review literature that TLP will be the most effective for O&M, both in terms of cost and ease of maintenance, even though no TLPs have been installed at the commercial level (2021). Wang et al. [32], Henderson & Witcher [33], and Liu et al. [34] identify O&M as a key area for future research.

Rinaldi et al. [40] review current and future trends in O&M within offshore wind that covers fixed and floating turbines with a focus on reliability and maintainability through methods such as condition monitoring and the use of artificial intelligence and drones. The findings showed that condition monitoring is not currently widely used for FOW. This is due to several factors, the main being the infancy of the technology/industry. However, the floating nature of the platform will bring about a series of new requirements, such as additional

Table 2.3 Summary of reviews of FOW within the literature.

Paper	TLP	Sem-Sub	Barge	Other	Paper Topics	O&M Summary
Wang et al. [32]	✓	✓	✓		Support structures	Recommended future work to stablish cost effectiveness for towing, installation, and maintenance
Henderson & Witcher [33]	✓	✓	✓	Mini TLP	Turbine control, support structures	O&M procedures identified as key challenges
Muskulus & Schafhirt [35]			✓	Fixed Structures	Support structures	Recommendation of O&M considerations being included in the design phase
Stewart & Muskulus [36]	✓	✓	✓		Support structures	N/A
Liu et al. [34]	✓	✓	✓		Support structures	O&M ranked best to worst (TLP, Spar, Semi-sub). Acknowledgement of O&M cost reduction as a key research area
Leimeister et al. [37]	✓	✓	✓	10 total structures	Support structures	Spar - simple structure, easy manufacturing, and maintenance Semi-sub - more challenging manufacturing and maintenance TLP - easy maintenance, complex and risky installation, and disconnection for onshore maintenance
Wu et al. [38]				Fixed: Monopile, gravity, tripod, and jacket	Support Structures	
Chen et al. [39]	✓	✓	✓		Support structures – numerical and experimental methodologies	N/A

environmental parameters to monitor, e.g., hydrodynamic loadings and platform motions. Although corrosion is expected to cause problems, fatigue due to wave and wind, loadings must be assessed due to platform motion. Increased use of control systems to monitor platform motions can lead to a higher number of electrical-related failures. These additional challenges reinforce the need for accurate O&M modelling of the technology and highlight the need for dedicated modelling of failure rates of such systems. The deployment of FOW is in line with the uptake of new technologies discussed in [40], therefore, it is likely that the overall maintenance strategy of the site will change due to these technological advancements. The expected challenging environmental conditions of FOW sites are likely to benefit from unmanned inspections using drones due to issues with accessibility.

2.2. Offshore Wind O&M Overview

OpEx can account for up to one third of the total levelised cost of energy (LCoE) for a conventional BFW site [41], making it a key area for cost reduction. Within offshore wind, LCoE is a common KPI used to compare the economic feasibility of offshore wind projects against each other, and against other generation technologies. The calculation of LCoE is described in Equation 2.1.

$$LCoE = \frac{Total\ Lifetime\ Cost}{Total\ Lifetime\ Output} \tag{2.1}$$

Where total lifetime cost is the combination of capital expenditure (CapEx), the cost of CapEx, OpEx and decommissioning expenditure (DecEx). Of these key components, once operational, OpEx is the only cost which can still be, somewhat, controlled. The LCoE is characterized as the revenue needed (from any revenue source) to achieve a consistent rate of return on investment, equal to the discount rate (also known as the weighted average cost of capital - WACC), throughout the entire lifespan of the wind farm [42]. Accurate modelling of LCoE is vital for project success, with significant impact in the project financing stage. Due to the large contribution of OpEx, it is vital to have accurate modelling, for accurate predictions, and to identify potential areas for innovation to reduce cost.

Figure 2.3 shows a breakdown of OpEx costs into the four main categories: staff, lost production, repair, and transport. Many of the factors presented in Figure 2.3 feature in more than one category because they have an impact on the costs in each category. For example, an increase in the wind farm distance from shore will increase the staff cost to complete that task, the size of the weather window required hence the downtime, and the quantity of fuel used to complete the task.

OpEx encompasses all expenses incurred from the moment of takeover, comprising both one-time and recurring costs associated with the wind farm, measured annually. These costs can be split as direct and indirect costs

Within this work, direct costs are defined as those which have a “direct” impact on the operation of the site finances such as cost of repair, transport, and staff (Figure 2.3, where arrows indicates sub categories). Indirect costs, such as lost production costs, are more difficult to predict, due to uncertainty in the prediction of unscheduled failures and met ocean conditions. Lost revenue is viewed within industry as an “opportunity cost”. One of the main costs associated with OpEx is the opportunity cost from downtime. An opportunity cost is defined as the revenue which could have been generated, had the turbine been operational. This is a key area of focus to reduce overall OpEx.

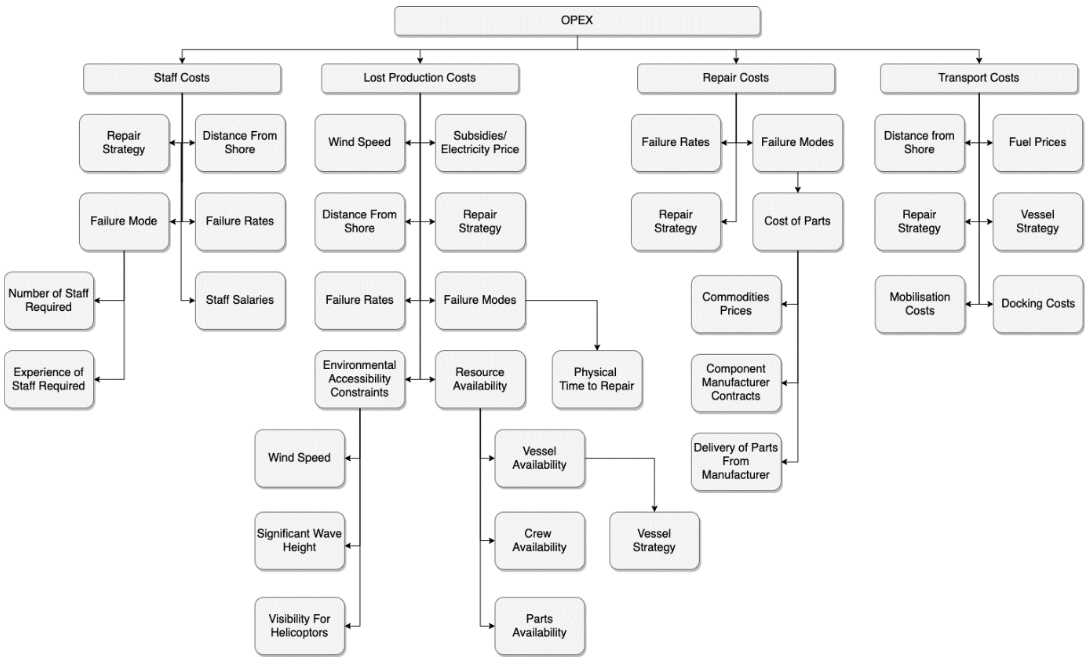


Figure 2.3. Breakdown of OpEx cost elements [4]**.**

2.2.1. O&M Strategies

Maintenance strategy can be simply divided into scheduled and unscheduled. Corrective maintenance (unscheduled) is when components are repaired upon fault with no attempt to pre-empt failure. This constitutes the majority of maintenance actions for all wind farms. However, as distance to shore increases, this approach becomes increasingly challenging. Preventive maintenance (scheduled) is performed proactively to inspect and repair degrading components at fixed time intervals to reduce unexpected downtime [43]. This can include scheduled annual servicing or condition-based maintenance (CBM), where maintenance is carried out depending on the condition of the component, hence specialist condition-monitoring equipment is necessary. This can provide an optimised maintenance schedule that prevents failures without resorting to over-maintenance [44] [45]. Artigao et al. [46] provides a review of the state-of-the-art condition monitoring techniques.

Models typically include a mixture of strategies [47] [48] [49] [50] [51]. This is important to allow for flexibility in the cost model analysis, especially for new technologies. Dalgic et al. [51] present three different strategies with increasing importance of preventive maintenance with respect to corrective maintenance. Preventative maintenance can occur to a varying degree of frequency, but it should be noted that the achieving the highest availability leads to large direct costs. CBM has a high initial cost for the system, and itself will require maintenance, but can theoretically yield the least expensive proactive maintenance schedule. Most models that consider CBM usually do so independently of other techniques [52] [53] [54] [55].

Future sites are facing increasing challenges due to the expected move to more challenging locations. To overcome these challenges, flexible, cost-effective maintenance strategies must be exploited. One such strategy, which has been gaining traction in recent years, is opportunistic maintenance, OM. This strategy was first proposed in 2009 by Besnard et al. [56]. This strategy typically, involves performing non-critical maintenance actions (such as inspections/preventive maintenance) during author-defined “opportunities”. Opportunities can be: during low wind speed [56], performing scheduled maintenance during unscheduled trips [57], and group-based maintenance [58]. There is increasing interest in multilevel decision-making and strategy by introducing opportunistic thresholds based on age [59] [60] [61] [62] [63], locational clustering [64], and condition [65].

2.2.2. OpEx Modelling

There has been extensive work in developing O&M modelling tools for offshore wind. A comprehensive list of academic and industry models can be found in [66]. A great deal of time, effort, and cost goes into developing accurate offshore wind O&M models. Therefore, there is a question as to whether these existing (and sometimes validated models) should be adapted for FOW use, or if a new model should be created to deal with the additional complexities of FOW farms.

Offshore wind farm operations and strategy are influenced by several factors: failure modelling, resource logistics, transportation, weather, and economic cost parameters [67] which are discussed further in Chapter 4. A successful O&M cost model should be able to present the influence of each of these factors in a realistic way that can give valuable insight to the user. The results should be clear to any user based in a series of KPIs. A desirable model will have flexibility in the inputs. For a good comparison of lifetime O&M cost estimation, the model should allow the user to investigate different control and operating strategies for the turbines, as well as be able to capture changes to the turbine design. To facilitate this, the ideal model would run the simulation multiple times and provide a probability distribution of cost data and other outputs such as availability and vessel utilisation.

Most of the highly developed models use Monte Carlo simulations combined with other types of modelling [47] [48] [68] [49] [69] [51]. Markov chain models are the most popular modelling technique and can be discrete time or continuous [47], [48], [49]. In discrete time, stochastic processes consist of states and the probabilities to get from one state to another, called the transition probability, while in continuous time the transition probabilities are replaced with transition rates states [70] [71]. Continuous Markov chains are required to capture the continuous nature of parameters in the model, such as electricity price, wind speed and wave height. However, discrete Markov models would be sufficiently accurate with appropriately fine time-steps. Discrete time models are the most common in highly developed O&M models [67]. Another popular technique of modelling is an auto-regressive model [68], [51]. An auto-regressive model is used to model a random process. This states that the variable depends linearly on its own previous values multiplied by some weight and follows a stochastic process [72]. The advantage of Markov chains is that they are memory-less. Due to this, Markov chains are computationally less expensive. However, this has a downside of decreased accuracy compared with auto-regressive models. Other modelling techniques used include Weibull distributions [68], binomial processes [49], Petri nets [73], (detailed in Murata [74]) and Poisson process [69].

2.3. Floating Offshore Wind Maintenance Challenges

The limitations of floating offshore wind turbines can have a significant impact on their accessibility and other key performance indicators. Factors such as the size and weight of the turbine, as well as the complexity of the control systems used to stabilise it, can make it difficult to install and maintain the turbine in offshore environments. Additionally, the motion of the platform caused by waves and currents can affect the performance of the blades and other components, reducing the efficiency and output of the turbine. This can have a negative impact on the profitability of the turbine, making it less attractive for investors and operators.

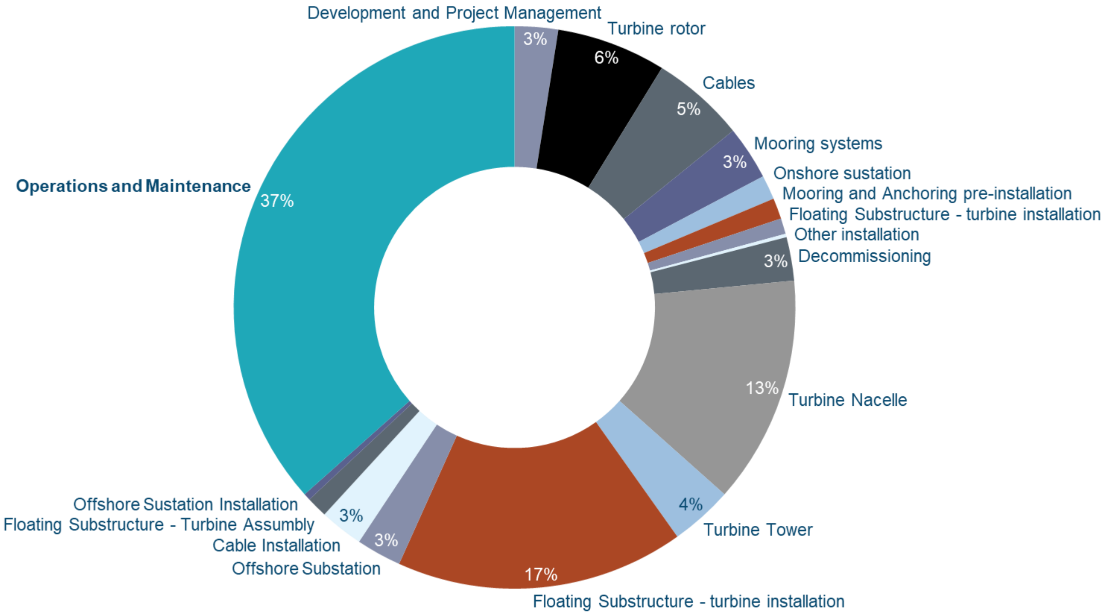


Figure 2.4. Breakdown of cost of energy for future FOW sites [75]

The turbine/platform motion is also set to have a significant impact on how turbines are maintained, due to the possible impact of the motion on technician wellbeing.

As previously discussed, at present, O&M costs can account for up to 30% of the total cost of energy of a BFW site [41]. However, due to the challenges discussed, there is potential for this to increase for future FOW sites. Recent work by BVG Associates estimate at O&M procedures for FOW sites could reach almost 40% [75]. A breakdown of cost of energy for FOW is provided in Figure 2.4.

Like BFW, FOW concepts will still be affected by access restrictions caused by poor weather. Weather conditions such as wind speed, wind turbulence, wave height and sea condition, temperature and humidity can all have significant impact on the reliability and maintainability of the asset [76]. It is expected that the FOW will allow stronger and more constant wind to be used to its benefit, due to the anticipated increase in distance to shore. However, an increased distance from shore results in harsher weather conditions leading to a decrease in accessibility to site. This, combined with the increase in travel time, makes the use of access and weather windows vital to efficient and profitable operation. One of the main costs associated with operational expenditure (OpEx) is the opportunity cost from downtime. An opportunity cost is defined as the revenue which could have been generated, had the turbine been operational. Exposure to harsher and more challenging environmental conditions also has the potential to result in a rapid progression of the degradation of the asset, increasing the requirement for maintenance visits to site.

2.3.1. Motion

The motion of the turbine will have a significant impact on O&M, making access and egress by personnel more challenging, as the process moves from a floating-fixed transition to a floating-floating system [77]. This could increase the difficulty of performing on-site inspections and repairs, due to the inherent dynamics of floating wind turbines, and raises concern about the safety of technicians performing maintenance on the floating structure.

It is vital that future works regarding O&M modelling have an appreciation of this additional factor when considering the health and safety parameters and limitations required for safe working conditions for technicians. It is expected that additional weather and environmental factors such as peak wave period (Tp) and wave direction will be required to assess the workability of the asset [78].

The motion of the asset is also expected to have an impact on the rate of degradation of the components, particularly within the drivetrain [79] [80, 81].

2.3.2. Scale

As shown in Table 2.1, current operating FOW sites have a small installed capacity, due to the demonstration nature of these farms. However, the average proposed capacity of the allocated FOW ScotWind zones was found to be 1.4 GW [79].

It is not just total installed capacity which is expected to increase for future FOW sites. Recent studies have estimated turbines of up to 15 MW will be installed as part of the

ScotWind sites in 2030 and beyond. Recent trends in increasing turbine size have a number of practical challenges. The scaling of turbines will be a challenge faced by both FOW and BFW sites. Increased size of components leads to logistical transportation, manufacturability, and vessel utilisation challenges.

Increase capacity of turbines also introduces OpEx based challenges. Based on expert opinion and assuming all variables are unchanged, OpEx typically halves on a per MW basis as capacity doubles [80]. While this seems advantageous, it does not consider practical limitations such as increased supply chain competition and increase in opportunity cost/downtime. Therefore, as turbine, and site, capacity increases, so does the potential loss. The balance between expected OpEx savings and potential opportunity cost is shown in Figure 2.5.

Opportunity cost is calculated using a value of £47.38/MWh based on the assumption of 2% indexing for the 2012 strike price of £39.65 as provided in the Round 3 CfD Crown Estate (2019) and operating at full capacity during the downtime period.

The pressure of increased lost revenue due to turbine size, puts additional emphasis on ensuring all access periods to site are effectively utilised to minimise potential downtime.

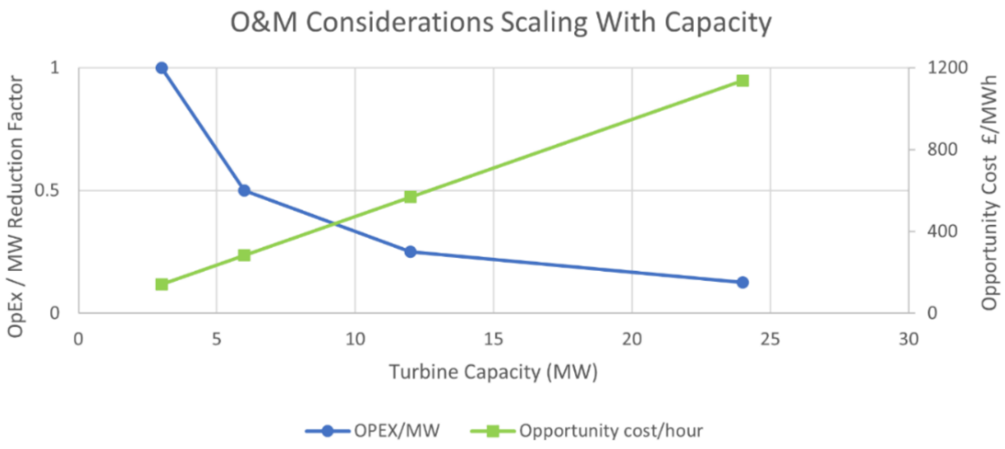


Figure 2.5. Predicted reduction in OpEx (£/MW) and calculated opportunity cost based on UK Crown Estate CfD Round 3 strike price. [80]

2.3.3. Experience/Convergence

The studies detailed in Table 2.4 provide varying results in terms of LCOE for the spar, TLP, and semi-sub platform due to variable inputs such as water depth, installed capacity, distance from shore, balance of plant, number of turbines, etc. However, the publications also disagree in terms of which support structure will result in the highest LCOE as shown in Table 2.4. This work the LCOE provided in each publication as high, med(ium) and low, to allow for comparison in the most site optimal design. These results are ranked according to the results of each publication and have not been bench-marked against each other due to differences in methodology, case studies, and terminology used. Castro-Santos et al 2016 [19] only considers one type of structure and Maienza [81] provides an average LCOE for all structures. Therefore, the results of these works are not included.

The difference in results indicates that there is no clear choice of the most cost-effective support structure highlighting the importance of external factors such as location, facilities and environmental elements having more of an impact on the overall LCOE than the choice of structure.

Table 2.4 LCoE ranking for different substructure types.

Publication	Spar	Semi-Sub	TLP
Myhr et al. (Standard) [15]	MED	HIGH	LOW
Myhr et al. (Optimised) [15]	MED	HIGH	LOW
Bjerkster et al. [16]	MED	HIGH	LOW
Heidari et al. [82]	LOW	HIGH	MED
Castro et al. (Portugal) [12]	LOW	MED	HIGH
Castro et al. (Spain) [13]	MED	LOW	HIGH

2.3.4. Other Considerations

Due to the expected depths of FOW sites, the use of conventional major component replacement vessels will not be viable [83]. This creates an interesting challenge of how major component replacements will be conducted. New solutions have been considered including on-site solutions such as floating-to-floating transfer, floating cranes, and self-hoisting equipment, and off-site methods such as Tow to Shore and Tow to Shallow [84].

Some FOW configurations offer the opportunity to be towed to shore for extensive maintenance activities. This maintenance activity is only applicable to shallow draft structure types and those FOW structures able to satisfy the intact stability requirements even when not moored, such as a TLP. The viability of this strategy also depends on the port facilities. The port must have sufficient water depth, equipment (such as an onsite crane), and general scale to meet the maintenance needs of floating turbines. There is also an adapted version of this strategy known as "tow to shallow" where the turbine is towed to shallow water for maintenance at depths suitable for heavy lift vessel assistance.

The overall uptake of FOW is limited by the availability of suitable port and grid infrastructure. Most European ports and harbours are not equipped to deal with the scale of operations required for the installation and maintenance of such assets; this becomes an increasing issue due to the pace of installation of new BFW and FOW sites. While this is a key issue for future FOW sites, major component replacement operations typically only make up 5% of all offshore failures.

While these failure types have the highest cost/failure, the focus of this work is on day-to-day maintenance operations including scheduled maintenance, and minor/major repairs only.

Human Factor

Human uncertainty can make insuring a floating project particularly challenging, especially because the technology is relatively new and untested compared to traditional fixed structures.

Insurers are often wary of emerging technologies due to the steep learning curve involved. There is a general lack of experience and historical data to accurately assess risks, leading to fears of unforeseen complications. Therefore, floating projects may also experience an increase in the cost of borrowing, this will then impact LCOE as the cost will be distributed across the project.

2.4. Chapter Outcomes and Summary

This chapter has presented a comprehensive overview of floating offshore wind technology, highlighting its concepts and potential challenges. Additionally, it delved into the crucial aspect of operation and maintenance practices for both conventional bottom fixed sites and floating wind farms, with a particular focus on operational expenditure modelling. Furthermore, this research has effectively identified key challenges faced in operating and maintaining floating offshore wind farms as follows:

- **Motion**: turbine motion is expected to place additional strain on accessibility and therefore additional inputs will be required to determine accurate accessibility and OpEx predictions
- **Location:** FOW sites are more likely to be located further from shore placing strain on weather window availability
- **Scale:** recent trends have seen a steady increase in turbine size. It is expected that future FOW sites will contain turbines upwards of 15 MW being deployed. As previously highlighted, while this will have a positive impact on project revenue, periods of downtime will be critical.
- **Experience/convergence**: the selection of substructure is highly site dependent. Each substructure has its unique set of challenges, where the economic feasibility of designs is highly site dependent.

The above is based on that highlighted within the literature. In addition to the presented concerns, there are a number of uncertain factors which may influence OpEx for future FOW sites including: the addition of new parts which will require maintenance (e.g., the substructure and mooring lines); failure rates of existing components due to turbine motions; and major component replacement alternative strategies [85].

The key outcomes is that O&M currently is the highest contributor to LCoE for conventional turbines [41], and it is expected that this contribution will be further increased for FOW sites [75]. Due to recent trends in increase in the cost of commodities [86], and the risk of investment for a new technology, project financing for future FOW sites will be challenging. Therefore, OpEx has been identified as a key area of cost reduction.

Based on the findings from this chapter, the importance of OpEx modelling and the FOW challenges have been identified. The remainder of the thesis is focused on the following areas:

- The impact of FOW identified operational challenges on non-financial KPIs (Chapter 3)
- The economic impact of FOW identified operational challenges on OpEx (Chapter 4)
- Identification of potential maintenance strategies for OpEx reduction for FOW sites (Chapters 5 and 6)

2.5. Chapter References

[1] W. E. Heronemus, “Pollution-free energy from offshore winds,” in *8th Annual Conference and Exposition Marine Technology Society*, Washington D.C., 1972.

[2] The Carbon Trust, “Floating Wind Joing Industry Project: Plase II Report,” 2020.

[3] Wind Europe, “Floating Offshore Wind Vision Statement,” 2017.

[4] M. Scheu, D. Matha, M.-A. Schwarzkopf and A. Kolios, "Human exposure to motion during maintenance on floating offshore wind turbines," *Ocean Engineering,* vol. 165(3), pp. 293-306, 2018.

[5] L. Castro-Santos and V. Diaz-Casas, Floating Offshore Wind Farms, Switzerland: Springer International Publishing, 2016.

[6] M. Leimeister, A. Kolios and M. Collu, "Critical review of floating support structures for ofshore wind farm development," *Journal of Physics: Conference Series,* vol. 1104, no. 1, p. 12007, 2018.

[7] Equinor, "Hywind Scotland remains the UK's best performing offshore wind farm," Equinor, 23 March 2021. [Online]. Available: https://www.equinor.com/news/archive/20210323-hywind-scotland-uk-best-performing-offshore-wind-farm. [Accessed January 2022].

[8] reNEWS, "Kincardine facing turbine repair job," reNEWS.biz, 4 May 2022. [Online]. Available: https://renews.biz/77609/kincardine-facing-turbine-repair-job/#:~:text=The%20pioneering%2050MW%20Kincardine%20floating,be%20in%20need%20of%20replacement. [Accessed 6 May 2022].

[9] Power Technology, "WindFloat Atlantic Project," Power Technology, 6 February 2020. [Online]. Available: https://www.power-technology.com/projects/windfloat-atlantic-project/. [Accessed January 2022].

[10] C. Brons-Illing, "Analysis of operation and maintenance strategies for floating offshore wind," in *Master's Thesis,* University of Stavanger, Norway, 2016.

[11] G. Rinaldi, P. R. Thies and L. Johanning, "Improvments in the O&M modelling of floating offshore wind farms," in *4th International Conference on Renewable Energies Offshore (RENEW 2020),* Lisbon, 2020.

[12] L. Castro-Santos, D. Silva, A. R. Bento, N. Salvação and C. Guedes Soares, "Economic feasibility of floating offshore wind farms in Portugal," *Ocean Engineering,* vol. 207, 2020.

[13] L. Castro-Santos, D. Silva, A. Bento, N. Salvacao and C. Soares, "Economic feasibility of floating offshore wind farms in Portugal," *Ocean Engineering,* p. 207, 2020.

[14] A. Dewan and M. Asgarpour, "Reference O & M concepts for near and far offshore wind farms," ECN Petten, 2016.

[15] A. Myhr, C. Bjerkseter, A. Ågotnes and T. Nygaard, "Levelised cost of energy for offshore floating wind turbines in a life cycle perspective," *Renewable Energy,* vol. 66, pp. 714-728, 2014.

[16] C. Bjerkseter and A. Ågotnes, "Levelised costs of energy for offshore floating wind turbine concepts," Master's Thesis, Norweigan University of Life Sciences, 2013.

[17] G. Katsouris and A. Marina, “Cost Modelling of Floating Wind Farms,” ECN, 2016.

[18] L. Castro-Santos and V. Diaz-Casas, “Life-cycle cost analysis of floating offshore wind farms,” *Renewable Energy,* no. 66, pp. 41-48, 2014.

[19] L. Castro-Santos, E. Martins and C. Guedes Soares, “Methodology to calculate the costs of a floating offshore renewable energy farm.,” *Energies* , vol. 9, 2016.

[20] Wind Europe, “Floating Offshore Wind is Gearing Up for Take-Off,” Wind Europe, 8 September 2020. [Online]. Available: https://windeurope.org/newsroom/news/floating-offshore-wind-is-gearing-up-for-take-off/#:~:text=WindEurope%20analysed%20the%20potential%20for,to%207%20GW%20by%202030.. [Accessed 10 April 2021].

[21] R. Davies, “Floating Wind: The Signifcance of Hywind Scotland,” Power Technology, 2020 February 15. [Online]. Available: https://www.power-technology.com/features/floating-wind-significance-hywind-scotland/#:~:text=The%20simple%20basis%20for%20the, depths%20of%20up%20to%2050m.. [Accessed 10 April 2021].

[22] Statoil, “Hywind Pilot Park - Environmental Statement,” 2015. [Online]. Available: https://marine.gov.scot/datafiles/lot/hywind/Environmental_Statement/Environmental_Statement.pdf. [Accessed 10 April 2021].

[23] Department for Energy Security and Net Zero and Department for Business, Energy and Industrial Strategy, “Energy White Paper: Powering Our Net Zero Future,” HM Government, 2020.

[24] Prime Minister's Office, “New plans to make UK world leader in green energy,” October 6 2020. [Online]. Available: https://www.gov.uk/government/news/new-plans-to-make-uk-world-leader-in-green-energy. [Accessed 10 April 2021].

[25] Crown Estate, “Contract for Difference Allocation Round 4 Results,” 7 July 2020. [Online]. Available: https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/1103022/contracts-for-difference-allocation-round-4-results.pdf. [Accessed 10 April 2021].

[26] J. Wright, A. Colling and D. Park, Waves, tides and shallow-water processes. Volume 4, Gulf Professional Publishing, 1999.

[27] M. Rathbone, “The next frontier for infrastructure investments: Renewable Energy in Asia-Pacific Region,” PWC, Singapore, 2018.

[28] D. Evans, “Floating Offshore Wind Could be Massive in Asia,” 23 February 2021. [Online]. Available: https://www.energyvoice.com/renewables-energy-transition/301543/floating-offshore-wind-could-be-massive-in-asia/. [Accessed 10 April 2021].

[29] J. Bocobza, N. Davies and Rebbapragada, “An Evolving Marker in Asia for Offshore Widn,” Noron Rose Fulbright: Projec Finance, 2020.

[30] C. Butterfield, W. Musial and K. Jonkman, “Overview of Offshore Wind Technology,” NREL, Denver, 2007.

[31] US Government, “FACT SHEET: Biden Administration Jumpstarts Offshore Wind Energy Projects to Create Jobs,” 29 March 2021. [Online]. Available: https://www.whitehouse.gov/briefing-room/statements-releases/2021/03/29/fact-sheet-biden-administration-jumpstarts-offshore-wind-energy-projects-to-create-jobs/. [Accessed 10 April 2021].

[32] C. Wang, T. Utsunomiya, S. Wee and Y. Choo, “Research on floating wind tubines: a literature survey,” *The IES Journal Part A: Civil and Structural Engineering,* vol. 3, no. 4, pp. 267-277, 2010.

[33] A. Henderson and D. Witcher, “Floating offshore wind energy—a review of the current status and an assessment of the prospects,” *Wind Engineering,* vol. 31, no. 1, pp. 1-16, 2010.

[34] Y. Liu, S. Li, Q. Yi and D. Chen, “Developments in semi-submersible floating foundations,” *Renewable and Sustainable Energy Reviews,* vol. 60, pp. 433-449, 2016.

[35] M. Muskulus and S. Schafhirt, “Design optimization of wind turbine support structures - a review,” *Journal of Ocean Wind Energy,* vol. 1, no. 1, pp. 12-22, 2014.

[36] G. Stewart and M. Muskulus, “A review and comparison of floating offshore wind turbine model experiments,” *Energy Pocedia,* vol. 94, pp. 227-231, 2016.

[37] M. Leimeister, A. Kolios and M. Collu, “Critical review of floating support structures for offshore wind farm deployment,” *Journal of Physics: Conference Series,* vol. 1104, no. 1, p. 12007, 2018.

[38] X. Wu, Y. Hy, J. Yang, L. Duan, T. Wang, T. Adcokc, Z. G. Z. Jian and Z. Lin, “Foundations of offshore wind turbines: a review,” *Renewable and sustainable enegry reviews,* vol. 104, pp. 379-393, 2019.

[39] P. Chen, J. Chen and Z. Hu, “Review of experiemental-numerical methodologies and challenges for floating offshore wind turbines,” *Journal of Marine Science Applied,* pp. 1-23, 2020.

[40] G. Rinaldi, T. Phillip and J. Lars, “Current status and future trends in the operation and maintenance of offshore wind turbines: a review,” *Energies,* vol. 14, no. 9, p. 2484, 2021.

[41] Y. Feng, P. Tavner and H. Long, “Early experiences with UK round 1 offshore wind farms,” in *Institution of Civil Engineers - Energy*, 2010.

[42] BVG Associates, “Guide for an Offshore Wind Farm,” The Crown Estate and ORE Catapult, 2019.

[43] J. Nielsen and J. Sorensen, “On risk-based operation and maintenance of offshore wind turbine components,” *Reliability engineering & sustem safety,* vol. 96, no. 1, pp. 218-229, 2011.

[44] E. MacMahonn, A. Stock, W. Leithead and P. Jamieson, “Yaw control for 20MW offshore multi rotor system,” in *European Wind Energy Association Annual Even (EWEA),* 2015.

[45] K. Verbert, B. De Schutter and R. Babuska, “Timeley conditions-based maintenance planning for multi-component systems,” *Reliability Engineering & System Safety,* pp. 310-321, 2017.

[46] E. Artigao, S. Martín-Martínez, A. Honrubia-Escribano and E. Gomez-Lazaro, “Artigao E, Martín-Martínez S, Honrubia-Escribano A, Gomez-L ´ azaro ´ E. Wind,” *Applied Energy,* vol. 228, pp. 1569-1583, 2018.

[47] F. Douard, C. Domecq and W. and Lair, “A probabilistic approach to introduce risk measurement indicators to an offshore wind project evaluation–improvement to an existing tool ecume.,” *Energy Procedia,* vol. 24, pp. 255-262, 2012.

[48] M. Scheu, D. Matha, M. Hofmann and M. Muskulus, “Maintenance strategies for large offshore wind farms.,” *Energy Procedia,* vol. 24, pp. 281-288, 2012.

[49] M. Hofmann and I. Sperstad, “NOWIcob–A tool for reducing the maintenance costs of offshore wind farms,” *Energy Procedia,* vol. 35, pp. 177-186, 2013.

[50] I. Dinwoodie, F. Quail and M. D, “Analysis of offshore wind turbine operation and maintenance using a novel time domain meteo-ocean modeling approach.,” in *Turbo Expo: Power for Land, Sea, and Air, American Society of Mechanical Engineers*, 2012.

[51] Y. Dalgic, I. Lazakis, I. Dinwoodie, D. McMillan and M. Revie, “Advanced logistics planning for offshore wind farm operation and maintenance activities,” *Ocean Engineering,* vol. 101, pp. 211-226, 2015.

[52] J. Helsen, D. S. G and P. Jordaens, “Long-term monitoring of wind farms using big data approach.,” IEEE Second International Conference on Big Data Computing Service and Applications (BigDataService). IEEE, 2016.

[53] S. Ambühl, K. Morten and J. Sørensen, “Ambühl S, Kramer M, Sørensen JD. Risk-based operation and maintenance,” in *ISOPE International Ocean and Polar Engineering Conference,* 2016.

[54] M. Bach-Andersen, B. Rømer-Odgaard and O. Winther, “Bach-Andersen M, Rømer-Odgaard B, Winther O.,” *Wind Energy,* vol. 20, no. 5, pp. 753-764, 2017.

[55] T. Welte, I. Sperstad, E. Sørum and M. Kolstad, “ Integration of degradation processes in a strategic offshore wind farm O&M simulation model,” *Energies,* vol. 10, no. 7, p. 925, 2017.

[56] F. Besnard, M. Patriksson, A. B. Strömberg, A. Wojciechowski and L. Bertling, “An optimization framework for opportunistic maintenance of offshore wind power system,” in *IEEE bucharest powertech,* 2009.

[57] J. Kang and C. Soares, “An opportunistic maintenance policy for offshore wind farms.,” *Ocean Engineering,* vol. 216, p. 108075, 2020.

[58] M. Yildirim, N. Gebraeel and X. Sun, “Integrated predictive analytics and optimization for opportunistic maintenance and operations in wind farms.,” *IEEE Transactions on power systems,* vol. 32, no. 6, pp. pp.4319-4328., 2017.

[59] F. Ding and Z. Tian, “Opportunistic maintenance for wind farms considering multi-level imperfect maintenance thresholds,” *Renewable Energy,* vol. 45, pp. 175-182, 2012.

[60] F. Ding and Z. Tian, “Opportunistic maintenance for wind farms considering multi-level imperfect maintenance thresholds,” *Renewable Energy,* vol. 45, pp. 175-182, 2012.

[61] B. Sarker and T. Faiz, “Minimizing maintenance cost for offshore wind turbines following multi-level opportunistic preventive strategy,” *Renewable Energy,* vol. 85, pp. 104-113, 2015.

[62] X. Lubing, R. Xiaoming, L. Shuai and H. Xin, “An opportunistic maintenance strategy for offshore wind turbine based on accessibility evaluation,” *Wind Engineering,* vol. 44, no. 5, pp. 455-468, 2020.

[63] C. Su, Z. Y. Hu and Y. Liu, “Multi-component opportunistic maintenance optimization for wind turbines with consideration of seasonal factor,” *Journal of Central South University,* vol. 27, no. 2, pp. 490-499, 2020.

[64] S. Song, Q. Li, F. A. Felder, H. Wang and D. W. Coit, “Integrated optimization of offshore wind farm layout design and turbine opportunistic condition-based maintenance.,” *Computers & Industrial Engineering,* vol. 120, pp. 288-297, 2018.

[65] M. Li, M. Wang, J. Kang, L. Sun and P. Jin, “An opportunistic maintenance strategy for offshore wind turbine system considering optimal maintenance intervals of subsystems.,” *Ocean Engineering,* vol. 216, p. 108067, 2020.

[66] A. Kolios and D. Brennan, “Review of existing cost and O&M models, and development of a high-fidelity cost/revenue model for impact assessment,” ROMEO, 2018.

[67] H. Seyr and M. Muskulus, “Decision support models for operations and maintenance for offshore wind farms: a review,” *Applied Sciences,* vol. 9, no. 2, p. 278, 2019.

[68] I. Dinwoodie, D. McMillan, M. Revie, I. Lazakis and Y. Dalgic, “Development of a combined operational and strategic decision support model for offshore wind,” *Energy Procedia,* vol. 35, pp. 157-166., 2013.

[69] O. Endrerud, J. Liyanage and N. Keseric, “Marine logistics decision support for operation and maintenance of offshore wind parks with a multi method simulation model,” in *winter simulation conference,* 2014.

[70] S. Ross, Stochastic Processes, John Wiley & Sons., 1995.

[71] A. Hoyland and M. Rausand, System reliability theory: models and statistical methods, John Wiley & Sons., 2009.

[72] K. Chan and J. Cryer, Time series analysis with applications in R, Springer Publication, 2008.

[73] J. Leigh and S. Dunnett, "Use of Petri nets to model the maintenance of wind turbines," *Quality and Reliability Engineering International,* vol. 32, no. 1, pp. 167-180., 2016.

[74] T. Murata, "Petri nets: Properties, analysis and applications," in *IEEE,* 1989.

[75] BVG Associates, "Guide to Floating Offshore Wind - Floating Wind Lifecycle Overview," 2023. [Online]. Available: https://guidetofloatingoffshorewind.com/floating-wind-lifecycle-overview/. [Accessed 10 June 2023].

[76] P. Tavner, "Offshore wnd power reliability, availability and maintenance," in *Energy Engineering, Institution of Engineering and Technology,* 2021.

[77] R. Proskovics, "Intro Risk Float Wind," ORECatapult, 2017.

[78] B. Jenkins, A. Prothero, M. Collu, J. Carroll, D. McMillan and A. McDonald, "Limiting wave conditions for the safe maintenance of floating wind turbines," in *Journal of Physics: Conference Series (Vol. 2018, No. 1, p. 012023).*

[79] J. McMorland, M. Collu, D. McMillan and J. Carroll, "Operation and maintenance for floating wind turbines," *Renewable and Sustainable Energy Reviews,* vol. 163, p. 112499, 2022.

[80] S. Uzunoglu, "Yaw motion of floating wind turbine platforms induced by pitch actuator fault in storm conditions," *Renewable Energy,* vol. 134, 2019.

[81] O. Gaidai, V. Yakimov, F. Wang, F. Zhang, R. Balakrishna, "Floating wind turbines structural details fatigue life assessment," *Scientific Reports,* vol. 13, no. 1, p. 16312, 2023.

[82] Crown Estate Scotland, "Awards: Lead Applicants, Project Partners, Area, Capacity and Foundations," Crown Estate Scotland, 2022.

[83] J. McMorland, C. Flannigan, J. Carroll, M. Collu, D. McMillan, W. Leithead and A. Coraddu, "A review of operations and maintenance modelling with considerations for novel wind turbine concepts," *Renewable and Sustainable Energy Reviews,* vol. 165, p. 112581, 2020.

[84] C. Mainexa, A. M. Avossa, F. Ficciardelli, D. Corio, G. Troise and C. Georgakis, “Maienza C, Avossa A, Ricciardelli F, Coiro D, Troise G, Georgakis CT. A life cycle,” *Applied Energy,* vol. 266, p. 114716, 2020.

[85] S. Heidari, “Economic modelling of floating offshore wind power: Calculation of levelized cost of energy.,” Mälardalen University, 2017.

[86] D. Ahn, S. Shin, S. Kim, H. Kharoufi and H. Kim, “Comparative evaluation of different offshore wind turbine installation vessels for Korean west-south wind farm,” *International Journal of Naval Architecture and Ocean Engineering,* vol. 9, no. 1, pp. 45-54, 2017.

[87] I. Bayati, “Challenges and opportunities of major maintenance for floating offshore,” World Forum Offshore Wind, 2021.

[88] I. Bayati and L. Efthimious, “Challenges and opportunities of major maintenance for floating offshore wind,” World Forum Offshore Wind, 2021.

[89] M. Duka, A. Gumber, F. Egil and B. Steffen, “The role of policies in reducing the cost of capital for offshore wind,” *Iscience,* 2023.

Chapter 3 : Impact of FOW Limitations on Site Accessibility

This chapter aims to understand the operational impact of the additional challenges and limitations on non-financial KPIs for floating offshore wind sites.

As discussed in Chapter 2, forthcoming FOW sites will encounter new obstacles alongside the existing limitations on site accessibility, including extended distances to shore, more remote deployment locations, and potential constraints on turbine motion. A KPI crucial for assessing future accessibility, which measures the frequency of safe site/asset access, is thoroughly examined in this chapter. The discussion encompasses an overview of accessibility, encompassing prevailing weather limitations on maintenance operations. Furthermore, this chapter evaluates additional location-related challenges, such as water depth and distance to shore, utilizing UK and specific Scottish sites for analysis. The unique challenges posed by FOW and the concept of workability is introduced, with details of the methodology used in existing literature, the differences in results for different platforms, and a comparison with a bottom-fixed equivalent site. An overview of the Chapter is provided in Figure 3.1.

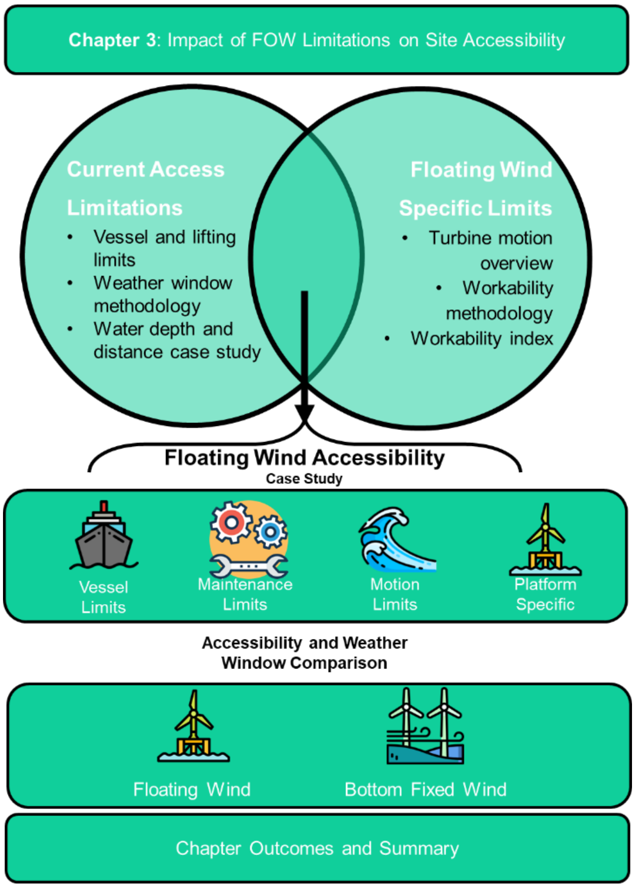


Figure 3.1. Chapter 3 overview and summary

3.1. Background

Accessibility refers to the ease and frequency with which maintenance personnel and equipment can safely access and operate at offshore wind farms. Factors influencing accessibility include the proximity of the wind farm to shore, water depth, weather conditions, and the design and layout of the platform or support structure. Ensuring optimal accessibility is crucial for efficient and cost-effective O&M activities, as it directly impacts the overall performance and profitability of offshore projects.

Access to site for BFW sites, and other offshore generation technologies, is limited by weather conditions. While periods of strong and consistent wind resource are advantageous for maximising project revenue, this will limit access to site, and in the event of a turbine failure, will prolong downtime, and therefore increase OpEx (see Chapter Figure 2.3 for full OpEx breakdown) . Limits are placed on met-ocean conditions to ensure the safety of the technicians and the use of resources, such as cranes and maintenance vessels. The exact limitations and details of the met ocean parameters monitored and limited are provided in Section 3.2.

Within offshore wind accessibility, and more specifically time-based accessibility (TBA), is a statistical measure of how easy a site is to access. This is a time-based metric where quantifying the number of hours (typically per year) are with safe operational limits for O&M activities, as described in Equation 3.1

$$TBA = \frac{\sum(T < MOL)}{T} \tag{3.1}$$

Where T is the number of timesteps, MOL is met-ocean limits.

This is a vital KPI used within offshore wind and is closely related to economic measures such as availability, downtime/lost revenue, and therefore total OpEx. The accessibility of offshore sites is therefore a critical factor that will determine the cost of operating an offshore wind farm. However, in order to fully understand the accessibility challenges of a site, consideration must be given to the duration of the access periods.

A commonly used metric within offshore wind O&M is weather days. This is defined as the number of full workable days where weather conditions would allow for work to be completed. This metric is most commonly used for large maintenance campaigns such as major component replacement (MCR) and within the installation campaign.

3.1.1. Formal Weather Window Definition

A weather window (WW) is an uninterrupted period of access. The WW required (WW_R) for maintenance is defined by Dowel et al. [1], as "a period of time during which if a given maintenance action is started, it can be completed". This work defines WW_R components are in Equation (3.2).

$$WW_R = 2 \times TT + TTR \tag{3.2}$$

Where WW_R is the required weather window length [hours], TT is the travel time between the port/base and the site [hours], and TTR is the time to repair [hours]. Site accessibility (WW_A) is determined based on the number of WWs which satisfy the WW_R conditions, as shown in Equation 3.3

$$WW_A = \frac{\sum WW_R < WW_L}{time\ duration} \tag{3.3}$$

Where WW_L is the available weather window length at any given timestep (in hours), WW_R is the required weather window length, and time duration is the total number of hours being analysed (e.g., 8760 – 87600 for 1 – 10 years). WW_R can vary based on the distance to shore, vessel capabilities, and the type of maintenance action required. WW_R can range from a few hours for minor repairs and scheduled maintenance actions, to several days for major component replacements. WW analysis plays a vital role both within the scheduling of O&M activities and the construction campaign. Full details on the calculation of WW_L for a given site is provided in Section 3.2.1.

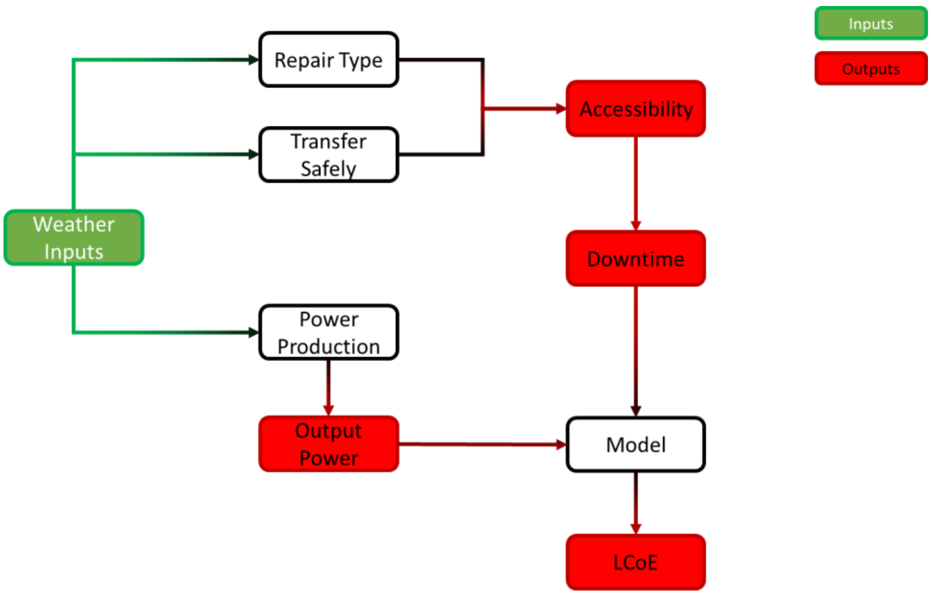


Figure 3.2. Impact of weather inputs on offshore wind operations KPIs [3]

In addition to the direct impact of weather conditions on accessibility, met-ocean conditions can have significant impacts on several aspects of the O&M modelling process as shown in Figure 3.2. Weather inputs also have additional impact on other operational metrics such as availability [2]. Weather inputs influence both the revenue calculation, and OpEx estimates, making it vital for accurate prediction of levelized cost of energy (LCoE) (Chapter 2, Section 1.2).

Reduced accessibility prolongs the downtime of unexpected failures due to increased waiting times for suitable weather windows. As discussed in previous Chapters, downtime represents the cost of lost revenue. The total cost is dependent on turbine rating, wind speed, revenue per MW and the duration of the downtime period. conditions This can be increased due to increased turbine capacity, increased WW_R, and prolonged waiting times. Therefore, realistic accessibility analysis is vital to providing rational OpEx predictions.

As well as being vital for corrective maintenance procedures, in terms of estimation of waiting time and downtime predictions, WW_L and accessibility analysis is vital for the scheduled maintenance campaign. As these activities take considerable planning, annual servicing is typically based within the summer months (in the Northern Hemisphere) when high access rates are expected, due to mild weather conditions. This is especially important for scheduled activities which require the use of specialist expensive maintenance equipment, such as JUVs or HLVs utilised for major repairs. For FOW sites, it is expected that T2S activities will be scheduled for summer months accordingly due to the long periods of access required for the towing of the asset.

3.2. Current Limitations Analysis

Accessibility to site is a growing concern as sites move further from shore, as the WW_R is lengthened, and met-ocean conditions become harsher. For BFW, Access/No Access decisions are based on the weather operational limitations of the chosen transport/vessel. At present, the key input parameters for O&M modelling of conventional turbines are significant wave height (Hs) and mean wind speed. Hs is defined as the mean height (measured from trough to crest) of the highest one-third (33%) of waves that occur in a given period [4]. Wind speed limits impact both vessel safety and the type of maintenance activity. Other transport options, such as helicopters, require additional weather inputs such as visibility. Each met ocean parameter has its own direct and indirect impact on the different areas of the modelling process and the KPI as highlighted in Table 3.1

Wind speed is one of the most important parameters. It directly determines accessibility, maintenance activity, power output, and site revenue. To accurately measure power production, the wind speed at hub height for the specific site is used in partnership with the turbine-specific power curve, typically found in the manufacturer's datasheet. This informs capacity factor, power generated and therefore project income. Wind speed also limits activities that typically involve crane operation, such as blade maintenance, which is limited to 12.5 m/s [5]. Vessels are typically limited to a wind speed of 20 m/s [6] [7] for safe transfer. However, in most cases, Hs is viewed as the limiting factor for transfer, as vessel limits are often included in charter contracts. For maintenance to be carried out, a suitable weather window must be available. A weather window is defined as the total length of time needed for a maintenance operation to be completed, including TTR, vessel mobilisation, and travel time. Where vessel mobilisation consists of preparing the vessel, e.g. fuel checks, loading equipment. This requires that all inputs from the met ocean model be within safe operational limits. The relationship between met ocean inputs and output KPIs is shown in Figure 3.2.

The main met ocean limits imposed are vessel related. Crew Transfer Vessels (CTVs) are the most commonly used vessels for this purpose, characterized by their ability to transfer in wave heights (Hs) of 1.5-2 meters. CTVs are preferred for their cost-effectiveness and efficient transfer of technicians and equipment between the shore and wind turbines. On the other hand, Service Operation Vessels (SOVs) are larger vessels specifically designed to accommodate up to 60 technicians and are capable of withstanding harsher sea conditions. SOVs typically remain within the wind farm for extended periods, with some able to stay offshore on a 2 week on/off basis. Supported by smaller daughter craft, SOVs can transport technicians to individual turbines, enhancing maintenance capabilities. Although SOVs are capable of operating in wave heights of 3-5 m, their costs can be up to ten times that of a CTV.

Met-ocean inputs to O&M models can be collected/generated using hindcast models. Hindcast models are the most common substitutes for measured data [8] typically used in the planning stage of a site by using on-site measurements to determine the available resource [9] [10]. Alternatively, probabilistic models can be used to model wind variations and sea states. The frequency distribution of wind speeds at most sites is typically represented by the two-parameter Weibull distribution as used in [11]. Wind speed and Hs show a strong correlation;

hence, Weibull distributions can also be used to determine the sea state of a site [12]. A sea state is defined as the state of the surface of the water at a given location at a given time. It is defined by three parameters: Hs, mean zero crossing period (Tz), and wave spectrum type, where Tz is the average time interval between consecutive points where the wave crosses the baseline (zero level) in an upward or downward direction. It is assumed that the sea state is constant for 1-3 hours [13]. Markov theory is another method of modelling environmental conditions and is used extensively within existing work to determine wind speed across a site. Weather and sea state are often regarded as a stationary first-order Markov process [14] using historical weather data to determine a Markov matrix. [15] [16] [17] all use a variety of Markovian methods to simulate the inputs. Other methods include auto-regression techniques (AR). AR techniques can be used to determine both wind speed and wave height. There are also data transformations required for AR use, such as removal of the monthly mean and diurnal variations.

Publications [18] and [21] make use of historical data such as the CEFAS wave net open-source data for wave parameters. The type of maintenance activity and vessel transfer will continue to be limited by Hs and mean wind speed. For FOW operations, the specific limits may change due to the impact of met ocean conditions on turbine motion. The overall modelling and collection of these inputs will remain unchanged.

For FOW sites, BFW accessibility limitations will continue to restrict access to site. In addition, locational factors such as distance to shore, and potential harsher met-ocean conditions, are set to reduce the access to these sites.

Table 3.1. Offshore wind maintenance met ocean O&M parameters and their influence on project KPIs [3]

Met ocean Parameter	**Format**	**Direct Impact**	**Indirect Impact**
Wind Speed	Metres Per Second (m/s) in hourly timesteps	Type of maintenance Vessel Impact Lost Power Production	Accessibility Availability Capacity Factor LCoE
Significant Wave Height	Metres	Vessel accessibility Site accessibility	Downtime LCoE
Visibility	Statute Miles	Helicopter Accessibility Site Accessibility	Downtime LCoE
Wind/Wave Direction	Degrees	Vessel Ability to Push on Safely (failed transfer)	Downtime LCoE
Tide	Metres	Ability for vessels to leave port (failed transfer)	Site Accessibility Downtime LCoE

3.2.1. Weather Window Accessibility Methodology Simulation Tool

This thesis uses a sequential weather window model as used in [22] and described in Figure 3.3. Detail of the models/simulation tools used within this thesis is provided in Appendix B. This methodology calculates the total duration of access at each time step of the data series, known as the weather window length, WW_L. Therefore, a single “block” of access contains various WW_L’s. The model defined weather windows sequentially, where one larger weather window is made up of smaller length windows, e.g., an access period of 3 hours contains 3 windows of 3 hours, 2 hours and 1 hour. It is assumed that the weather conditions taken at the centre of the site are consistent throughout the travel path of the vessel to and from site. It is also assumed that all resources, such as spare parts, vessels and crew, are always available for deployment.

The inputs to the model are a pre-processed timeseries of Access/No Access decisions based on the met ocean conditions at site, and the vessel/maintenance action limits set. When conditions are within these limits, safe access to site is permitted. A flow chart illustrating the process is also shown in Figure 3.4.

The model assumes that the conditions at site, are consistent with the conditions along the vessel travel path. Each timestep where $WW_R > WW_L$ are deemed as NO ACCESS, and therefore waiting time is prolonged. This then has a significant impact on overall downtime and therefore can result in an increase in overall OpEx.

Within offshore wind, activities are typically classed as minor, major, or replacement [23]. The average duration of such activities is detailed in Table 3.2 with details on their contribution to total failures. While replacements have the smallest contribution to the overall failure rate, this does not necessarily indicate the lowest contribution to total turbine downtime or OpEx. Due to the longer TTR, and therefore longer WW_R, there can be an increased waiting time for access.

As the taxonomy of the turbine remains the same for both FOW and BFW turbines in terms of components and subcomponents, it is assumed that TTR will be similar. However, it is noted that the FOW will encounter additional failures due to the addition of the substructure. As of yet, the failure rates, and TTR, of these components are unknown. It could also be argued that the addition of these components will have little to no impact on the total asset failure rate as design such as the Stiesdal Tetra concepts, which aim to have zero maintenance conducted on the floater [118].

In addition to the TTR, the WW_R is also highly dependent on the location and distance to shore of the wind farm.

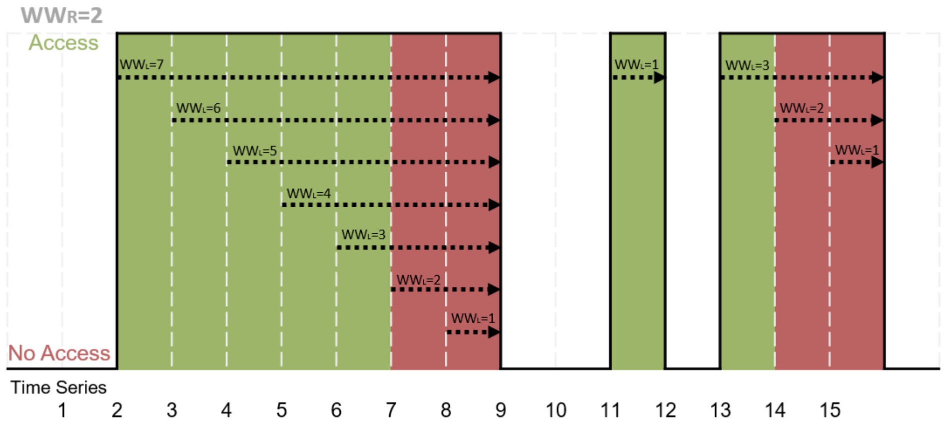


Figure 3.3. Weather Window (WW) methodology showing access for a WW requirement of 2 hours. where WW_L shows the length of available WW at each timestep (1 hour). Green indicates access period is sufficient and red indicates that the WW length does not meet the requirement for maintenance.

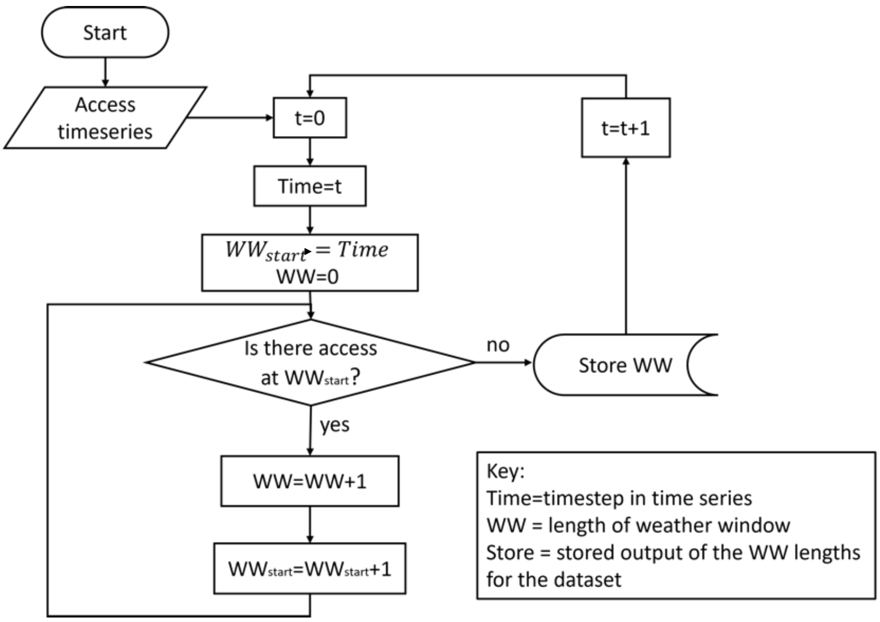


Figure 3.4. Weather Window methodology flow chart

Table 3.2. Average TTR for each failure category and the overall contribution to total failure rate taken from Carroll et al. [23] for 2 – 4 MW offshore turbines.

	Minor	Major	Replacement
Average TTR [hours]	6	16	66
Contribution to Total Failure Rate	82%	14%	4%

3.2.2. Distance Case Study

As previously mentioned, as distance to shore increases, as does the length of WW_R, making accessibility more challenging. It is widely accepted that long access durations are less frequent. As of 2020, the majority of commercial offshore windfarms currently operating are deployed within 20 km to shore, at a maximum water depth of 30 m. However, more recent offshore wind leasing rounds are seeing this dramatically increase, with 2022 ScotWind sites having an average distance to shore exceeding 85 km. However, it should be noted that the ScotWind leasing round is part of a more established market. The progression of distance to shore for previous UK leasing rounds is highlighted in Figure 3.5.

Figure 3.5 shows a clear trend in the increase in distance to shore. This is further amplified by the introduction of the FOW sites. Rowell et al. [26], compares the accessibility of future ScotWind FOW sites with existing BFW sites. The study investigates the potential challenges associated with the accessibility of FOW sites by conducting a comprehensive analysis of the accessibility of 10 FOW and ten BFW farm sites located in different regions worldwide. Using the same weather limitations, the results of the study indicate that the accessibility of floating wind farm sites is generally more challenging than that of BFW sites. The authors found that floating wind farm sites are typically located farther from shore and in deeper waters, requiring longer and more elusive weather windows. Additionally, the wave and wind conditions at floating wind farm sites can be more severe, which may increase the operational and maintenance costs of the turbines.

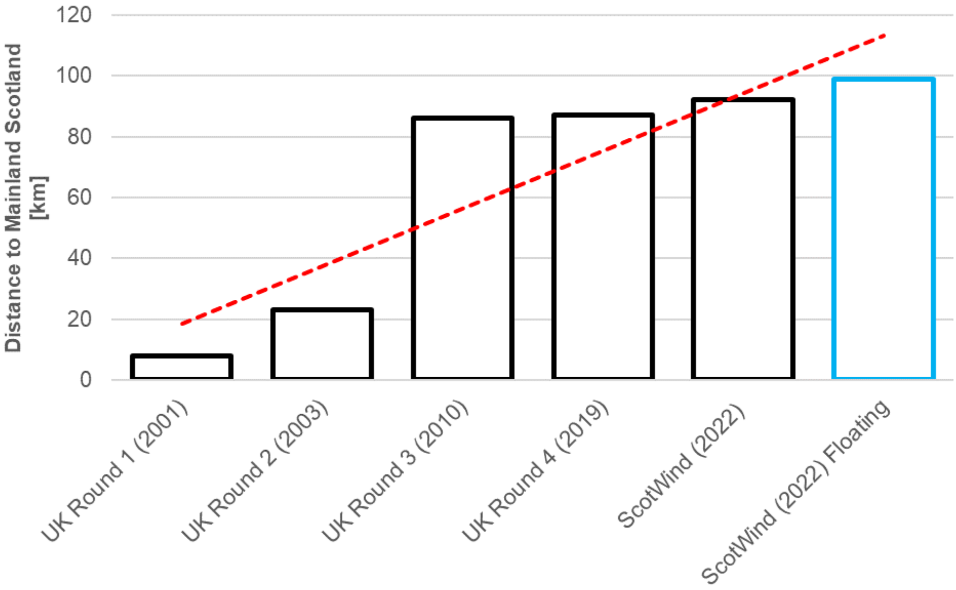


Figure 3.5. Average distance to shore of UK leasing round zones from 2001 to present. (Site database taken from [25]).

Table 3.3 Site details for median site for UK offshore wind leasing rounds (2000-2023).

	Round 1	Round 2	Round 3	Round 4	ScotWind	ScotWind (Floating Only)
Site	Gunfleet Sands	Sheringham Shoal	East Anglia ONE	Morgan (Area 6)	NE4	NE8
Distance to shore [km]	8	20	55	65	55	90
Average Hs [m]	0.80	1.16	1.24	1.12	1.43	1.90

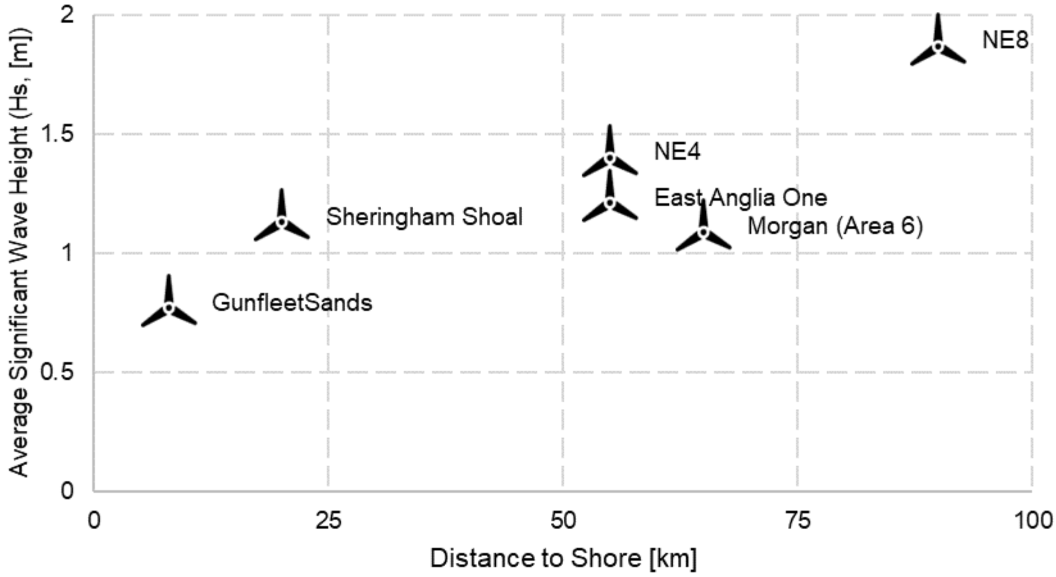


Figure 3.6 Relationship between distance to shore and average significant wave height (Hs) for average sites from Table 3.3

The median site from each leasing round is determined based on the distance to shore (Figure 3.6). The median is selected, as site conditions cannot be averaged due to scaling of conditions, therefore the median is selected to use a specific site as reference. Using the selected case studies, the TBA, minor, major and replacement accessibility is determined for each of the leasing rounds. The selected sites, with details of distance to shore and mean Hs is given in Table 3.3. It is assumed that maintenance actions will be carried out by a CTV with Hs limits of 1.5 m and a speed of 15 knots. Subsequent results for time based accessibility are shown in Figure 3.7, showing the percentage where weather limits are within safe working limits. It is assumed that all sites will be serviced by CTV Therefore, a Hs limit of l.5 m and a wind speed limit of 15 m/s is applied,

It should be noted that the challenging accessibility of the ScotWind, and more specifically FOW ScotWind sites is dependent on several factors such as site conditions. However, as highlighted in Table 3.5, as distance to shore increases as does the average Hs.

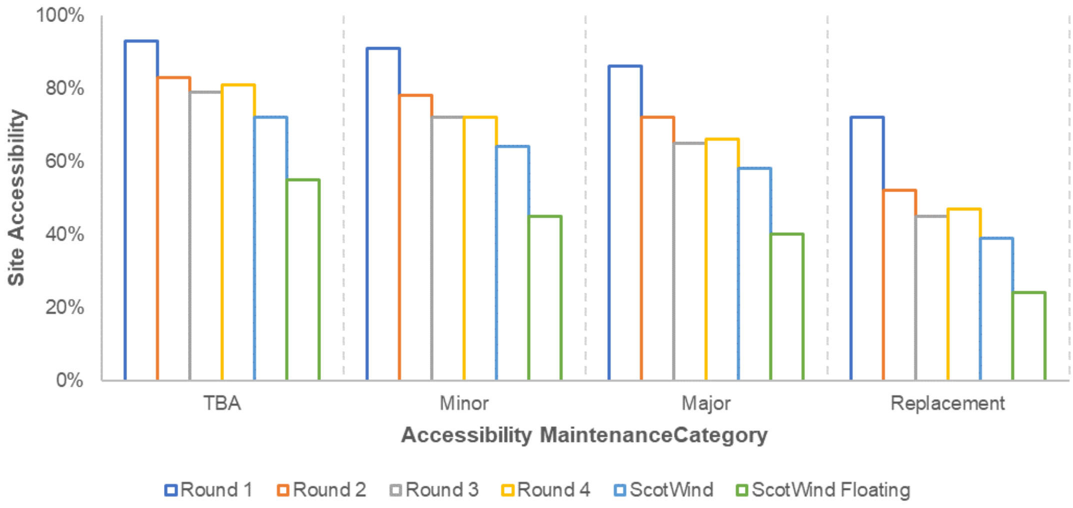


Figure 3.7. Site accessibility of sites from table 3.3 for time-based accessibility (TBA), minor, major and replacement maintenance action

These challenging environmental factors are heightened due to the requirement of longer WW_R, due to increased travel time to site.

However, for less established markets such as US and Asia who have been unable to compete in the BFW market due to water depth restrictions, distance to shore will be much less than that of the UK market. Therefore, the WW_R is also expected to be reduced.

3.2.3. Depth Impact

As highlighted in Section 3.2.2, the trend, particularly within UK waters, is that as distance from shore increases, as does water depth and average Hs. However, for a few regions, deep water sites are located in close to shore regions. Using ScotWind regions, with varying water depth, and distance to shore, in addition to European case studies, TBA of the sites against water depth are determined. Results are shown in Figure 3.8 with details of the case studies provided in Table 3.4.

Table 3.4. Water depth time-based accessibility case study regions

Name	**Morro Bay**	**Mayflower Demo**	**Provence Grand Large**	**NE7**	**Firefly**	**Goto Sakiyama**
Water Depth [m]	500-1200	35-65	100	120	200-250	100 - 300
Location	Northern California, US	Massachusetts, US	France, Europe	Scotland, UK	South Korea, Asia	Japan, Asia

Results show that for very deep sites, such as Morro Bay, accessibility is limited. However, other factors must be considered such as bathymetry. In addition to depth, bathymetry has a significant impact on the interaction between waves The bathymetry across the site will capture specific underwater topography such as trenches and ridges could have significant influence over wave conditions in particular regions of the wind farm area, or even along the travel path to site.

Results shown in Figure 3.8 highlight that there is a more consistent relationship between distance to shore and accessibility, than there is between water depth and TBA. However, both factors influence wave conditions at site.

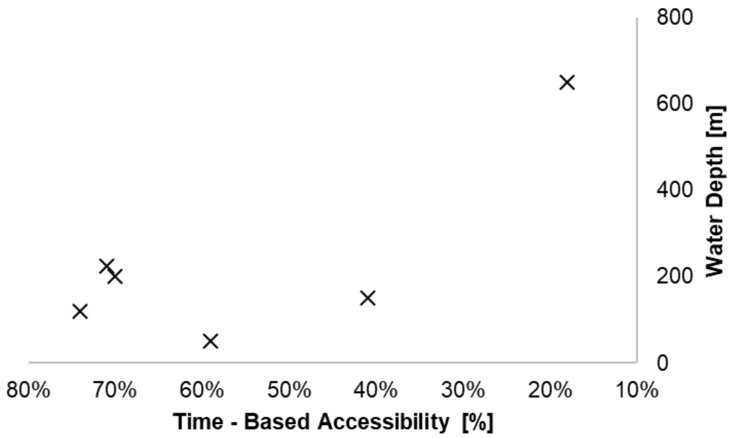


Figure 3.8. Water depth versus time-based accessibility for case studies provided in Table 3.4

3.3. FOW Specific Limitations

It is widely cited in the literature that turbine motion will be one of the biggest challenges for FOW O&M activities. In recent years there has been significant research on turbine response in specific sea state conditions [27] [28] [29], with the majority of these works focusing on determining turbine motion during extreme weather conditions to determine the survivability of the asset or the impact of motion on turbine degradation and fatigue. However, research into determining turbine motion for maintenance sea states (e.g., conditions with Hs of less than 4 m [30]) is limited.

It is vital that future works regarding O&M modelling have an appreciation of this additional factor when considering the health and safety parameters and limitations required for safe working conditions for technicians. It is expected that additional weather and environmental factors, such as peak wave period (Tp) and, potentially, wave direction, will be required to assess the workability of the asset [31] . In wave measurement, Tp is the time interval between successive wave crests corresponding to the frequency at which the wave energy is most concentrated. This concept has been explored by Jenkins et al. [32], Scheu et al [33] [34], and the CoreWind project [35].

Jenkins et al. [32] explored limiting wave conditions to allow for safe maintenance procedures in floating offshore wind farms. This was done by characterising the structure's motion response to varying wave frequencies, to determine the response amplitude operator (RAO). This work used the 15 MW UMaine semi-submersible NREL reference platform [36] [37]. This work elaborated on the initial work of Scheu et al. [34].

The impact of turbine motion on technician wellbeing has been quantified in the CoreWind project and in the work of Scheu et al. through the introduction of the Workability Index (WI). This thesis aims to extrapolate the workability results from the CoreWind project

[35] and the results from Scheu et al. [33] to future ScotWind sites. Both works utilise results from the LIFES50+ project [31]. The LIFES50+ project aimed to optimise and qualify a technology readiness level (TRL) of 5 for two innovative substructures for 10 MW turbines. The project focused on the following regions with varying sea state conditions: the Mediterranean Sea (calm), US East Coast (moderate) and Scotland's West Coast (severe). These are the same conditions used to evaluate workability in both Scheu et al. [33] and CoreWind [35]. Both works use a similar methodology and provide workability and limiting sea state conditions for maintenance operations for a few different platform designs.

3.3.1. Workability

Workability is defined by CoreWind as "the ability of technicians to perform their work without being impaired by negative factors influencing their human comfort" [35]. The work by CoreWind [35] places high importance on technician wellbeing, as they also consider transportability within their work. This is the technician's ability to travel without impairing human discomfort. As sites move further offshore this becomes an increasing concern as travel time from shore to site increases and therefore does potential crew discomfort.

The work of Scheu et al. [33] focuses solely on human comfort when working on the asset, and therefore the focus of the work is workability only. Workability is defined as in CoreWind [35].

The CoreWind project [35] aims to achieve cost reduction through the enhancement of floating wind technology. The project focuses on two concrete-based floater concepts, supporting large-scale turbines (NREL 15 MW reference turbine). Work package four focuses on optimising O&M strategies and installation techniques. Within this report [35], they simulate OpEx for a 1.2 GW reference wind farm in the case study regions defined in the LIFES50+ project [31]. One of the key focuses of this work is an analysis of the accessibility methods and limitations for floating turbines, due to technicians' working limitations during specific predefined limiting motions. These results are then used to conduct a full OpEx lifecycle analysis with a comparison of a tow to shore and in situ maintenance for major component replacements.

Scheu et al. [33] present a motion assessment of an 8 MW turbine upon 5 different platform designs: a monopile reference BFW substructure, and unspecified floater designs A, B, C, and D. The respective floater design/concept of Designs A-D is not disclosed. However, it is stated that the work considers a spar [38], a tension leg platform (TLP) [39], a simplified semi-submersible [40], and an in-house designed barge concept. This work highlights that the motion response critically depends both on the floater configuration and on the site met ocean conditions. This research builds upon earlier work from Scheu et al. [34] where a methodology for assessing the influence of motions on personnel located on the structure was created. This allowed for the comparison of availability and downtime with/without the consideration of turbine motion limits.

A comparison of both works inputs is provided in Table 3.5.

The work by Scheu et al. [33] is limited to wave conditions of 4m due to this being defined as the highest expectable Hs conditions during which personnel could safely access a site [30]. The CoreWind project has larger simulation bins than that of the work of Scheu et al., with a difference of 2s between defined Tp sea state definitions, and a maximum Hs of 8.5 m considered.

Both works follow the same general methodology to determine turbine motion response, as simplified in Figure 3.9. Within these works, a sea state is defined as a specific Hs and Tp combination.

Table 3.5. Comparison of input data used by Scheu et al. [33] and WP4 of the CoreWind project [35].

	CoreWind [35]	**Scheu et al. [33]**
Geographical Focus	Mediterranean Sea, US East Coast, Scotland West Coast	
Platform Designs	Spar (WindCrete) Semi-submersible (ActiveFloat)	Designs A-D Specific platform unknown but includes (spar [38], TLP [39], semi-submersible [40], barge (inhouse))
Software	OrcaFlex WAMIT	LACflex and ROSAP simulation suite (Ramboll in house tool)
Hs Values [m]	0.5:1:8.5	0.5:0.5:4
Tp Values [s]	1:2:23	2:1:15
Wind Turbine	NREL 15MW Reference Turbine	8 MW (107 m hub height from mean sea level)

The hydrodynamic parameters of each structure (in particular, added mass, radiation damping, wave load transfer functions), as well as the mass distribution and mooring system characteristics, are unique for each configuration, and therefore must be determined before beginning the motion response analysis. When designing an offshore wind turbine, specific design load cases are considered for the conceptual/preliminary design, as specified in the relevant IEC Design Load Case (DLC). However, the load cases documented here are focused on determining structural integrity, with no provision for human exposure/comfort. In both [35] and [33], the specific load cases, or sea states, are Hs and Tp combinations where maintenance could safely be performed, based on existing vessel limitations. The structure aero-servo-hydro-elastic response is then determined using software detailed in Table 3.5. The time series data could include movements in six degrees of freedom, occurring at various points on the structure. As a result, not only the nacelle but also the regions of the substructure

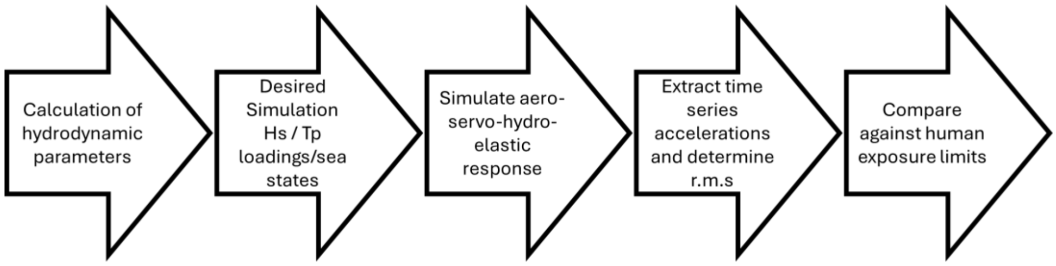


Figure 3.9. Streamlined process for determining technician motion during maintenance operations.

where technicians perform inspection tasks may be significant for evaluation. The root mean square (r.m.s.) values of combined lateral and rotational acceleration signals are then compared against existing legalisations detailing safe human exposure limits to motion to determine workability.

3.3.2. Workability Index

Workability Index has been discussed within the literature in CoreWind [35] and Scheu et al. [33], identifying the workability index (WI) for several different floating platform designs. Workability is a measure of how safe it is for technicians to perform maintenance on the asset in several sea states which are a combination of Hs, mean wind speed, and Tp. Currently, there is no definitive guidance to determine an acceptable WI for offshore wind operations. This introduces a balance between site accessibility and technician health and safety.

Using the results generated from the r.m.s. and the subsequent turbine lateral motion, workability of the asset in specific met ocean conditions can be determined. This can then be normalised to allow for comparisons using a workability index (WI). The WI is defined in Equation 3.4.

$$\mathrm{WI} = \frac{\sum t_{wc_i}}{\mathrm{T_t}} \tag{3.4}$$

Where t_{wc_i} is the number of workable hours (workability is equal to one) and $\mathrm{T_t}$ is the total number of hours.

For one sea state condition, individual WIs from different motion directions (lateral, vertical, and rotational) are calculated and multiplied to provide the WI of the specific Hs-Tp combination. The resulting WI is calculated for each Hs-Tp combination of interest. A WI of 1 indicates no impairment of working conditions due to motion, a value of 0 means that work is not possible under the respective conditions.

CoreWind [35] and Scheu et al. [33] reference the Nordforsk [41] limiting criteria for r.m.s. accelerations and roll motions on vessels for different types of activity consisting of light manual work, heavy manual work, and intelligent working. However, there is no concrete definition of these types of activities within offshore wind O&M. Within CoreWind [35], the limitations for *intelligent working* and *transit passenger limits* are used as workability limits. Within Scheu et al. [33], the suitability of the Nordforsk limits is discussed. Within ISO 261/3 (1985), intelligent working is described as "half an hour exposure period", making it non-representative of technicians' offshore working shift pattern. Within the Nordforsk [41] working reference, the maximum working duration is two hours, which is still insufficient in capturing the 10–12-hour shifts of offshore personnel. Therefore, now legislation and limitations which capture motion limitations during this timeframe are required. Using existing legislation, "transit passenger" criterion is recommended as this has the highest exposure duration. For both works, it was found that the conservative motion criteria "Transit passenger" allows for less workable conditions than the motion criteria "Intellectual Work".

While there is existing guidance detailing safe human exposure, there is no specific limit provided detailing a safe WI for offshore operations. Scheu et al. (Scheu et al., 2018a) detail that WI > 90 % has slight influence, 60 % < WI < 90 % has a significant influence and WI < 60 % as having a major influence.

No suitable WI is detailed in CoreWind work package 4 [35] as the non-workable conditions lie outside the wave conditions relevant for the operation and maintenance activities. The CoreWind project utilised Hs limits of 3 m for SOV and 1.5 m for CTV strategies, with limiting sea states only occurring in Hs/Tp combinations where Hs exceeded these boundaries.

3.4. Floating Wind Accessibility Case Study

At present, offshore wind access/no access decisions are based on significant wave height (Hs) and mean wind speed. Vessels used in the maintenance procedure all have a specific Hs limit for safe transfer. This is the most common weather restriction imposed on access offshore. The wind speed limit is determined based on the type of maintenance operation, such as lifting operations or working at height. Wind speed limitations are typically between 12 - 15 m/s and Hs from 1.5 - 5 m depending on the capability of the vessel and the type of repair. Of the two metrics, Hs is the most used.

As discussed in Section 3.3, the motion of the turbines and the safe working conditions of technicians is captured through the WI, based on a combination of Hs and Tp values. This section provides an overview of the impact of these additional limitations on site accessibility and provides a comparison of workability limitations and vessel limitations.

3.4.1. Case Study

This case study aims to highlight the impact of workability limitations on future floating wind farms, by assessing its impact on key operational KPIs.

The global ambition has been accelerated by the results of the historic 2022 ScotWind leasing round, which saw over 17 GW being allocated to FOW projects [136]. Within the previous literature (Chapter 2, Section 2.1.2), the focus of case studies has been placed in offshore locations surrounding mainland Europe. As of 2020, the majority of commercial offshore windfarms operating were deployed within 20 km to the shoreline at a maximum average water depth of 30 m [43]. The ScotWind allocation zones used in this case study have an average distance to shore of 85 km, many of which are located in previously untapped areas with high wind resource. A total of 13 FOW projects across nine zones have been allocated. This work models a single FOW farm for each of the zones indicated in Table 3.6, where details of distance to shore, vessel strategy and capacity are given. For zones, such as E1, which will host multiple projects, the average capacity for FOW projects in that region is selected as the wind farm capacity.

The average Hs at site is based on 30 years of hindcast ERA 5 [44] data from the centre of the site. It is assumed that conditions across the travel path to site are less than or equal to that at site, as in the work of Rinaldi et al. [45], Dinwoodie et al. [46] and Joschko et al. [47]. As offshore wind sites move further from shore, this is an area for further investigation.

The vessel strategy was selected based on the distance to port and average Hs across the site. It is generally assumed that above 50 nautical miles (nm) from site (~90 km) an SOV strategy will be utilised due to the long travel times to site [48]. The SOV can stay at sea for weeks at a time. The SOV also has the added advantage of an increased Hs limit; however, the charter cost of an SOV can be ten times more than that of a CTV [49]. In this analysis, it is assumed that the CTV and SOV have Hs limits of 2 and 4 m respectively.

Table 3.6. Floating ScotWind zones with distance to shore, installed capacity, average significant wave height [Hs] and selected vessel strategy.

Zone	Distance to Port [km]	Site Capacity [GW]	Average Hs [m]	Vessel Strategy
E1	120	1.9	1.7	SOV
E2	135	1.3	1.9	SOV
NE1	55	1.4	2.2	SOV
NE2	65	1	1.5	CTV
NE3	55	1	1.6	CTV
NE6	45	0.5	1.6	CTV
NE7	100	3	2.0	SOV
NE8	95	0.96	1.9	SOV
N2	85	1.5	2.5	SOV

3.4.2. Access Limitations

Due to the complex designs of floating wind platforms, the platform design will have its own unique response in different weather conditions. Therefore, it is not possible to make a generalisation regarding the workability of all floating turbines. Using the results from Scheu et al. [33] and the CoreWind [35] project, the workability limits are imposed on the ScotWind zones detailed in Figure 3.10. This work utilises the hourly ERA 5 database [44]. ERA5 is a comprehensive global climate reanalysis dataset produced by the European Centre for Medium-Range Weather Forecasts (ECMWF), providing hourly estimates of atmospheric, oceanic, and land-surface variables from 1950 to the present. Using hourly ERA 5 data [44], a wave scatter diagram is created for each region by normalising the Hs and Tp combinations seen at site to show the frequency of occurrence.

Values were categorised using a binning method of 1s for Tp and 0.5 for Hs, with the value stated in the table being the centre of the bin. These values were selected to match that of Scheu et al. [33]. The wave scatter diagrams for CoreWind [35] platforms ActiveFloat and WindCrete use a binning of 1 m Hs and 2 s Tp to match the original source. The workability for each platform type (WindCrete, ActiveFloat, Design A, Design B, Design C and Design D) is then imposed, along with the vessel limiting conditions. An example of this process is given in Figure 3.10 for Designs A and B, at site NE1. In this part of the analysis, WI ≤ 100 % is deemed unacceptable. For the CoreWind project, it is the WI based on the ability to carry out passenger transit.

As highlighted in Figure 3.10, the WI results greatly differ from design to design, therefore, it is clear that the accessibility of each platform design will be unique. While Scheu et al. [33] does not state the platform designs considered, the 4 designs include both a SPAR and a semi-submersible – the same platform types used within CoreWind.

NE1 - Design A

Hs [m] \ Tp [s]	3	4	5	6	7	8	9	10	11	12	13	14	14+
1	0.000	0.014	0.033	0.053	0.034	0.031	0.031	0.018	0.010	0.006	0.003	0.001	0.000
1.5	0.000	0.001	0.022	0.038	0.030	0.029	0.030	0.026	0.013	0.007	0.004	0.002	0.000
2	0.000	0.000	0.004	0.034	0.023	0.029	0.021	0.022	0.021	0.009	0.004	0.002	0.000
2.5	0.000	0.000	0.000	0.014	0.022	0.024	0.021	0.014	0.017	0.011	0.004	0.002	0.000
3	0.000	0.000	0.000	0.002	0.016	0.022	0.017	0.011	0.009	0.008	0.004	0.001	0.000
3.5	0.000	0.000	0.000	0.000	0.005	0.017	0.015	0.010	0.005	0.004	0.003	0.001	0.000
4	0.000	0.000	0.000	0.000	0.001	0.009	0.012	0.008	0.004	0.003	0.002	0.001	0.000

NE1 - Design B

Hs [m] \ Tp [s]	3	4	5	6	7	8	9	10	11	12	13	14	14+
1	0.000	0.014	0.033	0.053	0.034	0.031	0.031	0.018	0.010	0.006	0.003	0.001	0.000
1.5	0.000	0.001	0.022	0.038	0.030	0.029	0.030	0.026	0.013	0.007	0.004	0.002	0.000
2	0.000	0.000	0.004	0.034	0.023	0.029	0.021	0.022	0.021	0.009	0.004	0.002	0.000
2.5	0.000	0.000	0.000	0.014	0.022	0.024	0.021	0.014	0.017	0.011	0.004	0.002	0.000
3	0.000	0.000	0.000	0.002	0.016	0.022	0.017	0.011	0.009	0.008	0.004	0.001	0.000
3.5	0.000	0.000	0.000	0.000	0.005	0.017	0.015	0.010	0.005	0.004	0.003	0.001	0.000
4	0.000	0.000	0.000	0.000	0.001	0.009	0.012	0.008	0.004	0.003	0.002	0.001	0.000

Vessel limits   Platform Limits

Figure 3.10. Wave Scatter diagram for ScotWind Zone NE8 with vessel limits and workability limits highlighted, for Design A and Design B floating wind turbines.

Within [33] and [35] WI results differ due to the methodology used as Scheu et al. [33] focus on whole-body motions following the low-frequency motion of the floater, whereas CoreWind [35] uses the nacelle as the reference point.

When analysing only the workability it is clear that even for very high significant waves workable conditions exist. However, these specific sea states are removed due to vessel limitations. Environmental conditions such as water depth and soil conditions are not included within these works as potential limiting factors for substructure design suitability at the ScotWind sites considered within this work.

3.4.3. Modelling Assumptions

This modelling is based on the statistical based weather window model, as described in Figure 3.4. This model is limited to the data that has been available. The weather data utilised within this work is the ERA 5 hindcast 30 years database (1989-2019) [143]. Hindcast data relies on numerical models that simulate past conditions based on historical data and model physics. These models have inherent uncertainties, and their accuracy may vary depending on the specific variables being simulated and the spatial and temporal scales involved. It should be noted that while the hindcast data can give an understanding of the conditions at site, these models do not account for climate change effects which may have impact on future weather conditions.

In addition, the hindcast data, workability index limitations have been imposed as an input to the weather window model [134] [132]. The data provides a clear and transparent methodology which places confidence on its use. However, there is still potential bias within the original results. As presented in Chapter 4, the credibility of output results is dependent on the input values.

The modelling process involves averaging of weather window lengths across the 30-year period and therefore results may be sensitive to outliers.

3.4.4. Weather Window Model Adaptations

Using the weather window model described in Figures 3.3 and 3.4, the vessel-based access is replaced with the access limitations described in 3.4.1, where access is dependent on both Hs, wind speed, and Hs/Tp combinations. Outputs of ACCESS/NO ACCESS are then inputted through the same methodology.

3.5. Floating Wind vs Bottom Fixed Wind Accessibility Comparison

Both the operability and accessibility of an offshore wind farm are vital to the overall performance and economic viability of a project. For a site to achieve an availability of 90%, accessibility of 80% is required [2]. Accessibility is a statistical measure of how often a site can be safely accessed. For bottom-fixed offshore wind, this is the time in which weather conditions are within vessel limits. While this will still be true for FOW sites, platform motion must also be considered.

As the turbine experiences motion, workability becomes an increasing concern. Therefore, both workability and vessel limit accessibility must be considered to make access/no access decisions. This work proposes the concept of **sea state-based accessibility**, which combines both workability and accessibility.

3.5.1. Time Based Accessibility

The most common accessibility reporting is TBA. ECN describes this as “the percentage of time that an offshore wind farm can be approached and accessed by technicians” [50]. This gives a quick understanding of the conditions at site, based on the chosen weather limits. TBA is also sometimes referred to as approachability [26]. Window-based accessibility (WBA) considers the length of the periods of TBA. A weather window is defined by Dowel et al. [1] as "a period of time during which if a given maintenance operation is started, it can be completed". Any access period less than the required access period is deemed inaccessible.

As stated in Section 3.3, FOWT access is the combination of both vessel TBA and workability limitations. This does not consider the impact of transferability. Transferability is defined within this work as the ease of transfer from vessel to platform. This is one of the most safety critical elements of O&M and can be called off due to incompatibility between the vessel and tower. Using vessel-based access as a baseline, the FOWT accessibility is analysed. Results showing the change in access, Δ FOWT Access, to the site are given in Table 3.7. Sites using an SOV strategy are highlighted in grey.

Design D has proven to be the most challenging platform in terms of maintainability, with this design consistently having the highest impact of reduced access. As previously discussed, the impact of workability has a more significant impact on sites using an SOV-based strategy (highlighted grey in Table 3.7). While WindCrete and ActiveFloat have minimal impact on the SOV sites, aside from Design D, these are the only platforms which impact CTV strategy sites.

3.5.2. Workability Index Impact

The WI gives a statistical representation of how safe it is for technicians to perform maintenance on the asset under different motion accelerations. However, this does not give a straightforward go/no-go output. Instead, it gives a percentage of which conditions under the specific Hs and Tp combinations are safe for working. In Sections 3.1-3.4, it is assumed that for any WI < 1 the asset would be considered inaccessible. This section explores the impact of the WI acceptable threshold. In this work, this is defined as the limit for which all WI above the value is classified as safe working, and all values below as unsafe, and therefore inaccessible. Figure 3.11 shows the impact of reducing this and its impact on FOWT accessibility. This method has no impact on the WindCrete design. There was also no change to any of the CTV site's accessibility for all platform types, apart from Design D. Design D showed the most significant changes across all regions.

For "All Sites", CTV only, and SOV only categories are the average of all substructures excluding Design D. For the CTV sites, there is no change in accessibility for ActiveFloat, WindCrete, Design B and Design C. For WI > 0.9 acceptable thresholds, Design A becomes equal to the access of the aforementioned platforms.

Table 3.7. Δ Access resulting from the addition of workability limits on offshore accessibility

	E1	E2	NE1	NE2	NE3	NE6	NE7	NE8	N2
ActiveFloat	-3%	-2%	-2%	-6%	-5%	-5%	-3%	-3%	-1%
WindCrete	0%	0%	0%	-6%	-5%	-5%	0%	0%	1%
Design A	-2%	-3%	-6%	0%	-1%	-1%	-2%	-2%	-13%
Design B	-10%	-12%	-15%	0%	0%	0%	-13%	-12%	-12%
Design C	-7%	-7%	-5%	0%	0%	0%	-8%	-7%	0%
Design D	-21%	-19%	-18%	-10%	-11%	-7%	-22%	-22%	-16%

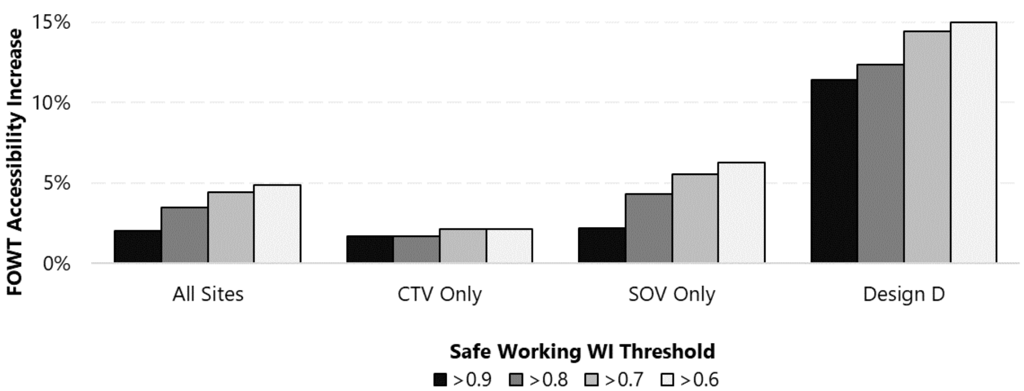


Figure 3.11. WI Sensitivity FOWT Accessibility increase averaged for all sites, CTV strategy sites (SOV strategy sites, and Design D for all sites.

Design D, which was initially viewed as the most challenging design, in terms of FOWT accessibility, sees the highest increase in terms of accessibility when the WI acceptable limit is altered (~4%, whereas the average of the remaining designs is <3%). For SOV sites, Design D is no longer the platform with the lowest access. This introduces a challenging balance between KPIs such as accessibility and availability, and technician safety and welfare. The ranking of the most accessible platforms for SOV sites, based on the results from the acceptable sensitivity analysis, is shown in Table 3.8.

For both the WindCrete and the ActiveFloat designs, WI>0.6 equates FOWT access to vessel-based access, as WI criteria occur at Hs values above 4.5m. The platform designs A – D all still have unsuitable Hs/Tp combinations at Hs of 3-4 m. Design C is the most suitable for all SOV zones, following the CoreWind designs. For WI<1 threshold, Design D was consistently the worst-ranking platform design, however, for WI>0.6, this is no longer the case. This highlights the importance of having an industry-standard acceptable WI threshold as this can significantly impact the most suitable design choice.

Table 3.8. Ranking of platforms for SOV strategy ScotWind zones from highest accessibility (1) to lowest accessibility (6)

Zone	E1&2		NE1		NE7		NE8		N2		
WI Tolerance	**>1**	**>0.6**	**>1**	**>0.6**	**>1**	**>0.6**	**>1**	**>0.6**	**>1**	**>0.6**	key
Access Ranking (Highest = 1, Lowest =6) **1**	WindCrete	WindCrete = Active Float	WindCrete	WindCrete = Active Float	WindCrete	WindCrete = Active Float	WindCrete	WindCrete = Active Float	Design C	WindCrete = Active Float	Active Float ●
2	Design A		Active Float		Active Float		Design A		WindCrete		WindCrete ●
3	Active Float	Design C	Design A	Design C	Design A	Design C	Active Float	Design C	Active Float	Design C	Design A ●
4	Design C	Design A	Design C	Design A	Design C	Design A	Design C	Design A	Design A	Design B	Design B ●
5	Design B	Design D	Design B	Design D	Design B	Design D	Design B	Design D	Design B	Design D	Design C ●
6	Design D	Design B	Design D	Design B	Design D	Design B	Design D	Design B	Design D	Design A	Design D ●

3.5.3. Workability vs Accessibility

Workability results from the WindCrete and ActiveFloat designs highlight a decrease in workability for wave conditions of exceeding 3.5 m Hs. Therefore, for sites which are using a strategy where vessel limitations fall below this threshold (e.g., CTV), then vessel accessibility will capture the workability limitations. To determine the potential impact of sea state limitations, the vessel accessibility and workability are analysed independently. Using limits from the WI and vessel limits, the access percentage of each is determined. To compare, workability access is compared against vessel TBA as shown in Figure 3.12. Using vessel based TBA as the baseline, the percentage difference, Δ Access [%], is given for each platform type of each ScotWind zone. This compares time based accessibility for exclusive CTV vessel limits, against workability only accessibility.

There is a clear trend in sites which use an SOV-based maintenance strategy (E1, E2, NE1, NE7, NE8, N2) having lower workability than TBA. Therefore, it must be noted that while an SOV has a higher Hs limit, it is subject to more of an impact in the reduction of

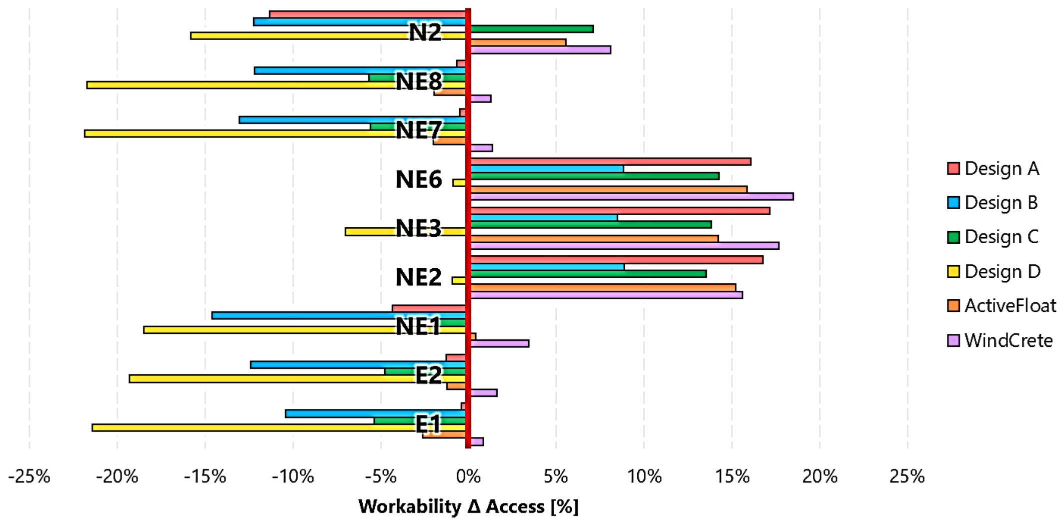


Figure 3.12. Comparison of Workability Access vs Time-Based Accessibility (TBA). A negative value indicates that workability has a higher influence on access than vessel-based limitations.

accessibility due to turbine motion limitations, as WI limitations are typically at Hs over 1.5, and therefore already captured by the CTV limitations. It was also found that for WindCrete, workability was always more than TBA, showing that of all platforms considered this will have the least significant impact on total access. It is assumed that SPAR and TLP designs, typically have a low motion response.

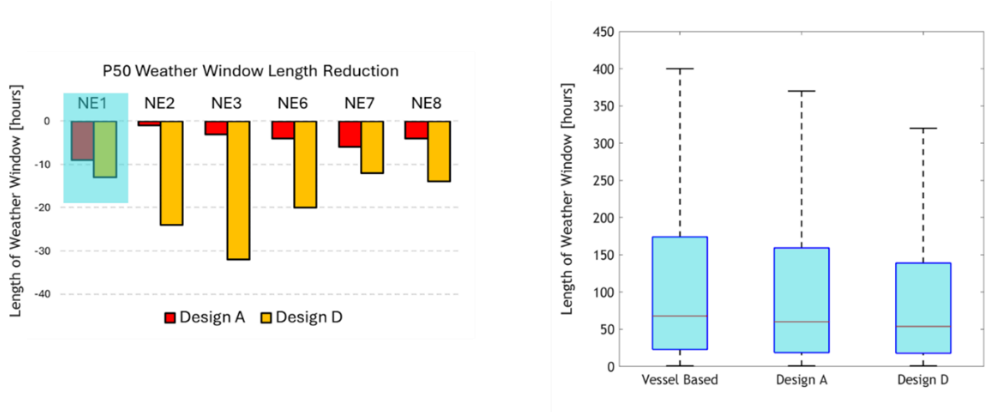
Workability alone would never be the only limitations imposed on access to a turbine, as these would always be coupled with vessel TBA. However, the aim of this analysis is to highlight that in the overall impact / key limiter can change between WI and TBA, dependent on the site conditions.

3.6. Weather Window Behaviour

Accessibility is an important KPI to provide estimates for site performance and maintenance campaigns. However, for a more in-depth analysis the WW behaviour at site must be determined.

The weather window model previously discussed in Figure 3.3, is adapted to account for the impact of WI, on total access. Where is access decision (Figure 3.4) is adapted to meet the conditions of both WI and met-ocean vessel limits meeting the safe working criteria. Using this adapted model, the impact on WI on weather window length can be determined. This weather window analysis is focused on the NE regions and platform Designs A and D [33]. The results, as a result of subsequent reduction in length are given in Figure 3.11 a and b, with as assumed workability index of >1.

It is important to understand the behaviour of weather windows, as well as accessibility. This allows more effective maintenance planning to be carried out, as maintenance activities have the potential to be grouped together. As discussed in Table 3.2, different maintenance activities have specific WW_R's. Using the updated accessibility



(a) (b)

Figure 3.11. (a) P50 weather window length reduction by site, (b) Distribution of length of weather windows

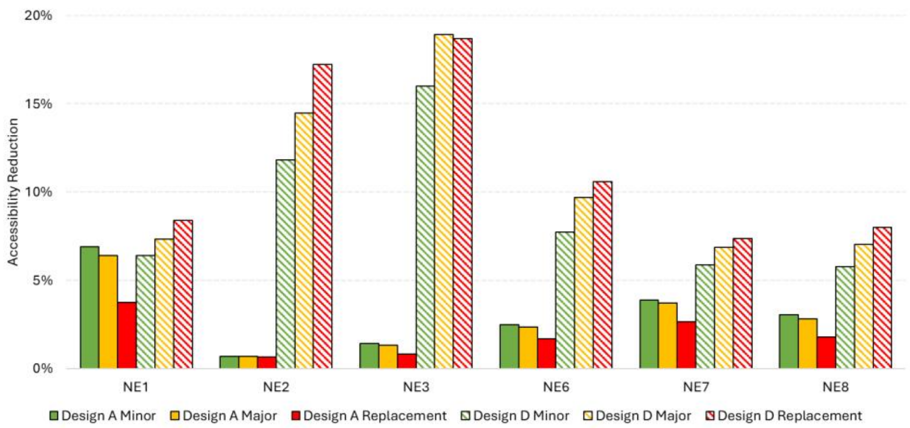


Figure 3.12 Reduction in Accessibility for minor, major and replacement maintenance actions

requirements including WI thresholds, the updated weather window length at each NE region can be determined. This is shown in Figure 3.14.

As expected, Design D shows the most significant impact in terms of accessibility reduction. When analysing the TBA, this design saw the highest decrease in accessibility. This behaviour is consistent across all WW_R. However, interestingly, both designs show opposite response in terms of accessibility response to increased weather window length. For Design

A, as the WW_R increases, the impact on accessibility decreases. The opposite is true for Design D, where larger WW_R's are more impacted than shorter WW_R. For Design A, the limiting WI threshold occur between the higher Tp ranges of 10 – 15 s. The availability of WWs suitable for major replacement were already limited to periods of lower Tp.

This, once again, highlights the unique response and maintenance impact of each substructure design.

3.7. Scheduled Maintenance Impact

Upon further inspection of the weather windows, from a monthly average, it was found that the addition of workability limitations not only had an impact on the availability of certain weather window profiles, but also on the pattern of weather window occurrence. Figure 3.15 shows the average length of weather window for each month for Designs A and D using site NE1 as a case study.

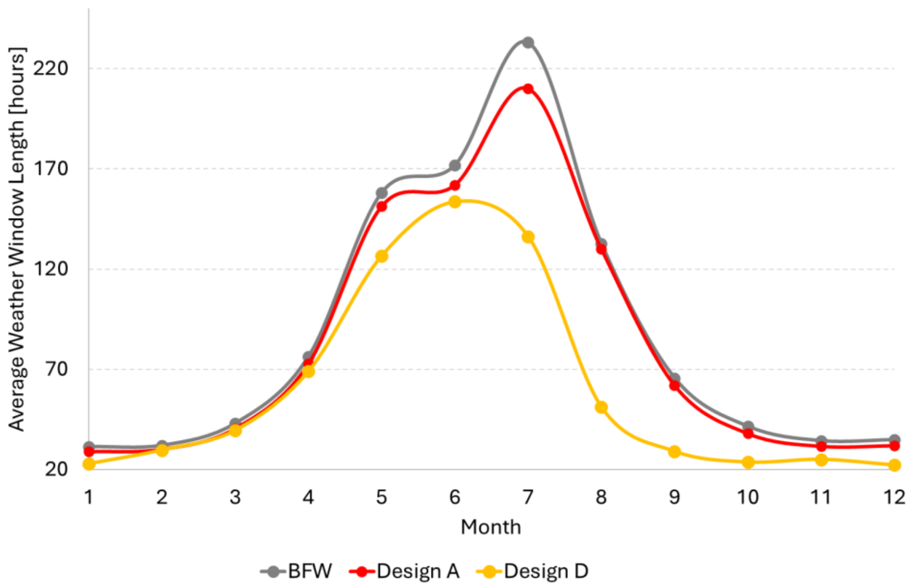


Figure 3.13 Average monthly weather window length for site NE1

The peaks in the data reflect the seasonal changes in weather patterns, where historically July has significantly lower Hs averages. Scheduled maintenance activities, such as annual servicing, are typically scheduled for the summer months with higher probability of long weather windows and high TBA. This finding shows that platform selection can have a significant impact on maintenance planning, with for Design D, the most suitable month for scheduled activities shifting from July to June.

3.8. Practical Impact

There are several other factors which may impact the applicability of workability to a site, including human exposure and experience. Sea sickness is a topic which has always been of importance for offshore technicians, however, although there are limits in place, as highlighted by Scheu et al. [31], these limits are highly dependent on the individual. Other factors such as technician's lifestyle and offshore experience may impact workability limitations, where a workable condition for one individual may be different to that of another. Another factor to consider is the travel time to turbine, where the technician may be exposed to vessel motion for a prolonged period before transferring to the turbine, therefore personal workability limits and sickness levels may change.

Workability limitations guidelines are vital for effective modelling and understanding the working windows for projects to estimate finances, however, in practice workability limits and go/no go decisions should be held by those performing the maintenance.

3.9. Outcomes Summary

This chapter has examined the impact of FOW limitations and challenges on the non-financial KPI of accessibility. Accessibility is a key KPI and has high influence on project planning and financing.

Findings show a trend in increasing distance to shore, as the offshore wind market becomes more mature, exposing sites to more challenging met-ocean conditions and having a significant impact on site accessibility. It was found that for both depth and distance, an increase results in an increase in OpEx. However, this is more of a general rule, with exceptions based on unique locations with extreme weather conditions.

Additionally, the implementation of motion limits to protect technician safety during the dynamic movement of the floating structures poses an additional obstacle to accessibility, requiring careful planning and adaptation of maintenance procedures in order to maintain optimal operational performance. The impact of workability on accessibility has the potential to impact the whole maintenance lifecycle with significant impact on both unscheduled and scheduled maintenance actions due to the decrease in overall accessibility and the shift in monthly peak accessibility and WW_L.

Key findings from this chapter include:

- Accessibility will *decrease* for FOW sites due to distance to shore and workability limits.
- The decrease in accessibility is dependent on both the site conditions and the platform design.
- There is not yet a defined workability index limit. Findings show this can have a significant impact on the most suitable platform for specific sites. It is expected that industry must collaborate with legislative bodies to determine safe working limitations.
- FOW accessibility must combine both vessel limitations and workability considerations, as shown in Figure 3.15.

- FOW additional limitations will have significant impact on both scheduled and unscheduled maintenance actions due to the shift in the most accessible calendar month.

At present, workability limits imposed are based on those taken from the oil and gas industry. However, these current limitations fail to consider the impact of technician travel to site, and the type of work conducted. There are different limitations imposed for travel and intelligent working. It is recommended that specific WI limits be imposed for minor and major maintenance actions, with consideration to total time offshore.

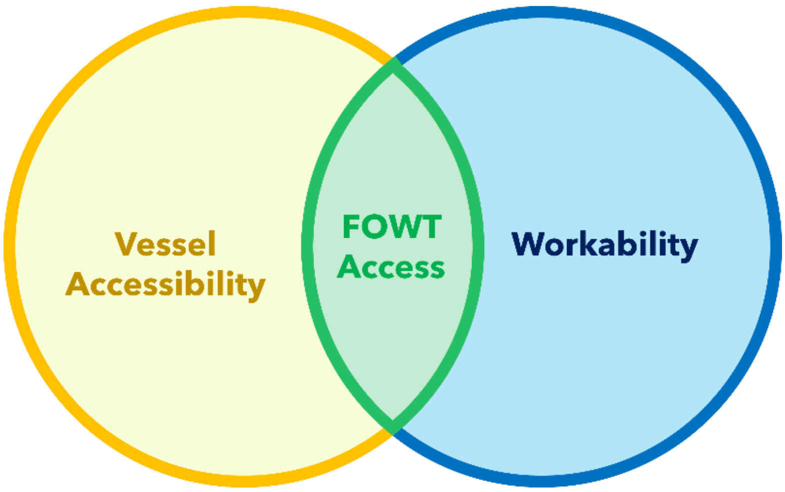


Figure 3.14. FOWT access is the combination of both workability and accessibility.

This work assumes that the transferability will be the same for both the CTV and SOV based maintenance strategies. In reality, there may be concerns regarding the walk to work system of specific SOVs where technicians deploy a walkway between the vessel and the floating turbine. This introduces floater-to-floater motion, where the frequencies of both bodies interact. This could further limit accessibility for SOV strategies, as highlighted. Therefore, the argument that SOV strategies will see the biggest impact in terms of accessibility is further amplified.

3.10. Chapter References

[1] J. Dowell, A. Zitrou, L. Walls, T. Bedford and D. Infield, "Analysis of wind and wave data to assess maintenance access to offshore," in *European Safety and Reliability Association Conference*, 2013.

[2] G. J. Van Bussel and W. A. A. M. Bierbooms, "The DOWEC Offshore Reference Windfarm: analysis of transportation for operation and maintenance," *Wind Engineering,* vol. 27, no. 5, pp. 381-391, 2003.

[3] J. McMorland, C. Flannigan, J. Carroll, M. Collu, D. McMillan, W. Leithead and A. Coraddu, "A review of operationa and maintenance modelling with considerations for novel wind turbine concepts," *Renewable and Sustainable Energy Reviews,* vol. 165, p. 112581, 2022.

[4] K. Thomsen, "Offshore wind: a comprehensive guide to successful offshore wind farm installation," *Academic Press,* 2014.

[5] G. Marsh, "Meeting the challenge of wind turbine blade repair," *Renforc Plast,* vol. 55, pp. 32-36, 2011.

[6] A. Dewan and T. Stehly, "Mapping operation and maintenance strategy for US offshore wind farms," National Renewable Energy Lab (NREL), Golden, CO, 2017.

[7] W. Stavenuiter, I. Hopman, I. Boonstra and K. IL, "The missing link in the offshore wind industry: offshore wind support ship," 2009.

[8] V. Jacobsen and R. M, "Offshore wind farms - the need for metocean data," Copenhagen Offshore Wind, 2005.

[9] T. Soukissian, A. Papadopoulos, P. Skrimizeas, F. Karathanasi and P. Axaopoulos, "Assessment of offshore wind power potentil in the agean and ionian seas based on high-resolution hindcast model results," 2017.

[10] F. Ferrari, G. Besio, F. Cassola and A. Mazzino, "Optimized wind and wave energy resource assessment and offshore exploitability in the mediterranean sea," *Energy,* vol. 190, 2020.

[11] H. Abdollahzadeh, K. Atashgar and M. Abbasi, “Multi-objective opportunistic maintenance optimisation of a wind farm considering limited number of maintenance groups,” *Renewable energy,* vol. 261, no. 88, p. 247, 2016.

[12] J. Feuchtwang and D. Infield, “Offshore wind turbine maintenance access: a closed-form probabilistic method for calculating delays caused by sea-state,” *Wind Energy,* vol. 16, pp. 1049-1066, 2013.

[13] G. Komen, L. Cavaleri, M. Donelan, S. Hasselmann and J. P, Dynamic and modelling of ocean waves, 1996.

[14] G. De Masi, R. Bruschi and M. Drago, “Synthetic metocean time series generation for offshore operability and design based on multi-variate markov model,” in *IEEE OCEANS*, Genova, 2015.

[15] F. Douard, C. Domecq and W. Lair, “A probabilistic approach to introduce risk measurement indicators to an offshore wind project evaluation - improvement to an existing tool ecume.,” *Energy Proceedings,* vol. 24, pp. 255-262, 2012.

[16] M. Scheu, D. Matha, M. Hofmann and M. Muskulus, “Maintenance strategies for large offshore wind farms,” *Energy Proceedings,* vol. 24, pp. 281-288, 2012.

[17] M. Hofmann and I. Sperstad, “NOWIcob - a tool for reducing the maintenance costs of offshore wind farms,” *Energy Proceddings,* vol. 35, pp. 177-186, 2013.

[18] I. Dinwoodie, F. Quail and D. McMillan, “Analysis of offshore wind turbine operation and maintenance using a novel time domain meteo-ocean modeling approach,” in *Turbo Expo: power for land, sea and Air,* American Society of Mechanical Engineers, 2012.

[19] P. Ailliot and V. Monbet, “Markov-switching autoregressive models for wind time series,” *Environ Model Software,* vol. 30, pp. 847-857, 2012.

[20] C. Soares and C. C, “Bivariate autoregressive models for wind time series of significant wave height and mean period,” *Coast Engineering,* vol. 30, pp. 297-311, 2000.

[21] C. Dao, B. Kazemtabrizi, C. Crabtree and P. Tavner, “Integrated condition-based maintenance modelling and optimisation for offshore wind turbines,” *Wind Energy,* 2021.

[22] K. Saeed, J. McMorland, M. Collu, J. Carroll and D. McMillan, “Adaptations of offshore wind operation and maintenance models for floating wind,” in *Journal of Physics*, IOP Publishing, 2022.

[23] J. Carroll, A. McDonald and D. McMillan, “Failure rate, repair time and unscheduled O&M cost analysis of offshore wind turbines,” *Wind Energy,* vol. 19, no. 6, pp. 1107-1119, 2016.

[24] Stiesdal, “The TetraSpar full-scale demonstration project,” 2022. [Online]. Available: https://www.stiesdal.com/offshore/the-tetraspar-full-scale-demonstration-project/. [Accessed 3 June 2023].

[25] BVG Associates, “https://guidetoanoffshorewindfarm.com/offshore-wind-history,” 2019. [Online]. Available: https://guidetoanoffshorewindfarm.com/offshore-wind-history. [Accessed 15 Jun 2020].

[26] D. Rowell, B. Jenkins, J. Carroll and D. McMillan, “How does the accessibility of floating wind farm sites compare to existing fixed bottom sites,” *Energies,* vol. 15, no. 23, p. 8964, 2022.

[27] C. Wang, T. Utsunomiya, S. Wee and Y. Choos, “Research on floating wind turbines literature survey,” *The IES Journal Part A: Civil & Strucutral Engineering,* vol. 3, no. 4, pp. 267-277, 2010.

[28] S. Bashetty and S. Ozelik, “Review on dynamics of offshore floating wind turbine platforms,” *Energies,* vol. 14, no. 19, p. 6026, 2021.

[29] A. Otter, J. Murphy, V. Pakrashi, A. Robertson and C. Desmond, “A review of modelling techniques for floating offshore wind turbines,” *Wind Energy,* vol. 25, no. 5, pp. 831-857, 2022.

[30] I. Sperstad, M. Stalhane, I. Dinwoodie, O. Endrerud, R. Martin and E. Warner, “Testing the robustness of optimal vessel fleet selection for operation and maintenance of offshore wind farms,” *Ocean Engineering* , vol. 145, pp. 334-343, 2017.

[31] LIFES50+, “Qualification of innovative floating substructures for 10 MW wind turbines and water depths greater than 50m,” 2015.

[32] B. Jenkins, A. Prothero, M. Collu, J. Carroll, D. McMillan and A. McDonald, “Limiting wave conditions for the safe maintenance of floating wind turbines,” in *Journal of Physics: Conference Series,* IOP Publishing, 2021.

[33] M. Scheu, D. Kaufer, M. Schwarzkopf and A. Kolios, “Workability on Offshore Wind Turbines - a Comparative Study of Fixed-Bottom and Floating Applications,” in *The 28th International Ocean and Polar Engineering Conference,* OnePetro, 2018.

[34] M. Scheu, D. Matha, M. Schwarzkopf and A. Kolios, “Human exposure to motion during maintenance on floating offshore wind turbines,” *Ocean Engineering,* vol. 15, no. 23, pp. 293-306, 2018.

[35] CoReWind , "D4.2 Floating Wind O&M Strategies Assessment," EU-2020, 2020.

[36] E. Gaerter, J. Rinker, L. Sethuraman, F. Zahle, B. Anderson, G. Barter, N. Abbas, F. Meng, P. Bortolotti, W. Skyrzpinski and G. Scott, "Definition of the IEA 15-megawatt offshore reference wind turbine," IEA, 2020.

[37] C. Allen, A. Viselli, G. Dagher, A. Groupee, E. Gaertner, N. Abbas, M. Hall and G. Barter, "Definition of the UMaine VolturnUS-S Reference platform developed for the IEA wind 15-Megawatt Offshore Reference Wind Turbine," 2020.

[38] W. Xue, "Design, numerical modelling and analysis of a spar floater supporting the DTU 10 MW wind turbine," Master's thesis, NTNU, 2016.

[39] C. Wehmeyer, F. Ferri, M. Andersen and R. Pedersen, "Hybrid model representation of a TLP including flexible topsides in non-linear regular waves," *Energies,* vol. 7, no. 8, pp. 5047-5064, 2014.

[40] University of Stuttgart, "Public definition of the two LIFES50+ 10MW floater concepts," LIFES50+ Qualification of innovative floating substructures for 10MW wind turbines and water depths greater than 50m, 2018.

[41] I. Nielsen, "Assessment of ship performance in a seaway," NORDFORSK, Copenhagen, 1987.

[42] Crown Estate Scotland, "Scotwind: List of Successful Partners 2022," 2022. [Online]. Available: https://www.crownestatescotland.com/resources/documents/scotwind-list-of-successful-project-partners-170122. [Accessed 10 June 2022].

[43] H. Diaz and C. Soares, "Review of the current status, technology and future trends of offshore wind farms," *Ocean Engineering,* vol. 209, p. 1107381, 2020.

[44] LAUTEC ESOX, "ERA 5 Data Point Map".

[45] G. Rinaldi, P. Thies and L. Johanning, "Improvements inthe O&M modelling of floating offshore wind farms," in *Developments in Renewable Energies Offshore,* CRC Press, 2020, pp. 481-487.

[46] I. Dinwoodie, O. Endrerud, M. Hofmann, R. Martin and I. Sperstad, "Reference cases for verification of operation and maintenance simulation models for offshore wind farms," *Wind Engineering,* vol. 39, no. 1, pp. 1-14, 2015.

[47] P. Joschko, A. Widok, S. Appel, S. Greiner, H. Albers and B. Page, "Modelling and simulation of offshore wind farm O&M processes.," *Environmental Impact Assessment Review,* vol. 52, pp. 31-39, 2015.

[48] G. Hassan, “A guide to UK offshore wind operations and maintenance,” Scottish Enterprise, 2013.

[49] I. Lazakis and S. Khan, “An optimisation framework for daily routine planning and scheduling of maintenance vessel activities in offshore wind farms,” *Ocean Engineering,* vol. 225, p. 108752, 2021.

[50] H. Stumpf and B. Hu, “Offshore wind access 2018,” ECN Report, 2018.

Chapter 4 : Quantifying FOW Access Reduction Through OpEx Lifecycle Modelling

This chapter aims to estimate the operational expenditure impact of additional challenges and limitations placed on O&M activities for future FOW sites.

Based on the findings of Chapter 3, this Chapter aims to quantify the accessibility decrease of future floating sites in terms of OpEx. The analysis in this chapter revolves around existing literature concerning the modelling of operational expenditure for FOW projects. This work reviews models specifically tailored for FOW and those originally developed for other purposes are examined. Additionally, this chapter delves into the necessary adjustments required to make existing OpEx models suitable for FOW applications. The economic impact of the additional limitations imposed by FOW sites is determined through ScotWind case studies using a bottom fixed wind (BFW) site as a comparative baseline. An overview of the Chapter is provided in Figure 4.1.

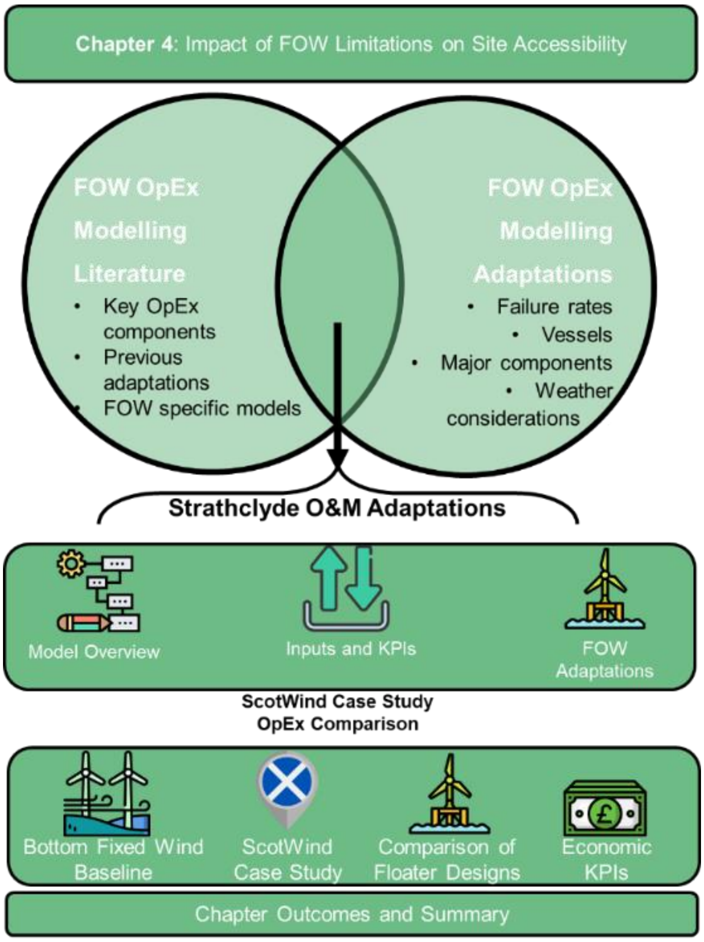


Figure 4.1. Chapter 4 overview and summary

4.1. Background

As stated by statistician George E. P. Box, "All models are wrong, but some are useful". Accurate O&M projections are becoming more important throughout the project lifecycle and are vital when preparing bids for auction. Once a wind farm is commissioned, O&M remains one of the few areas where significant costs and innovation can occur throughout the project lifecycle. The importance of O&M planning is also vital to end-of-life projections for existing sites entering lifetime extension periods [1].

There has been extensive work in developing O&M modelling tools for offshore wind. A comprehensive list of academic and industry models can be found in [2]. A great deal of time, effort, and cost goes into developing accurate offshore wind O&M models. Therefore, there is a question as to whether these existing (and sometimes validated models) should be adapted for FOW use, or if a new model should be created to deal with the additional complexities of FOW farms.

Over the past twenty years, several models have been specifically generated to model the O&M process for offshore wind [2]. The O&M process, and modelling, are much more complex than that of onshore due to environmental limits on access to the turbine. As a result, O&M is more challenging, and costly, than onshore. An increase in the number of components needed to successfully maintain the asset also results in an increase in uncertainty during the modelling of the activity. Despite the cost reduction of the technology in recent years, OpEx still contributes to around 30% of the overall cost of energy [3]. Accurate O&M modelling and effective management is a vital part of preparing bids for CfD auctions and is essential to driving down the cost of energy for the technology. O&M simulation software tools are typically used to derive operational expenditure (OpEx) estimations for the lifetime of the project. Within this the tools often report additional key performance indicators (KPIs) such as availability (both time and energy), capacity factor and LCOE. Due to the advancement of the tools, and the increase in experience of using them, O&M models can aid in optimisation of strategy and resources supporting decisions such as fleet management and logistics. A number of BFW models have also been developed to support day-to-day scheduling and decision-making within the site such as [4], [5] and [6].

The creation of a 'useful' model required a high level of investment, time and expertise. A number of developers such as SSE and ScottishPower Renewable have developed their own in-house O&M models. Commercial tools such as shoreline [153] and ForeCoast Marine [154] are also available at a cost. A number of open-source models generated by the universities of

Strathclyde and Exeter are also available with varying levels of complexity and capability. A number of these existing models have been tried and tested at current BFW operational sites. The development of FOW brings new challenges. FOW turbines are very similar to BFW turbines in terms of how they operate and will be maintained. However, the addition of the floating substructure presents a new range of both challenges and opportunities such as T2S maintenance and the impact of the turbine motion of maintenance activities. This then raises the question of "should new models be created specifically for FOW O&M activities, or can current FOW O&M models be adapted for a new application?"

4.1.1. Existing Models

Several offshore wind OM models are already in existence, with many of them validated and used extensively within the industry, as highlighted in Table 4.1. The list of models was, in part, informed by the Romeo project [2] and Gray 2020 [7]. Several commercial OM decision support tools are also available including BMT MWCOST, ForeCoast Marine Gamer Mode, Mermaid, Orsted OM Tool, and Shoreline. It is unknown if these models are suitable for FOW modelling due to the lack of available information available in the public domain. WES and DTOcean models used in Gray [8] have been omitted from the list as they were originally developed for wave energy application.

Table 4.1. List of BFW O&M models

Model	Developer	Year	Ref.
CONTOFAX	Delft	1997	[9]
DNVGL O2M	DNV GL	2005	[10]
ECN	ECN	2017	[11]
MWCOST 2007	BMT	2007	[12]
OMCE (adapted TNO Tool)	ECN	2008	[13]
ECUME	EDF	2012	[14]
Scheu et al.	University Stuttgart, SINTEF, Norwegian University of Science and Technology	2012	[15]
NOWIcob	SINTEF	2013	[16]
SIMLOX	Systecon	2013	[17]
Besnard et al	Chalmers University of Technology, Fraunhofer IWES	2013	[18]
StrathOW-O&M	University of Strathclyde	2014	[19]
Endrerud et al	University of Stavanger & Statoil	2014	[20]
Santos et al.	Marine Renewable Energy - Energy Extraction and Hydroenvironmental Sustainability (MAREN)	2015	[21]
Sahnoun	CESI – IRISE Laboratory, University of Exeter	2015	[22]
Ambühl and Sørensen	Aalborg University	2017	[23]
Rinaldi et al.	University of Exeter	2019	[24]
CL Windcon	CL Windcon	2019	[25]
Offshore TIMES	Fraunhofer IWES	2020	[26]
Pietro D. Tomaselli	GHI Copenhagen	2020	[27]
ROMEO O&M Tool	ROMEO PROJECT	2022	[2]

4.1.2. Modelling Factors

In general, BFW O&M models can be described as being made up of modules and/or elements. Each module models a specific area of the operations and repair process. Based on the review of Seyr and Muskulus [28], a typical model consists of the following elements: failures, resources, transportation, site logistics, and economic factors. The outputs of the models can also be generalized to include OpEx, availability, and capacity factor. Figure 4.2 shows a schematic of a generic O&M model showing the different modules required for an O&M model with details of inputs/influential factors required within them.

Elements such as costs and personnel and turbine parts are unlikely to change during the transition from BFW to FOW O&M modelling. The modelling techniques and the use of these elements within the model will be unchanged. The key differences will come from the values inputted into the model which are, typically, user defined. However, the remaining elements: climate, failure and degradation, turbines, site details, and transport will require significant changes in the way in which they are modelled/generated.

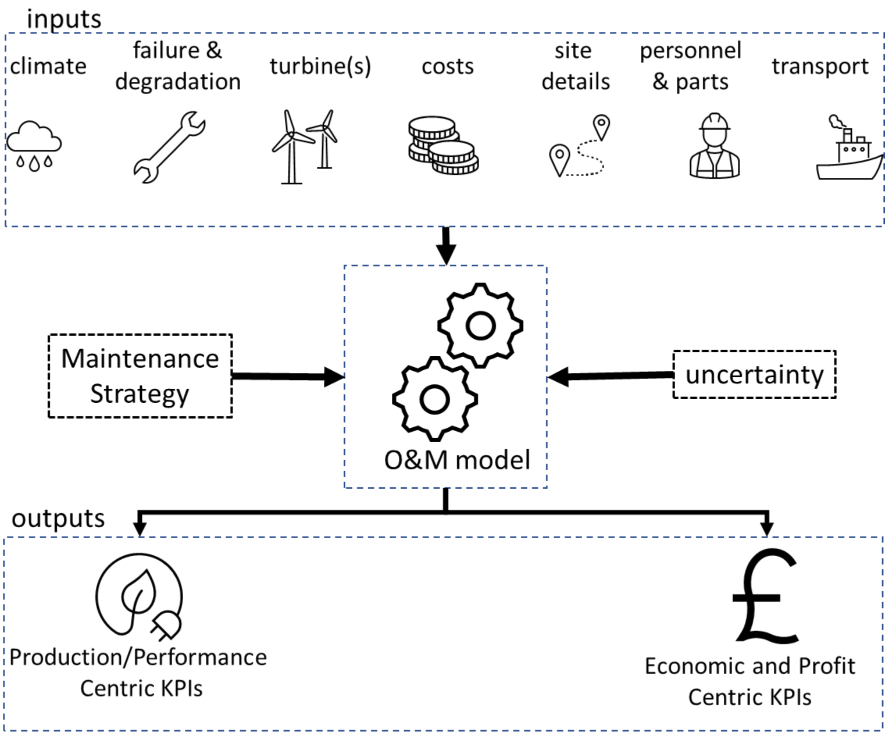


Figure 4.2. O&M simulation tool schematic

4.1.3. Weather Data

The use of the weather data within the models is likely to be the same within the FOWT and BFW applications. However, additional care will be required when collecting the data, particularly for FOW sites which are expected to be far from shore where data may be more difficult to acquire. Increased distance from shore increases the uncertainty about the weather conditions offshore based on a shore-based measurement, therefore, increasing the number of transfers. Work by Li [29] also acknowledges the use of wave period as an indicator for access/no access conditions. Therefore, it is likely that this will be added to the model. A list of weather inputs used within each of the models is detailed in Table 4.2.

As highlighted in Chapter 3, additional limitations placed on FOW operations are workability. Workability conditions are determined using the combination of both Hs and Tp. Therefore, if a model is to be adapted it will require these weather inputs to be either pre-existing or added to the model. Table 4.2 shows that Hs and mean wind speed are always included within the model, however the use of Tp is limited in existing models.

Models such as [11] [19] [9] [4] which include visibility metrics have the ability to simulate helicopter operations. The use of helicopters for O&M is site/developer dependent and therefore is not included in the majority of modelling tools.

4.2. Floating Wind O&M Modelling

This section aims to review the existing literature surrounding FOW O&M simulations. There is a split between existing models, which were previously created for BFW development, and new models created specifically for FOW application.

4.2.1. Previous Model Adaptions

Castella [30], Dewan & Asgarpour [11], Rinaldi et al. [31], Kastorous & Marina [32], Amorim [44], and Gray [8] all use modified versions of existing models. Gray [8] uses existing O&M tools which have previously only been used for wave energy converter applications. They combine the DTOcean and WES O&M tools with modifications for use on a hybrid floating wind and wave device. Amorium [33] uses the commercial tool - Shoreline [34].

[30], [11] [32] all use versions of the models developed by TNO (formerly ECN). Katsourus & Marina [32] use ECN install, ECN "OWEOP" and ECN O&M tool. ECN Install is a MATLAB based offshore wind installation simulation tool. The "OWECOP" model uses the programming language Python, and also utilises a number of Microsoft Excel worksheets to model the cost components of a site. To adjust the model for FOW applications, the Excel model utilised to calculate the dimensions of the monopile, transition piece, and tower was modified in order to calculate the main dimensions of the turbine tower used for a floating structure.

Castella et al. [30] and Dewan & Asgarpour [11] use the existing ECN O&M Access tool, originally designed for BFW. The model has been adapted to include T2S within it for a FOW application. The GL-validated ECN tool has been used for nearly fifteen years within industry as a tool for BFW applications. This work forms the basis for an updated version of the ECN O&M Access tool which will introduce features such as human fatigue and vessel hydrodynamics.

Rinaldi et al. [31] adapts the model used in [35] for offshore wind, wave, and tidal energy applications. The tool has also been verified for use in [36]. This model is based on the Markov Chain Monte Carlo approach, which combines random processes representing a sequence of events with repeated sampling of the same scenario subject to random variations.

Key changes were required to make it suitable for FOW applications, including the addition of a T2S option for maintenance. Two T2S options are implemented, the first requiring a continuous weather window from failure to repair and the second being split into sections where the onshore repair does not require a weather window. While details are not provided, it is likely the continuous weather window for T2S is modelled as a major component failure with a large associated time to repair.

4.2.2. FOW Specific Models

Brons-Illing [37], Martini et al. [181] and Elusakin et al. [39] use models specifically designed for FOW applications with varying levels of complexity. Brons-Illing [37] uses an Excel model for three scenarios with two sub scenarios each: near, mid, and far from shore, with and without T2S operations.

Martini et al. [181] have one of the most complex models. They used three separate models to map out the O&M logistics of a site and the impact of downtime. The first is a discrete event model, the second a floating turbine model, and finally a wind farm model which are then integrated into a single simulator. Failure and repair times are simulated stochastically and referred to as "events". The operational envelope for BFW is typically defined by the mean wind speed. However, for FOW, this is much more complex. This work uses a simplified FOW model from [40] considering both the environment loads (wind, currents, waves) and the reaction of the system (displacements, accelerations). Structural, mechanical, and electrical components are designed to withstand specific loads, which are often related to the platform motions. Rigid body dynamics is solved considering first-order wave loads, quasistatic mooring loads, and quasi-static aerodynamic loads providing statistical information, such as mean and standard deviation, of displacement, velocity, or acceleration of any point in the structure. When any of these parameters is above a specific operational threshold, it is assumed

Table 4.2. Weather inputs of existing BFW models

	Wind Speed	Wind Direction	Wind Shear	Significant Wave Height	Wave Current Speed	Wave Current Direction	Peak Wave Period	Tide	Daylight Hours	Visibility	Lightning	Temperature
ECN [11]	✓			✓						✓	✓	
ECUME [14]	✓			✓								
NOWIcob [16]	✓			✓								
ROMEO O&M Tool [2]	✓			✓								
Offshore TIMES [26]	✓			✓								
DNVGL O2M [10]	✓			✓								
Strath OW-O&M [19]	✓			✓			✓		✓	✓		
Rinaldi 2019 [24]	✓			✓	✓							
Ambühl and Sørensen [23]	✓			✓								
ROMEO O&M Tool [2]	✓			✓								
Endrerud et al. [20]	✓			✓								
SIMLOX [17]	✓			✓								
MWCOST [12]	✓			✓				✓	✓			
CONTOFAX [9]	✓			✓						✓		
Scheu et al. [15]	✓			✓								
Dalgic et al. [4]	✓		✓	✓			✓	✓	✓	✓		
Sahnoun [22]	✓	✓		✓							✓	✓
Pietro D. Tomaselli [27]	✓	✓		✓	✓	✓						
CL Windcon [25]	✓	✓		✓								
OMCE (ECN Tool) [13]	✓			✓								

that the wind turbine must be shut down. The model also considers the impact of wakes through the use of the Jensen model [41].

Elusakin et al. [39] uses a Petri network model. This is a graphical interface tool used to model and interpret complex systems which are described as concurrent, distributed, stochastic and/or nondeterministic. A Petri Network is like a flowchart or block diagram consisting of four fundamental graphical features: places, transitions, arcs, and tokens. Elusakin et al. [39] state that O&M modelling for FOW is different to that of onshore and BFW due to the difference in the type of substructure used. The support structures introduce additional components and their associated lifetime uncertainties. They also cite poor accessibility due to dependence on weather conditions, higher failure rates of components due to harsher environment conditions, resource constraints to execute activities and spare parts availability as factors which impact the O&M scheduling problem. One of the key reasons for choosing a Petri network model is the use of a Weibull distribution for time-to-failure, making it useful for applications with limited or unavailable data, such as FOW.

4.2.3. Bottom Fixed Wind Comparisons

Based on the literature, the key factors of a FOW case study are installed capacity (MW), distance from shore (km) and water depth (m) with the trends summarised in Figure 4.3. Additional input included the number of turbines (#), wind resource (m/s), type of structure, and location. FOW case studies used within the literature tended to also model a BFW site for direct comparison.

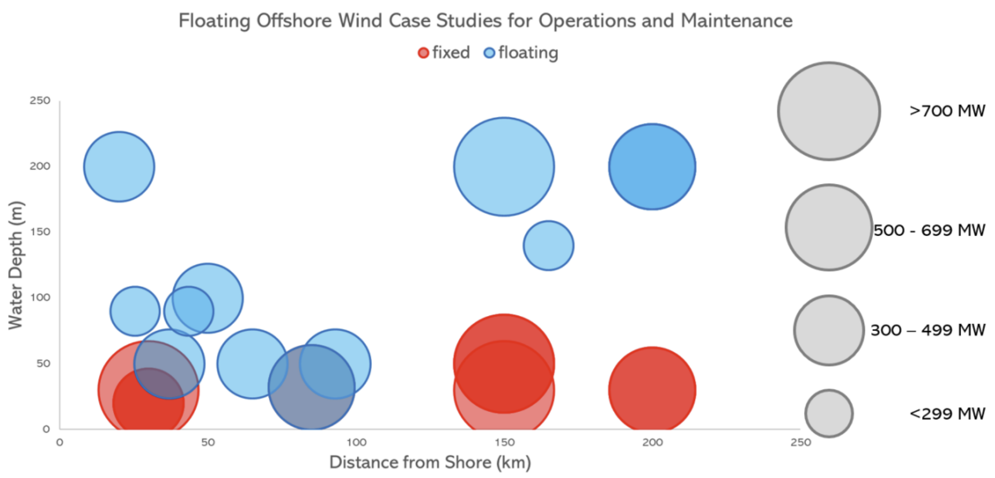


Figure 4.3. Summary of case studies in the literature in terms of water depth (m), distance from shore (km), and installed capacity.

Comparisons between the technology are provided by [30] [11] [42] [43] [31] [32]. Castella [30] use case studies first presented in [11] with a total of five fictional scenarios with the intention of creating baseline sites near and far from shore, the fifth site being FOW. The distance from shore for BFW sites ranges from 30-150 km, with the FOW site being the closest to shore at 20 km. Myhr et al. [42] uses the studies provided by [43] that compare BFW and FOW within the same site with a total of nine turbine concepts. Details regarding distance to shore, site size, installed capacity, weather conditions, and losses are identical for all sites with the only difference being water depth, at 30 m for fixed and 200 m for floating. This allows for direct comparison to be made between the concepts. The case studies first presented in [11] use different locations and strategies, making it difficult to critically compare the concepts.

Rinaldi et al. [31] and Katsourus et al. [32] base their comparisons on existing sites Westermost Rough and Gemini, respectively. Both works include three scenarios, one for BFW, and the remaining two for FOW, with different major component replacement strategies. Rinaldi et al. [31] compares two T2S strategies which differ based on weather windows required. The taxonomy of BFW and FOW for all scenarios is identical. Katsouris et al. [32] model FOW with and without a T2S strategy in place, assuming that T2S would reduce costs by one third. However, the focus of this work was cost modelling, and therefore assumptions were made regarding the effectiveness of a T2S strategy.

Brons-Illing [37] and Castro-Santos et al. 2014 [44] only model FOW sites. Brons-Illing [37] compares the same site (installed capacity, turbine type, location, water depth) at varying distances to shore (37 km, 65 km and 93 km). Castro-Santos et al. 2014 [44] compares the same support structures and installed capacity at two differing locations, Agucadoura and Sao Pedro within Portugal.

It is recommended that studies which compare fixed and floating structures within the same site should be performed within marginal sites, where water depth could accommodate both technologies. If doing direct comparison, then details regarding weather conditions and maintenance strategy should be consistent unless the work is aiming to determine the effectiveness of a T2S approach.

From Figure 4.3, it is clear that most FOW case studies lie within waters less than 100 km, with many relatively close to shore at distances less than 50 km. Although this fits the profile of existing coastal FOW sites such as Hywind and WindFloat (20-25 km), it is not representative of the far-from-shore FOW sites expected in the future [45] .

Many of the case studies provided are within regions which have already benefited from BFW. While the E/NE sites within the ScotWind allocation are in close proximity to established ports and within well studied met-ocean locations, the sites located within the N region are expected to have more challenging conditions. These new, more remote locations will have to manage existing O&M BFW challenges, in addition to specific FOW requirements.

4.3. Floating Wind Modelling Adaptations Required

It is also important to identify the types of structures modelled as this may limit the maintenance strategy. Details of the works studied in this section are given in Table 4.3 with additional information on the type of support structure used. In the following subsections, we comment on the individual influencing factors presented in the literature. Based on the existing FOW O&M literature, the following key inputs have been identified:

- **Met ocean conditions**: all weather data needed for analysis, typically inputted to the model as a time series. This typically includes Hs and mean wind speed.
- **Taxonomy and Reliability**: details of the turbine structures and substructures, including associated failure rate and repair times. This section is particularly important within FOW modelling due to the increase in components, e.g., support structure, mooring system.
- **Maintenance**: the type of maintenance (corrective/preventive, onsite/offshore) and the general maintenance schedule.
- **Transport:** details relating to all vessels/transport needed to perform O&M activities, including cost, speed, capacity, and operational limits.
- **Site logistics**: turbine and site modelling with details such as power curves, distance to shore, number of turbines, depth of site, etc.
- **Cost data**: cost of repair, electricity price, and other direct O&M costs such as spare parts, tax, rent & rates, and balance of plant.
- **Crew**: crew availability and capacity. Some models state this as an independent input and others included within their cost data as a direct cost.

4.3.1. Weather

BFW literature has identified wind speed and H_s as the key weather considerations. Table 4.4 identifies the type of weather inputs included in O&M modelling of FOW sites.

Rinaldi et al. [31] uses time series weather windows which using hindcast or synthetic forecast data, refer to wind, wave, and current characteristic parameters. These weather inputs are based on previous work by Rinaldi [47] which provides details of the model used for both wind and wave energy converters. These inputs are no different to that of the BFW application of the model. Wind speed, H_s and wave currents are also modelled within Katsouris & Marina [32]. Within the model after the weather restrictions are defined, the accessibility vectors are formed for each step by examining the climate data. They cite the inclusion of additional limiting factors such as swell and fog as areas of future work, however, these parameters are not specific to FOW.

Brons-Illing [37] and Dewan & Asgarpour [11] use a similar weather window approach based on H_s and wind speed. Within Brons-Illing [37] the meteorological and oceanographic data used are taken from the met ocean report compiled by the Danish Hydraulic Institute that contains H_s and wind speed in 30-minute time intervals based on hindcast data for a 29-year period for a site in the German Bight of the North Sea. Dewan Asgarpour [11] account for the true weather conditions at these sites using satellite weather data representative of the locations of the five case studies considered.

Martini et al. [48] provides one of the most comprehensive lists of weather conditions. They use databases developed at the Environmental Hydraulics Institute of Cantabria using long-term time series of wind and wave conditions with high spatial and temporal resolution, which have been calibrated through satellite data and validated against field data. The model simulates nonlinear wave interactions, white capping, and effects of depth-induced refraction.

Table 4.3: Existing O&M modelling literature with known model inputs and floating support structure

Publication	Inputs	Support Structure
Castella et al. [30]	failure rates, characteristic values of vessels and equipment, and weather conditions (ECN O&M Access Tool)	Spar
Rinaldi et al. [31]	**met ocean data** of the offshore location, taxonomy (sub-assemblies and components), **reliability** (failure rates, redundancies, criticalities, dependencies), power performance of the devices; specifics of the access systems (**vessels, workboats, helicopters**); planned **maintenance schedule**	Generic/not stated
Katsouris & Marina [32]	Geographic Information System (GIS) parameters, turbine parameters, **farm parameters**, electrical infrastructure parameters, construction **costs**, project funding	Spar, semi-sub, TLP.
Brons-Illing [37]	**site logistics** (wind farm size, turbine size, distance to shore, maintenance strategy (tow to shore or maintain at site), **cost data**, feed in tariff, energy production, annual **scheduled maintenance**, time to repair, **met ocean conditions**, **vessel types**	Generic
Utne [46]	**weather conditions**, wind turbine design/quality, **maintenance strategy**, **personnel**, **transport**, **spare parts**, lifting and hoisting equipment	Generic.
Martini et al. [181]	**failure and repair time**, turbine model, wind farm model	Semi-sub
Amorim [33]	weather conditions and vessel and technician's availability	Semi-sub
Gray* [8]	platform, wave energy converter (power matrix, wave height wave period), **wind turbine** (power curve, wind speed), **failure rates**, **costs**, **vessels**	Hybrid Wind/Wave Device
Elusakin et al. [39]	**taxonomy** (subsystems and components), **type of maintenance** and **site logistics** (travel to and from WT), **failure rate** (logistic time, repair time degraded condition)	Spar
Dewan & Asgarpour [11]	**wind farm characteristics** (depth, distance, turbine size, no turbines, capacity), **vessels** (speed, charter), **maintenance strategy**, ownership of JUV, equipment	Generic
Ginatautas et al. [47]	forecast **met ocean conditions**, operation model input (cranes, vessels, lifting equipment), time series of relevant response, equipment acceptance criteria, estimates of statistical parameters of extreme equipment response distributions	Spar
Martini et al. [48]	weather inputs, time, reliability	Generic

* Gray models a hybrid wind and wave device, however the modelling techniques and methodology are still applicable to FOW systems.

The time resolution is 1 hour, and the data are available from 1979 to 2014. The data are provided in the form of undisturbed mean wind speed (extracted at a height of 90 m) and prevailing wind direction.

Table 4.4 Key weather inputs used within FOW O&M Modelling

Publication	Weather and Environmental Condition					
	H_s	Wind Speed	Wave Current	Wind direction	Peak Wave Period	Wave Direction
Dewan & Asgarpour [11]	✓	✓				
Rinaldi et al. [31]	✓	✓	✓			
Katsouris & Marina [32]	✓	✓	✓			
Brons-Illing [37]	✓	✓				
Martini et al. [181]	✓	✓		✓	✓	✓
Gintautas et al. [47]	✓	✓			✓	
Martini et al. [48]	✓	✓		✓	✓	✓

Martini et al. [181] also utilises the Hydraulics Institute Cantabria databases. Data include wind data (mean speed, mean direction) and wave data (H_s, wave period, mean direction) with a time resolution of 1 hour extracted for the twenty years period between 1994 and 2013.

Within industry, turbines across the site are generally fitted with met ocean monitoring equipment. H_s is often viewed as the determining factor for access/no access decisions, as this is the KPI typically written into the vessel contract. However, data collected about wind speed are also vital for the overall control and monitoring of the asset.

Mean wind speed and H_s remain the key weather factors for O&M modelling offshore as these inputs are consistent across all models. However, other characteristics, specifically additional wave data, are becoming increasingly important for FOW modelling as presented within the literature. This parameter is currently lacking in existing models.

4.3.2. Taxonomy and Reliability

Reliability data and failure rates are used within O&M modelling to determine the number of transfers per annum. Failure rates also impact the direct costs of the site as they influence maintenance activity and therefore the cost of labour, vessel charter, fuel, materials, and spare parts. In some cases, failures are assumed to occur after a certain amount of time and are therefore modelled in a deterministic way. In other models, failures occur with a certain probability that is assessed based on collected data, so the failures occur randomly according to a defined probability distribution. Details of how failure rates are modelled for FOW are given in Table 4.5 with details of the taxonomy and components modelled.

Only one of the publications discussed [31] uses existing failure rate data. This data are from Carroll et al. [58], which is used extensively within BFW modelling. The data presented in [58] is based on 350 offshore wind turbines throughout Europe and provides failure rates for the overall wind turbine and its sub-assemblies. Due to confidentiality, specific details cannot be given. However, the collected data are for a geared turbine with an induction machine with nominal power between 2 and 4MW. The data have been adapted for this work by averaging the values for the maintenance categories [59]. [31] assumes that both the BFW and FOW scenarios have the same taxonomy, components, and sub-components. However, in reality, there would be an increase in the number of components for a FOW turbine. A total of

16 components are modelled, eight of which would require T2S maintenance for the FOW scenario. Due to the timeline of FOW installation, the machines are expected to exceed 10/12 MW capacity. Hence, these failure rates may be outdated.

Brons-Illing [37] did not provide details of reliability and failure data, however, they did provide details of how the failures were grouped. The failures were split into the following categories: wind turbine generator, floating substructure, and tower and subsea installation.

Elusakin et al. [39] used a system of eight FOW subsystems comprising of components: drivetrain unit, hydraulic brake system, yaw system, pitch system, rotor system, power system, and structure. They also give details of the components which make up these systems (total of 20). The structure system accounts for elements such as the tower, the floating foundation, and mooring lines. The eight subsystems are connected in series with each other, which means that the wind turbine cannot function if any of these components fails. To model the degradation process of components, four states are defined: normal, degraded, critical, and functional failure. The component moves from normal state to degraded state after a delay represented by a Weibull distribution.

The work by Martini et al. [181] aimed to simulate increased failure probability for FOW sites compared to onshore, due to more severe weather conditions and platform motions. [181] uses a constant failure rate within the summation. The methodology proposed in their work has more complex failure rates included such as a bathtub curve failure modelling approach. The duration of maintenance activities offshore is characterised by a relatively high degree of uncertainty, which is associated with the variability of met ocean conditions and the availability of technicians and vessels. Reparation times are modelled by a lognormal pdf.

Table 4.5 Failure and degradation modelling within FOW publications

Publication	Failure Modelling	Taxonomy
Rinaldi et al. [31]	Adjusted (Carroll et al. 2016 [49])	16 components
Martini et al. [181]	Exponential probability density function (pdf) with constant failure rate (γ)	12 components
Gray [8]	Monte Carlo analysis	N/A
Elusakin et al. [39]	Weibull distribution with shape parameter, β, and scale parameter, η	8 FOW subsystems comprising of components

Gray [8] highlights the importance of failure rate data within O&M modelling and its associated uncertainty. The number of components modelled is unknown, however a total of 12 failure modes (IDs) were modelled. [8] models failure rates using Monte-Carlo analysis.

There is a clear move from the classification of repairs being major/minor to at-shore/at-port due to the possibility of T2S. FOW turbines also introduce additional components with largely unknown failure rates. The literature does not address how motion and a harsh environment will impact the overall degradation of assets. The scaling of turbines and its impact on failures must also be addressed, both for BFW and FOW. Despite the lack of operational failure data for FOW, other methods of failure modelling should be applied as explored in [60] by analysing future trends and using available data.

4.3.3. Vessel

CTV and SOV are the typical BFW vessels. During major component replacement and repairs, a JUV, HLV or specialist field vessel (SFV) may be required. Helicopters are also utilised for O&M activities but are limited due to space and weight restrictions. This section examines the fleet selection used for FOW maintenance. Due to the addition of a T2S strategy, specific towing vessels are expected to be included. The types of vessels used are described in Table 4.6.

None of the works include heli-operations. Martini et al. [181] do not provide details of the vessel used, only vessel expenses as a direct cost. Dewan & Asgarpour [11] provide the most comprehensive details of potential vessels including weather limitations (both H_s and wind speed), speed, technician capacity and cost. There is no change to the H_s and wind speed transfer limit of the vessel, therefore assuming transfer from fixed to floating will be the same as floating to floating. Additional details such as charter rates, number of available vessels, and mobilisation times for both the towing vessel and the jack-up barge are also provided.

Table 4.6 Vessels considered for FOW O&M activities.

Publication	CTV	SOV/OSV	HLV/JUV	SFV	Helicopter	Tug vessel	AHTS	Additional Information
Rinaldi et al. [31]	✓		✓	✓				No limit on availability
Castella et al. [30]	✓	✓	✓					Other vessels include Davit crane, cable repair vessel and diving vessel.
Brons-Illing [37]	✓	✓					✓	
Dewan & Asgarpour [11]		✓				✓		
Amorim [33]	✓							
Gray [8]	✓					✓		

Brons-Illing [37] models three vessel types in their work, CTV, SOV, and an anchor handling tug supply vessel (AHTS). The use of an AHTS is omitted from BFW models as T2S is not considered. They include details of the number of vessels used, crew capacity, and day rates for each of the vessels used.

Gray [8] uses a tug vessel for T2S operations but does not explicitly state details surrounding the vessel capabilities.

In [37] the H_s limit for CTV remains at 1.5 m - 2 m for safe transfer. Specialist maintenance vessels such as an SOV, SFV or mothership limiting conditions ranges from 2.5 - 4 m. Rinaldi et al. [31] states that the weather limits during T2S operations decrease by 70% and the vessel speed is reduced by 30%.

However, there is a lack of standardised data surrounding T2S operations. There are discrepancies regarding the speed of a tugboat (both when towing and not towing) within the literature. Maienza et al. [40] state the lowest tug speed at 1.86 knots and Dewan & Asgarpour [11] the highest at 8-10 knots.

Works including [11] [50] [37] [51] [52] all provide details of the cost of charter of the vessels. Harrison et al. [52] acts as a reference document providing details of the vessels and their applicability to specific support structures. A summary of the expected day rates for typical maintenance vessels is presented in Figures 4.4 and 4.5. The figures were created by determining the interquartile range of the data set generated from the literature. Outliers were classified if they exceeded the equation 4.1.

$$Q_i \pm (1.5 \times [InterQuartile\ Range]) \tag{4.1}$$

Where Q_i represents the first (Q_1 -) or third (Q_3+) quartile depending on identification of maximum or minimum outliers.

It is important to differentiate between a tug vessel and an anchor handling tug supply (AHTS) as seen in Figures 4.4 and 4.5. The price difference between the two methods is significant and therefore will have an impact on OpEx and LCOE. AHTSs are more likely to be utilised in the installation and decommissioning phase of the lifecycle, whereas the cheaper tugboat will be utilised in day-to-day operations. However, if a T2S strategy is utilised for major component replacement, it is likely AHTSs will be used for the connection/disconnection process. The JUV remains the most expensive element of the fleet; this may increase due to the expected peak in demand before 2030 [53]. The JUVs are also limited in depth to 60m [54], making them unsuitable for FOW. Results are excluding mobilisation costs.

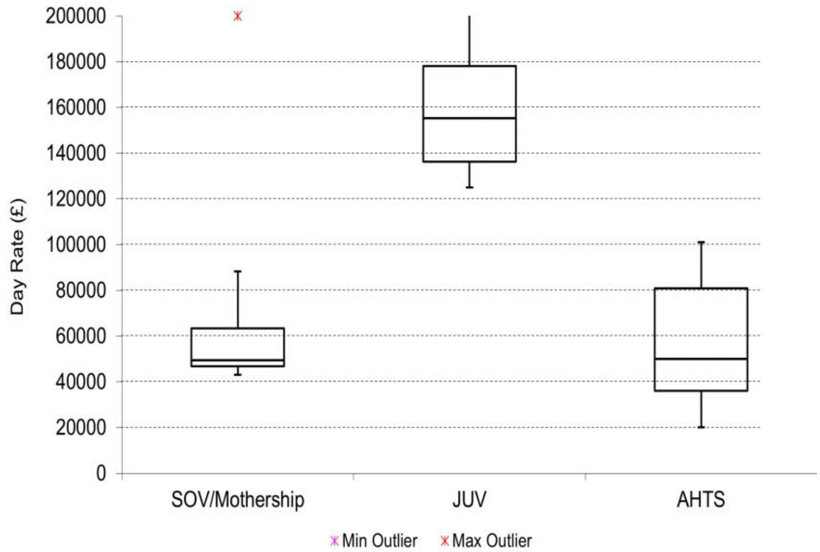


Figure 4.4 Average day rate (£) for SOV, JUV and AHTS as found in the FOW literature [193]

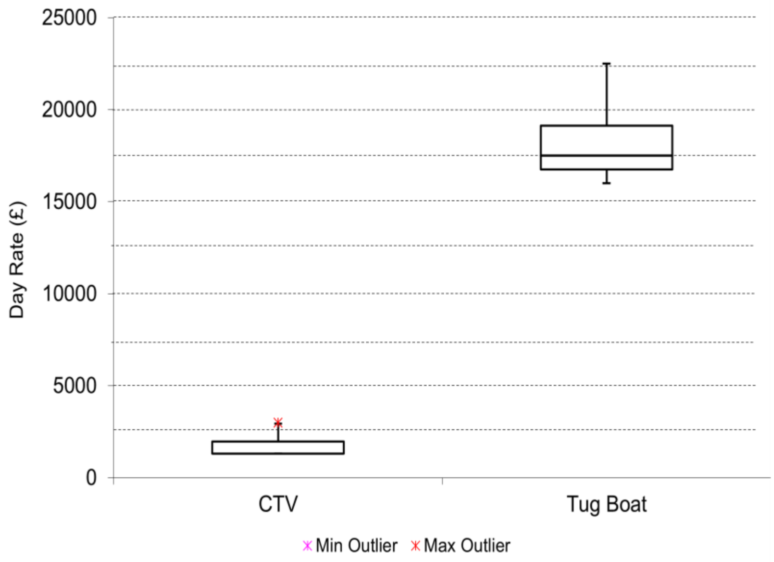


Figure 4.5 Average day rate (£) for CTV and Tug Boats as found in the FOW literature [193]

4.3.4. Economics and Cost Parameters

This section includes publications which produce cost estimations for FOW farms. Due to the infancy of the FOW industry, there is an additional risk for investors, making LCOE/cost reduction a key area of research. Key outputs include LCOE, Net Present Value (NPV), Internal Rate of Return (IRR), Cost Breakdown Structure (CBS), and Life Cycle Cost Analysis (LCCA). In general, LCOE studies provide more detail in their site description giving factors such as availability, capacity factor and annual energy production as known site inputs.

Castro Santos has been identified as one of the leaders in research in this area with a number of publications focused on FOW cost modelling [56] [57] [58] [59]. Works by Castro Santos et al. [58] [57] act as feasibility studies for Portugal and Northern Spain respectively, using the same methodology. The study is divided into three sections: geographical, economic, and restrictions in order to determine the feasibility of the site. The geographical phase examined weather factors, such as wind and wave conditions, using statistical methods such as the Weibull distribution. This is to determine overall available resource and site accessibility. Both studies also consider bathymetry to determine the feasibility of the location. The restrictions section analyses the three main substructure designs, spar, TLP and semi-sub, as well as distance to shore/port/shipyard. The economic phase was first developed in Refs. [56] [59], where a CBS is used to define the main costs and associated sub-costs, considering the disaggregation of the process. Wind farm costs are categorised as follows: concept definition, design and development, manufacturing, installation, exploitation, and dismantling. O&M costs are incorporated within the exploitation phase. The exploitation phase also includes revenue streams [57]. varies the electricity tariff from 200 to 300€/MWh to reflect the variability in the Portuguese system. [57] also varies the electricity tariff from 50 to 200 €/MWh [57] found that to be economically feasible a FOW farm, a tariff of 200€/MWh is required [58] also found that FOW farms would only be feasible at the upper end of the tariff range (300€/MWh). The values used in these works are above the current tariff received through the Hywind Scotland Pilot Park Renewable Obligation scheme at £160/MWh [60]. It was found that the exploitation cost consistently made up 25–30% of the total lifetime cost for all three structures considered.

Myhr et al. [61] uses the methodology described in Ref. [50] which echoes [56] by splitting the overall costs of the site into distinct phases: development and consenting, production and acquisition, installation and commissioning, operations and maintenance, and decommissioning [61] [50]. It included a wider range of turbine types including spar, semi-sub, tension leg spar, tension leg wind turbine, and tension leg buoy. The results indicate that LCOE values are strongly dependent on depth and distance from shore, due to mooring costs and export cable length, based on the findings, depth is the dominant parameter to determine the optimal concept for a site.

Heidari [62] is a more financially driven publication containing the most in-depth analysis of the cost structure, breaking it into 9 sections. This work also includes details regarding cost of equity and debt. The main output LCoE is given in £/MWh using the formula developed by PWC [63].

All the studies provide varying results in terms of LCoE for the spar, TLP, and semi-sub platform due to variable inputs such as water depth, installed capacity, distance from shore, balance of plant, number of turbines, etc. However, the publications also disagree in terms of which support structure will result in the highest LCoE as shown in Table 4.7. Table 4.7 ranks the LCoE results within each stated publication as high, med (ium) and low. These results are ranked according to the results of each publication and have not been bench-marked against each other due to differences in methodology, case studies, and terminology used. Castro-Santos et al. [59] only considers one type of structure and Maienza [51] provides an average LCoE for all structures. Therefore, the results of these works are not included. The difference in results indicates that there is no clear choice of support structure, highlighting the importance of external factors such as location, facilities, and environmental elements have more of an impact on the overall LCOE than the choice of structure.

Details of the CapEx and cost breakdown structure is beyond the scope of this review. It is important to understand the financial period in which large-scale FOW sites will become operational.

Castro-Santos 2014 [56] provides detail of the OpEx methodology used within [56] [57] [58] [59]. The O&M cost is split into preventive and corrective maintenance. Preventive maintenance includes cost of transport, direct labour, and materials for the entire system (including anchor and mooring). In addition, the number of elements needed, the type of vessel or helicopter used for maintenance, and the distance from farm to port are evaluated.

Within the works by Bjerkster & Agnotes [50] and Myhr et al. [61] the O&M modelling inputs were calculated using the Operation and Maintenance Cost Estimator "OMCE" Calculator [13]. Details of the exact inputs of the O&M modelling were not included in either publication due to their sensitive nature. This simulation tool computes the results before performing a sensitivity analysis in high- and low-scenarios to identify the main contributions to risk and uncertainty in each of the proposed concepts.

Maienza [51] calculates OpEx analytically and/or as a function of the installed power of the site. Costs are divided into operational and maintenance categories. Operational costs include the cost of seabed rental, insurance, and grid access feed. Maintenance expenditures are split into direct and indirect costs. Direct costs are presented as a sum of the preventive and corrective maintenance. Indirect maintenance expenditures include fixed costs faced to guarantee repair service including port fees, vessel hiring fixed costs, and maintenance planning and managing cost.

Table 4.7 LCoE ranking for different substructure types.

Publication	Spar	Semi-Sub	TLP
Myhr et al. (Standard) [61]	MED	HIGH	LOW
Myhr et al. (Optimised) [61]	MED	HIGH	LOW
Bjerkster et al. [50]	MED	HIGH	LOW
Heidari et al. [62]	LOW	HIGH	MED
Castro et al. (Portugal) [58]	LOW	MED	HIGH
Castro et al. (Spain) [58]	MED	LOW	HIGH

4.3.5. Additional Factors

While comparisons can be made between the BFW and FOW modelling processes, there are certain additional factors that must be considered in the modelling process specific to FOW operations. Rinaldi et al. [31], Brons-Illing [37] and Dewan & Asgarpour [11] explored the possibility of T2S as part of their maintenance operations. This has been identified as the main additional factor when modelling O&M processes for FOW.

Eluskin et al. [39] includes details of the mooring lines as an additional component with the potential to fail. They also acknowledge that performing FOW maintenance is more difficult, time-consuming, and risky for the personnel involved. Bjerksters [27], Martini et al. [181] and Katsouris & Marina [32] also provide details of the mooring system components within their analysis.

Within the LCOE papers such as [35, 36] bathymetry was used as an indicator of feasibility dependent on the substructure, and draft, used in the design. The mooring and anchoring system is included as a CAPEX cost in [40] and as a direct labour cost in [31, 37].

Works including Dewan & Asgarpour [11] also identify port logistics and additional weather restrictions as areas of future research. Within the existing literature, the key addition to the work to account for the FOW structure is the inclusion of components such as the mooring lines, anchoring, etc., in addition to the T2S strategy. Other factors such as turbine motion, workability, floating-floating transfer are not considered within these works. However, this may be due to the lack of understanding of the area at this point, with a more detailed analysis of these features being integrated into the modelling process later.

4.4. Strathclyde O&M Model Adaptation

The Strathclyde University offshore wind OpEx model utilises a time domain Monte-Carlo simulation approach. The focus of this model is detailed analysis of the O&M fleet. This model has been previously validated for its intended use [13] and has been used to assist with commercial operational projects.

The model uses a Monte Carlo time domain simulation approach and consists of four input modules: climate, vessel specifications and fleet configuration, wind farm/turbine, and cost and failures. For this analysis, the model has been adapted for FOW day-to-day maintenance procedures, excluding major replacement procedures.

This model comprises three main parts: climate modelling, turbine failure modelling, and resource and cost modelling. Users input sample data, allowing the model to simulate wind speed and significant wave height time-series over the defined wind farm lifetime using a multivariate autoregressive model. These values play a crucial role in calculating energy production and losses, as well as determining turbine accessibility for maintenance tasks.

Wind turbine failures are generated using a Markov Chain Monte Carlo simulation throughout the time-series. The hazard rate, determined by a user-defined failure rate, and the severity of failures are considered. Failures impact maintenance requirements, wind farm availability, and lost energy production.

Based on the chosen maintenance strategy, repair tasks may be initiated upon a failure. The model assesses the availability of necessary resources, like vessels, and verifies whether weather conditions fall within predefined operational limits for the required maintenance window duration. The model then estimates maintenance costs, taking into account aspects such as vessel hire, repair costs, and lost revenue due to turbine downtime.

An overview of the model, taken from [64], is provided in Figure 4.6. The model has capabilities including mobilisation times, use of CTV, SOV, HLV and bespoke vessel types, as well as potential delays including spare parts and technician availability. The model does

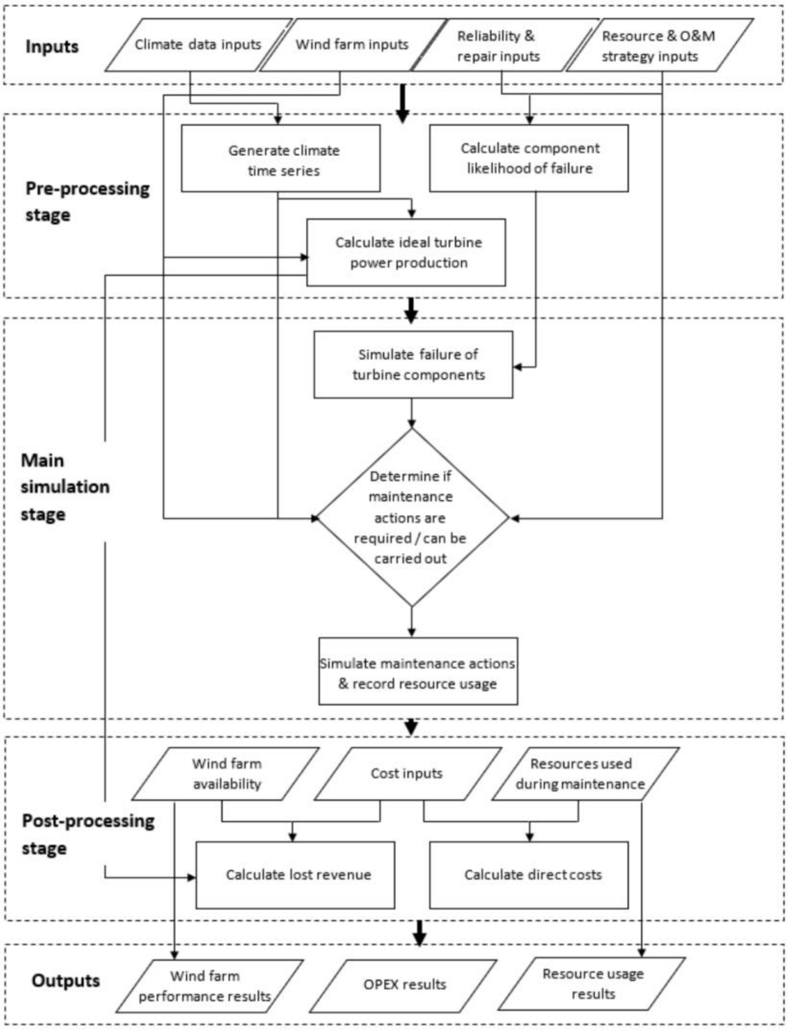


Figure 4.6 Strathclyde O&M Model Overview

not consider the location of specific turbines, but instead introduces an "average" distance between turbines to determine travel times between activities.

4.4.1. Updated Floating Wind Model

At present, there has yet to be modelling completed analysing the impact of workability on both accessibility and OpEx for CTV and SOV based maintenance strategies. The literature has highlighted that the majority of OpEx simulations for FOW analysis have been based on the T2S strategy. While the T2S strategy has been successfully carried out, as seen in the

Kincardine project [65], there is still uncertainty surrounding the most effective strategy for major component replacement for FOW sites such as the use of new floating vessels, tow to shallow or floating cranes [66]. While major component replacement of FOW sites has notable challenges [67], this work will focus on repair operations which can be carried out by CTV or SOV as these operations make up almost 90% of the maintenance operations [49].

As previously discussed, the key components of O&M modelling are weather/met ocean; failure and degradation; transportation and vessel routing; vessel, personnel, and spare part logistics; and economic parameters and cost estimation. As shown in Table 4.2, the Strathclyde O&M model already has the input of Tp. However, this metric is currently used to determine CTV speed when travelling from base to site. Within this adapted model, Tp & Hs limitations are applied. As the aim of this work was to determine the difference in OpEx between a BFW and FOW equivalent site, for day-to-day operations, the focus of the adaptations for FOW were met ocean and accessibility based. The logic of the access no/access decision metric used within the simulation tool is shown in Figure 4.7, with additions for floating wind shown in blue.

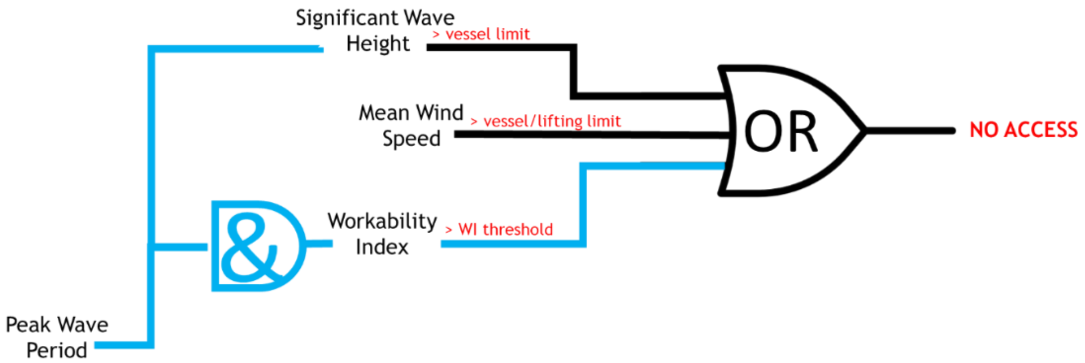


Figure 4.7. Decision logic for access/no access in Monte Carlo simulation

While existing databases on failure rates such as Carroll et al. [49] are for much smaller turbines than those which will be installed, this dataset was used for both BFW and FOW to allow for a direct comparison. The aim of this work is to determine the changes in OpEx due to increased limitations imposed on workability of FOW, not the prediction of specific OpEx budgets. It is also therefore assumed that all costs of repairs, vessels and personnel will be the same for both BFW and FOW.

While the FOW design will have additional maintenance requirements, such as the substructure/mooring system, the specific failure rates are currently unknown. Specific new designs, such as the Stiesdal Tetra concept, aim to have zero maintenance conducted on the floater [118].

Specific Adaptations

This work adapts the model to account for the influence of turbine motion on technician safety. Full details of the models used as part of this work are detailed in Appendix B. The key adaptation of the model is the behaviour of Tp within the model. Previously, access decisions are based on Hs and wind speed inputs (hourly).

The adaptation of the model involved the introduction of a FOW ACCESS pre-processing module, where the Hs input is replaced with an ***access*** input. The value of the access input (1 or 0), as detailed in Figure 4.7, then determines accessibility within the model. The FOW ACCESS module inputs WI specific to Hs and Tp combination matrix, in the format of that shown in both CoreWind [71] and Scheu et al. [72], where Hs/Tp combinations exceeding a predetermined WI index (provided by user input), is then combined with the Hs vessel threshold previously selected.

The FOW ACCESS output, then replaces the climate input as described in Figure 4.6 of the full Strathclyde model.

The addition of the FOW ACCESS module allows for the model to be run with and without the addition of WI, to allow the model to cater to both FOW and BFW projects.

4.5. Floating Wind OpEx Modelling

While accessibility gives an overview of the met-ocean conditions at site and allows assumptions to be made regarding KPIs such as availability, to determine the true impact of the additional limiting sea states on access to site, a lifecycle analysis is required to determine the impact on OpEx. There is a clear link between poor site accessibility and higher annual OpEx, therefore it is important to determine the financial implication of reduced site accessibility.

4.5.1. Case Study

The selection of the strategy of the vessel for each of the zones is provided in Chapter 3, Table 3.6 and repeated here in Table 4.8 and is based on the distance to shore and the average Hs at site. Each site with a CTV-based approach has a fleet of five vessels. Those with an SOV strategy will have one SOV per site, assisted by five daughter crafts. Vessel operations are not limited by daylight working hours. CTV and SOV-based strategies have Hs limitations of 2 and 4 m, respectively. The impact of reduced access for each of the platform designs is determined using a WI threshold limit of WI=1. The use of these case studies allows for conclusions to be drawn regarding the relationship between accessibility and OpEx.

Table 4.8 ScotWind case study details

Zone	Distance to Port [km]	Site Capacity [GW]	Average Hs [m]	Vessel Strategy
E1	120	1.9	1.7	SOV
E2	135	1.3	1.9	SOV
NE1	55	1.4	2.2	SOV
NE2	65	1	1.5	CTV
NE3	55	1	1.6	CTV
NE6	45	0.5	1.6	CTV
NE7	100	3	2.0	SOV
NE8	95	0.96	1.9	SOV
N2	85	1.5	2.5	SOV

For each wind farm listed in Table 4.8, a reference BFW farm of the same capacity, in the same region, is also simulated to provide a baseline comparison. Each farm has a lifetime of 25 years, with failure and cost data taken from Carroll et al. [49]. Failure and cost of additional components such as mooring lines and platform-specific components are not included within these simulations as the main focus is to identify the impact of the reduction of access on total OpEx. The Monte Carlo based simulation ran 200 iterations of the full project lifecycle, in line with that performed with the Shoreline model in the CoreWind project [69]. For platform designs, A-D [70], the wind farm capacity is made up of 10 MW reference turbines, and for WindCrete and ActiveFloat, 15 MW turbines are used based on the reference turbines used in the initial workability work.

It is assumed that the sites are supported under a guaranteed revenue stream with a cost of £50/MWh in line with Round 4 CfD priced adapted for 2023 prices. Staff costs, cost of repair, and the number of technicians required are taken from Carroll et al. [49]. These inputs remain consistent throughout all simulations.

4.5.2. Annual OpEx

OpEx can be upwards of 30% of the total cost of energy of a conventional BFW farm [45]. It is expected that OpEx will continue to largely contribute to the total levelized cost of energy (LCoE) for future floating sites, with the initial predictions seeing the OpEx contribution to FOW LCoE exceeding this [71]. Initial OpEx estimations are critical to the initial project financing phase and instrumental in a project's feasibility decision. Within the Strath-OW model, OpEx consists of both direct and indirect costs.

The aim of this work is to determine the impact of reduced accessibility for several platforms at different ScotWind zones, not to compare the OpEx of each zone against each other. Therefore, the results are presented as a percentage increase of total OpEx, based on the BFW equivalent wind farm with vessel Hs limits only. This section views any combination of Hs and Tp in which WI<0.9, as unsuitable working conditions, for each platform type.

As expected, sites and platform combinations with a high decrease in accessibility resulted in a high increase in OpEx, as shown in Figure 4.8. The analysis of the relationship between access and OpEx reveals a varied spread of results, with no uniform patterns. Notably, this diversity is partially explained by the installed capacity of individual sites, as those with higher capacity encounter a more pronounced influence, where sites require a higher number of weather windows in order to maintain all turbines.

With the exception of Design, A and WindCrete, NE7 exhibited the most pronounced influence on OpEx. This outcome results from NE7's turbine count, leading to a greater need for access periods. This underscores that while met-ocean factors aid in identifying optimal

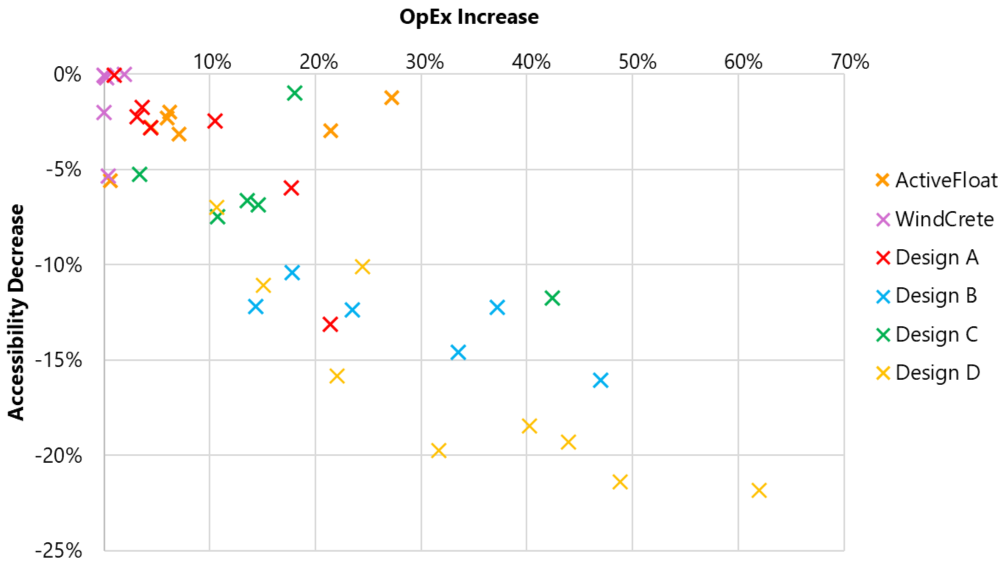


Figure 4.8. Comparison of reduction in accessibility versus increase in OpEx for the 6 platform types across all considered ScotWind zones.

platforms, it's noteworthy that sites with preexisting access complexities or a high demand for accessible periods will be notably affected by further maintenance access restrictions.

Design A, N2 saw the highest increase in OpEx. As shown in Figure 4.9, Design A workability limits impact Tp/Hs combinations where Tp exceeds 9 s. Of all sites, N2 has the highest average site Tp, making it more susceptible to these conditions in which access is limited. N2 also had the highest average Hs of all sites. Therefore, for the WindCrete design, which saw the lowest decrease in access of all sites, the impact of workability amplifies the already challenging access conditions, leading to an increase in OpEx.

As expected, due to a high number of workability-limiting combinations, Design D has the highest increase. This is shown for each specific ScotWind zone in Figure 4.9, showing the total OpEx percentage increase. This provides more information on the difference in OpEx between the different zones for the different platform types.

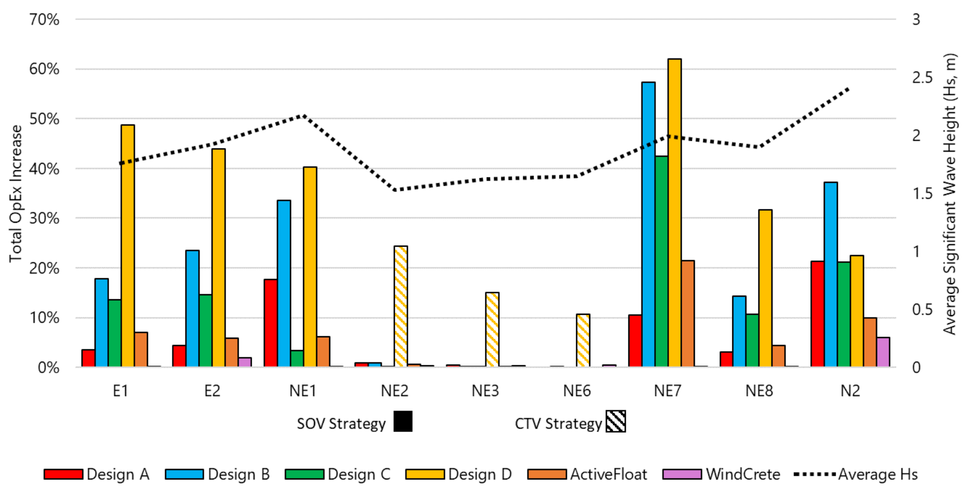


Figure 4.9. Total OpEx increase across all sites, using all platform types, with BFW as baseline.

As expected, due to the accessibility results, Design D is consistently the most operationally expensive platform, with the exception of N2. Results show that E regions have similar response to the platforms in terms of OpEx. However, NE zones show significantly different results, even for those with the same vessel strategy. However, it should be noted that NE regions are more spatially diverse than the E zones. Overall, NE7 is the most impacted site, again reflecting the results of the TBA study (Table 3.7, Figure 3.13). However, the differences in the increase in OpEx in comparison to other sites is much more exaggerated that the difference in accessibility. One potential reason for this is that NE7 has the highest installed capacity of all sites modelled. Therefore, it could be expected that this difference in results could be minimised by optimising the available resources.

SOV sites were more impacted than CTV sites, however, it should be noted that in terms of £/MWh, SOV sites are consistently cheaper than those with a CTV strategy in this analysis.

N2 is the most challenging in terms of accessibility, before additional constraints of workability were added. This is the only site to have Design B as the most challenging platform, despite design D having the highest impact on accessibility. After investigation, it was determined that this is due to weather window-based accessibility. It was found that for Design B, weather windows were typically below 5 hours, which is insufficient to perform maintenance and therefore classed as no access conditions.

4.5.3. Lost Revenue

When exploring the components which make up total OpEx, it was determined that the increase in total cost was due to the increase in lost revenue. One of the key components of OpEx is lost revenue, also known within the industry as opportunity cost or lost production cost. This is revenue that could have been generated had the turbine been operational. Reduced accessibility prolongs the downtime of unexpected failures due to increased waiting times for suitable weather windows. The comparison of total OpEx increase against the increase in lost revenue is shown in Figure 4.10. In all results presented OpEx includes the impact of lost revenue. Upon analysis of OpEx increase, it was determined that lost revenue increased the most.

Results show a linear correlation between an increase in total OpEx and an increase in lost revenue. While direct costs such as vessels and staff can be optimised, lost revenue is dependent on met ocean conditions and therefore more difficult to minimise. Among the designs studied, Design D stands out for displaying the greatest deviation from the linear relationship. This discrepancy is attributed to Design D experiencing the most substantial rise in OpEx. Due to the most significant impact on accessibility, the simulations of Design D encountered a number of failed transfers within the simulations, leading to increases in transportation costs which contributed to the overall increase in OpEx, as well as the increase in lost revenue. However, for all sites the increase in lost revenue was the most significant contributor towards the total increase in OpEx.

Furthermore, the impact that reduced workability under certain sea states may have with respect to a potential increase in downtime, is highly site-specific. It is therefore required to compare the motion response of the asset with the site conditions to be expected. In the case that non-workable conditions are to be expected in sea states with a high occurrence level, design adjustments or modifications may be required.

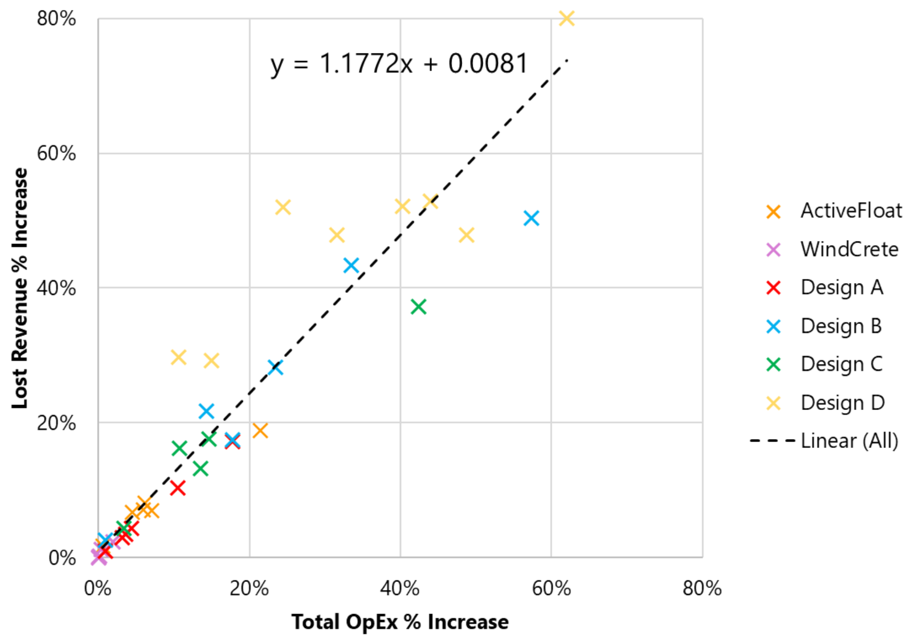


Figure 4.10. Total OpEx increase vs increase of lost revenue.

4.5.4. Workability Index Impact

As demonstrated in Section 3.5, the WI acceptable threshold has a significant impact on the most suitable platform type. The methodology of Section 4.2 is repeated using WI>0.6 as the acceptable threshold value. As detailed in Chapter 3, this saw an average increase in accessibility of 5% across all sites. Therefore, it is expected that there will be a significant decrease in OpEx. The WindCrete design is not included in this analysis as the WI threshold has no impact on accessibility, and therefore OpEx results for WI>0.6 and WI>0.9 are the same.

The above analysis (Section 4.5.2) is repeated using the updated acceptable WI threshold with results summarised in Figure 4.9 for all SOV sites. As discussed in Section 3.5, there is little change for CTV sites as WI changes.

The use of WI > 0.6 as the acceptable threshold yields more consistent results across both platforms and sites. WindCrete and ActiveFloat are omitted from these results as WI > 0.6 have no impact on accessibility, or therefore OpEx. Results show the most significant changes in Design D, in comparison to the results of Figure 4.11. Results for WI>0.6 also show more consistent results across sites.

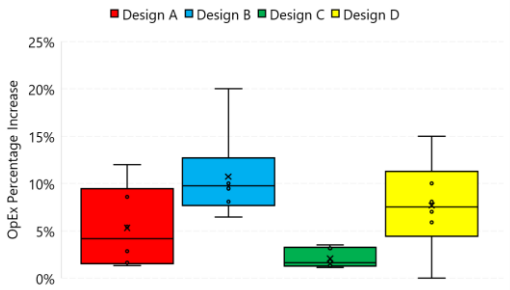


Figure 4.11. OpEx percentage increase against BFW equivalent baseline for all SOV ScotWind floating sites, where x is the average, and O show the quartiles based on a WI = 0.6.

4.6. Outcomes Summary

This work provides an overview of the impact of motion and workability limitations on FOW minor/major repair maintenance activities. Results highlight that the design of the platform can have a significant impact on both accessibility and OpEx, therefore a "one fits all" approach is insufficient for accurate O&M modelling. It was found that sites with existing accessibility challenges (N2 and NE7) will be most impacted by the addition of Hs/Tp combination limitations.

It was also found that for CTV sites, the impact of the addition of workability limitations had minimal impact, in comparison to SOV strategy sites, as most Hs/Tp combinations for the selected platforms occurred in Hs of 1.5 m or above, and therefore this limit was already captured by vessel limits.

The link between accessibility, OpEx and lost revenue has been demonstrated within this work. This is an important indicator for early project financing decisions. Therefore, it is vital that when selecting the most suitable platform for the site, both capital expenditure (CapEx) and OpEx must be considered. This work highlights the importance to the consideration of the operational impact of the selected platform during the design phase.

Another key finding of this work is the impact of the selected acceptable WI index. This introduces a balance between OpEx savings and technician wellbeing. The WI index sensitivity also highlighted how this can alter the suitability of a platform from an accessibility perspective. For an OM model to provide useful results, accurate inputs and assumptions are required. This work has highlighted how different WI thresholds yield very different results in terms of platform selection. To have effective planning, an industry standard of acceptable WI threshold must be determined to protect technician working conditions. The introduction of workability as a limiting accessibility factor also raises concerns concerning risk ownership.

Weather risk is often written in offshore wind contracts; however, it is unclear how workability concerns should be included as workability is the result of both weather considerations and the platform design.

The authors recommend the following areas for future work:

- **Platform suitability**: The study has emphasised that platform suitability varies significantly depending on the site. Therefore, to determine the most appropriate platform, it's crucial to consider various environmental factors, such as water depth and soil conditions, specific to that location. This filtering will remove unsuitable platform designs before more in depth analysis is conducted.
- **IEC Design Load Case (DLC):** The IEC standards cover various aspects of floating wind technology, including safety, performance, and reliability, and aim to ensure that floating wind turbines are designed and operated in a safe and sustainable manner. The authors recommend that one/more DLC/s for technician working is introduced to ensure a safe, and consistent, standard within the industry. The recommended design situation is for both typical CTV and SOV safe working conditions, with the external condition being determined by the type of work carried out by technicians (e.g., manual labour/intelligent working).

4.7. Chapter References

[1] P. B, A. Ermakova and A. Memanparast, "A review of extension strategies for offshore wind farms using techno-economic assessments," *Energies*, vol. 14, no. 7, p. 1936, 2021.

[2] A. Kolios and F. Brennan, "Review of Existing Cost and O&M Models, and Development of a High-Fidelity Cost/Revenue Model for Impact Assesment," ROMEO: Deliverable 8.1, 2019.

[3] B. Maples, G. Saur, M. Hand, R. Van De Pietermen and T. Obdam, “Installation, operation and maintenance strategies to reduce the cost of offshore wind energy,” National Renewable Energy Lab (NREL), Golden, CO, 2013.

[4] Y. Dalgic, I. Laxakis, I. Dinwoodie, D. McMillan and M. Revie, “Advanced logistics planning for offshore wind farm operation and maintenance activities,” *Ocean Engineering,* vol. 101, pp. 211-226, 2015.

[5] Dai, M. L. Stalhane and I. Utne, “Routing and scheduling of maintenance fleet for offshore wind farms,” *Wind Engineering* , vol. 39, no. 1, pp. 15-30, 2015.

[6] R. Dawid, D. McMillan and M. Revie, “Development of an O&M tool for short term decision making applied to offshore wind farms,” in *Wind Europe Summit*, 2016.

[7] A. Gray, “What are operations and maintenance simulation tools?,” ORE Catapult, 2020.

[8] A. Gray, “Operations and maintenance modelling of floating hybrid systems,” in *Wind Europe*, 2019.

[9] E. Koutoulakos, “Wind turbine reliability characteristics and offshore availability assessment,” 2008.

[10] F. Montoya, DNV-GL, Operations planning (O2M) for offshore wind farms.

[11] A. Dewan and M. Asgarpour, “Reference O&M Concepts for Near and Far Offshore Wind Farms,” ECN, Petten, 2016.

[12] P. Stratford, “Assessing the financial viability of offshore wind farms,” in *European Wind Energy Conference (EWEC 2007),* Milan, Italy, 2007.

[13] I. Radeamkers, H. Braam, T. Obdam, P. Frohbose and N. Kruse, “2008,” in *European Wind Energy Conference (EWEC 2008)*, Brussels, Belgium, Tools for estimating operation and maintenance costs of offshore wind farms: state of the Art.

[14] F. Douard, C. Domecq and W. Lair, “A probabilistic approach to introduce risk measurement indicators to an offshore wind project evaluation=improvement to an existing tool ecume,” *Energy Procedia,* vol. 24, pp. 255-262, 2012.

[15] M. Scheu, D. Matha, M. Hofmann and M. Muskulus, “Maintenance strategies for large offshore wind farms,” *Energy Procedia*, vol. 24, pp. 281-288, 2012.

[16] M. Hofmann and I. Sperstad, “Nowicob- a tool for reducing the maintenance costs of offshore wind farms,” *Energy Procedia*, Vols. 177-186, p. 35, 2013.

[17] J. Johansson, “Operational validation of SIMLOX as a Simulation Tool for Wind Energy Operations and Maintenance (O&M),” KTH Master's Thesis, Stockholm, 2013.

[18] F. Besnard, K. Fischer and L. Tjernberg, “A model for the optimization of the maintenance support organization for offshore wind farms,” *IEEE Transactions on Sustainable Energy,* vol. 4, pp. 443-450, 2013.

[19] I. Dinwoodie, F. Quail and D. McMillan, “Analysis of offshore wind turbine operation and maintenance using a novel time domain meteo-ocean modelling approach,” in *Turbo Expo: Power for Land, Sea and Air, American Society of Mechanical Engineers*, 2012.

[20] O. Endrerud, J. Liyange and N. Keseric, “Marine logistics decision support for operation and maintenance of offshore wind parks with a multi method simulation model,” in *Winter Simulation Conference 2014 IEEE*, 2014.

[21] F. Santos, A. Teixeria and C. Soares, “Modelling and simulation of the operation and maintenance of offshore wind turbine,” in *Institution of Mechanical Engineers, Part O: Journal of Risk and Reliability*, 2015.

[22] M. Sahnoun, D. Baudry, N. Mustafee, A. Louis, P. Smart, P. Godsiff and B. Mazari, “Modelling and simulation of the operation and maintenance strategy for offshore wind farms based on multi-agend system,” *Journal of Intelligent manufacturing,* vol. 30, pp. 2981-2997, 2019.

[23] S. Ambühl and J. Soorensen, “Sensitivity of risk-based maintenance planning of offshore wind turbine farms,” *Energies,* vol. 10, p. 505, 2017.

[24] G. Rinaldi, A. Pillai, P. Thies and J. L, “Multi-objective optimization of the operation and maintenance assets of an offshore wind farm using genetic algorithmn,” *Wind Engineering,* vol. 44, pp. 390-409, 2020.

[25] J. Walgern, M. Schwarzkopf, U. Smolka, G. Potenza and I. Andueza, “O&M Cost Modelling,” CL-Windcon - closted loop wind farm control, 2019.

[26] M. Wiggert, “Offshore TIMES,” Fraunhofer IWES, 2020.

[27] P. Tomaselli, M. Dixen, R. Bolanos Sanchez and J. Sorensen, “A decision-making tool for O&M activities of offshore wind farms using simulated actual decision drivers,” *Frontiers in Marine Science,* vol. 7, p. 1189, 2021.

[28] H. Seyr and M. Muskulus, “Decision support mofels for operation and maintenance of offshore wind farms: a review,” *Applied Science,* vol. 9, p. 278, 2019.

[29] B. Li, “Operability study of walk-to-work for floating wind turbine and service operation vessel in the time domain,” *Ocean Engineering,* vol. 220, p. 108397, 2021.

[30] F. Castella, “Operation and maintenance costs for offshore wind farm. Analysis and strategies to reduce O&M costs,” Master's Thesis, Univeritat de Politecnica de Catalunya, 2020.

[31] G. Rinaldi, P. Thies and L. Johanning, Improvements in the O&M modelling of floating offshore wind farms, CRC Press, 2020.

[32] G. Katsouris and A. Marina, “Cost modelling of floating wind farms,” ECN, 2016.

[33] L. Amorim, “On Optimization of Operation and Maintenance for a Floating Offshore Wind Farm,” Students Thesis, KTH, 2019.

[34] Shoreline, “Design - Simulate and model the design of wind farms,” [Online]. Available: https://www.shoreline.no/solutions/design/.

[35] G. Rinaldi, L. Johaning, P. Theis and R. Walker, “A novel reliability-baded simulation tool for offshore renewable technologies,” in *Progress in renewable energies (RENEW2016)*, 2016.

[36] G. Rinaldi, A. Pillai, P. Theis and L. Johanning, “Verification and benchmarking methodology for o&m planning and optimization tools in the offshore renewable energy sector,” in *ASME 2018 37th international conference on ocean, offshore and arctic engineering*, 2018.

[37] C. Bron-Illing, “Analysis of operation and maintenance strategies for floating offshore wind farms,” PhD Thesis, University of Stavanger, 2015.

[38] M. Martini, R. Guanche, I. Losada-Campa and I. Losada, “The impact of fowntime over the energy yield of a floating wind farm,” *Renewable Energy,* vol. 117, pp. 1-11, 2018.

[39] T. Elusakin, M. Shaifee, T. Adedipe and F. Dinmohammadi, “A stochastic Petri Net model for O&M planning of floating offshore wind turbines,” *Energies,* vol. 14, p. 1134, 2021.

[40] M. Karimirad and T. Moan, “A simplified method for coupled analysis of floating offshore wind turbines,” *Marine Structures,* vol. 27, pp. 45-63, 2012.

[41] I. Katic, J. Hojstrup and N. Jensen, “A simple model for cluster efficiency,” in *European wind energy association conference and exhibition*, 1986.

[42] A. Myhr, C. Bjerkseter, A. Ågotnes and T. Nygaard, “Levelised cost of energy for offshore floating wind turbines in a life cycle perspective,” *Renewable Energy,* vol. 66, pp. 714-728, 2014.

[43] C. Bjerkseter and A. Ågotnes, “Levelised costs of energy for offshore floating wind turbine concepts,” Master's Thesis, Norweigan University of Life Sciences, 2013.

[44] L. Castro-Santos, D. Silva, A. R. Bento, N. Salvação and C. Guedes Soares, “Economic feasibility of floating offshore wind farms in Portugal,” *Ocean Engineering,* vol. 207, 2020.

[45] Y. Feng, P. Tavner and H. Long, “Early experiences with UK round 1 offshore wind farms,” in *Institution of Civil Engineers - Energy*, 2010.

[46] I. Utne, “Methodology and theory: maintenance strategies for deep-sea offshore wind tubrines,” *Journal of Quality Maintenance Engineering,* vol. 16, pp. 367-381, 2010.

[47] T. Gintautas, J. Sorensen and S. Vatne, “Towards risk-based devision support for offshore wind tubrine installation and operation maintenance,” *Energy Procedia,* pp. 207-207, 2016.

[48] M. Martini and R. L. I. V. C. Guanche, “Accessibility assessment for operation and maintenance of offshore wind farms in the North Sea,” *Wind Energy,* vol. 20, pp. 637-656, 2017.

[49] J. Carroll, A. McDonald and D. McMillan, “Failure rate, repair time and unscheduled O&M cost analysis of offshore wind turbines,” *Wind Energy,* vol. 19, no. 6, pp. 1107-1119, 2016.

[50] C. Bjerkster and A. Agotnes, “Levelised cost of energy for offshore floating wind turbines in a life cycle perspective,” Master's Thesis, Norwegian University of Life Sciences, 2013.

[51] C. Maineza, A. Avossa, F. Ricciardelli, D. Corio, G. Troise and C. Georgakis, “A life cycle cost model for floating offshore wind farms,” *Applied Energy,* vol. 266, p. 114716, 2020.

[52] J. Harrison, “Blackfish Engineering - floating offshore wind: installation, operation & maintenance challenges,” Blackfish Engineering, 2020.

[53] D. McMillan and I. Dinwoodie, “Forecasting long term jack up vessel demand for offshore wind,” *ESREL ,* 2013.

[54] D. Ahn, S. Shin, S. Kim, H. Kharoufi and H. Kim, “Comparative evaluation of different offshore wind turbine installation vessels for Korean west-south wind farm,” *Naval Architecture Ocean Engineering,* vol. 9, pp. 45-54, 2017.

[55] J. McMorland, M. Collu, D. McMillan and J. Carroll, “Operation and maintenance for floating wind turbines,” *Renewable and Sustainable Energy Reviews,* vol. 163, p. 112499, 2022.

[56] L. Castro-Santos and V. Diaz-Casas, “Life-cycle cost analysis of floating offshore wind farms,” *Renewable Energy,* vol. 66, pp. 41-48, 2014.

[57] L. Castro-Santos, D. Silva, A. Bento, N. Salvacao and C. Soares, “Economic feasibility of floating offshore wind farms in Portugal,” *Ocean Engineering,* vol. 207, p. 107393, 2020.

[58] L. Castro-Santos, A. Bento, D. Silva, N. Salvacao and G. Soares, “Economic feasibility of floating offshore wind farms in the north of Spain,” *Journal of Marine Science Engineering,* vol. 8, p. 58, 20202.

[59] L. Castro-Santos, E. Martins and C. Soares, “Methodology to calculate the costs of a floating offshore renewable energy farm,” *Energies,* vol. 9, p. 324, 2016.

[60] Scottish Energy News, “Renewable wind industry calls for more subsidies to launch floating turbine farms,” 2019. [Online]. Available: http://www. scottishenergynews.com/renewable-wind-ustry-calls-for-more-subsidies-to-launch-floating-turbine-farms-off-scotland/. [Accessed 5 February 2020].

[61] A. Myhr, C. Bjerkster and A. N. T. Agotnes, “Levelised cost of energy for offshore floating wind turbines in a life cycle perspective,” *Renewable Energy,* vol. 66, pp. 714-728, 2014.

[62] S. Heidari, “Encomonic modelling of floating offshore wind power: calculation of levelised cost of energy,” Master's Thesis, Mälardalens Universitet, 2017.

[63] PwC, “Offshore wind cost reduction pathways study - Finance Work Stream,” PwC, 2012.

[64] B. Jenkins, “O&M Cost modelling of large component major replacement in next-generation offshore wind turbines with uncertain failyre rates,” *PhD Thesis, University of Strathclyde,* 2022.

[65] reNEWS.biz, “Kincardine Facing Turbine Repair Job,” 4 May 2022. [Online]. Available: https://renews.biz/77609/kincardine-facing-turbine-repair-job/#:~:text=The%20pioneering%2050MW%20Kincardine%20floating,be%20in%20need%20of%20replacement. [Accessed 5 May 2022].

[66] M. Duka, A. Gumber, F. Egil and B. Steffen, “The role of policies in reducing the cost of capital for offshore wind,” *Iscience,* 2023.

[67] I. Bayati and L. Efthimious, “Challenges and opportunities of major maintenance for floating offshore wind,” World Forum Offshore Wind, 2021.

[68] Stiesdal, “The TetraSpar full-scale demonstration project,” 2022. [Online]. Available: https://www.stiesdal.com/offshore/the-tetraspar-full-scale-demonstration-project/. [Accessed 3 June 2023].

[69] CoReWind , “D4.2 Floating Wind O&M Strategies Assessment,” EU-2020, 2020.

[70] M. Scheu, D. Kaufer, M. Schwarzkopf and A. Kolios, “Workability on Offshore Wind Turbines - a Comparative Study of Fixed-Bottom and Floating Applications,” in *The 28th International Ocean and Polar Engineering Conference,* OnePetro, 2018.

[71] BVG Associates, “Guide to Floating Offshore Wind - Floating Wind Lifecycle Overview,” 2023. [Online]. Available: https://guidetofloatingoffshorewind.com/floating-wind-lifecycle-overview/. [Accessed 10 June 2023].

[72] S. Heidari, “Economic modelling of floating offshore wind power: Calculation of levelized cost of energy.,” Mälardalen University, 2017.

[73] L. Castro-Santos, D. Silva, A. Bento, N. Salvacao and C. Soares, “Economic feasibility of floating offshore wind farms in Portugal,” *Ocean Engineering,* p. 207, 2020.

Chapter 5 : Opportunistic Maintenance for Floating Offshore Wind

This chapter aims to investigate the suitability of an opportunistic maintenance strategy for FOW applications.

Due to additional access limitations for FOW, a more flexible, and cost-effective maintenance strategy is required in a bid to reduce OpEx. This chapter introduces the concept of "opportunistic maintenance", known as OM, which is a flexible strategy where maintenance is conducted during user-defined opportunities with an economic benefit. This chapter reviews existing literature on the use of OM and its application within offshore wind. This Chapter identifies potential cost-saving opportunities and highlights the potential challenges and limitations. Finally, this Chapter demonstrates why this strategy would be particularly beneficial for FOW application. An overview is provided in Figure 5.1.

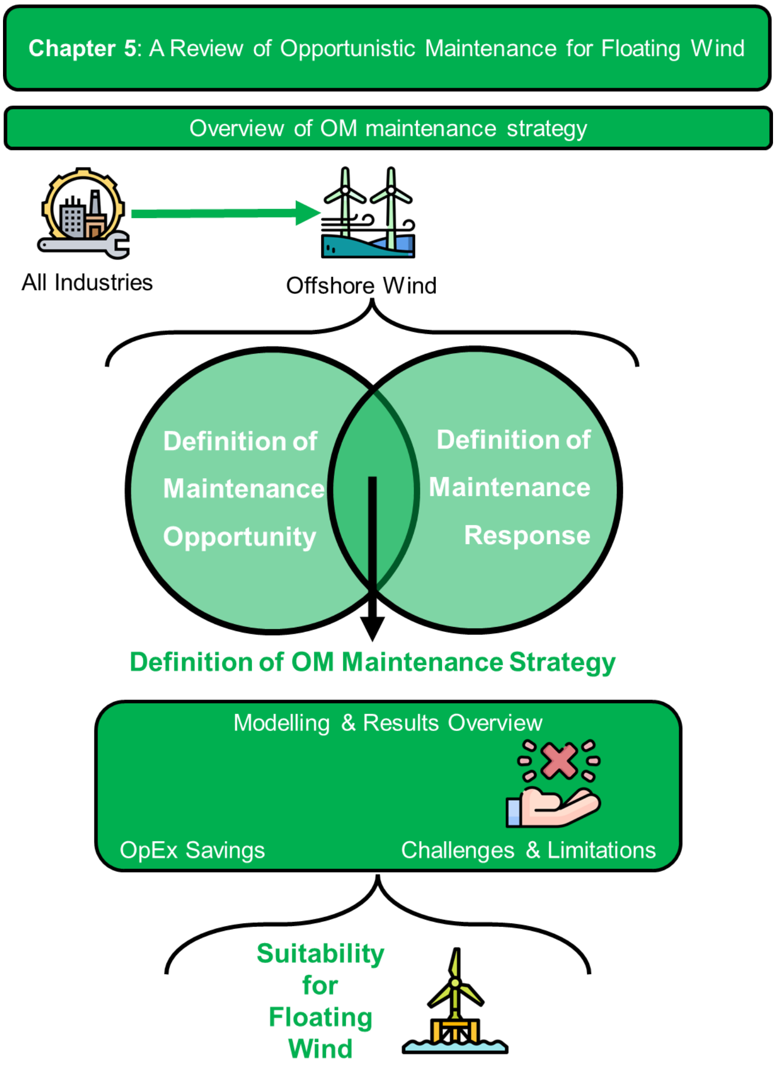


Figure 5.1. Chapter overview and summary

5.1. Background

OpEx can account for up to one-third of the total cost of energy for conventional BFW sites [1], however, as highlighted in Chapter 4 (and according to recent estimates [2]), this is expected to increase for future FOW sites. OpEx is an important financial indicator which has significance in both the initial investment and financial investment decision (FID) phases and is also the only cost which can still be controlled once a site becomes operational. When proposing OpEx budgets, it is vital to consider the post-subsidy and end-of-life operation of the asset in order to maximise income.

These factors have highlighted the requirement for a cost-effective, and flexible maintenance strategy. Periods of limited access must be effectively utilised to ensure economic operation. To overcome these challenges, flexible and cost-effective maintenance strategies must be utilised. One such strategy, which has been gaining traction in recent years, is opportunistic maintenance, OM. This strategy was first applied to offshore wind in 2009 by Besnard et al. [3] by applying an existing maintenance technique used in the aerospace industry to a small-scale offshore wind site. This strategy typically involves performing multiple repair actions during a single trip offshore triggered by author-defined "opportunities". This grouping of activities and opportunistic planning allows for sharing resources, such as vessels and crew, between maintenance actions, which results in an overall decrease in OpEx. Dispatch/transport operations are a significant area of cost reduction and have been shown to account for more than 70% of total O&M costs [4] [5]. This methodology also has operational safety advantages, as it decreases the number of trips offshore, which is a safety-critical process.

This strategy is commonly used within the industry as it is common to "never waste a weather day" and therefore make effective use of both resources and technicians. However, the existing literature fails to find a universal definition of both OM and an "opportunity". Part of this work aims to analyse the current literature and the definition of such terms.

This chapter aims to review the existing literature surrounding OM, highlight its effectiveness for FOW sites, and highlight potential maintenance opportunities for future markets.

5.1.1. Maintenance Strategy

Maintenance strategies within offshore wind are typically classified as scheduled and unscheduled [6]. Unscheduled maintenance, also called corrective maintenance (CM), is a reactive maintenance practice in which components are repaired upon fault without an attempt to pre-empt failure. While this offers a straightforward solution and minimal initial cost while maximising the remaining useful life (RUL) of components, there is significant unplanned downtime involved and further damage costs due to secondary damage in other components. As the scale of offshore wind farms expands rapidly, a CM strategy is no longer suitable and is gradually being replaced by preventive maintenance (PM) strategies [7].

Preventive maintenance (PM) is classified as scheduled maintenance, which is performed proactively to inspect and repair degrading components in an attempt to reduce unexpected downtime [8]. There are various approaches to determine when exactly to perform the maintenance action, which distinguishes the various subcategories shown in Figure 5.2. This can include condition-based maintenance, (CBM) or predictive maintenance (PrM).

CBM involves ongoing monitoring of component health to identify potential issues at an early stage and determine the most suitable maintenance actions. When a component deteriorates to a particular state, a preventive repair or replacement is undertaken. While this has the advantage of reduced unplanned downtime, this strategy introduces additional upfront capital costs for equipment. Artificial intelligence techniques, particularly deep learning, are now being utilised within the CBM methodology to facilitate in decision-making [9].

PrM instead allows maintenance to be performed just in time before a failure occurs, minimizing downtime, reducing costs, and extending the lifespan of assets. Early intervention can save up to 8% of direct O&M costs [10]. Currently, it is more common to use combinations of machine learning methods and statistical approaches in data-driven models rather than linking data-driven models with model-based models externally [11][[12].

OM aims to carry out maintenance actions whenever the opportunity arises in an effort to further reduce costs. This can result in the sacrifice of the RUL of a component, due to early intervention triggered by a maintenance opportunity. In Figure 5.2, both CM and PM are linked to OM. CM can provide an opportunity to carry out PM activities. Opportunities for maintenance are not only limited to CM occurrences, however, the OM strategy focus remains on cost-effective maintenance practices [13] [14].

5.2. Opportunistic Maintenance Definition

The concept of OM, or opportunistic replacement, was first proposed by McCall, Radner, and Jorgenson in 1963 [16] as an optimal maintenance policy of a single component in a multi-component system. The key methodology within this policy is that maintenance is to be performed on a given part at a given time, depending on the state of the rest of the system. The simple approach of using the opportunity of a component failure to conduct maintenance tasks on other related components was tried and altered to satisfy numerous system conditions. Since then, this methodology/framework has been adapted for several industries.

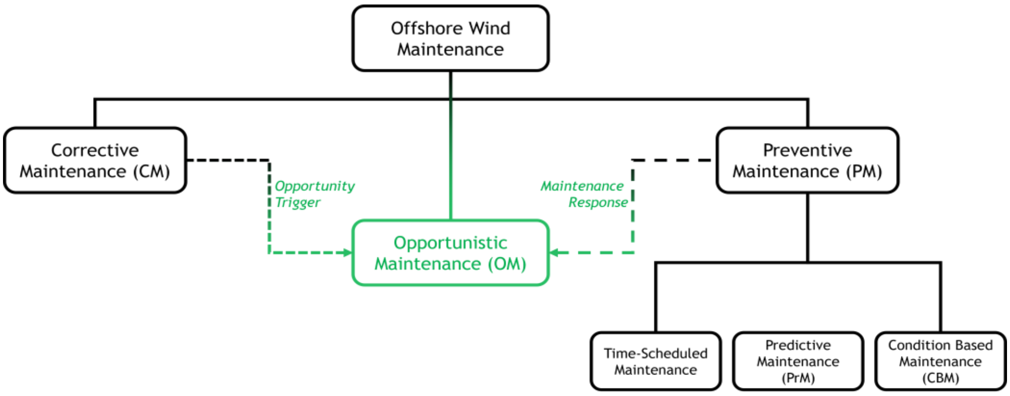


Figure 5.2. Offshore wind maintenance strategies and their relation to opportunistic maintenance [15]

Several reviews on developments in OM policy and strategy have been conducted, including the most recent by Ab- Samat & Kamaruddin [17]. The core issue in OM research concerns the technical and economic conditions of the components for conducting replacement or repair. Therefore, taking an opportunity should not have a negative impact on the income/cost of the overall system.

5.2.1. Key Industries

While the focus of this review is publications specifically relating to the application of OM within offshore wind, this section provides a brief overview of the use of the strategy within other industries.

The top industries in which this method has been applied within the literature can be determined. The results are summarised in Figure 5.3. The literature was gathered using WebOfScience using the keywords "opportunistic maintenance". All review articles or papers published after 2022 were excluded.

The majority of the existing publications are focused on an unspecified multi-component, or multi-unit, system. The universal definition of the system in terms of independent and dependent components experiencing failure allows the methodology to be applied to several specific case studies. The common theme within these publications was that the systems and subsequent subsystems were economically linked.

The most common industry-specific application of the methodology is within manufacturing/production. Manufacturing facilities have the same objectives as offshore wind farms of maximising output, by reducing downtime and improving reliability while maximising availability. Manufacturing facilities consist of a given number of machines, each consisting of a given number of sub-systems/components.

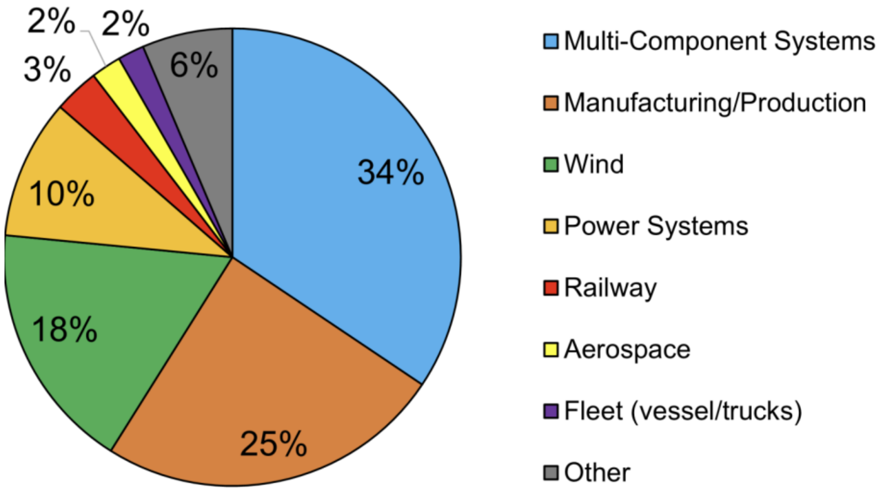


Figure 5.3 Split of applications applied with OM publications based on 380 publications on "opportunistic maintenance”.

The degradation of manufacturing machines occurs according to their production rates, which affects the availability and quality of their output products [18]. This is the same process seen in offshore wind, where the degradation of the asset can lead to reduced power output.

Like offshore wind, manufacturing also has set limitations surrounding the operation of the system. Maintainability of the systems is challenging due to weather factors [19 – 22] and the waiting time for parts or staff [23 – 28]. System outages can also be forced due to lack of demand [29] [30] or low commodity prices [20] [21] [31].

The most common application of OM within this industry is performing scheduled maintenance during unplanned outages [21] [32] [33] [34] [25]. A similar trend is found within the offshore wind literature as seen in Section 5.3

5.3. Literature Overview

OM was first applied to the offshore wind industry by Besnard et al. [3] in 2009, by adapting an OM methodology specific to the aircraft industry. The strategy involves performing additional (non-critical) maintenance activities when there is an "opportunity" to do so. The definitive definition of both OM and the arising "opportunity" is still disputed within the literature. However, all agree that the approach encourages a flexible O&M methodology which has economic benefits due to the sharing of resources, and/or performing maintenance activities in economically favourable periods. This section identifies key contributors to the knowledge of OM within an offshore wind context and analyses key trends within the literature. The definition of maintenance actions and opportunities is also explored.

5.3.1. Overview

OM for offshore wind is becoming more popular within the literature and therefore is now included within recent O&M reviews such as [7] [14] [35] [36]. However, to the authors' knowledge, there has yet to be a review focused solely on this strategy. Work by Erguido et al. [37], provides a clear overview of the current state of the literature surrounding OM. This work also analyses the use of the levels of maintenance used including one level, perfect/imperfect, and several levels.

Li et al. [38] also include a brief review of the existing literature in their work, where they consider failure modelling, the inclusion of environmental impact, and preventive dispatch. Li et al. [38] introduce the concept of a "maintenance trigger". This is the event which triggers an OM strategy to be applied, also known within this work as an opportunity. Within their review, they concluded that the environmental impact (such as weather limits on access) was overlooked and was a key element of the overall OM-based approach. [38] highlights the trade-off between the frequency of crew transfer taking the opportunity and the cost of performing maintenance which is reflective of that found in the work of Ab-Samat et al. [17] in their review of OM within all industries.

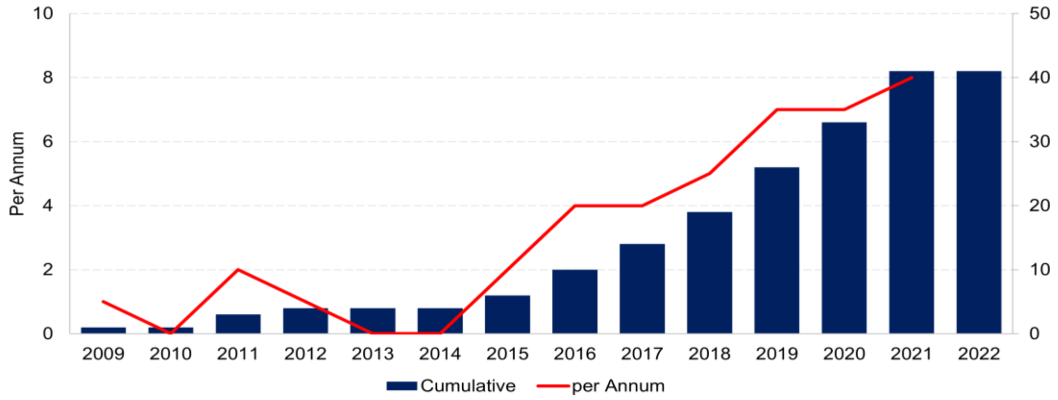


Figure 5.4. Growth in research dedicated to opportunistic maintenance within offshore wind

There has been a steady growth in academic interest in the topic, as seen in Figure 5.4. Interest in this area has seen a steady growth in the number of publications annually since 2015. 2015 also saw a dramatic increase in annual installed capacity across Europe with 419 offshore wind turbines installed. In terms of installed capacity, this was a 108.3% increase over 2014 and the largest annual increase in capacity to date [39].

5.4. Definition of an Opportunity

Within this work, the authors define an opportunity as "a pre-determined event which triggers a decision to perform a predefined set of tasks". These opportunities can be simply categorised as internal or external, as first presented by Erguido et al. 2018 [40]. Internal opportunities are from within the wind farm (typically maintenance-based), and external opportunities come from influences out with the wind farm, such as weather. Figure 5.5 provides an overview of the classification of the opportunities considered in existing publications. The majority of publications only consider internal opportunities within their OM framework. Opportunity triggers are rarely based solely on external factors, as seen in Kennedy et al. [41].

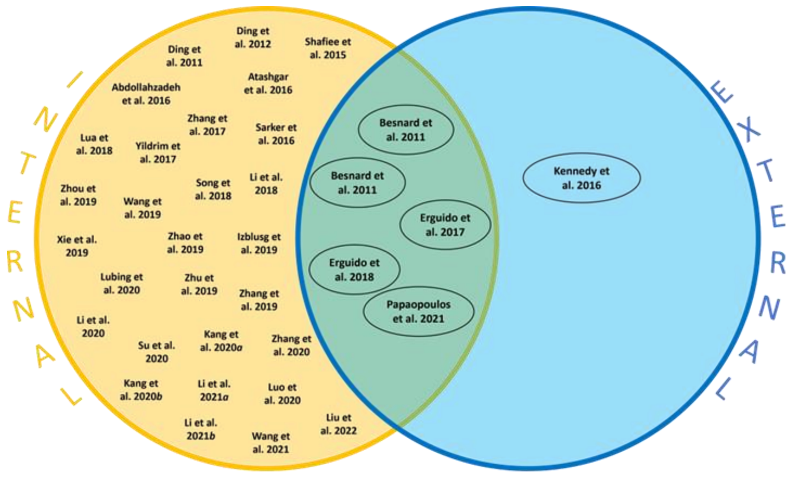


Figure 5.5 Classification of opportunities used within the literature.

5.4.1. Internal Opportunity

An internal maintenance opportunity is triggered by an action within the wind farm. The most common opportunity within the literature is a maintenance action. If a maintenance action is triggered (either scheduled or unscheduled), then this presents an opportunity to perform additional maintenance activities during a single trip offshore, as staff and vessel resource are already deployed. Other internal opportunities can include incident-based transfers where the arriving environmental impact is set to have a critical impact [42] [43]. Classification of internal opportunities is CM only, PM only or CM & PM activities.

As discussed in Section 2, CM activities make up the majority of offshore maintenance actions. Due to the critical nature of these failures and the high cost associated with asset downtime, it is logical that CM activities are viewed as the key opportunity or trigger to perform OM activities. Works by Ding & Tian [44] [45] Shafiee et al. [46], Sarker et al. [47] and Li et al. [48] only consider CM opportunities for OM maintenance actions. It is most common for publications to use both CM and PM maintenance actions [3] [37] [40] [42-64].

Figure 5.6 shows the proportion of publications which consider CM & PM, CM only, PM only, or a different internal opportunity, "other". Within this work, "other" refers to maintenance actions which were not specifically classified as CM or PM. These included "any maintenance action" [65], and the event of a crew dispatch [62] [53].

In the event of a CM maintenance action, there is an immediate attempt to repair and therefore take the opportunity. However, the treatment of PM opportunities is more complex. PM can range from scheduled maintenance activities based on time, such as inspections, to more complex defects detection and CMB activities.

The most common classifications of PM activities used as opportunities are as follows.

- **Scheduled**: PM triggered based on a pre-defined time schedule
- **Reliability threshold**: when the reliability threshold is reached, PM is triggered.
- **Defect detection**: if a specific defect on a specific component is detected
- **Generic CBM**: outputs from CMB trigger PM activities

Table 5.1 summarises their use within the literature.

The most common version of PM used within the literature is generic/scheduled. This is the simplest to implement, as it requires a list of predetermined PM tasks with a specified frequency, duration, and resource requirement. The use of PM based on reliability and defect detection requires a greater understanding of failure distributions and maintenance thresholds.

The work of Zhang et al. [66] uses a defect-centred maintenance approach that examines the impact of environmental disturbance on both the initialisation and propagation

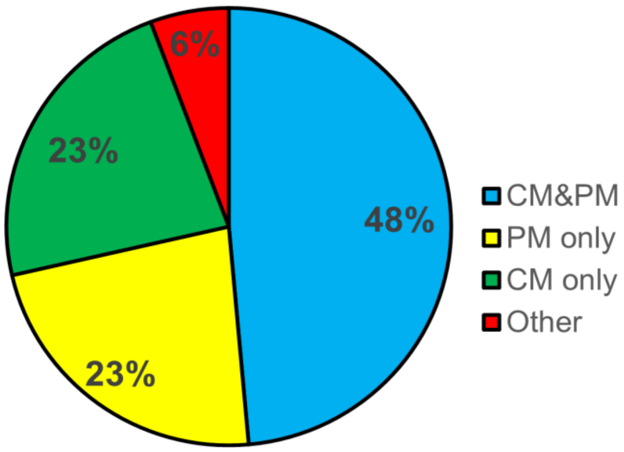


Figure 5.6 Types of internal opportunities considered within the existing literature.

of the defect. This then introduces three types of maintenance windows: regular, opportunistic, and postponed, dependent on the severity of the defect detected. Shafiee et al. [46] also introduce defect detection, but only for a single component. If the length of a crack in a blade reaches a predetermined threshold, an opportunity is triggered. In the event of a defect, a complete replacement of the blade is performed, with PM performed on the other blades.

Zhou et al. [55] propose a dynamic opportunistic condition-based maintenance strategy through the use of predictive analysis. When a maintenance lead time is introduced, maintenance actions can be scheduled more economically. For publications which exclusively consider one type of maintenance trigger (corrective or preventive), the literature can easily be split before/after 2018. A number of works consider only corrective opportunities to perform preventive tasks [3] [37] [44 – 49]. This approach is more common in earlier articles (pre-2018). This may be due in part to the infancy of the use of CBM techniques within the industry. Those who exclusively view preventive maintenance as an opportunity and a trigger are more commenting in recent years (for example, post-2018 [38] [67 – 72]. Zhang et al. [57] is the only publication, post-2018, which performs "traditional" PM tasks, such as inspections, when operational, based on a PM trigger/opportunity. The PM opportunity is based on condition monitoring, including age-based spare parts replacement upon defect identification. This is illustrated in Figure 5.7.

Table 5.1 PM classifications used within the literature.

	Predictive Maintenance Classification			
	Scheduled	Reliability Threshold	Defect Detection	CBM
Shafiee et al. [46]		✓		
Abdollahzedeh et al. [50]		✓		
Atashgar et al. [51]		✓		
Zhang et al. [52]	✓		✓	
Erguido et al. [37]	✓			
Lua et al. [67]	✓			
Zhou et al. [55]				
Xie et al. [56]		✓		
Zhang et al. [57]		✓		
Izblusg et al. [58]		✓		
Wang et al. [59]	✓			
Zhao et al. [68]	✓			
Li et al. [38]	✓			
Kang et al. [69]	✓			
Lubing et al. [61]	✓			
Zhang et al. [66]				✓
Su et al. [70]	✓			
Kang et al. [60]	✓			
Luo et al. [71]	✓			
Li et al. [43]	✓			
Papaopoulos et al. [62]	✓			
Xia et al. [63]	✓			
Li et al. [42]				
Wang et al. [64]	✓			
Lui et al. [72]	✓			

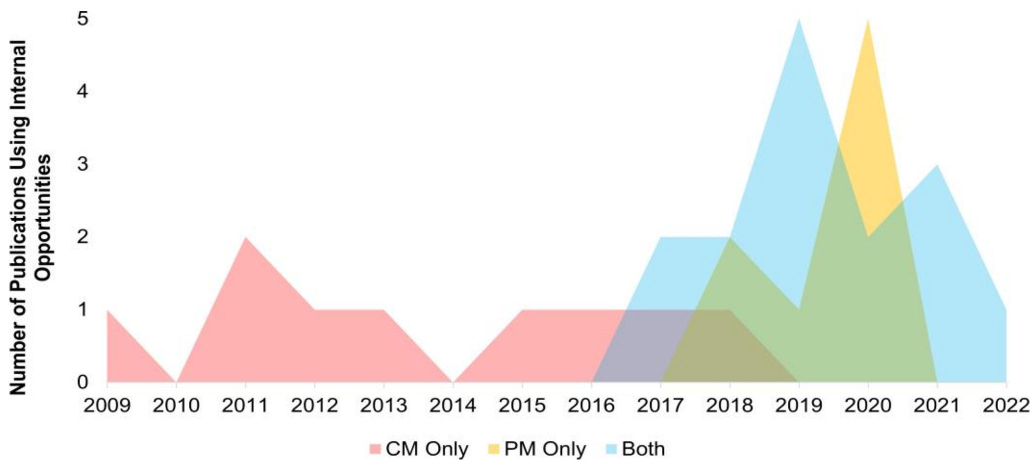


Figure 5.7 Breakdown of publications using internal opportunities.

5.4.2. External Opportunity

An external maintenance opportunity is triggered by an influence independent of the wind farm. Within the existing literature, this is most commonly weather-based using wind speed. If the wind speed falls below the cut-in speed defined by the manufacturer, the turbine will not operate. Therefore, this may be an opportune time to perform maintenance activities. One of the main focuses on operational cost reduction is minimizing downtime. Many developers view downtime as an opportunity cost, this is the income which would have been generated had the turbine been operational. Therefore, the opportunity cost occurs during failure and is maximised by prolonged downtime due to weather and travel restrictions. Therefore, there are savings to be made by performing maintenance during periods of low wind speed when revenue will be reduced.

Performing maintenance during periods of low wind speed/power production was first proposed by Besnard et al. 2009 [3]. Besnard et al. 2011 later expanded on this approach [49]. The methodology has since been used in works by Kennedy et al. [41] and Papadopoulos et al. [62].

The works of Kennedy et al. [41] and Besnard et al. [49] are based on the first offshore wind OM publication [3]. It was found that significant cost savings can be achieved by scheduling maintenance tasks at times of predicted low power production. Weather forecasts are generated using a short horizon interval, which is discretised into time steps, each consisting of one day. This modelling work falls into the realm of operational planning [73], where the chosen strategy is used to inform day-to-day scheduling decisions. The works of Besnard et al. [3] [49] considered the impact over the lifecycle of the site.

Works by Eguido [40] [37] combine both internal and external maintenance actions. The maintenance decision- making process is based on the dynamic reliability threshold, where the value of the threshold depends on the weather condition. This ties reliability to low wind speeds and ensures that any OM actions/responses to the opportunity of low wind speed are beneficial to the overall system to avoid wasted journeys to the site to perform unneeded maintenance during "favourable" conditions.

Yildirim et al. [53] consider the effects of maintenance on electricity production by coordinating wind turbine maintenance schedules with turbine dispatch. This is based both on the forecast wind power and the electricity price. The optimization model determines whether it is more profitable to conduct maintenance right away so that the wind turbine can start generating electricity, or if it would make more sense to delay maintenance so that the maintenance can be grouped. The electricity price was varied from $12.5/MWh to $100/MWh to study the sensitivity of market price on O&M performance metrics. As expected, an increase in the price of electricity results in an increase in net profit. There is also a significant dependency between the length of idle time and the price of electricity. As electricity prices rise, the opportunity cost of lost revenue also increases, allowing maintenance policy to schedule more crew visits to minimise loss of production. Although the price of electricity influences the decision, low pricing periods are not considered a distinct opportunity. However, they inform other potential opportunities.

Shafiee et al. [46] include the impact of weather conditions on operations. Within their work, they consider environmental shocks to the system. The impact of such a shock can be minor or catastrophic. However, the environmental shock then triggers PM activity, which is viewed as an opportunity. Therefore, Shafiee et al. [46] only consider internal opportunities, however, these opportunities are influenced by external parameters.

The works of Li et al. [42] [43] also consider environmental impacts/incidents within their work. They consider maintenance opportunities created by the degradation of assets and incidents, in addition to age based PM. If the arriving environmental impact is critical so that the component fails, the maintenance opportunity will appear. However, as in Shafiee et al. [46], the environmental impact triggers the need for maintenance action. Therefore, it could be argued that this should also be classed as an internal opportunity with external influence.

Papadopoulos et al. [62] create a unique model that combines dispatch, turbine production, and access-based opportunities. This model is benchmarked against the [3] model, which does not account for access-based opportunities. Papadopoulos et al. [62] is the only publication considered that views any period of weather access as an opportunity. 12 MW turbines are used within the case study, in line with current deployments. As the rated power of the machine increases, so does the opportunity cost during downtime. Therefore, the validity of an access-based OM strategy will be determined by the opportunity cost vs the cost of dispatch. Papadopoulos et al. [62] also acknowledge the impact of the variable price of electricity. [62] use two distinct case studies. The first does not consider electricity price variability in order to ensure that the differences in maintenance performance are solely attributed to the impact of accessibility, production loss, and crew dispatch. The second case study introduces market electricity prices from the US transmission organisation, PJM, and also includes curtailment of 2%. Curtailment is deducted from the final production revenue output; the specific time occurrence of the curtailment is not included. Although Papadopoulos et al. [62] acknowledge the influence of market conditions, they do not view these periods as an opportunity. Therefore, the only external opportunity is weather accessibility based within this work.

5.5. Maintenance Action/Response

The overall OM strategy consists of two distinct parts, the opportunity and the response/maintenance action. Like internal opportunities, the response/maintenance action is typically divided by PM or CM activities. In the literature, it is most common to respond to an opportunity trigger with a PM action, as PM activities are known in advance and therefore can be scheduled or placed on a waiting list accordingly. As PM tasks can be scheduled ahead of time, downtime is already minimised if scheduling is proactive. As the cost of repair and technician salary cannot be altered, sharing of resources, e.g., vessels, is one of the few ways in which this cost can be reduced.

Besnard et al. [3] [49] define PM as all maintenance tasks performed that reduce the probability of failure before it occurs. Preventive maintenance tasks are performed at fixed time intervals of 6 months, 1 year, or 5 years. They include visual inspections, changes of consumables (greasing, lubrication, oil filters), oil sampling, and re-tightening of the bolts. A similar approach is taken by [41]. The list of PM tasks is predefined, each with a specific deadline for completion. This is the simplest definition of a PM action.

Of all the publications considered, only one publication does not respond with a PM action. Yildrim et al. [53] respond to an opportunity with any maintenance action. This work considers a trade-off between a sensor-driven optimal maintenance schedule and the grouping of wind turbine maintenance activities through OM. The maintenance response can be CM or PM depending on the economic benefit of performing such activities.

5.5.1. OM Maintenance Action Thresholds

PM activities are often based on some predetermined threshold, as discussed in Section 5.4.1. However, this methodology also applies to OM response activities, where additional OM response/action is only performed during periods of opportunity if a specific criterion is met, which typically satisfies some economic requirement.

Due to the introduction of monitoring software and a more in-depth understanding of reliability, some components will only be maintained, preventively, if some predetermined threshold is reached. Therefore, it is common for an OM limitation or threshold to be placed within the strategy where the response/action to the opportunity will only be taken if certain criteria are met. The most common limits/thresholds were age-based, CBM/reliability, time and cost as shown in Figure 5.8.

Half of existing publications place a basic reliability or CBM-based limitation on any maintenance action in response to an opportunity. Further detail of the specific literature and their corresponding PM maintenance thresholds is given in Table 5.2.

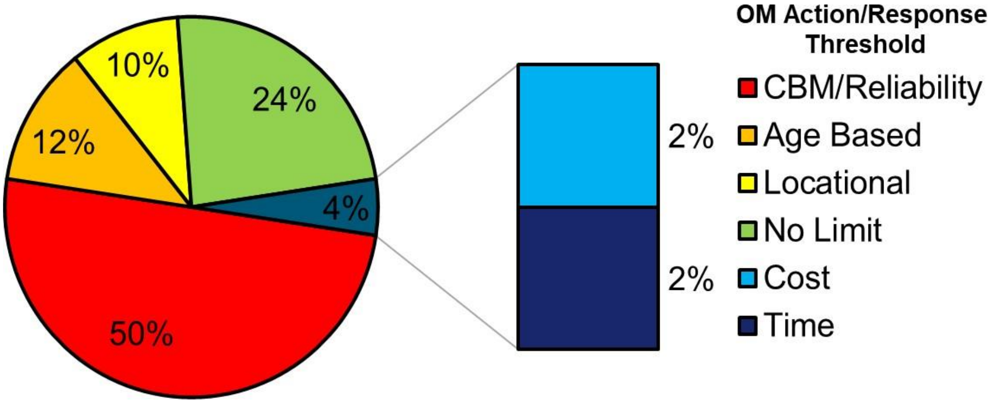


Figure 5.8 OM action / response thresholds imposed within the literature.

Table 5.2 Maintenance limits imposed on PM maintenance actions in response to an opportunity.

	age-based	condition monitoring thresholds	locational	reliability	time	cost
Ding et al. [44]	✓					
Ding et al. [45]	✓					
Shafiee et al. [46]		✓				
Sarker et al. [47]	✓					
Abdollahzedeh et al. [50]	✓			✓		
Atashgar et al. [51]				✓		
Zhang et al. [52]				✓		
Yildrim et al. [53]		✓				
Erguido et al. [37]				✓		
Li et al. [48]				✓		
Song et al. [65]			✓	✓	✓	
Lu et al. [54]		✓				
Erguido et al. [40]				✓		
Zhou et al. [55]		✓				
Xie et al. [56]	✓					
Zhang et al. [57]				✓		
Izblusg et al. [58]				✓		
Wang et al. [59]		✓				
Zhao et al. [68]		✓				
Li et al. [48]						✓
Lubing et al. [61]		✓				
Zhang et al. [66]		✓	✓			
Su et al. [70]		✓		✓		
Kang et al. [60]			✓			
Luo et al. [71]		✓				
Li et al. [42]		✓				
Li et al. [43]		✓				
Wang et al. [64]				✓		
Liu et al. [72]			✓			

Ding & Tian [45] [44] were the first to impose a limitation on response to an opportunity. They introduce an age threshold, in addition to different imperfect maintenance thresholds for failed turbines and working turbines. When a downtime opportunity is created by the failed components, the maintenance team may perform PM for other components satisfying pre-specified age thresholds. The same age-based limitation methodology is applied by Shafiee et al. [46], Sarker et al. [47], Abdollahzedeh et al. [50] and Xie et al. [56]. This method involves assigning a component age that is renewed each time a replacement/repair takes place. These works also consider imperfect maintenance strategy whereby a component's age is only returned to zero if a complete replacement is conducted, and the age is only reduced for minor repairs.

The most common limitation/threshold is CBM/reliability based. This follows the same procedure as an age- based limitation, where a specific (reliability-based) threshold must be reached before maintenance is conducted. Within these works, the reliability threshold not only limits the OM action but also informs the type of OM action which will take place. These works often use a multilevel maintenance framework, from complete replacement to imperfect maintenance; the type of maintenance carried out depends on the input from the reliability of the component.

Location limitations were imposed in the works of Zhang et al. [66], Kang et al. [69] and Liu et al. [72] which was first introduced by Song et al. [65]. Song et al. [65] combined location limits with the reliability threshold, where the aim of the work was to optimise the turbine layout considering the impact of maintenance. The turbines were grouped into geographical clusters where OM activity could only be carried out if the failed turbine was within the same cluster as a turbine that met the reliability threshold conditions. This was imposed to reduce the fuel consumption of vessels and limit time offshore. This approach is well suited to larger sites, such as Doggerbank, as the distance between turbines can be as large as 100 km. Song et al. [65] was the only work that included time as a limiting factor. This was closely aligned with the travel distance between the geographical clusters.

Li et al. [38] was the only publication that explicitly considered cost as a limiting factor through an economic assessment that compared the cost of repair versus the cost of downtime to determine whether an OM activity should be performed. It is recommended that future publications include this as a limitation as economic advantage is one of the key factors of an OM based strategy, as highlighted in [17].

5.6. Combined Strategy

The overall OM strategy consists of both opportunities/triggers and responses/actions. Although it was most common for a strategy to contain multiple opportunities, this was typically addressed by a single type of maintenance action. The combinations of opportunities and responses are shown in Figure 5.9. The most common OM strategy presented in the literature is to use corrective or preventive opportunity to perform preventive maintenance action, as seen in [43 – 64] [72]. Unexpected failures, or corrective maintenance, constitute the largest part of OpEx [74] breakdown, and therefore utilising CM activities for OM opportunities spreads the resource cost across multiple maintenance activities and, therefore, reduces the cost per maintenance action. By responding with a planned/expected PM action there is still a degree of certainty within the operation. However, this will depend on the weather conditions on-site. An overview of the combined OM strategy is given in Figure 5.9.

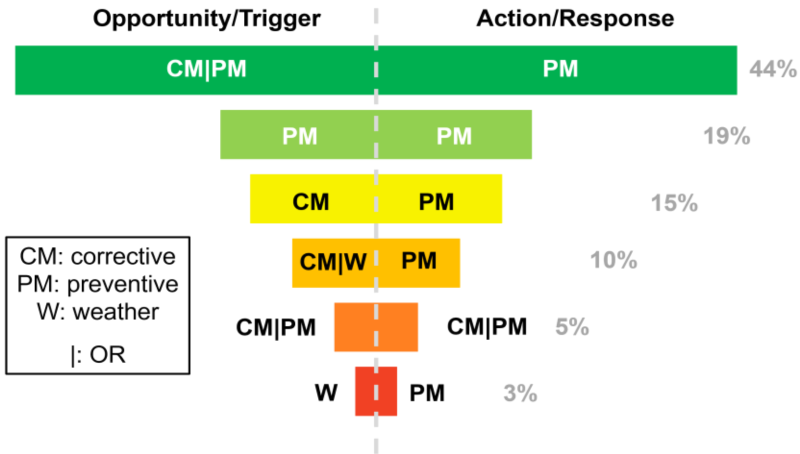


Figure 5.9 Breakdown of the full OM strategy consisting of an opportunity/trigger and a corresponding action/response.

Figure 5.9 compares the selected Opportunity/Trigger and Action/Response triggers used within the literature.

The combination of PM opportunity and trigger is commonly referred to as group maintenance. This is a subset of OM where activities are scheduled to occur in parallel. This has the same advantages as OM due to the sharing of resources and reduced time at sea. This methodology is more suited to PM tasks as pre-planning can be performed to determine whether specific tasks can be performed simultaneously or not. This is also the most common OM application seen within the industry, particularly in terms of summer seasonal campaigns. PM activities do not hold the same criticality as CM tasks therefore, more refined effort can be placed to effectively schedule PM operations during favourable times.

5.7. Modelling Results and Limitations

Literature findings agree that there can be significant OpEx savings achieved by adopting an OM-based strategy. It is difficult to draw conclusions between the results presented in the literature due to the differences in reporting on key performance indicators (KPIs), and their

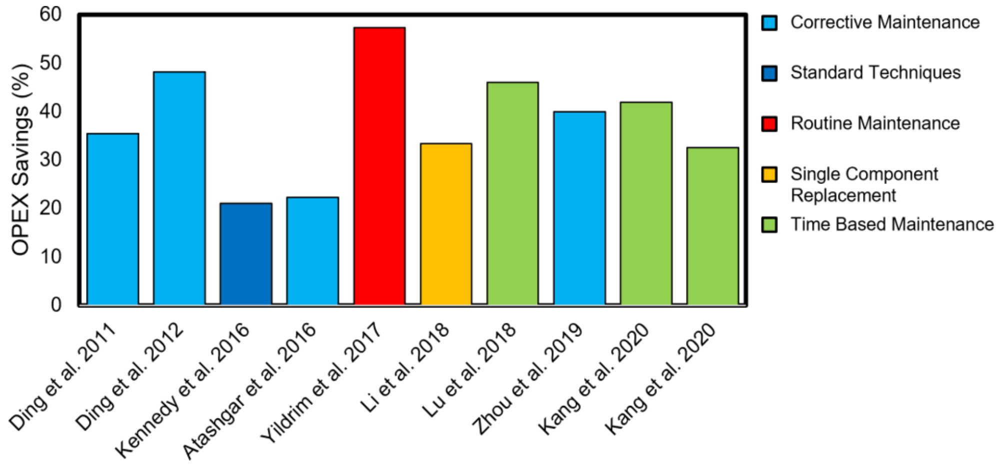


Figure 5.10. OPEX savings stated from using an OM approach in the case studies in the literature.

associated benchmarks. The impact of KPIs on O&M activities has been explored by Hawker et al. [75] and Gonzalez et al. [76]. Both works found that different parties within the supply chain will have different KPIs which in some cases can be conflicting.

The most common KPI in the literature was total annual OpEx, as shown in Figure 5.10. However, there were different benchmarks in which OpEx was compared including the CM-based approach [45] [44] [51] [55], "standard" maintenance techniques [41], routine maintenance [53], single component replacement [48], and a time-based maintenance approach [67] [69] [60]. Routine maintenance as used by Yildirim et al. [70] is most commonly aligned with a scheduled maintenance-only approach. Due to the differences in benchmarking, it is difficult to draw conclusions between the results. However, OpEx savings are typically around 20% to 50% compared to a non-OM-based strategy. The most common benchmarking metric used was a business-as-usual single CM repair approach.

5.7.1. Limitations

However, these impressive results may not be a realistic representation of the true challenges associated with an OM-based approach. To effectively execute the framework, it must take into account the weather conditions under which maintenance can be performed. The weather window methodology is typically used to schedule maintenance activities (both CM and PM). A weather window is known as a period of uninterrupted access where maintenance actions can be carried out safely [77]. Accessibility to the site is a growing concern as sites move further from shore, resulting in harsher weather environments and increased travel time from port. If an OM strategy is to be adopted, then it must be considered that there is a suitable weather window which can accommodate the original trigger (e.g., PM or CM) and the additional maintenance action/response.

Within offshore wind O&M, weather accessibility restrictions are typically based on wind speed and significant wave height (Hs) thresholds. Imposed wind speed limits are placed on lifting activities, such as blade operations, and are limited to 12.5 m/s [78]. Vessels have both Hs and wind speed limitations, with a wind speed limit of typically around 20 m/s [79] [80]. The Hs limit is dependent on the vessel selection. Typical Hs limitations for vessels are 1.5 and 3-4 m for the crew transfer vessel (CTV) and the service operational vessel (SOV), respectively. It is most common for Hs to be the key limitation imposed on the weather window. Weather limitations used within the reviewed literature is given in Table 5.3.

The majority of publications reviewed within this work omitted the inclusion of weather limits on maintenance actions. Publications such as Besnard et al. [3], and Li et al. [43] [42] state that weather limitations are removed as a constraint.

Of the publications which do include weather limitations, these tend to include both Hs and wind speed limits specific to vessel capabilities [49] [41] [62]. Both Besnard et al. 2011 [49] and Kennedy et al. [41] also include the possibility of introducing a Hs limitation for helicopter operations. Both Xie et al. [56] and Lubling et al. [61] include the same Hs and wind speed limit. However, it is not specified if these are vessel specific.

Kang et al. [60] [69] uses a Hs limit of 3.5m for both works. This is in line with the limitations of an SOV, rather than a CTV as seen in other publications.

Several publications referenced an unspecified "weather restriction" within their work [57] [53] [52] [66]. Song et al. [65] imposes an unspecified wind speed limitation.

Lua et al. [67] examine the impact of accessibility and downtime on the OM strategy - but weather limitation values are not provided.

Although the works of Erguido et al. [40] [37] and Izquierdo et al. [58] do not impose weather restrictions on site accessibility, wind speed is a direct input to the OM-decision-making process. As wind speed and Hs are coupled, periods of low wind speed, where maintenance actions are preferred, are likely to correspond to periods of low Hs, and therefore will be accessible.

The works of Zhang et al. [52] [57] and Lubing [61] are the only works which consider the additional time required to conduct additional OM maintenance tasks during periods of opportunities, resulting in the need for a prolonged weather window. However, in all works the impact of shift/working patterns are not considered.

The original work of Besnard et al. [3] included the need to include weather limitations as an area of future work. In the later work in 2011 [49], accessibility limitations are imposed. However, the impact of the inclusion of weather limits on income and other KPIs is unknown, as the results cannot be directly compared due to differences in the case study used and the reported KPIs.

Table 5.3 Weather limitations imposed with OM strategy modelling literature.

	Wind Speed	Significant Wave Height (Hs)	Other
Besnard et al. [49]	12 km/h	1.5 m	
Kennedy et al. [41]	12 m/s	1.5 m	
Zhang et al. [52]			weather restriction
Yildirim et al. [53]			weather restriction
Song et al. [65]	unspecified		
Lua et al. [67]			accessibility
Xie et al. [56]	10 m/s	2 m	
Zhang et al. [57]			weather restriction
Kang et al. [60]		3.5 m	
Lubing et al. [61]	10 m/s	2 m	
Zhang et al. [66]			weather restriction
Kang et al. 2020 [69]		3.5 m	
Papaopoulos et al. [62]	15 m/s	1.5 m	

To avoid underestimating the impact of OM on weather window requirements, and also accessibility, it is important that the prolonged time at sea is captured within simulations [53]. However, at present the inclusion of weather considerations is currently lacking from the literature.

5.8. Opportunity for Floating Wind

As discussed in Chapter 4, OpEx for FOW sites are expected to increase. As OpEx is expected to have a higher contribution to LCoE for FOW than BFW equivalents, this is a key area of cost reduction. An OM strategy is suited to FOW as it aims to make effective use of limited access. As shown in Chapter 3, while weather windows are limited, their duration would allow for effective group maintenance.

An opportunistic maintenance strategy would be beneficial for a floating offshore wind farm because it allows for flexibility in scheduling maintenance activities. This approach enables maintenance tasks to be carried out when weather conditions are favourable, minimizing downtime and maximizing energy production. OM is particularly favourable for FOW as one of the aims is to reduce the number of transfers. As discussed in Chapter 3, workability, and exposure to motion for technicians is a growing concern. While this thesis has focused on the conditions while performing maintenance, technicians also experience discomfort during the travel to and from site due to vessel motion. It is predicted that due to the additional motion of the asset when performing maintenance, it will be beneficial, particularly for FOW, to aim to reduce technician exposure as much as possible. By adopting an OM strategy, the number of transfers has the potential to reduce, gaining savings in resource utilisation and technician welfare.

5.9. Chapter Overview

OM is a flexible maintenance strategy with several operational benefits. Reducing the number of offshore wind transfers for technicians offers several advantages. Firstly, it enhances safety by reducing the exposure of technicians to potentially hazardous offshore conditions during transfer operations. Secondly, it optimizes the utilization of resources, such as crew time and vessel availability, leading to cost savings and increased efficiency. Lastly, minimizing offshore transfers helps to reduce the carbon footprint and environmental impact associated with vessel operations, promoting a more sustainable approach to offshore wind maintenance.

In this work, a review of the application, and suitability, of OM to offshore wind has been discussed. Previous utilisation of the practice within manufacturing and other industries such as power systems show clear similarities to the O&M activities required for an offshore wind farm. Therefore, the advantages of the strategy utilisation within these industries can be replicated within an offshore wind context.

This Chapter proposes an all-encompassing definition of the term, reviewing maintenance 'opportunities' and their corresponding 'action/response'. The review found that maintenance opportunities are either internal or weather-based, with each opportunity having a pre-determined trigger/response. There is a clear growth in the interest of OM within offshore wind as highlighted in Figure 5.4. From the literature overview, specific to OM within offshore wind opportunities can be divided by internal or external. The most common opportunity was CM actions, which were responded to by a set of predetermined PM activities. While the literature failed to provide a cohesive definition of the OM strategy, each application of the technique consisted of an opportunity/trigger which had a corresponding response/action. Simulations of the technique have shown that this methodology can provide OpEx savings of up to 20%.

However, there are still several gaps within the literature which have still to be addressed. Currently literature fails to address the challenge of the additional time at sea required for group maintenance activities. A cost benefit analysis was shown in [38] however this should be given more priority in the decision-making process. As highlighted by Ab-Samat et al [17] in the review of all OM publications, there should not be a negative economic impact of taking a maintenance opportunity.

There are also limits in the literature regarding the met ocean limitations on site accessibility. The existing literature considering vessel limitations is also focused on CTV rather than SOV. As sites move further from shore, it is more likely that an SOV approach be utilised. Therefore, it is recommended that this be included in future case studies.

Finally, within the literature, external opportunities are limited to weather-based events. However, market considerations such as periods of curtailment could be potential maintenance opportunities for sites. This concept is further expanded within the next Chapter.

OM aims to reduce the number of transfers, and therefore share the cost of resources amongst maintenance actions. This is particularly beneficial for FOW as it will reduce technicians to exposure by limiting their travel time on the vessel. At present workability limits used within the literature [81] do not provide details of the duration in which a human is exposed to such conditions. By minimising transfers, vessel-based motion exposure is also reduced. This is particularly important for FOW due to the exposure faced by the dynamic response of the asset during maintenance actions.

5.10. Chapter References

[1] B. Maples, G. Saur, M. Hand, R. Van De Pietermen and T. Obdam, "Installation, operation and maintenance strategies to reduce the cost of offshore wind energy," National Renewable Energy Lab (NREL), Golden, CO, 2013.

[2] BVG Associates, "Guide to Floating Offshore Wind - Floating Wind Lifecycle Overview," 2023. [Online]. Available: https://guidetofloatingoffshorewind.com/floating-wind-lifecycle-overview/. [Accessed 10 June 2023].

[3] F. Besnard, M. Patriksson, A. B. Strömberg, A. Wojciechowski and L. Bertling, "An optimization framework for opportunistic maintenance of offshore wind power system," in *IEEE bucharest powertech,* 2009.

[4] Y. Dalgic, I. Lazakis, I. Dinwoodie, D. McMillan and M. Revie, "Advanced logistics planning for offshore wind farm operation and maintenance activities," *Ocean Engineering,* vol. 101, pp. 211-226, 2015.

[5] J. Carroll, A. McDonald and D. McMillan, "Failure rate, repair time and unscheduled O&M cost analysis of offshore wind turbines," *Wind Energy,* vol. 19, no. 6, pp. 1107-1119, 2016.

[6] G. Hassan, "A guide to UK offshore wind operations and maintenance," Scottish Enterprise, 2013.

[7] Z. Ren, A. Verma, Y. Li, J. Teuwen and Z. Jiang, “Offshorew wind operations and maintenace: A state-of-the-art review,” *Renewable and Sustainable Energy Reviews,* vol. 144, p. 110886, 2021.

[8] J. Nielsen and J. Sorensen, “On risk-based operation and maintenance of offshore wind turbine components,” *Reliability engineering & sustem safety,* vol. 96, no. 1, pp. 218-229, 2011.

[9] J. Chatterjee and N. Dethlefs, “Scientometric review of artificial intelligence for operations & maintenance of wind turbines. The past, the present, and the future,” *Renewable and Sustainable Energy Reviews,* vol. 111051, p. 144, 2021.

[10] A. Turnbull and J. Carroll, “Cost benefit of implementing advanced monitoring and predictive maintenance strategies for offshore wind farms,” *Energies,* vol. 14, no. 16, p. 4922, 2021.

[11] W. Zhang, J. Vant and A. Rasheed, “A review of failure propgnostics for predictive maintenance of offshore wind turbines,” *Journal of Physics: Conference Series,* vol. 2362, p. 12043, 2022.

[12] H. Fox, A. Pillai, D. Fredrich, M. Collu, T. Dawood and L. Johanning, “A review of failure prognostics for predictive and prescriptive offshore wind farm operation and maintenance,” *Energies,* vol. 15, no. 2, p. 504, 2022.

[13] J. McMorland, C. Flannigan, J. Carroll, M. Collu, D. McMillan, W. Leithead and A. Coraddu, “A review of operations and maintenance modelling with considerations for novel wind turbine concepts,” *Renewable and Sustainable Energy Reviews,* vol. 165, p. 112581, 2020.

[14] G. Rinaldi, T. Phillip and J. Lars, “Current status and future trends in the operation and maintenance of offshore wind turbines: a review,” *Energies,* vol. 14, no. 9, p. 2484, 2021.

[15] J. McMorland, M. Collu, M. McMillan, J. Carroll and A. Coraddu, “Opportunistic maintenance for offshore wind: a review and proposal of future framework,” *Renewable and Sustainable Energy Reviews,* vol. 184, p. 113571, 2023.

[16] J. McCall, “Operating characteristics of opportumistic replacement and inspection policies,” *Management science,* vol. 10, no. 1, pp. 85-97, 1963.

[17] H. Ab-Samat and S. Kamaruddin, “Opportunisric maintenace (OM) as a new advancement in maintenance approaches A review,” *Journal of Quality Maintenance Engineering,* vol. 20, no. 2, pp. 98-121, 2014.

[18] P. Megoze, G. Kibouka, J. Kenne and L. Hof, “Production, maintenance and quality inspection of a hybrid manufacturing/remanufacturing system under production rate-dependent deteriroation,” *The International Journal of Advanced Manufacturing Technology,* vol. 121, no. 1-2, pp. 1289-1314, 2022.

[19] A. Valet, T. Altenmuller, B. Waschneck, M. MC, A. Kuhnle and H. Lanza, “Opportunistic maintenance scheduling with deep reinforecemetn learning,” *Journal of Manufacturing Systems,* vol. 64, pp. 518-534, 2022.

[20] B. Ba, M. Cholette, P. Borghesani and L. Ma, “A quantitative study on the impact of opportunistic maintenance in the presence of time-varying,” in *IEEE International Conference on Industrial engineering and Engineering Management*, 2016.

[21] B. Ba, M. Cholette, P. Borghesani and L. Ma, “Opportunistic Maintenance considering non-homogenous opportunity arrivals and scochastic opportunity durations,” *Reliability Engineering & System Safety,* vol. 190, p. 106512, 2019.

[22] W. Zh, B. Castanier and B. Bettayeb, “A dynamic programming-based maintenance model of offshore wind turbine considering logistic delay and weather conditions,” *Reliability Engineering & System Safety,* vol. 190, p. 106512, 2019.

[23] B. Iung, P. Do, E. Levrat and Voisin, “, A Opportunistic maintenance based on multi-dependent components of manufacturing system.,” *CIRP Annals,* vol. 65, no. 1, pp. 401-404, 2016.

[24] Q. Chang, J. Ni, P. Bandyopadhyay, S. Biller and G. Xiao, “Maintenance staffing management,” *Journal of Intelligent Manufacturing.,* vol. 18, pp. 351-360, 2007.

[25] R. Mena, P. Viveros, E. Zio and S. Campos, “ An optimization framework for opportunistic planning of preventive maintenance activities,” *Reliability Engineering & System Safety,* vol. 215, p. 107801, 2021.

[26] A. Yazdekhasti and Y. Mehrjardi, “Two-echelon three-indenture warranty distribution network: a hybrid branch and bound, Monte-Carlo approach.,” *Operational Research,* vol. 20, pp. 1113-1115, 2020.

[27] M. Rebaiaia and D. Ait-Kadi, “A Remaining Useful Life Model for Optimizing Maintenance cost and Spare-parts replacement of Production Systems in the Context of Sustainability,” *IFAC,* vol. 2022, pp. 1562-1568, 2022.

[28] J. Zhang, X. Zhao, Y. Song and Q. Qiu, “Joint optimization of condition-based maintenance and spares inventory for a series–parallel system with two failure modesl,” *Computers and Industrial Engineering,* vol. 168, p. 108094, 2022.

[29] T. Xia, X. Fang, N. Gebraeel, L. Xi and E. Pan, “Online analytics framework of sensor-driven prognosis and opportunistic maintenance for mass customization,” *Journal of Manufacturing Science and Engineering,* vol. 141, no. 5, 2019.

[30] L. Yang, Y. Zhao, R. Peng and X. Ma, “Opportunistic maintenance of production systems subject to random wait time and multiple control limits.,” *Journal of Manufacturing Systems,* vol. 47, pp. 12-34, 2018.

[31] F. Fallahi, I. Bakir, M. Yildirim and Z. Ye, “A chance-constrained optimization framework for wind farms to manage fleet-level availability in condition based

maintenance and operations," *Renewable and Sustainbale Engergy reviews,* vol. 168, p. 112789, 2022.

[32] R. Wang, Z. Cheng, E. Dong, C. Guo and L. Rong, "Reliability-based opportunistic maintenance modeling for multi-component systems with economic dependence under base warranty," *Discrete Dynamics in Nature and Society,* vol. 2021, pp. 1-16, 2021.

[33] J. Wakiru, L. Pintelon, P. Muchiri and P. Chemweno, "Integrated maintenance policies for performance improvement of a multi-unit repairable, one product manufacturing system," *Production Planning & Control ,* vol. 32, no. 5, pp. 347-367, 2021.

[34] M. Assid, A. Gharbi and A. Hajji, "Production planning and opportunistic preventive maintenance for unreliable one-machine two-products manufacturing systems.," *IFAC,* vol. 48, no. 3, pp. 478-483, 2015.

[35] M. Tusar and B. Sarker, "Maintenance cost minimization models for offshore wind farms: A systematic and critical review.," *International Journal of Energy Research,* vol. 46, no. 4, pp. 3439-3765, 2022.

[36] J. Kang, J. Sobral and C. Soares, "Review of condition-based maintenance strategies for offshore wind energy.," *Journal of Marine Science and Application,* vol. 18, no. 1, pp. 1-16, 2019.

[37] A. Erguido, A. Márquez, E. Castellano and J. Fernández, " A dynamic opportunistic maintenance model to maximize energy-based availability while reducting the life cycle cost of wind farms," *Renewable Energy,* vol. 114, pp. 843-856, 2017.

[38] M. Li, M. Wang, J. Kang, L. Sun and P. Jin, "An opportunistic maintenance strategy for offshore wind turbine system considering optimal maintenance intervals of systems," *Ocean Engineering,* vol. 216, p. 108067, 2020.

[39] A. Ho, A. Mbistrova and G. Corbetta, "The European Offshore Wind Industry - key trends and statistics 2015," European Wind Energy Association (EAWE), 2016.

[40] A. Erguido, A. Crespo, E. Castellano and J. Flores, "After-sales services optimisation through dynamic opportunistic maintenance: a wind energy case study," *Part O: Journal of Risk and Reliability,* vol. 232, no. 4, pp. 352-367, 2018.

[41] K. Kennedy, P. Walsh, T. Mastaglio and T. Scully, "Genetic optimisation for a stochastic model for opportunistic maintenance planning of offshore wind farms," in *2016 4th International Symposium on Environmental Friendly Energies and Applications (EFEA),* 2016.

[42] M. Li, X. Jiang and R. Negenborn, " Opportunistic maintenance for offshore wind farms with multiple-component age-based preventive dispatch.," *Ocean Engineering,* vol. 231, p. 109062, 2021.

[43] M. Li, X. Jiang, J. Carroll and R. Negenborn, "Influence of uncertainty on performance of opportunistic maintenance strategy for offshore wind," in *OCEANS 2021,* San Diego, 2021.

[44] F. Ding and Z. Tian, “Opportunistic maintenance optimization for wind turbine systems considering imperfect maintenance actions,” *International Journal of Reliability,* vol. 18, no. 05, pp. 436-481, 2011.

[45] F. Ding and Z. Tian, “Opportunistic maintenance for wind farms considering multi-level imperfect maintenance thresholds,” *Renewable Energy,* vol. 45, pp. 175-182, 2012.

[46] M. Shafiee, M. Finkelstein and C. Bérenguer, “An opportunistic condition-based maintenance policy for offshore wind turbine blades subjected to degradation and environmental shcoks,” *Reliabiltity Engineering & Systems Safety,* vol. 142, pp. 463-471, 2015.

[47] B. Sarker and T. Faiz, “ Minimizing maintenance cost for offshore wind turbines following multi-level opportunistic preventive strategy.,” *Renewable Energy ,* vol. 85, pp. 104-113, 2016.

[48] H. Li, P. Li, N. Gao, L. Niu, Y. Zhang and Y. Bao, “Opportunistic maintenance model for wind turbine based on reliability constraint.,” *IOP Conference Series: Materials Science and Engineering,* vol. 336, p. 12026, 2018.

[49] F. Besnard, M. Patriksson, A. Strömberg, A. Wojciechowski, K. Fischer and L. Bertling, “A stochastic model for opportunistic maintenance planning,” in *IEEE Power Tech,* Trondheim, 2011.

[50] H. Abdollahzadeh, K. Atashgar and M. Abbasi, “Multi-objective opportunistic maintenance optimization of a wind farm considering limited number,” *Renewable Energy,* vol. 88, pp. 247-261, 2016.

[51] K. Atashgar and H. Abdollahzadeh, “Reliability optimization of wind farms considering redundancy and opportunistic maintenance strategy.,” *Energy Conversion and Management,* vol. 112, pp. 445-458, 2016.

[52] C. Zhang, W. Gao, S. Guo, Y. Li and T. Yang, “Opportunistic maintenance for wind turbines considering imperfect, reliability-based maintenance.,” *Renewable Energy,* vol. 103, pp. 606-612, 2017.

[53] M. Yildirim, N. Gebraeel and X. Sun, “Integrated predictive analytics and optimization for opportunistic maintenance and operations in wind farms,” *IEEE Transactions on power systems,* vol. 32, no. 6, pp. 4319-4328, 2017.

[54] Y. Lu, L. Sun, J. Kang, H. Sun and X. Zhang, “Opportunistic maintenance optimization for offshore wind turbine electrical and electronic system based on a rolling horizon approach,” *Journal of Renewable and Sustainable Energy,* vol. 9, no. 3, p. 33307, 2017.

[55] P. Zhou and P. Yin, “ An opportunistic condition-based maintenance strategy for offshore wind farm based on predictive analytics.,” *Renewable and Sustainable Energy Reviews,* vol. 109, pp. 1-9, 2019.

[56] L. Xie, X. Rui, S. Li and X. Hu, "Maintenance optimization of offshore wind turbines based on an opportunistic maintenance strategy.," *Energies,* vol. 12, no. 14, p. 2650, 2019.

[57] C. Zhang, W. Gao, T. Yang and S. Guo, "Opportunistic maintenance strategy for wind turbines considering weather conditions and spare parts inventory management," *Renewable Energy,* vol. 133, pp. 703-711, 2019.

[58] J. Izquierdo, A. Crespo Márquez, J. Uribetxebarria and A. Erguido, " Framework for managing maintenance of wind farms based on a clustering approach and dynamic opportunistic maintenance," *Energies,* vol. 12, no. 11, p. 2036, 2019.

[59] J. Wang, V. Makis and X. Zhao, " Optimal condition-based and age-based opportunistic maintenance policy for a two-unit series system.," *Computers & Industrial Engineering,* vol. 134, pp. 1-10, 2019.

[60] J. Kang and C. Soares, "An opportunistic maintenance policy for offshore wind farms," *Ocean Engineering,* vol. 216, p. 108075, 2020.

[61] X. Lubing, R. Xiaoming, L. Shuai and H. Xin, "An opportunistic maintenance strategy for offshore wind turbine based on accessibility evaluation.," *Wind Engineering,* vol. 44, no. 5, pp. 455-468, 2020.

[62] P. Papadopoulos, D. Coit and A. Ezzat, "Seizing Opportunity: Maintenance Optimization in Offshore Wind Farms Considering Accessibility, Production, and Crew Dispatch," *IEEE Transactions on Sustainable Energy,* vol. 13, no. 1, pp. 111-121, 2021.

[63] T. Xia, Y. Dong, E. Pan, M. Zheng, H. Wang and L. Xi, "Fleet-level opportunistic maintenance for large-scale wind farms integrating real-time prognostic updating," *Renewable Energy,* vol. 163, pp. 1444-1454, 2021.

[64] D. Wang, W. Teng, G. Zhang, X. Qu, Y. Liu and Z. Ma, "An opportunistic maintenance strategy for wind turbines.," *IET Renewable Power Generation,* vol. 15, no. 16, pp. 3793-3805, 2021.

[65] S. Song, Q. Li, F. Felder, H. Wang and D. Coit, "Integrated optimization of offshore wind farm layout design and turbine opportunistic conditionbased maintenance.," *Computers & Industrial Engineering.,* vol. 120, pp. 288-297, 2018.

[66] Z. Zhang and L. Yang, "State-based opportunistic maintenance with multifunctional maintenance windows.," *IEEE Transactions on Reliability.,* vol. 70, no. 4, pp. 1481-1494, 2020.

[67] Y. Lua, L. Suna, J. Kanga and X. Zhang, "Maintenance grouping optimization for offshore wind turbine considering opportunities based on rolling horizon approach," *Polish Maritime Research,* 2018.

[68] H. Zhao, F. Xu, B. Liang, J. Zhang and P. Song, "A condition-based opportunistic maintenance strategy for multi-component system.," *Structural Health Monitoring,* vol. 1, p. 18, 2019.

[69] J. Kang, Z. Wang and C. Guedes Soares, "Condition-based maintenance for offshore wind turbines based on support vector machine.," *Energies,* vol. 13, no. 14, p. 3518, 2020.

[70] C. Su, Z. Hu and Y. Liu, "Multi-component opportunistic maintenance optimization for wind turbines with consideration of seasonal factor.," *Journal of Central South University,* vol. 27, no. 2, pp. 490-499, 2020.

[71] H. Luo and C. Su, "Multi-Level opportunistic Maintenance optimization of Offshore Wind Turbines Based on Rolling Horizon Approach.," in *IEEE International Conference on Mechatronics and Automation (ICMA),* 2020.

[72] Q. Liu, Z. X. T. Li, M. Hsieh and J. Li, "Integrated Structural Dependence and Stochastic Dependence for Opportunistic Maintenance of Wind Turbines," *Energies,* vol. 15, no. 2, p. 625, 2022.

[73] M. Shafiee, "Maintenance logistics organization for offshore wind energy: Current progress and future perspectives.," *Renewable Energy,* vol. 77, pp. 182-193, 2015.

[74] C. Röckmann, S. Lagerveld and J. Stavenuiter, "Operation and maintenance costs of offshore wind farms and potential multi-use platforms in the Dutch North Sea," in *Aquaculture perspective of multi-use sites in the opern ocean,* Cham, 2017.

[75] G. Hawker and D. McMillan, " The impact of maintenance contract arrangements on the yield of offshore wind power plants.," *Journal of Risk and Reliability,* vol. 299, no. 5, pp. 394-402, 2015.

[76] E. Gonzalez, E. Nanos, H. Seyr, L. Valldecabres, N. Yürüşen and U. Smolka, "Key performance indicators for wind farm operation and maintenance," *Energy Procedia,* vol. 137, pp. 559-570, 2017.

[77] M. O'Connor, T. Lewis and G. Dalton, "Weather window analysis of Irish west coast wave data with relevance to operations & maintenance of marine renewables," *Renewable Energy,* vol. 52, pp. 57-66, 2013.

[78] G. Marsh, "Meeting the challenge of wind turbine blade repair.," *Reinforced plastics.,* vol. 55, no. 4, pp. 32-36, 2011.

[79] A. Dewan and T. Stehly, "Mapping Operation and Maintenance Strategy for US Offshore Wind Farms," National Renewable Energy Lab (NREL), Golden, CO, 2017.

[80] W. Stavenuiter, I. Hopman, I. Boonstra and I. Keuning, "The missing link in the offshore wind industry: Offshore wind support ship;," TU Delft, 2009.

[81] I. Nielsen, "Assessment of ship performance in a seaway," NORDFORSK, Copenhagen, 1987.

Chapter 6 : The Potential Benefits of an Opportunistic Maintenance Strategy

This chapter provides a number of case studies detailing the potential benefits of adopting an OM-based maintenance strategy.

FOW operations require a flexible and cost-effective maintenance strategy to effectively make use of limited weather windows. As explored in Chapter 5, OM can see OpEx savings of up to 20%. This chapter challenges the gaps in the existing literature. A new OM+ framework is introduced which introduces market-based opportunities, such as periods of curtailment and negative pricing. This chapter also provides an analysis of the cost-benefit of taking such opportunities. An overview of the chapter is provided in Figure 6.1.

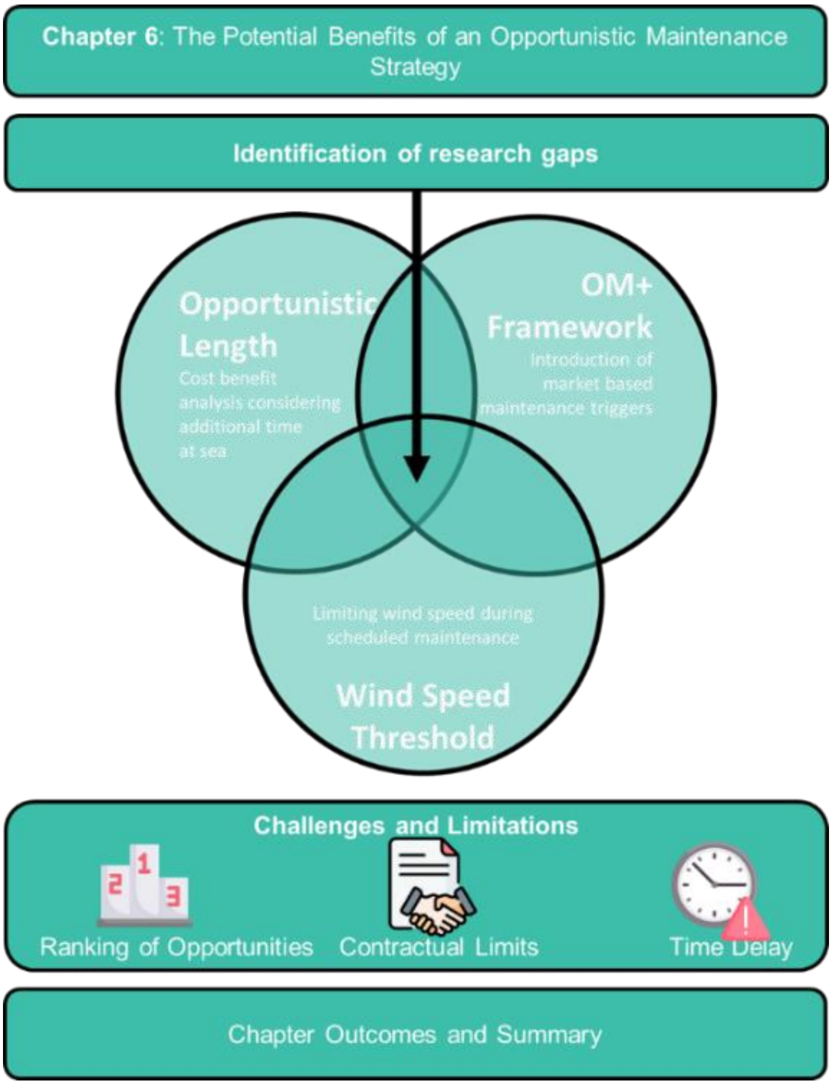


Figure 6.1. Chapter 6 overview and summary

6.1. Background

OpEx budgets for FOW projects are expected to be higher than that of current BFW sites. Therefore, a new flexible maintenance approach, such as opportunistic maintenance (OM) should be applied in a bid to reduce OpEx. Chapter 5 provided an overview of the existing literature. While the literature failed to provide a cohesive definition of the OM strategy, each application of the technique consisted of an opportunity/trigger which had a corresponding response/action. Simulations of the technique have shown that this methodology can provide OpEx savings of up to 20% [1] [2]. However, there are still several gaps within the literature:

- **Additional time at sea**: the performance of OM activities reduces overall time at sea, however, can prolong the time spent on a single trip. A cost benefit analysis was shown in [55], however this should be given more priority in the decision-making process. As highlighted by Ab-Samat et al. [3] in the review of all OM publications, there should not be a negative economic impact of taking a maintenance opportunity.
- **Met-ocean limits**: at present, most of the literature ignores met-ocean limitations within their OM framework. Those which do include Hs and wind speed limits are typically only considering CTVs, apart from [4] [5]. As sites move further from shore, it is more likely that an SOV approach be utilised. Therefore, it is recommended that this be included in future case studies.
- **Limited external opportunities:** within the literature, external opportunities were limited to weather-based events. Other external factors such as market pricing and curtailment are set to have significant impact on future operation of offshore sites, and therefore should be given consideration.

With the addition of new maintenance opportunities, a ranking system must be determined. As stated in the review by Ab-Samat et al. [3], an OM approach must have an economic benefit. Therefore, not all opportunities are equal, and some should not be taken at all. As OM becomes more prominent within offshore wind applications, it is important to capture the key motivation of the strategy, which is to be economically beneficial.

This chapter aims to introduce the OM+ framework, which introduces the concept of market-based opportunities. This framework also provides a more inclusive definition of the

OM methodology as "any period where the turbine production is less than a predetermined threshold or any time a maintenance crew is dispatched". By introducing market-based opportunities, the concept of "free downtime" is proposed to make effective use of forced outages at the site. This work also highlights the potential for OM to be applied to major component replacement operations for floating wind, during tow to shore procedures, to reduce the overall cost of maintenance, by planning PM activities to take place at port. The framework also introduces the next-generation "Availability" measurement, moving away from time and yield- based measurements to a market-based approach.

Case studies are also presented to determine the benefit of taking specific opportunities. The concept of “opportunistic length”, OM_L is introduced, where the cost of the additional time at sea to complete predetermined OM activities is determined and compared against the OM cost benefit of the sharing of resources.

Through use of the adapted Strath-OW O&M tool [6], as described in Chapter 4, the benefit of performing maintenance actions during wind speed thresholds, during curtailment, and during periods of negative pricing are analysed using the FOW ScotWind zones, with comparison against a BFW equivalent, and a FOW “standard” maintenance strategy where scheduled maintenance is carried out in the summer months.

6.2. OM+ Framework

To understand the potential maintenance strategies for OpEx reduction, it is important to understand the future markets in which FOW will operate. During the next decade, the UK is set for rapid expansion in the offshore wind sector. In 2019, the Offshore Wind Sector deal put forward a proposed 30 GW of installed offshore wind capacity by 2030 [7]. The Committee on Climate Change have suggested that the UK may need to reach 75 GW of offshore wind by 2050 to satisfy the UK’s net zero targets [8].

Although these ambitious targets show confidence in the ability of the sector and are expected to have a positive impact on climate change, an increased capacity of wind within the GB system could have negative impact on key electricity market parameters. With a high increase in wind (onshore and offshore) capacity within the UK, the current network capabilities in Scotland and Northern England may become constrained. This could result in damage to the system and network, increased unnecessary wind curtailment, and increased frequency of negative prices within the electricity market.

As sites enter their post-subsidy operational phase, operational decisions will become more heavily influenced by market conditions, as income is no longer protected from periods of low, or negative, market prices. This will also be a challenge for the next round of UK-subsidised sites. Previous rounds included a rule that stated that generators would not be compensated for power exported to the grid if day-ahead prices dipped into the negative for six hours or more. New CfD sites will no longer be protected from negative pricing periods under the new terms for Allocation Round 4 (AR4). The new contract terms will remove the subsidy from a plant if the price they are assumed to receive from the market is negative [9]. Within current OM literature surrounding offshore wind, the impact of negative pricing on maintenance operations is not considered.

Furthermore, high levels of wind penetration on the system also increase the threat of curtailment. At present, it is reported that offshore wind curtailment within Europe is limited to 5% annually [10], despite current high levels of wind penetration. The Offshore Wind Sector Deal commits to an additional 30 GW of offshore wind installed capacity by 2030 [7], and most recently, the historic ScotWind leasing round allocated over 25 GW of capacity leasing, over doubling the planned and expected 10 GW allocation [11]. High levels of generation may result in bottlenecks in the grid, such as the B6 boundary [12], and other interconnectors, such as Moyle and GridLink, becoming unsuitable as generation exceeds national demand and interconnector capacity during periods of high wind, leading to the curtailment of wind generation technology.

Following the review of the literature presented in Chapter 5, maintenance opportunities can be categorised as internal or external. It is found that the most common opportunity was internal, with external opportunities being weather-related. While some works such as [13] [14] [15] acknowledged the impact of external market parameters such as electricity pricing, this was used to inform decisions rather than as independent opportunities. This section introduces novel market-based external opportunities which arise from periods of negative pricing and curtailment. As these events will result in the shutdown of the turbine, they provide maintenance opportunities.

6.2.1. Curtailment

At present, offshore wind curtailment rates range between 4% and 5% in both Europe and the US. Studies [10], including Brouwer et al. [16] report that wind curtailments are mainly driven by network constraints. The current UK boundary has limited capacity of 6.1 GW to a thermal constraint at the Harker substation. The lack of interconnection from high utilised wind resource areas, far from where population and demand are concentrated, can result in curtailment of wind generation, as well as wholesale price volatility. European Union Twenties Project examined market scenarios for 2020 and 2030 in Northern Europe finding that large-scale offshore wind development is likely to lead to an increase in curtailment, due to both an increase in wind generation and the additional variability from offshore wind plants concentrated in a geographic region [17] Market simulations show that wind curtailment is expected to increase by over 2000% - from 0.4 TWh in 2020 to 9.3 TWh in 2030 [18].

All things being equal, the curtailment rates of offshore wind (and other renewable generation sources) are generally expected to increase coincident with higher penetration levels. This curtailment of renewable energy sources imposes limits on the achievement of climate change targets and can have a negative impact on the financing of future projects. High rates of curtailment may hamper investment in new renewable projects. Therefore, it is vital to take advantage of these periods of curtailment as opportunities to deploy a flexible maintenance framework.

The rise of curtailment has been shown in recent trends within the UK system as highlighted in Figure 6.2. From 2016 there has been a steady increase in curtailment of wind energy. 2020 saw a peak in curtailment, however, it is expected that this is due to the drop in demand due to the 2020 COVID-19 pandemic lockdown within the UK. Similar trends were seen in other electricity markets such as the US [19]. With almost 30 GW of additional development, the threat of curtailment has potential to impact all generation sources. While the challenge of curtailment is not specific to FOW sites, it is important to understand the market in which these future sites will operate.

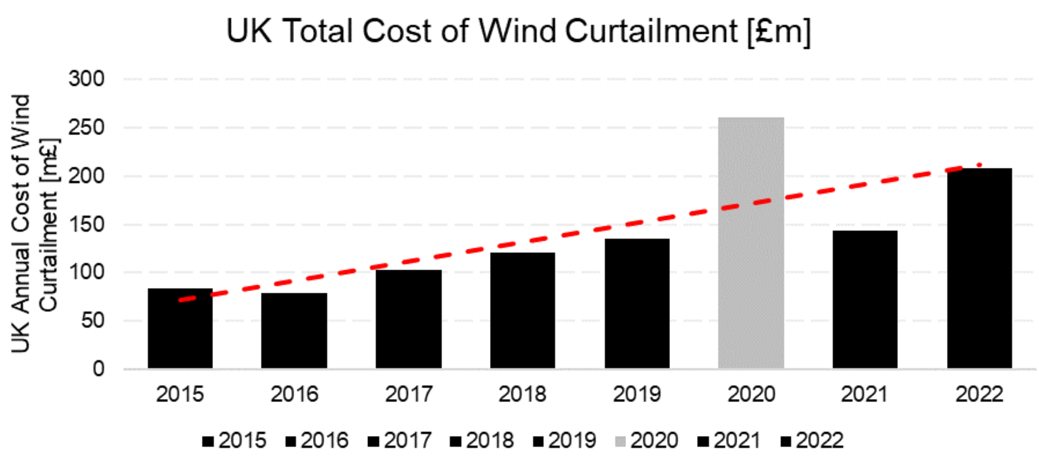


Figure 6.2. Total cost of curtailment within UK wind [20]

6.2.2. Negative Pricing

Negative prices occur in situations of oversupply when the marginal generator would prefer to pay the price rather than reduce its output. An increase in renewable generation has been shown to lead to a price drop, as seen in the German market analysis performed by Ketterer et al. [21] and Parachiv et al. [22]. More recently, Fraundorfer et al. [23] explored the same problem within the Brazilian emerging market, where the same trends in a drop-in electricity price as the penetration of renewable generation on the grid increased. This phenomenon is called merit-order effect for low levels of load where an increase in renewable generation has a price-dampening effect and may lead to negative prices. Since electricity cannot be stored at a wholesale scale, electricity prices are highly volatile, with the existence of both positive and negative price peaks.

Trends in negative pricing can be seen internationally. In 2020, average wholesale electricity prices in the United States fell to their lowest level since the beginning of the 21st century. Negative wholesale prices in real-time occurred in about 4% of all hours and wholesale market nodes in the US. Although this increase in negative pricing could be attributed to the COVID-19 pandemic, Seel et al. [19] found that there was a trend prior to this period that indicated that resources such as wind and solar had already established a trend toward lower wholesale prices. However, it was found that the negative pricing was not evenly distributed across the US and was concentrated in areas of high renewable penetration. With the US beginning their deployment of offshore wind, the revenue stream is not yet defined (e.g. government subsidy or power purchase agreements) and therefore, these sites may rely on the wider electricity market prices.

At present, most offshore wind sites operating in the UK are protected from volatile electricity market prices due to CfD contracts. However, CfD contracts only have a lifetime of 15 years. With a large interest in life extension, it is likely that current sites will operate within the post-subsidy market for more than 10 years [24]. The loss of guaranteed price revenue in conjunction with the reality of ageing assets and components is expected to put increased pressure on the site's operations, as OpEx is one of the few remaining expenses that can be controlled.

However, it is not just post-subsidy sites which will be exposed to potentially extreme market conditions. CfD Allocation Round 4 contracts have plans to remove a plant's subsidy if the price they are assumed to receive from the market becomes negative [9]. Previously, CfD sites were protected from periods of negative pricing through the scheme, for up to 6 hours. The new rules state that support payments will not be paid in any period where the day-ahead market price (i.e., their reference price) is negative. If this rule continues to be applied for future CfD auctions (AR4+), it will apply to all new wind and solar generation, and they will not be willing to sell power at a negative price in the day-ahead market. This will effectively set a floor price of zero in the day-ahead markets.

6.2.3. OM+ Framework Proposal

Based on the findings from the literature and the acknowledgement of the threat of market-based external factors, the authors propose a new future framework for OM, here defined as OM+. The literature has shown that there is, at present, no clear definition of the strategy or the definition of an opportunity. The new framework here proposed defines an opportunity as "**any period where the turbine production is less than a predetermined threshold or any time a maintenance crew is dispatched**", which is a novel contribution of this work. This definition encompasses all opportunities provided in the literature, both internal and external, and additional market factors explored in Chapter 5.

The trigger of curtailment can then be responded to by PM or CM activities dependent on the level of planning/operational information available. Periods of forced shutdown, during negative pricing and curtailment, can be viewed as opportunities to perform maintenance activities. These are periods of "forced downtime" which can be used to the advantage of the operator. These periods of downtime can be viewed as "free downtime" from a maintenance perspective. This proposed framework, OM+, is described in Figure 6.3.

The OM+ framework divides opportunities into maintenance-based and revenue-based. Maintenance-based opportunities are identical to the internal opportunities discussed and defined in Section 4.2.1. Any crew transfer for any maintenance action can be classed as an opportunity. The revenue-based opportunities include both weather and market opportunities. Weather opportunities include periods of low wind speed, based on a threshold set by the operator. Market opportunities include both periods of negative pricing and periods of curtailment, as discussed in Chapter 5.

Once an opportunity is triggered, the need for additional maintenance must be checked. Other requirements include the suitability of available weather windows, and the availability of resources such as personnel and spare parts before attempting OM.

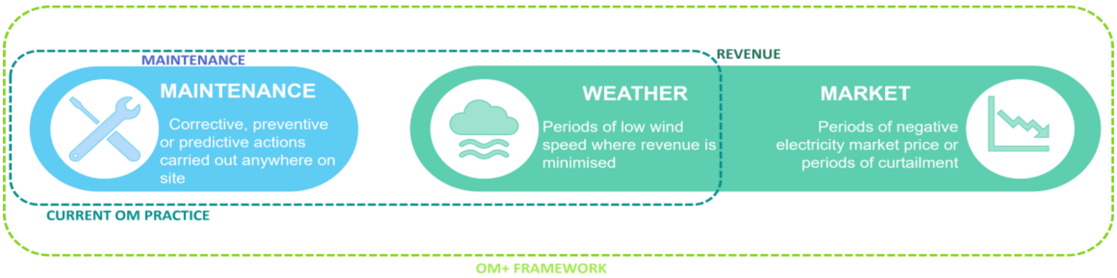


Figure 6.3. The new OM+ methodology here proposed, highlighting the additional opportunities.

This work identifies curtailment and negative pricing times as periods of "free downtime", e.g., periods where the turbine would already be shut down due to external influences. Therefore, it is proposed that these events should be included as ’opportunities’ within an OM framework, where O&M activities can be scheduled to be performed during these intervals, such as preventive/predictive maintenance actions, scheduled inspections, or annual servicing. This thesis proposes a future OM + framework that combines existing OM-developed strategies with the addition of external market concerns and their impact on turbine maintenance.

6.2.4. Availability

In addition to the OM+ process, the present work also suggests a new definition for recording and reporting availability. During the early years of the industry, availability tended to be time-based, A_{time} (also known as operational availability, A_o). However, as the industry has progressed, availability is now typically reported as yield or energy-based availability, A_{yield}. However, both existing methods to calculate availability fail to incorporate the impact of curtailment and negative pricing. In addition to the proposed OM+ procedure, the present work also presents a new measure of availability. The proposed Market-Based Availability (A_{market}) includes the impact of negative pricing and curtailment on the operation of the asset. Differences between the three definitions of availability are described in Equations 6.1-6.3.

$$A_{time} = \frac{U_{time}}{U_{time} + D_{time}} \tag{6.1}$$

$$A_{yield} = \frac{E_{exported}}{E_{potential}} \tag{6.2}$$

$$A_{market} = \frac{E_{exported} + E_{market}}{E_{potential}} \tag{6.3}$$

Where U_{time} is the number of hours the turbine was operating, D_{time} is the number of hours the turbine was not operating, $E_{exported}$ is the total energy exported from the site, $E_{potential}$ is the maximum theoretical export if all turbines at site were continuously operating, and E_{market} is the energy that could have been exported during periods of reduction and/or negative pricing.

As highlighted in Chapter 5, different stakeholders in the project respond to different KPIs. Therefore, market conditions must be incorporated into KPI monitoring, to avoid contractual discrepancies and ensure that KPIs represent the operating conditions to meet contractual agreements.

Example

For example, assuming a 1 MW turbine is operating at rated wind speed at a site for a duration of 24 hours. During that period the turbine is curtailed for 6 hours. A_{market} is the only KPI which effectively captures this, as the turbine STOP is determined by the UK Grid, and not within the control of the wind farm.

$$A_{time} = \frac{18}{18+6} = 0.75 \tag{6.1}$$

$$A_{yield} = \frac{18}{24} = 0.75 \tag{6.2}$$

$$A_{market} = \frac{18+6}{24} = 1 \tag{6.3}$$

Both A_{time} and A_{yield} “incorrectly” classify the turbine STOP as downtime.

6.3. Opportunistic Length

As highlighted in Section 6.1, the existing literature surrounding OM within offshore wind does not acknowledge the challenges of additional time at sea. In practice, an OM-based approach has an additional time at sea, defined here as the opportunistic length, OM_L (hours). This is the *additional time* at sea required to perform OM-defined activities. The appropriateness of an OM strategy for a particular site will depend on the weather window length of the site, the waiting time for such weather window lengths, and their impact on the opportunity cost. The new proposed weather window length required (WW_R) specifically for an OM based approach is defined in Equation 6.4.

$$WW_{R\_OM} = (2 \times TT) + TTR + OM_L$$
$$WW_{R\_OM} = WW_R + OM_L \tag{6.4}$$

Where TT is the travel time, TTR is time to repair, and OM_L is the time to carry out the additional maintenance action. As discussed in Chapter 5 (Figure 5.9), the most common OM strategy is to perform planned/scheduled maintenance activities during periods of opportunity. Therefore, for this analysis, it is assumed that OM_L is based on a pre-determined maintenance action. This length is varied within the sensitivity analysis in 6.3.1.

6.3.1. OM Length – Waiting Time Simulation

Even if it is assumed that any additional OM maintenance activities will be performed in parallel, there will still be an additional time factor to consider such as transfer between turbines, or time taken to carry additional materials and equipment; therefore, it is assumed that within an OM approach, there is always an increased time at the site required and therefore a longer total weather window is required.

The waiting time model is based on the “reverse” of the weather window model (Appendix B). Where the model “counts” the number of no access periods, rather than the number of access periods, e.g. logic 0 instead of 1.

The additional time at sea required will require an additional waiting time as shown in Figure 6.4, which shows the relationship between WW_R and waiting time using E2, NE2, and N2. Within this analysis no workability limitations are placed on access. The relationship between weather window length and accessibility will follow a similar profile for all substructure designs described in Chapters 3 and 4.

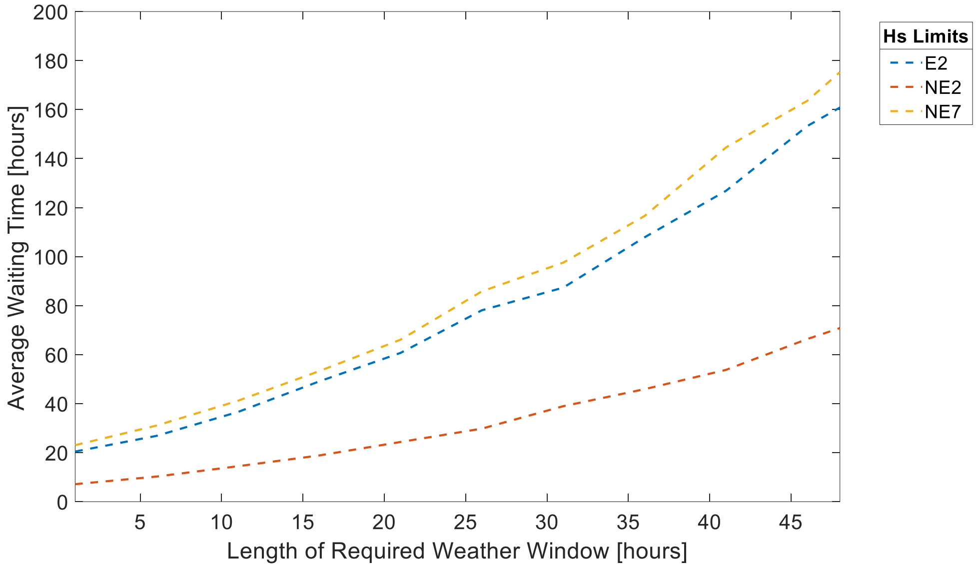


Figure 6.4 Average Waiting time for WW_R ranging from 0 to 48 hours.

As highlighted in Chapter 3, sites with high accessibility (such as NE2), will have a lower waiting time for suitable weather windows.

6.3.2. Opportunistic Length Threshold Model

Waiting time can make up a significant portion of the opportunity cost and downtime, which can make up a significant portion of overall OpEx. Savings from an OM based approach come from the sharing of resources, such as transportation. However, an increased weather window due to the additional OM_L also results in an increased waiting time, and therefore an increased opportunity cost. Therefore, a cost benefit analysis is required to determine if the additional cost due to increase waiting time is outweighed by the savings in shared transport.

The cost of transport is made up of two distinct parts: charter day rate (fixed) and fuel consumption (dependent on time). It is assumed that the day rate of the CTV used for this case study will have a time-based agreement with a daily charter rate of £3500, Hs limit of 2 m, and a fuel consumption of 200 litres/hour. The cost of additional downtime only considers the additional period at sea, as the time taken to perform the original maintenance action is confined within the original repair task.

The cost of OM_L is linked to the additional waiting time for the extended period. OM_L cost is defined as £39.65/MWh (in 2012 prices) in line with the round 4 contract for difference auctions. It is assumed that the additional maintenance task, which takes place within the WW_{R_OM} period, would require a full transfer to complete, e.g., hire of vessel and fuel consumption, to complete the activity and return to shore.

Using Monte Carlo simulation, the cost of OM vs the savings in transport are determined for minor, major, and replacement maintenance operations. The OM length is varied from 1-24 hours to capture a range of potential TTR values for an OM task. To be considered an economic approach, the OM savings must be more than the cost of additional downtime.

The model uses the weather window model (Appendix B) to determine weather window availability, and the waiting time model (Appendix B) to determine the additional waiting time for such a weather window. Model inputs are the site specific time series for ESOX LAUTEC, OM length minimum and maximum, OM_L cost and cost savings (vessel hire and fuel consumptions).

Table 6.1 Sensitivity Analysis Baseline Data

Significant Wave Height (Hs) [m]	Price Guarantee [£/MWh]	TTR [hours]
2 m	£39.65/MWh	28

Using sites E2, NE2, and NE7 as the case study, the cost of additional waiting time for a sufficient weather window for OM activities is determined. Three sensitivity analyses are performed, by varying TTR, CfD price guarantee, and Hs vessel limitations imposed on access. The baseline inputs are provided in Table 6.1

Figure 6.5 shows the relationship between the transport savings/OM benefit, against the cost of the additional time at sea. The cross-over points between the two are known as the ***OM Length Threshold***, where OM activities with a duration below this threshold will have an economic benefit, and those above will have a negative impact on OpEx.

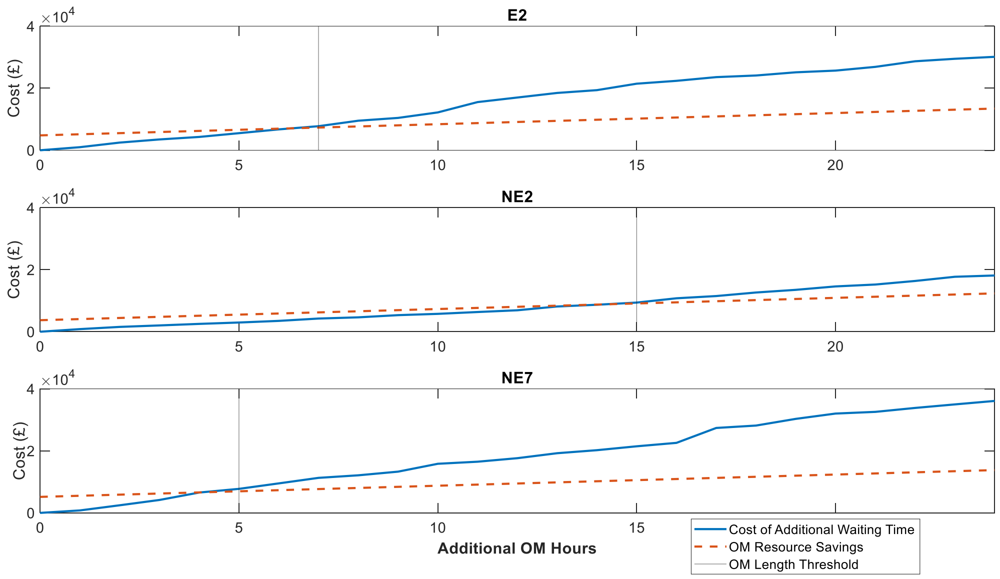


Figure 6.5. Additional OM length relationship between transport cost and OM savings

6.3.3. Time to Repair Sensitivity Analysis

Using the definition of the OM threshold introduced in Section 6.3.1, the types of maintenance actions which can be performed within OM defined opportunities are identified. Within offshore wind, maintenance activities are typically divided in to three categories: minor, major, and replacement [25]. Typical TTR requirements are highlighted in Figure 6.6 with TTR shown in green for minor, yellow for major and red for replacements.

Results highlight that for activities with a smaller required window, allow for more substantial OM activities to be additionally completed. Based on findings, minor primary maintenance activities, could have sufficient weather window length to complete additional minor, or even (for the case of NE2) major maintenance actions. As the WW_R increases, the length of the OM threshold decreases. Therefore, for replacement actions, only small tasks of a few hours' length could be completed, without incurring additional costs. The figure highlights the site dependent nature of these decisions, where NE2 would be capable of supporting minor and major opportunistic repair actions (10+ hours) across all WW_R. However, for E2 and NE7, it is recommended that OM activities be limited to below 10 hours. This is in line with technicians shift patterns.

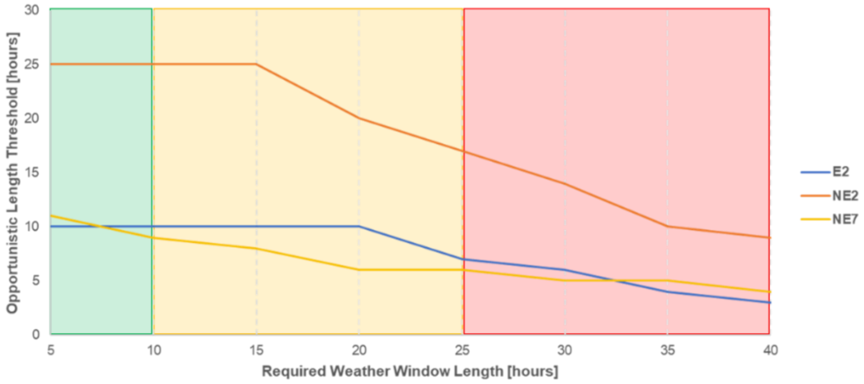


Figure 6.6. Opportunistic Length Threshold sensitivity analysis where green indicates a minor repair, yellow a major repair and red a replacement operation.

6.3.4. FOW Limitations Impact

Using E2 as the case study, the workability limitations from Designs A-D [26], the CoreWind ActiveFloat, and WindCrete designs, are introduced [27]. Using the baseline scenario detailed in Table 6.1, the OM Length Threshold for all 6 potential floater designs is determined. The designs A-D from Scheu et al. [28] and the ActiveFloat and WindCrete Designs from the CoreWind Project [27] as used for the analysis.

As shown in Figure 6.7, the impact of workability limitations has a significant impact on the OM Length Threshold. As expected, due to previous illustrations of poorer performance, Design D shows the most significant impact of a reduction in the acceptable threshold for the maintenance action to remain economically viable. All designs, even those which had minimal impact on OpEx such as WindCrete, all show a significant decrease, and therefore further limit the sort of activities which can be predetermined in a full OM strategy.

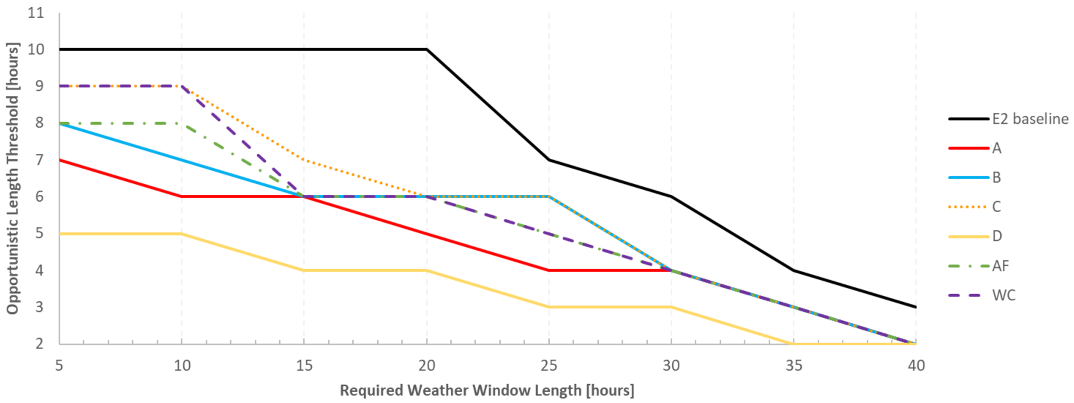


Figure 6.7. Impact of workability limitations on OM Length Threshold for floating platforms

6.4. Scheduled Maintenance Threshold Limits OPEX Modelling

In Chapter 5, the OM strategy was defined as having both a defined opportunity, and a specific pre-determined response to such opportunity. Section 6.3 highlighted the importance of ensuring that the predetermined activity duration will allow for the strategy to remain economically beneficial. This section focuses on the opportunity half of the full OM strategy.

The case studies presented within this section aim to use predefined opportunities of ***low income*** to perform scheduled maintenance actions. By performing these tasks during these periods, the cost of downtime is minimised and therefore should have a positive impact on overall OpEx estimations. Using sites E2, NE2 and NE7, the full operational lifecycle is modelled over a lifetime of 25 years. Each site is simulated as a BFW site, and with workability limitations placed on Designs A-D [26], WindCrete, and ActiveFloat [27]. As seen in Chapter 4, sites E2 and NE7 will have a SOV based maintenance approach, and NE2 will be serviced by CTVs. This modelling includes maintenance actions which do not require the use of a heavy lift vessel. Failure rates are taken from Carroll et al. [25], and weather data is provided from the ESOX LAUTEC ERA 5 database [29]. Further details of the site can be found in Chapter 3, Table 3.6.

The scheduled maintenance is scheduled to 60 hours per year and requires 2 technicians. For this analysis scheduled maintenance is not limited to summer months only and can be completed all year round.

To simulate the impact of scheduled maintenance thresholds, adaptations are made to the Strathclyde O&M model (Chapter 4). More details of the models created and adapted are given Appendix B.

Table 6.2. Scheduled maintenance threshold case studies

Site	Distance to Shore km	Average Hs m	Site Capacity GW
E2	135	1.9	1.3
N2	85	2.5	1.5
NE8	95	1.9	0.96
NE2	65	1.5	1

6.4.1. Wind Speed Threshold

For the adaptations of applying a wind speed threshold, the wind speed time series is a pre-required input to the model used to calculate turbine production, lost revenue, and accessibility, therefore no new inputs to the model were required.

The model was adapted within the "Main simulation stage" (Chapter 3, Figure 4.6). Previously, scheduled maintenance decisions were based on the vessel wind speed limitations, within the adaptation a "wind threshold" limitation was also added. The **wind threshold** is a pre-determined input by the user. All other logic within the model remained, such as 60 hours maintenance per year.

6.4.2. Curtailment Threshold

The original version of the Strathclyde O&M model did not include any market-based inputs such as curtailment levels, therefore in this adaptation, additional inputs were required. The curtailment inputs were pre-processed, where the user defined the top percentage of curtailment periods to be deemed "shut down", e.g. assuming the selected wind farm for the case study would be curtailed during this period. This is user defined within the "Curtailment

Input Module”. The Module required hourly time series of length equal to that of the weather time series. The outputs were then “1” indicating curtailment, or “0” indicating continued operation.

Within the Strathclyde O&M model, as with 1.4.1, an addition limitation was placed on the “Main simulation stage” where scheduled maintenance would only be performed **if** vessel limitations were met **and** curtailment = 1. Additional adaptations were also made in the “post-processing stage” where curtailment adjusted the wind farm revenue. The time series output of revenue was then compared against the time series of curtailment, any periods of curtailment resulted in a total loss of revenue for that period.

All other logic was unchanged within the model.

6.5. Scheduled Maintenance Threshold Case Studies

This Section shows the impact of introducing various limitations on scheduled maintenance activities.

6.5.1. Wind Speed Threshold

This section uses the opportunity of low wind speed, as seen in [30] [2] [15] , to perform ***scheduled maintenance.*** During all maintenance operations, the complete turbine must be shut down to ensure the safety of technicians, and therefore in addition to the cost of components, staff and vessel resources, there in a lost revenue cost also associated with the performance of scheduled activities. While the cost of lost revenue is reduced, compared to corrective maintenance actions due to the cost of waiting time, it is still an area which could benefit from cost reduction.

Low wind speed, or low power, limitations were the first application of an OM-based maintenance strategy as introduced by Besnard et al. [30]. However, it must be considered that within current studies there is already a wind speed limitation imposed, due to the limits of the vessel. Within the work of Besnard et al. [30], it is assumed that access is always available and therefore the wind speed limit already imposed by vessels is not considered within their work. As introduced in Chapter 3, vessel wind speed limitations are typically 15 – 20 m/s. Therefore, any wind limitations must be below this threshold, or power thresholds below the power rating for the vessel limit wind speed, to capture potential savings.

Using the Strathclyde OM Model, as described in Chapter 4, the model has been adapted to include a separate wind speed threshold which influences the decision-making process for scheduled maintenance activities, in addition to the wind speed limit imposed by vessel capabilities. The threshold for the simulations is 18 m/s, 15 m/s, 10 m/s and 5 m/s.

ScotWind sites E2, N2, NE6, and NE2 were used within this analysis as they represent a range of installed capacities, distance to shore, and average weather conditions. These are summarised in Table 6.2. The lifecycle of the wind farm was set at 25 years with failure rates and costs taken from Carroll et al. [25]. Due to the distance to shore and Hs, all sites utilise an SOV-based maintenance strategy with Hs limit of 3.5 m imposed.

Results of OpEx savings are shown in Figure 6.8. An equivalent wind farm with all year maintenance was used as the OpEx baseline. N2 exhibits the poorest OpEx savings compared to other wind farms, as it experienced instances where operational expenditures increased instead of decreasing. One significant contributing factor is N2's high capacity, resulting in a larger number of turbines that require maintenance, leading to higher costs. Additionally, N2 faces the challenge of severe weather conditions, which limit access to the turbines for maintenance activities, further impacting its OpEx savings potential. The combination of a substantial turbine count and restricted accessibility due to harsh weather conditions presents a considerable obstacle in achieving cost efficiency for N2.

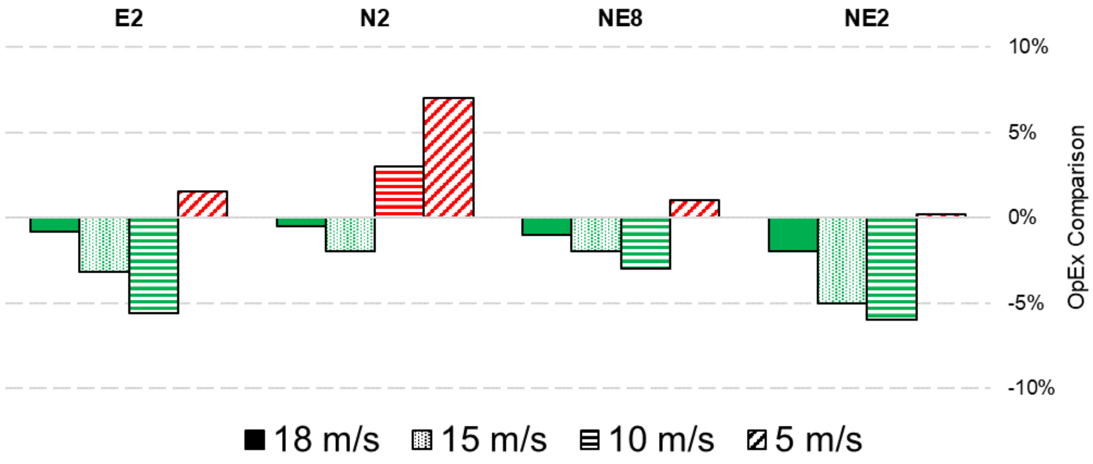


Figure 6.8. OpEx savings/increase resulting from a wind speed threshold on scheduled maintenance actions.

NE2 stands out as the most successful implementation for a wind threshold placed on scheduled maintenance, due to its advantageous location close to shore, reducing weather window length requirements. The site's exposure to milder weather conditions also improves overall accessibility and availability of weather windows. Moreover, the reduced number of turbines at NE2 reduces the criticality of repair.

As shown in Figure 6.8, there are periods where the implementation of a wind speed threshold results in ***an increase*** in OpEx (as seen for all sites for a limit of 5 m/s). This is due to the "wait on weather" period, where the waiting time for such a weather window outweighs the benefit of reduced revenue during the repair.

An additional benefit of performing maintenance during periods of low wind speed is that of the safety of technicians.

6.5.2. Curtailment Threshold

As previously mentioned, the threat of curtailment is increasing for offshore wind developers due to the rapid growth in installed capacity. As more wind farms are brought online, the potential for oversupply during periods of low electricity demand rises, leading to curtailment of generated power.

By utilising these periods of curtailment effectively, an effective maintenance strategy could potentially turn market constraints into maintenance opportunities. Performing maintenance operations during periods of curtailment in offshore wind farms is a strategic approach for several reasons. Firstly, it allows maintenance activities to be carried out without affecting the overall power generation, maximizing energy production during peak demand hours. Secondly, during curtailment, there is likely to be less strain on the grid, making it easier to disconnect turbines for maintenance without disrupting the electricity supply, leading to safer and more efficient maintenance operations.

By utilizing historical hindcast ERA 5 data for the specified sites listed in Table 6.2, the average daily met-ocean conditions are calculated. By applying a Hs limit of 2 m and a wind speed limit of 20 m/s, we made daily access/no access decisions. These decisions were then compared against the curtailment data, using data from 2022 as input from ELEXON [31]. The maximum 10% of UK wind curtailment during that period is highlighted in red. Due to the spatial and site specific nature of curtailment, it is assumed that **all wind farms** (both onshore and offshore) would be curtailed during these instances. Using E1 as an example, the results are shown in Figure 6.9.

While it is common for curtailment to take place during periods of high wind speed, and therefore expected high Hs and low accessibility, this is not always the case. Grid Constraints: curtailment may not solely depend on met-ocean conditions but can also be influenced by:

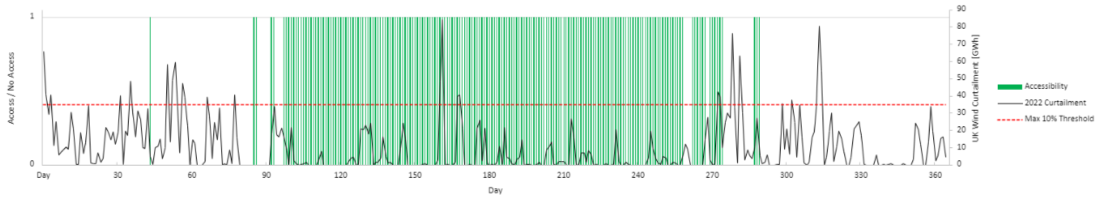


Figure 6.9. 2022 curtailment with highlighted accessibility periods based on hindcast averaged ERA 5 data.

- Grid constraints. If the power grid experiences limitations in absorbing the generated electricity, curtailment may be necessary to prevent overloading and maintain grid stability.
- Market Conditions: The availability and demand for electricity can also impact curtailment decisions. During periods of low demand or when the power grid cannot accommodate the surplus energy, wind farms may be curtailed to avoid oversupply and potential wastage.
- Operational Considerations: Other operational factors, such as maintenance work, could lead to curtailment during periods when met-ocean conditions might otherwise allow for power generation.
- Transmission Infrastructure: In some cases, the lack of adequate transmission infrastructure can lead to curtailment, preventing the efficient transfer of electricity from offshore wind farms to the onshore grid.
- Environmental Concerns: In specific regions, curtailment might be implemented to protect wildlife or marine habitats. For example, during certain migratory bird seasons or when marine mammals are present in the area, wind farms might be curtailed to reduce potential impacts.

- Contractual Obligations: Some power purchase agreements or regulatory requirements may necessitate curtailment under certain circumstances, irrespective of wind and wave conditions.

Using E2 as an example, and historical curtailment data from [32], the month of April is given as an example of potential curtailment periods in which maintenance could take place. If an SOV-based approach were to be utilised with Hs thresholds of 3-4 m, then maintenance could be carried out during all the curtailment “opportunities” presented. Figure 6.10 highlights the current CTV capabilities of 1.5 m Hs, showing that even with these access thresholds, there are still maintenance opportunities.

The cost-saving advantage of a curtailment-based maintenance approach stems from the concept of "free downtime". During maintenance actions, turbines need to be shut down for repairs. However, in cases of forced outages, the maintenance action is no longer the primary cause of the downtime period. As a result, the maintenance activities can be strategically scheduled during curtailment periods, utilizing the existing downtime, and minimizing the impact on overall energy production. The difference between the curtailment threshold and the wind speed threshold is that the wind speed threshold is performed maintenance in periods of low revenue, whereas the curtailment threshold takes advantage of periods of “no revenue”.

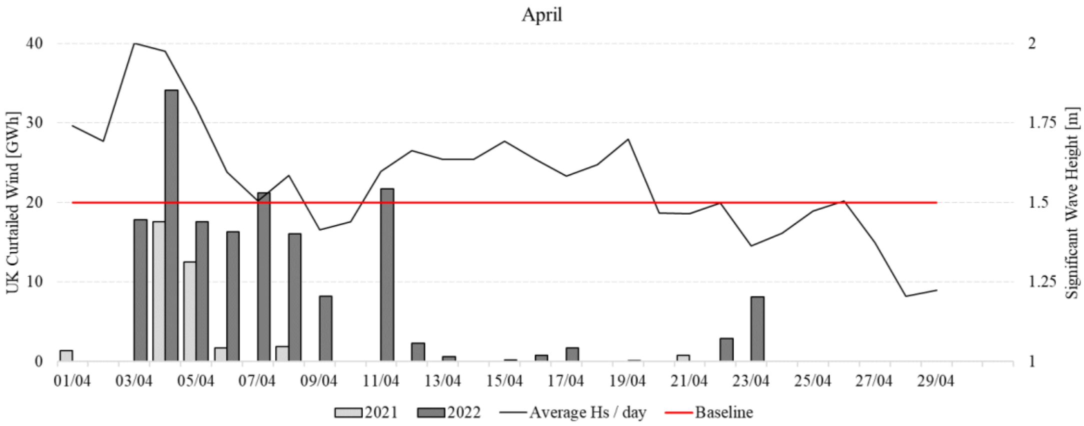


Figure 6.10. ScotWind site E2 historical average significant wave height and previous years curtailment levels for the month of April.

WindEurope reports estimates of curtailment 10% of the time. ScotWind is of importance as Scottish wind represented the vast majority of curtailment and costs, with 88% of the total wind curtailment volume in 2020-21 and 82% of the associated consumer costs [33].

By employing a Monte Carlo-based simulation, the present study calculates the potential savings of lost revenue for a curtailment opportunity maintenance strategy. In the sensitivity analysis, curtailment events are set to occur between 5% to 20% of the time. The power output from each site is determined using the IEA 15 MW reference turbine, corresponding to the wind speed at which curtailment takes place. Scheduled maintenance activities are assumed to have a fixed duration of 5 hours within this work. It is assumed that all potential curtailment maintenance actions are taken, and the remainder of scheduled maintenance hours remaining, if any, are performed as normal. Results are shown in Figure 6.11.

The savings are a result of savings in lost revenue for the scheduled maintenance activities. Periods of curtailment result in periods of loss of revenue. During “normal” operation, the scheduled maintenance tasks occur during summer months, where weather conditions are less severe, and also revenue is reduced (due to a seasonal reduction in wind speed). This approach allows for scheduled maintenance to occur at any time during the year, while there may be potential delays due to weather constraints, by taking advantage of the "forced" downtime due to curtailment, there are potential OPEX savings. This could be amplified as turbine MW scale increases; therefore, the value of lost revenue also increases.

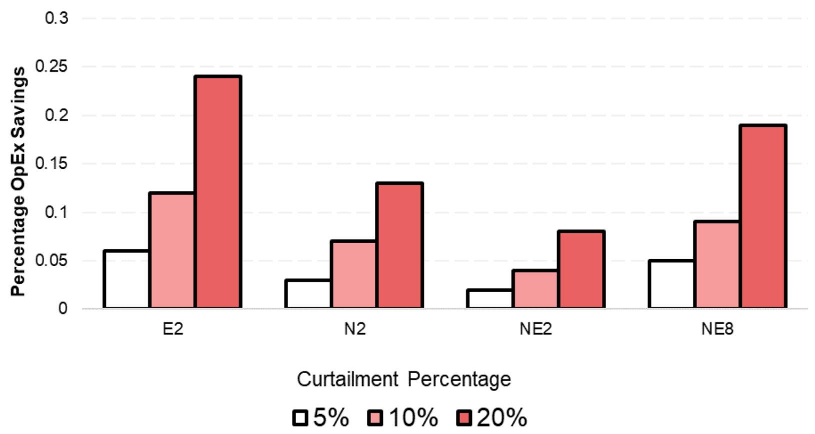


Figure 6.11 Curtailment OpEx savings

Because of the unpredictability of curtailment events, it becomes challenging to ascertain whether an opportunity should be seized or not. While curtailment-based maintenance can capitalize on existing downtime, not all maintenance activities align with curtailment events. Scheduled maintenance fills this gap, providing a structured approach to address maintenance needs that may not coincide with curtailment periods. Postponing scheduled maintenance actions in favour of a curtailment opportunity may have a negative impact on the overall reliability of the system.

It is recommended that until full predictive models of curtailment patterns and durations are available, curtailment opportunity maintenance would suit non-critical scheduled actions such as the painting of blades or replenishing of supplies. The creation of such a model would require a full UK generation and demand system to be simulated. The savings in OpEx are dependent in the number of opportunities available. With the increasing possibility of curtailment, the number of potential opportunities and, consequently, cost savings are expected to grow.

6.5.3. FOW Limitations Impact

The maintenance thresholds detailed in Sections 6.4.1 and 6.4.2 are applied to equivalent FOW sites. All six initial platform designs were utilized, enforcing a workability limit of <1. Outcomes were observed for FOW compared to BFW analysis. The scheduled maintenance does not lead to extended downtime, thus minimizing the criticality of repairs. The most considerable cost increase, when comparing FOW against BFW, was from the downtime associated with unplanned maintenance actions.

Among all platform designs, sites like NE2, which pose challenging access conditions, experienced the least impact in terms of both curtailment and wind speed thresholds. The wind speed threshold findings exhibited a consistent pattern with the bottom fixed wind results, indicating that the system's advantages were derived from sites with the highest capacity and consequently, the most scheduled operational hours. As with previous analysis, Design D proved to be the most challenging design. Due to the already challenging accessibility limitations, wind speed thresholds of 10 m/s saw an increase in OpEx for sites E2, N2 and NE8. Designs A, C, WindCrete and ActiveFloat saw the same results as seen in Figure 6.8 for the BFW equivalent. Design B saw a slight increase (>1%) in savings for all sites with the threshold.

For the curtailment strategy, a similar result was obtained. Due to the additional limitations placed on access, fewer maintenance opportunities were able to be taken, therefore the benefit of curtailment opportunities was reduced. As seen in the implementation of the wind speed maintenance threshold, Design D saw the least reduction across all sites, due to accessibility challenges. N2, NE2 and NE8 saw WindCrete having the highest cost reduction, in line with the reductions seen for the BFW scenario. For site E2, the most cost saving design was design C. For site E2, the reduction for all FOW sites was below that of the BFW scenario.

6.6. Limitations and Challenges

It is important to understand the complexity of the electricity market and curtailment decisions, and their influence and impact on offshore wind development. The market price is driven by the scale of industry development, supply and demand status, government policies, global politics, and individual generation agreements, etc. These factors therefore also have a significant impact on curtailment rates for current, and future, offshore sites.

The impact of wind energy forecast error can have a significant impact on the electricity market prices [110]. The two are co-dependent and therefore an accurate forecast of UK market prices for offshore sites is also required. For curtailment, the suitability of this framework, in practice, will be determined by the notice period given for the curtailment of assets. Changes in the market can be both instantaneous and suffer from delayed effects. To make use of the proposed market-based maintenance opportunities, accurate prediction of weather windows and available resources will be required for quick decisions to be made.

6.6.1. Industry Practice and Contractual Limitations

The implementation of OM within the industry is common, particularly during periods of low wind speed. It is common practice to "never miss a weather day". If a vessel is chartered, the agreement is typically for a 12-hour daily operating period. At offshore wind projects, vessels are usually chartered on a continuous and long-term basis. The potential savings of this approach will be determined by the charter agreement in place [99]. If under a voyage charter agreement, fuel consumption and crew expenses are covered within the agreement, making it advantageous for the operator to use the vessel as much as possible during the charter period. However, time charter agreements will require a cost analysis of the running costs of the vessel, such as fuel and crew, versus the potential maintenance savings of a weather-based OM strategy.

Grouping smaller maintenance tasks together is also common practice for small jobs, such as changing signs, implementing small design upgrades, or replenishing turbine equipment such as first aid kits, food rations, or eyewash stations, where the items have an expiration date. As these maintenance actions are non-critical to the operation of the site, there is typically a large window in which these tasks can be completed, making these suitable for an OM approach.

As well as being more efficient, there is also a safety advantage, as the total number of transfers will be reduced. There are some trends in the SPARTA data [100] which show reducing numbers of transfers – it is not clear what the cause of these are but is likely that increased bundling of tasks is contributing to this trend.

Despite the high potential savings found within the literature results, particularly those using PM action responses, it is important to be aware of the practical limitations of contractual agreements between the original equipment manufacturer (OEM) and the owner. During OEM Service Contract periods it is the turbine OEM who provides technicians and schedules maintenance work on site. If a PM maintenance action is triggered while the turbine is still under warranty, the OEM may choose not to carry out this work as they will incur additional costs and may not incur performance penalties under their contractual agreement if they wait for additional failures to emerge. Therefore, PM responses/actions may not always be possible as part of a wider OM strategy. Many operational sites have moved away from OEM contracts and now perform maintenance directly themselves and would be incentivised to use OM to prevent failures and enable low-wind speed days to be used for OM rather than risk prolonged downtime in the event of a sudden failure.

6.6.2. Ranking of Opportunities

The proposed framework includes numerous opportunities. However, some of these may contradict others, for example, performing maintenance during periods of low wind speed where the electricity price may peak could result in a potential loss of earnings. This concept is explored using a case study based in the United States using the Skipjack site.

Electricity price data are taken from the open-source data repository of PJM [108]. PJM is a regional transmission organisation covering the east of the US. The site is assumed to generate revenue from the wholesale electricity market and is located within the DOM transmission zone within the PJM region. Weather data is taken from the LAUTEC ESOX ERA 5 database for the same year [109]. Results are shown in Figure 6.12.

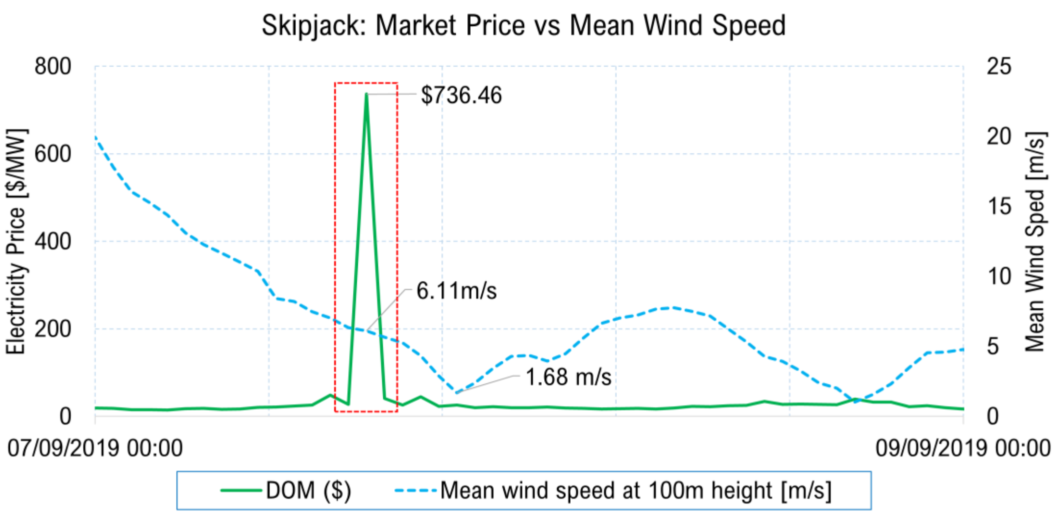


Figure 6.12. US Skipjack case study showing market price vs mean wind speed.

This case study indicates that taking opportunities can have a negative impact on potential revenue. Figure 6.12 shows a falling wind forecast, which would present itself as a maintenance opportunity, when viewed in isolation. However, when analysing the electricity market price, it shows a peak in pricing. Therefore, by taking low wind speed as an opportunity, there is a penalty taken in terms of potential profitability.

As discussed in Section 4.3.1, half of existing publications place a basic reliability or CBM-based limitation on any maintenance response to an opportunity. It is expected that for market-based maintenance, a similar threshold/ranking system will also be required to determine which turbines should benefit from the maintenance opportunity. Ranking can consist of a number of criteria including:

- **Reliability:** turbines with the lowest remaining useful life/quantified reliability are maintained first. As seen in [34] [1] [35] [36] [14] [37] [38] [13] [5] [39] [40] [41] [42] [43]
- **Locational**: if technicians are already at site when the opportunity occurs, a locational limit may be placed on potential turbines for repair [44] [45] [46] [38]
- **Power Output**: where turbines with historically high-power outputs are prioritised over other turbines.
- **Numbered:** Each turbine is maintained in turbine number order, regardless of output, location or remaining useful life.

6.6.3. Curtailment Specific Challenges

Implementing a curtailment-based opportunistic maintenance strategy for offshore wind farms presents several challenges that need to be carefully addressed:

- Uncertain Curtailment Patterns: The unpredictability of curtailment events poses challenges in planning and scheduling maintenance activities. It may be challenging to anticipate the timing and duration of curtailment periods accurately, making it difficult to optimize maintenance interventions.
- Technicians' Availability and Logistics: The successful implementation of the strategy relies on the readiness and availability of skilled technicians to carry out maintenance tasks during curtailment events. Logistics, including transportation to and from offshore wind farms during adverse weather conditions, can also be challenging.
- Safety and Weather Risks: Conducting maintenance during curtailment periods may expose technicians to more adverse weather conditions, potentially compromising safety. Ensuring proper safety protocols and risk assessment procedures are in place is crucial.
- Data and Monitoring: Real-time data on curtailment events, meteorological conditions, and turbine health is vital for effective decision-making. A robust monitoring and communication system must be established to support the opportunistic maintenance approach.
- Cost Implications: While the strategy aims to optimize maintenance costs, there may be additional expenses associated with reactive maintenance scheduling and mobilization during curtailment events. Evaluating the overall cost-effectiveness of the approach is essential.
- Integration with Existing Maintenance Practices: The opportunistic approach must be integrated seamlessly with the wind farm's existing maintenance practices and management systems to ensure a coordinated and efficient workflow.

By proactively addressing these challenges and developing robust strategies, offshore wind farm operators can unlock the full potential of curtailment-based opportunistic maintenance, improving the reliability and sustainability of their installations.

6.6.4. Additional Opportunities

The author's definition of an opportunity does not define the maintenance action which should be taken. In some cases, this may not be an opportunity to perform maintenance, but an opportunity to explore additional revenue streams in periods of forced downtime.

The identification of periods of curtailment and negative pricing may also provide opportunities for developers to explore additional revenue opportunities such as hydrogen production during these periods of "free" downtime. McDonagh et al. [111] have studied preliminary work on this concept. This development leads to an interesting balance between maintaining the main source of income (the wind farm) vs. maximising additional revenue streams (hydrogen production).

The Offshore Wind Policy Statement of the Scottish Government sets out a vision for up to 11 GW of offshore wind capacity in Scotland by 2030 [112]. This target has been greatly accelerated by the 2022 ScotWind leasing round which saw over 25 GW of offshore wind allocated. It is estimated that up to 240 GW of offshore wind could be deployed in the UK by 2050 to produce green hydrogen for export to Europe [113]. Scotland has a growing offshore wind sector, but with increased requirements for grid infrastructure upgrades and risk of curtailment, hydrogen production could act as an alternative revenue stream to electricity supply to support continued offshore wind development, while serving to decarbonise 'difficult-to-abate' sectors.

The introduction of floating turbines also provides additional opportunities to perform OM. The challenges associated with turbine motion, in addition to the remote/far from shore location of these sites, make an OM strategy advantageous for this technology. Currently, there is still no consensus on the maintenance methodology for performing major component replacements. As a result of the water depths, using Jack Up Vessels is unfeasible. One proposed solution is the tow to shore strategy (T2S). This process involves disconnecting the turbine from its moorings before towing the structure back to shore/port where maintenance will take place. This is expected to be a high-cost and time-intensive process. A review of the existing literature surrounding O&M for FOW and an overview of additional challenges can be found in McMorland et al. [114]. Therefore, the periods in which the turbine is returned to shore also introduce the opportunity to perform scheduled maintenance activities at port, such as inspections and small re- placements. This will help reduce the cost of the T2S process, as the cost is shared between multiple maintenance activities, not just major component replacements.

6.7. Chapter Outcomes and Summary

The advantage of group maintenance for FOW lies in the minimizing technicians' exposure to harsh offshore conditions. By grouping multiple repair tasks and scheduling them in a coordinated manner, maintenance activities can be efficiently executed during a single trip to the site. While the time spent at sea might be prolonged for the combined repairs, the overall time at sea is significantly reduced due to the sharing of travel time to the site between multiple repairs. This approach enhances logistical efficiency and safety by reducing the frequency of offshore visits, allowing technicians to carry out their tasks more efficiently and mitigating potential risks associated with frequent travels to the wind farm.

Implementing a wind speed threshold for maintenance actions offers potential benefits in terms of minimizing technicians' exposure to harsh conditions, as it limits maintenance activities to calmer weather conditions. Additionally, this approach provides economic advantages by reducing the value of lost income, as maintenance tasks are scheduled during periods of lower wind speeds, minimizing curtailment, and optimizing energy production. Sites with a larger number of turbines saw the greatest benefit from this strategy.

The advantages of adopting a curtailment-based opportunistic maintenance approach stem from several key factors. Firstly, it capitalizes on the frequency of curtailment events, allowing maintenance activities to be strategically scheduled during periods of reduced energy production, optimizing resources, and minimizing downtime. Secondly, the readiness of technicians to swiftly respond to curtailment instances further enhances the efficiency of maintenance operations. Lastly, effective management of maintenance actions within the curtailment-based framework ensures timely and targeted interventions, promoting the overall reliability and performance of the floating offshore wind farm.

The utilization of curtailment maintenance opportunities effectively capitalized on existing periods of downtime for both floating offshore wind (FOW) and bottom-fixed wind (BFW) installations, leading to operational expenditure (OpEx) reductions. While BFW sites experienced greater benefits, it is anticipated that FOW sites could leverage increased curtailment opportunities, as indicated by the trend in Figure 6.2. Consequently, FOW could potentially benefit from this strategy. However, as highlighted in Section 6.2, successful implementation of accurate curtailment opportunistic maintenance requires a high level of organization, modelling, and communication to ensure its effectiveness.

While bottom-fixed wind farms experienced the most significant benefits, floating offshore wind (FOW) did witness some improvements in operational expenditure (OpEx). However, the impact was more limited across all strategies due to the challenges posed by reduced accessibility in floating installations.

6.8. Chapter References

[1] K. Atashgar and H. Abdollahzadeh, "Reliability optimization of wind farms considering redundancy and opportunistic maintenance strategy.," *Energy Conversion and Management,* vol. 112, pp. 445-458, 2016.

[2] K. Kennedy, P. Walsh, T. Mastaglio and T. Scully, "Genetic optimisation for a stochastic model for opportunistic maintenance planning of offshore wind farms," in *2016 4th International Symposium on Environmental Friendly Energies and Applications (EFEA),* 2016.

[3] H. Ab-Samat and S. Kamaruddin, "Opportunisric maintenace (OM) as a new advancement in maintenance approaches A review," *Journal of Quality Maintenance Engineering,* vol. 20, no. 2, pp. 98-121, 2014.

[4] J. Kang, Z. Wang and C. Guedes Soares, "Condition-based maintenance for offshore wind turbines based on support vector machine.," *Energies,* vol. 13, no. 14, p. 3518, 2020.

[5] C. Zhang, W. Gao, T. Yang and S. Guo, "Opportunistic maintenance strategy for wind turbines considering weather conditions and spare parts inventory management," *Renewable Energy,* vol. 133, pp. 703-711, 2019.

[6] I. Dinwoodie, F. Quail and D. McMillan, "Analysis of offshore wind turbine operation and maintenance using a novel time domain meteo-ocean modelling approach," in *Turbo Expo: Power for Land, Sea and Air, American Society of Mechanical Engineers,* 2012.

[7] Department for Business, Energy and Industrial Strategy (BEIS), "Offshore Wind Sector Deal," H.M Government, London, 2019.

[8] The Committee for Climate Change (CCC), "Progress in reducing emissions - 2020," UK Parliament, London, 2022.

[9] Department for Buiness, Energy & Industrial Action (BEIS), "Proposed amendments to the Contracts for Difference scheme – Consultation Impact Assessment," HM Government, London, 2020.

[10] Wind Europe, "Wind Europe Views on Curtailment of Wind Power and its Links to Priority Dispatch," Wind Europe, 2016.

[11] Crown Estate Scotland (CES), "ScotWind offshore wind leasing delivers major boost to Scotland's net zero aspiratiosn," CES, 2022.

[12] S. Achenbach, V. Barry, C. Bayfield and P. Coventry, "Increasing the GB electricity transmission networks' power transfer capability between North and South - the Western HVDC Link," IET, 2012.

[13] A. Erguido, A. Crespo, E. Castellano and J. Flores, “After-sales services optimisation through dynamic opportunistic maintenance: a wind energy case study,” *Part O: Journal of Risk and Reliability,* vol. 232, no. 4, pp. 352-367, 2018.

[14] A. Erguido, A. Márquez, E. Castellano and J. Fernández, “ A dynamic opportunistic maintenance model to maximize energy-based availability while reducting the life cycle cost of wind farms,” *Renewable Energy,* vol. 114, pp. 843-856, 2017.

[15] P. Papadopoulos, D. Coit and A. Ezzat, “Seizing Opportunity: Maintenance Optimization in Offshore Wind Farms Considering Accessibility, Production, and Crew Dispatch,” *IEEE Transactions on Sustainable Energy,* vol. 13, no. 1, pp. 111-121, 2021.

[16] A. Brouwer, M. Van Den Broek, A. Seebregts and A. Faaij, “Impacts of large-scale Intermittent Renewable Energy Sources on electricity systems,,” *Renewable and Sustainable Energy Reviews,* vol. 33, pp. 443-466, 2014.

[17] TWENTIES Project, “Transmission system operation with a large penetration of wind and other renewable electricity sources in electricity networks using innovative tools and integrated energy solutions (TWENTIES),” EAWE, 2013.

[18] L. Bird, D. Lew, M. Milligan, E. Carlini, A. Estanqueiro and D. Flynn, “Wind and solar energy curtailment: A review of international experience,” *Renewable and Sustainable Energy Reviews,* vol. 65, pp. 577-586, 2016.

[19] J. Seel, D. Millstein, A. Mills, M. Bolinger and R. Wiser, “Plentiful electricity turns wholesale prices negative.,” *Advances in Applied Energy.,* vol. 4, p. 100073, 2021.

[20] R. Hawkes, “GB Renewables Map: An energy experiment by Robin Hawkes,” June 2023. [Online]. Available: https://renewables-map.robinhawkes.com/curtailment. [Accessed June 2023].

[21] J. Ketterer, “ The impact of wind power generation on the electricity price in Germany,” *Energy economics,* vol. 44, pp. 270-280, 2014.

[22] F. Paraschiv, D. Erni and R. Pietsch, “The impact of renewable energies on EEX day-ahead electricity prices.,” *Energy Policy.,* vol. 73, pp. 196-210, 2014.

[23] R. F. T. Fraundorfer M, “The Brazilian renewable energy policy framework: Instrument design and coherence.,” *Climate Policy,* vol. 20, no. 5, pp. 652-660, 2020.

[24] B. Pakenham, A. Ermakova and A. Mehmanparast, “A review of life extension strategies for offshore wind farms using techno-economic assessments.,” *Energies.*, vol. 14, no. 7, p. 1936, 2021.

[25] J. Carroll, A. McDonald and D. McMillan, “Failure rate, repair time and unscheduled O&M cost analysis of offshore wind turbines,” *Wind Energy*, vol. 19, no. 6, pp. 1107-1119, 2016.

[26] M. Scheu, D. Kaufer, M. Schwarzkopf and A. Kolios, “Workability on Offshore Wind Turbines - a Comparative Study of Fixed-Bottom and Floating Applications,” in *The 28th International Ocean and Polar Engineering Conference*, OnePetro, 2018.

[27] CoReWind , “D4.2 Floating Wind O&M Strategies Assessment,” EU-2020, 2020.

[28] M. Scheu, D. Kaufer, M. A. Schwarzkopf and A. Kolios, “Workability on offshore wind turbines – a comparative study of fixed-bottom and floating applications,” in *International Ocean and Polar Engineering Conference*, Japan, 2018.

[29] LAUTEC ESOX, “ERA 5 Data Point Map”.

[30] F. Besnard, M. Patriksson, A. B. Strömberg, A. Wojciechowski and L. Bertling, “An optimization framework for opportunistic maintenance of offshore wind power system,” in *IEEE bucharest powertech*, 2009.

[31] Elecon, “Elexon Curtailment Portal,” Elexon, [Online]. Available: https://www.elexonportal.co.uk/news/latest?cachebust=y1hxwwz26g. [Accessed May 2023].

[32] R. Hawkes, “UK Wind Curtailment Monitor,” 2021. [Online]. Available: https://wind-curtailment-app-ahq7fucdyq-lz.a.run.app/. [Accessed 25 January 2022].

[33] LCP, “Renewable curtailment and the role of long duration storage,” Drax, 2022.

[34] H. Abdollahzadeh, K. Atashgar and M. Abbasi, “Multi-objective opportunistic maintenance optimisation of a wind farm considering limited number of maintenance groups,” *Renewable energy*, vol. 261, no. 88, p. 247, 2016.

[35] C. Zhang, W. Gao, S. Guo, Y. Li and T. Yang, “Opportunistic maintenance for wind turbines considering imperfect, reliability-based maintenance.,” *Renewable Energy*, vol. 103, pp. 606-612, 2017.

[36] M. Yildirim, N. Gebraeel and X. Sun, “Integrated predictive analytics and optimization for opportunistic maintenance and operations in wind farms,” *IEEE Transactions on power systems,* vol. 32, no. 6, pp. 4319-4328, 2017.

[37] H. Li, P. Li, N. Gao, L. Niu, Y. Zhang and Y. Bao, “Opportunistic maintenance model for wind turbine based on reliability constraint.,” *IOP Conference Series: Materials Science and Engineering,* vol. 336, p. 12026, 2018.

[38] S. Song, Q. Li, F. A. Felder, H. Wang and D. W. Coit, “Integrated optimization of offshore wind farm layout design and turbine opportunistic condition-based maintenance.,” *Computers & Industrial Engineering,* vol. 120, pp. 288-297, 2018.

[39] Y. Lu, L. Sun, J. Kang, H. Sun and X. Zhang, “Opportunistic maintenance optimization for offshore wind turbine electrical and electronic system based on a rolling horizon approach,” *Journal of Renewable and Sustainable Energy,* vol. 9, no. 3, p. 33307, 2017.

[40] J. Izquierdo, A. Crespo Márquez, J. Uribetxebarria and A. Erguido, “ Framework for managing maintenance of wind farms based on a clustering approach and dynamic opportunistic maintenance,” *Energies,* vol. 12, no. 11, p. 2036, 2019.

[41] J. Wang, V. Makis and X. Zhao, “ Optimal condition-based and age-based opportunistic maintenance policy for a two-unit series system.,” *Computers & Industrial Engineering,* vol. 134, pp. 1-10, 2019.

[42] H. Zhao, F. Xu, B. Liang, J. Zhang and P. Song, “A condition-based opportunistic maintenance strategy for multi-component system.,” *Structural Health Monitoring,* vol. 1, p. 18, 2019.

[43] C. Su, Z. Y. Hu and Y. Liu, “Multi-component opportunistic maintenance optimization for wind turbines with consideration of seasonal factor,” *Journal of Central South University,* vol. 27, no. 2, pp. 490-499, 2020.

[44] Z. Zhang and L. Yang, “State-based opportunistic maintenance with multifunctional maintenance windows.,” *IEEE Transactions on Reliability.,* vol. 70, no. 4, pp. 1481-1494, 2020.

[45] J. Kang and C. Soares, “An opportunistic maintenance policy for offshore wind farms,” *Ocean Engineering,* vol. 216, p. 108075, 2020.

[46] Q. Liu, T. Li, M. Hsieh and J. Li, “Integrated Structural Dependence and Stochastic Dependence for Opportunistic Maintenance of Wind Turbines,” *Energies,* vol. 15, no. 2, p. 625, 2022.

[47] J. Blau, “The Paris Agreement: Climate Change, Solidarity, and Human Rights,” Springer, 2017.

[48] Department for Energy Security and Net Zero and Department for Business, Energy and Industrial Strategy, “Energy White Paper: Powering Our Net Zero Future,” HM Government, 2020.

[49] Scottish Government, “Update to the Climate Change Plan 2018 - 2032: Securing a Green Recovery on the Path to Net Zero,” Scottish Government, 2020.

[50] Global Wind Council, “Global Offshore Wind: Annual Market Report 2020,” Global Offshore Wind Report, 2020.

[51] The Carbon Trust, “Phase II Report,” Floating Wind Joint Industry Project, 2020.

[52] Cown Estate Scotland, “ScotWind: List of Successful Partners,” Technical Report, 2022.

[53] R. James and M. Ros, “Floating Offshre Wind: Market and Technology Review,,” Carbon Trust, UK, 2015.

[54] WindEurope, “Floating Offshore Wind Vision Statement,” WindEurope, Brussels, 2017.

[55] Q FWE, “Floating Wind Project Maps,” Quest Floating Wind Energy, 2020. [Online]. Available: https://questfwe.com/map-download-contact-form/. [Accessed 6 February 2023].

[56] S. Bradley, “Floating Wind Technology,” Energy Technologies Insitute, 2015.

[57] D. Ahn, S. Shin, S. Kim, H. Kharoufi and H. Kim, “Comparative evaluation of different offshore wind turbine installation vessels for Korean west-south wind farm,” *International Journal of Naval Architecture and Ocean Engineering,* vol. 9, no. 1, pp. 45-54, 2017.

[58] I. Bayati, “Challenges and opportunities of major maintenance for floating offshore,” World Forum Offshore Wind, 2021.

[59] B. Jenkins, A. Prothero, M. Collu, J. Carroll, D. McMillan and A. McDonald, “Limiting wave conditions for the safe maintenance of floating wind turbines,” in *Journal of Physics: Conference Series (Vol. 2018, No. 1, p. 012023)*.

[60] S. Butterfield, W. Musial, J. Jonkman and P. Sclavounos, “Engineering Challenges for Floating Offshore Wind Turbines,” National Renewable Energy Lab (NREL), Golden, 2007.

[61] M. Martini, R. Guache, I. Losada-Campa and L. IJ, “The Impact of Downtime Over the Long-Term Energy Yield of a Floating Wind Farm,” *Renewable Energy,* vol. 117, pp. 1-11, 2018.

[62] Y. Feng, P. Tavner and H. Long, “Early experiences with UK round 1 offshore wind farms,” in *Institution of Civil Engineers - Energy*, 2010.

[63] BVG Associates, “Guide to Floating Offshore Wind - Floating Wind Lifecycle Overview,” 2023. [Online]. Available: https://guidetofloatingoffshorewind.com/floating-wind-lifecycle-overview/. [Accessed 10 June 2023].

[64] The Carbon Trust, “Floating Wind Joing Industry Project: Plase II Report,” 2020.

[65] Wind Europe, “Floating Offshore Wind Vision Statement,” 2017.

[66] M. Scheu, D. Matha, M.-A. Schwarzkopf and A. Kolios, “Human exposure to motion during maintenance on floating offshore wind turbines,” *Ocean Engineering*, vol. 165(3), pp. 293-306, 2018.

[67] Equinor, “Hywind Scotland remains the UK’s best performing offshore wind farm,” Equinor, 23 March 2021. [Online]. Available: https://www.equinor.com/news/archive/20210323-hywind-scotland-uk-best-performing-offshore-wind-farm. [Accessed January 2022].

[68] Power Technology, “WindFloat Atlantic Project,” Power Technology, 6 February 2020. [Online]. Available: https://www.power-technology.com/projects/windfloat-atlantic-project/. [Accessed January 2022].

[69] reNEWS, “Kincardine facing turbine repair job,” reNEWS.biz, 4 May 2022. [Online]. Available: https://renews.biz/77609/kincardine-facing-turbine-repair-job/#:~:text=The%20pioneering%2050MW%20Kincardine%20floating,be%20in%20need%20of%20replacement. [Accessed 6 May 2022].

[70] C. Brons-Illing, “Analysis of operation and maintenance strategies for floating offshore wind,” in *Master's Thesis*, University of Stavanger, Norway, 2016.

[71] G. Rinaldi, P. R. Thies and L. Johanning, “Improvments in the O&M modelling of floating offshore wind farms,” in *4th International Conference on Renewable Energies Offshore (RENEW 2020)*, Lisbon, 2020.

[72] L. Castro-Santos, D. Silva, A. R. Bento, N. Salvação and C. Guedes Soares, “Economic feasibility of floating offshore wind farms in Portugal,” *Ocean Engineering*, vol. 207, 2020.

[73] L. Castro-Santos, D. Silva, A. Bento, N. Salvacao and C. Soares, “Economic feasibility of floating offshore wind farms in Portugal,” *Ocean Engineering*, p. 207, 2020.

[74] A. Dewan and M. Asgarpour, “Reference O & M concepts for near and far offshore wind farms,” ECN Petten, 2016.

[75] A. Myhr, C. Bjerkseter, A. Ågotnes and T. Nygaard, “Levelised cost of energy for offshore floating wind turbines in a life cycle perspective,” *Renewable Energy,* vol. 66, pp. 714-728, 2014.

[76] C. Bjerkseter and A. Ågotnes, “Levelised costs of energy for offshore floating wind turbine concepts,” Master's Thesis, Norweigan University of Life Sciences, 2013.

[77] G. Katsouris and A. Marina, “Cost Modelling of Floating Wind Farms,” ECN, 2016.

[78] L. Castro-Santos and V. Diaz-Casas, “Life-cycle cost analysis of floating offshore wind farms,” *Renewable Energy,* no. 66, pp. 41-48, 2014.

[79] L. Castro-Santos, E. Martins and C. Guedes Soares, “Methodology to calculate the costs of a floating offshore renewable energy farm.,” *Energies* , vol. 9, 2016.

[80] Wind Europe, “Floating Offshore Wind is Gearing Up for Take-Off,” Wind Europe, 8 September 2020. [Online]. Available: https://windeurope.org/newsroom/news/floating-offshore-wind-is-gearing-up-for-take-off/#:~:text=WindEurope%20analysed%20the%20potential%20for,to%207%20GW%20by%202030.. [Accessed 10 April 2021].

[81] R. Davies, “Floating Wind: The Signifcance of Hywind Scotland,” Power Technology, 2020 February 15. [Online]. Available: https://www.power-technology.com/features/floating-wind-significance-hywind-scotland/#:~:text=The%20simple%20basis%20for%20the, depths%20of%20up%20to%2050m.. [Accessed 10 April 2021].

[82] Statoil, “Hywind Pilot Park - Environmental Statement,” 2015. [Online]. Available: https://marine.gov.scot/datafiles/lot/hywind/Environmental_Statement/Environmental_Statement.pdf. [Accessed 10 April 2021].

[83] Prime Minister's Office, “New plans to make UK world leader in green energy,” October 6 2020. [Online]. Available: https://www.gov.uk/government/news/new-plans-to-make-uk-world-leader-in-green-energy. [Accessed 10 April 2021].

[84] Crown Estate, “Contract for Difference Allocation Round 4 Results,” 7 July 2020. [Online]. Available: https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/1103022/contracts-for-difference-allocation-round-4-results.pdf. [Accessed 10 April 2021].

[85] J. Wright, A. Colling and D. Park, Waves, tides and shallow-water processes. Volume 4, Gulf Professional Publishing, 1999.

[86] M. Rathbone, “The next frontier for infrastructure investments: Renewable Energy in Asia-Pacific Region,” PWC, Singapore, 2018.

[87] D. Evans, “Floating Offshore Wind Could be Massive in Asia,” 23 February 2021. [Online]. Available: https://www.energyvoice.com/renewables-energy-transition/301543/floating-offshore-wind-could-be-massive-in-asia/. [Accessed 10 April 2021].

[88] J. Bocobza, N. Davies and Rebbapragada, “An Evolving Marker in Asia for Offshore Widn,” Noron Rose Fulbright: Projec Finance, 2020.

[89] C. Butterfield, W. Musial and K. Jonkman, “Overview of Offshore Wind Technology,” NREL, Denver, 2007.

[90] US Government, “FACT SHEET: Biden Administration Jumpstarts Offshore Wind Energy Projects to Create Jobs,” 29 March 2021. [Online]. Available: https://www.whitehouse.gov/briefing-room/statements-releases/2021/03/29/fact-sheet-biden-administration-jumpstarts-offshore-wind-energy-projects-to-create-jobs/. [Accessed 10 April 2021].

[91] C. Wang, T. Utsunomiya, S. Wee and Y. Choo, “Research on floating wind tubines: a literature survey,” *The IES Journal Part A: Civil and Structural Engineering,* vol. 3, no. 4, pp. 267-277, 2010.

[92] A. Henderson and D. Witcher, “Floating offshore wind energy—a review of the current status and an assessment of the prospects,” *Wind Engineering,* vol. 31, no. 1, pp. 1-16, 2010.

[93] Y. Liu, S. Li, Q. Yi and D. Chen, “Developments in semi-submersible floating foundations,” *Renewable and Sustainable Energy Reviews,* vol. 60, pp. 433-449, 2016.

[94] G. Rinaldi, T. Phillip and J. Lars, “Current status and future trends in the operation and maintenance of offshore wind turbines: a review,” *Energies,* vol. 14, no. 9, p. 2484, 2021.

[95] BVG Associates, “Guide for an Offshore Wind Farm,” The Crown Estate and ORE Catapult, 2019.

[96] M. Muskulus and S. Schafhirt, “Design optimization of wind turbine support structures - a review,” *Journal of Ocean Wind Energy,* vol. 1, no. 1, pp. 12-22, 2014.

[97] G. Stewart and M. Muskulus, “A review and comparison of floating offshore wind turbine model experiments,” *Energy Pocedia,* vol. 94, pp. 227-231, 2016.

[98] M. Leimeister, A. Kolios and M. Collu, “Critical review of floating support structures for offshore wind farm deployment,” *Journal of Physics: Conference Series,* vol. 1104, no. 1, p. 12007, 2018.

[99] X. Wu, Y. Hy, J. Yang, L. Duan, T. Wang, T. Adcokc, Z. G. Z. Jian and Z. Lin, “Foundations of offshore wind turbines: a review,” *Renewable and sustainable enegry reviews,* vol. 104, pp. 379-393, 2019.

[100] P. Chen, J. Chen and Z. Hu, “Review of experiemental-numerical methodologies and challenges for floating offshore wind turbines,” *Journal of Marine Science Applied,* pp. 1-23, 2020.

[101] J. McMorland, C. Flannigan, J. Carroll, M. Collu, D. McMillan, W. Leithead and A. Coraddu, “A review of operations and maintenance modelling with considerations for novel wind turbine concepts,” *Renewable and Sustainable Energy Reviews,* vol. 165, p. 112581, 2020.

[102] J. Nielsen and J. Sorensen, “On risk-based operation and maintenance of offshore wind turbine components,” *Reliability engineering & sustem safety,* vol. 96, no. 1, pp. 218-229, 2011.

[103] E. MacMahonn, A. Stock, W. Leithead and P. Jamieson, “Yaw control for 20MW offshore multi rotor system,” in *European Wind Energy Association Annual Even (EWEA),* 2015.

[104] K. Verbert, B. De Schutter and R. Babuska, “Timeley conditions-based maintenance planning for multi-component systems,” *Reliability Engineering & System Safety,* pp. 310-321, 2017.

[105] E. Artigao, S. Martín-Martínez, A. Honrubia-Escribano and E. Gomez-Lazaro, “Artigao E, Martín-Martínez S, Honrubia-Escribano A, Gomez-L ´ azaro ´ E. Wind,” *Applied Energy,* vol. 228, pp. 1569-1583, 2018.

[106] F. Douard, C. Domecq and W. and Lair, “A probabilistic approach to introduce risk measurement indicators to an offshore wind project evaluation–improvement to an existing tool ecume.,” *Energy Procedia,* vol. 24, pp. 255-262, 2012.

[107] M. Scheu, D. Matha, M. Hofmann and M. Muskulus, “Maintenance strategies for large offshore wind farms.,” *Energy Procedia,* vol. 24, pp. 281-288, 2012.

[108] M. Hofmann and I. Sperstad, “NOWIcob–A tool for reducing the maintenance costs of offshore wind farms,” *Energy Procedia,* vol. 35, pp. 177-186, 2013.

[109] I. Dinwoodie, F. Quail and M. D, "Analysis of offshore wind turbine operation and maintenance using a novel time domain meteo-ocean modeling approach.," in *Turbo Expo: Power for Land, Sea, and Air, American Society of Mechanical Engineers*, 2012.

[110] Y. Dalgic, I. Lazakis, I. Dinwoodie, D. McMillan and M. Revie, "Advanced logistics planning for offshore wind farm operation and maintenance activities," *Ocean Engineering*, vol. 101, pp. 211-226, 2015.

[111] J. Helsen, D. S. G and P. Jordaens, "Long-term monitoring of wind farms using big data approach.," IEEE Second International Conference on Big Data Computing Service and Applications (BigDataService). IEEE, 2016.

[112] S. Ambühl, K. Morten and J. Sørensen, "Ambühl S, Kramer M, Sørensen JD. Risk-based operation and maintenance," in *ISOPE International Ocean and Polar Engineering Conference*, 2016.

[113] M. Bach-Andersen, B. Rømer-Odgaard and O. Winther, "Bach-Andersen M, Rømer-Odgaard B, Winther O.," *Wind Energy*, vol. 20, no. 5, pp. 753-764, 2017.

[114] T. Welte, I. Sperstad, E. Sørum and M. Kolstad, " Integration of degradation processes in a strategic offshore wind farm O&M simulation model," *Energies*, vol. 10, no. 7, p. 925, 2017.

[115] J. Kang and C. Soares, "An opportunistic maintenance policy for offshore wind farms.," *Ocean Engineering*, vol. 216, p. 108075, 2020.

Chapter 7 : Conclusions and Recommendations for Future Work

***This Chapter summarises the outputs of the thesis and recommends future development*.**

Chapter 7 provides a comprehensive summary the key findings and contributions of the thesis. It highlights how each chapter addressed the initial aims and objectives, underscoring their collective impact on advancing the understanding of floating offshore wind maintenance strategies. The chapter concludes by presenting recommendations for future research. An overview is provided in Figure 7.1.

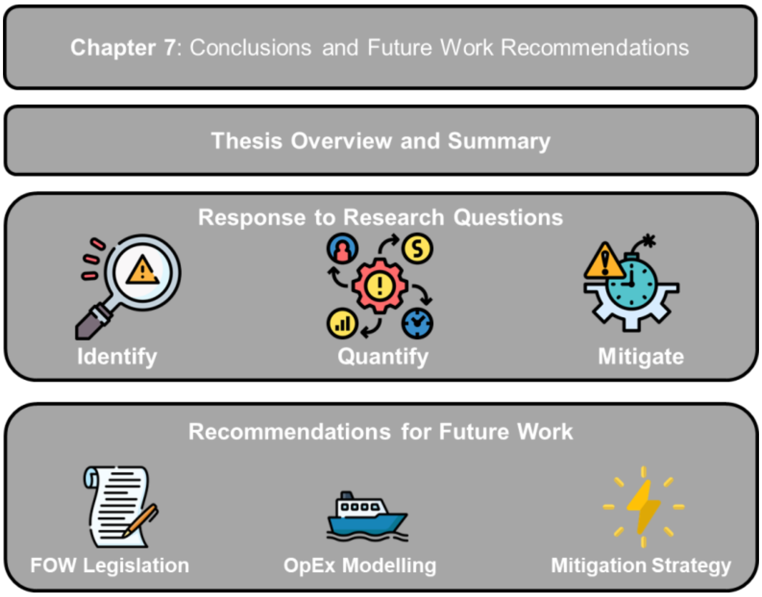


Figure 7.1. Chapter summary and overview

7.1. Overview

As set out at the start of this work, the installed capacity of FOW is set to expand rapidly in the coming decade, making it one of the key technologies to aid in the fight against climate change. At present, there are numerous small-scale developments operational within Europe. However, future developments are expected to be located within more challenging conditions, further from shore, and at a much larger scale. One of the obstacles FOW development faces is ensuring that the technology is cost-effective and can compete with conventional generation as well as BFW projects.

OpEx can be up to one-third of the total cost of energy for existing BFW projects [1], making it a key area for cost reduction. This proportion is expected to increase for FOW projects due to the challenges highlighted above [2]. The initial costs of developing floating offshore wind farms are higher than onshore or bottom-fixed offshore projects. Securing financing and achieving cost reductions through innovation and economies of scale are key challenges. By highlighting the importance of OpEx for FOW, the potential implications of having inaccurate inputs and the need to optimise maintenance strategies, this work aims to contribute to the industry's knowledge base, paving the way for more cost-effective, efficient, and sustainable FOW sites.

As outlined in Chapter 1, the primary focus of this thesis was to **identify** operational challenges, **quantify** their impact, and explore potential **mitigating** strategies to reduce OpEx. By understanding the critical factors impacting OpEx, more informed decisions can be made regarding the overall economic viability of floating wind installations. A graphical representation of the thesis findings is provided in Figure 7.2.

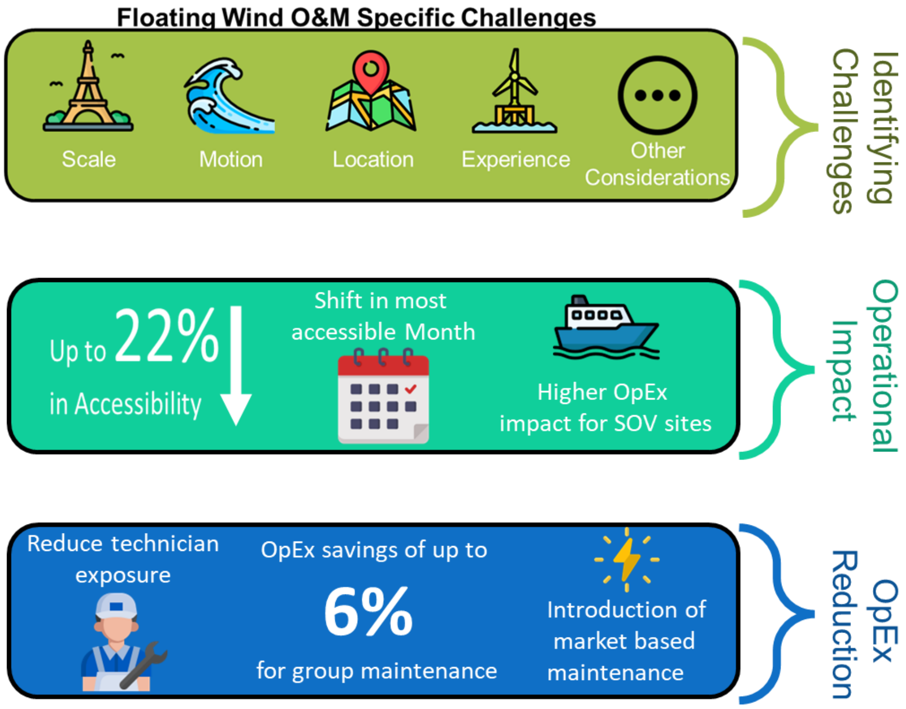


Figure 7.2. Thesis outputs overview

7.1.1. Identify

Chapter 2 provided an overview of FOW technology and its potential in future markets. It emphasized Scotland's leading position in the industry, with a commitment of nearly 20 GW of floating wind in the latest leasing round [3]. The chapter also delved into operational expenditure (OpEx), identifying it as an area for future development within existing FOW reviews and projecting it to be a higher proportion of total costs for floating wind compared to a bottom fixed. The key operational challenges identified based on these findings were:

- **Motion**: turbine motion is expected to place additional strain on accessibility and therefore additional inputs will be required to determine accurate accessibility and OpEx predictions
- **Location:** FOW sites are more likely to be located further from shore placing strain on weather window availability

- **Scale:** recent trends have seen a steady increase in turbine size. It is expected that future FOW sites will contain turbines upwards of 15 MW being deployed. As previously highlighted, while this will have a positive impact on project revenue, periods of downtime will be critical.
- **Experience/convergence**: the selection of substructure is highly site dependent. Each substructure has its unique set of challenges, where the economic feasibility of designs is highly site dependent.
- **Other**: other technology concerns impacting O&M are specific to major component replacement operations. At present existing heavy lift vessels are unable to operate in depths exceeding 60 m.

These challenges have been highlighted as an area for future development in Section 7.2.

7.1.2. Quantify

Chapters 3 and 4 quantified the impact of these highlighted challenges through common offshore wind KPIs of accessibility, lost revenue, and total annual OpEx.

Chapter 3 focused on examining the impact of limitations and challenges faced by floating offshore wind (FOW) on the non-financial key performance indicator (KPI) of accessibility, which plays a critical role in project planning and financing. The findings revealed a trend of increasing distance to shore in the mature offshore wind market, resulting in more challenging met-ocean conditions and reduced site accessibility. Both higher depth and higher distance were found to increase OpEx, with exceptions in extreme weather conditions. The implementation of motion limits (workability) to protect technician safety during floating structures' dynamic movement further complicated accessibility, requiring careful planning and adaptation of maintenance procedures. Key findings included the decrease in accessibility for FOW sites due to distance and workability limits, varying impact depending on site conditions and platform design, and the importance of considering vessel limitations and workability when assessing FOW accessibility. It was found that accessibility could be reduced by up to 22% in extreme cases for specific sites. The chapter recommended the establishment of specific workability index limits for different maintenance actions to address the limitations based on technician travel and work types.

Chapter 4 aimed to determine the financial impacts. This Chapter detailed the impact of motion and workability limitations on minor/major repair maintenance activities in FOW projects. The findings emphasize that a "one fits all" approach (i.e., one weather threshold across all designs) is inadequate for accurate O&M modelling due to the significant influence of platform design on accessibility and OpEx. The study highlights the importance of considering both CapEx and OpEx when selecting the most suitable platform for a site, as accessibility and lost revenue are closely linked, impacting early project financing decisions. The decrease in accessibility in Chapter 3 resulted in an increase in OpEx, where the increase in total annual OpEx was attributed to an increase in lost revenue due to prolonged downtime (Figure 4.10).

The work also stresses the need for an industry standard of acceptable WI threshold, where differences in acceptable WI threshold saw deviations of 15% within the OpEx estimations (Figure 4.11). This threshold aims to protect technician working conditions and recommends the introduction of dedicated IEC Design Load Case/s for technicians working to ensure a consistent and safe standard within the FOW industry. Beyond this, it would be recommended that specific standards for use within offshore wind maintenance actions. Exposure to motion thresholds should be dependent on the duration of time at sea, including transfer, the type of structure being maintained (fixed or floating) as well as the type of maintenance action being undertaken. Future work is suggested to focus on platform suitability analysis based on environmental factors specific to each location and to introduce a specific working limitation for safe working conditions for technicians.

7.1.3. Mitigate

Chapters 5 and 6 explored the mitigation strategy of opportunistic maintenance as a potential means of reducing site OpEx. One of the key advantages of such a strategy is that it aims to reduce the number of transfers. This is of particular benefit for FOW operations, as it is expected that there will be requirements to reduce technicians' exposure to motion as and where possible.

Chapter 5 reviewed existing literature surrounding the OM strategy. Drawing from similarities with other industries like manufacturing and power systems, the study proposes a comprehensive definition of OM, outlining maintenance opportunities and corresponding actions or responses. The review indicates a growing interest in OM within the offshore wind sector, with opportunities categorized as internal or weather-based triggers, often leading to cost-saving maintenance actions. While simulations demonstrate potential OpEx savings of up to 20%, the literature still lacks a cohesive definition of OM strategy, and there are gaps to address, including the challenge of additional time at sea for group maintenance activities, met ocean limitations on site accessibility, and the exploration of market considerations as potential maintenance opportunities. OM's goal of reducing transfers and shared resource costs benefits floating offshore wind farms by limiting technician exposure and reducing vessel-based motion during maintenance actions, which is crucial due to the dynamic response of assets in these environments.

Chapter 6 explored the potential benefits of FOW application of the strategy. As highlighted in 7.1.1, scale was identified as one of the key operational challenges faced by FOW developments. While this will have significant direct impact on OpEx due to size of components and the MW rating of lost revenue, such large-scale development is also expected to have significant impact on the market in which FOW sites will trade. This Chapter reviewed current group maintenance OM strategy as well as introducing market-based maintenance. By combining multiple repair tasks and scheduling them in a coordinated manner, maintenance activities can be efficiently executed during a single trip to the site, reducing overall time at sea and enhancing logistical efficiency and safety. Implementing a wind speed threshold for maintenance actions offers potential benefits in terms of minimizing technician exposure to harsh conditions and optimizing energy production by scheduling tasks during periods of lower wind speeds, especially beneficial for sites with a larger number of turbines. Adopting a curtailment-based opportunistic maintenance approach capitalizes on existing periods of downtime for both FOW and bottom-fixed wind installations, leading to OpEx reductions. While bottom-fixed wind farms experienced the most significant benefits, FOW also witnessed some improvements, but challenges of reduced accessibility limited the impact across all strategies for floating installations.

7.2. Recommendations for Future Research

It has hoped that this work has highlighted the importance of understanding OpEx for FOW sites and the impact of O&M throughout the whole project lifecycle. Therefore, it is recommended that O&M strategy and modelling be a key focus of future FOW research. Areas of future research are categorised as baseline scenarios, OpEx modelling, and strategy development.

7.2.1. Baseline Scenarios

Chapters 3 and 4 showcased the diversity in outcomes for various platform types and workability index thresholds. In the offshore wind industry, Hs limits of 1.5 m for Crew Transfer Vessel (CTV) operation are commonly acknowledged [4]. Nonetheless, a clear definition of acceptable working conditions for technicians conducting turbine maintenance is still lacking.

While there are guidelines in place for oil and gas practices [5], it is important that FOW has its own specific set of guidelines for specific maintenance actions. As highlighted, the distance to shore of offshore projects is increasing, for both BFW and FOW. Therefore, technicians will be exposed to a range of motion, and will be conducting a range of activities. It is recommended that there be clear guidelines surrounding the WI for a range of activities with specific details given for the duration of exposure to ensure technician wellbeing.

As highlighted in Chapter 4, the IEC standards encompass a wide range of aspects related to floating wind technology, encompassing safety, performance, and reliability, with the primary objective of ensuring the safe and sustainable design and operation of floating wind turbines. To maintain a secure and uniform standard within the industry, this thesis proposes the introduction of a workability limit specifically for technician working conditions. This recommended DLC should cater to both typical CTV and SOV safe working conditions, with the external condition tailored to the type of work performed by technicians, such as manual labour or intelligent working.

The consideration of turbine motion and its impact on the whole project lifecycle from installation to decommissioning could lead to savings throughout the whole project.

As highlighted in Chapter 2, there is a clear trend in the increasing distance to shore of the future FOW developments. Therefore, future work should consider the environmental conditions along the travel path, not just at port and at the centre of the site. This applies to both day-to-day maintenance activities, as well as analysis of the travel path for tow to shore activities.

7.2.2. OpEx Modelling

In this study, workability limitations utilized in the OpEx modelling were adopted from existing publications. However, to improve operational decision-making for specific technologies, it would be advantageous to develop a comprehensive OpEx model capable of determining motion outputs from the turbine at all timesteps. Nonetheless, it is acknowledged that modelling FOW turbines can be challenging due to the uniqueness of each structure, making the development of an all-encompassing model complex.

As discussed in Chapter 4, minor/major maintenance operations make up the majority of maintenance actions [6]. However, in future works, the development and modelling of major component replacements should be given attention. Component replacement will have a significant cost component and will make up a significant portion of the total project OpEx.

Furthermore, future research could explore innovative solutions to tackle the challenge of major component replacement operations in deep waters. Investigating alternative technologies or vessel designs capable of working efficiently at greater depths can significantly impact the accessibility and overall operational efficiency of floating offshore wind farms. At present, the key focus of existing model adaptations and replacement strategies has been surrounding the T2S strategy. However, additional research would be recommended for exploring alternative methodologies [7].

Within this work, the focus has been placed on the proposed ScotWind floating sites. While these sites offer a range of installed capacities and distances to shore, additional global case studies would be recommended in future markets identified in Chapter 2. Furthermore, conducting comparative studies on the O&M costs of floating offshore wind farms with various turbine sizes and configurations would provide valuable insights into the most cost-effective designs for future projects.

The use of more up-to-date data for vessel rates, failure rates, and component cost would also have a positive impact on OpEx modelling. Within this work, the aim was to determine the impact of the additional FOW challenges against a BFW equivalent, and therefore the same data were used to establish a baseline. However, for the purpose of project financing and budgeting, more accurate data would be required. In addition, the cost, and failures of FOW-specific components, such as the mooring and anchor system, would be required.

By refining and expanding the OpEx models, stakeholders can make more informed decisions on maintenance strategies and resource allocation, ultimately enhancing the cost-effectiveness and profitability of floating wind projects.

7.2.3. Mitigation Strategies

Due to the infancy of the technology, it is expected that, initially, FOW will be more expensive than the equivalent BFW. As OpEx is a clear contributor to total LCoE, it is important that potential mitigation strategies are explored.

While not included within the core work of this thesis, FOW-specific strategies such as opportunistic tow to shore, where all scheduled maintenance is conducted at port during major component replacements, should be considered. T2S is an extremely time-consuming and costly endeavour, and therefore by adopting the OM strategy of sharing costs between several maintenance actions, the overall cost would be reduced. This also has the additional advantage of further reducing technician time at sea.

This work highlighted the growing threat of curtailment and negative pricing. The analysis would be improved using a predictive maintenance model, rather than relying on historical data. Due to the complexities of curtailment, and consumer electricity data, this is challenging to predict, and historical data is not always representative of future events. There would be potential great value in having an integrated curtailment, maintenance, and motion OpEx model to aid in both project financing and budgeting, as well as in the day-to-day maintenance decision making process.

7.3. Chapter References

[1] Y. Feng, P.J. Tavner, H. Long, 2010. Early experiences with UK round 1 offshore wind farms. Proceedings of the Institution of Civil Engineers - Energy 163, 167–181. http://www.icevirtuallibrary.com/doi/10.1680/ener.2010More references.

[2] BVG Associates, "Guide to Floating Offshore Wind - Floating Wind Lifecycle Overview," 2023. [Online]. Available: https://guidetofloatingoffshorewind.com/floating-wind-lifecycle-overview/. [Accessed 10 June 2023].

[3] Crown Estate, "Contract for Difference Allocation Round 4 Results," 7 July 2020. [Online]. Available: https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/1103022/contracts-for-difference-allocation-round-4-results.pdf. [Accessed 10 April 2021].

[4] J. McMorland, C. Flannigan, J. Carroll, M. Collu, D. McMillan, W. Leithead and A. Coraddu, "A review of operations and maintenance modelling with considerations for novel wind turbine concepts," Renewable and Sustainable Energy Reviews, vol. 165, p. 112581, 2020.

[5] I. Nielsen, "Assessment of ship performance in a seaway," NORDFORSK, Copenhagen, 1987

[6] J. Carroll, A. McDonald and D. McMillan, “Failure rate, repair time and unscheduled O&M cost analysis of offshore wind turbines,” Wind Energy, vol. 19, no. 6, pp. 1107- 1119, 2016.

[7] I. Bayati, “Challenges and opportunities of major maintenance for floating offshore,” World Forum Offshore Wind, 2021.

Appendix A

Overview of PhD work

Conferences:

- Wind Europe, Copenhagen, 2019: Poster Presentation
    - "Disruptive Potential for Service Operations Vessels to Drastically Reduce Access Based Operational Costs for Offshore Wind Farms"
- Wind Europe Technology Workshop, Online, 2021: Poster Presentation
    - "Impact of health and safety on offshore wind operations and available resource"
- EAWE PhD Seminar, Online, 2021: Presentation
    - "Using Bathymetry to predict wave behaviour across a wind farm".
- University of Strathclyde Ocean Engineering, Marine & Transport Conference, Glasgow, 2021: Presentation
    - "Operation and Maintenance for Floating and Novel Turbines: An Introduction"
        - Award for best presentation
- FW&M2021
    - "Operation and Maintenance for Floating and Novel Turbines"
- DeepWind 2022, Trondheim: Presentation and Publication
    - "Adaptations of offshore wind operation and maintenance models for floating wind"
- FW&M 2022

    - OM
- Wind Europe, Bilbao 2022: Presentation, Poster, Publication
    - “Development of a multi rotor floating offshore system based on vertical axis turbines”.
    - “A New Proposed Framework for Opportunistic Maintenance for Offshore Wind (OM+)”
- Torque, Delft, 2022: Poster and Publication
    - “Operation and Maintenance Modelling for Multi Rotor Systems Bottlenecks in Operations”
- SuperGen, Oxford, 2022: Poster
    - “Opportunistic Maintenance for ScotWind Sites”
- DeepWind, Trondheim, 2023: Presentation and Publication
    - “Multi Rotor Wind Turbine Systems: An Exploration of Failure Rates and Failure Classification”
- Multi-Rotor Seminar, Hamburg, 2023
    - “O&M MRS Strategies and tools”
    - “O&M Floating Offshore Wind”
    - “Floating MRS based on VAWTs - concept and O&M”
- FW&M2023, Glasgow, 2023: Presentation
    - “Operational strategies for the next generation of offshore wind turbines”
- All Energy, Glasgow, 2023
    - “The impact of additional weather limitations on weather windows for floating offshore wind”
- WESC, Glasgow, 2023.

- "An Assessment of Accessibility and Workability for Floating Offshore Wind Sites"

Non-Thesis Related PhD Outputs

McMorland, J., Khisraw, A., Dalhoff, P., Störtenbecker, S. and Jamieson, P., 2023, October. Multi Rotor Wind Turbine Systems: An Exploration of Failure Rates and Failure Classification. In Journal of Physics: Conference Series (Vol. 2626, No. 1, p. 012027). IOP Publishing.

McMorland, J., Pirrie, P., Collu, M., McMillan, D., Carroll, J., Coraddu, A. and Jamieson, P., 2022, May. Operation and maintenance modelling for multi rotor systems: bottlenecks in operations. In Journal of Physics: Conference Series (Vol. 2265, No. 4, p. 042059). IOP Publishing.

Jamieson, P., Ferreira, C.S., Dalhoff, P., Störtenbecker, S., Collu, M., Salo, E., McMillan, D., McMorland, J., Morgan, L. and Buck, A., 2022, April. Development of a multi rotor floating offshore system based on vertical axis wind turbines. In Journal of Physics: Conference Series (Vol. 2257, No. 1, p. 012002). IOP Publishing.

McMorland, J., Flannigan, C., Carroll, J., Collu, M., McMillan, D., Leithead, W. and Coraddu, A., 2022. A review of operations and maintenance modelling with considerations for novel wind turbine concepts. Renewable and Sustainable Energy Reviews, 165, p.112581.

Hong, S., McMorland, J., Zhang, H., Halse, H., Collu, M., and McMillan, D., 2023. Floating Offshore Wind Installation, Challenges, and Opportunities [pending submission].

Appendix B

Model Overview

An overview of the models used in this work.

Model Name	Origin	Details
Weather Window Model	Created for this thesis.	MATLAB simulation tool using loops to determine weather window length. Used to predict the optimal periods during which specific operations can be safely and efficiently conducted, considering weather conditions. **INPUTS:** • Hs, Wind Speed hourly resolutions time series • Tp/Hs combination limiting (optional for FOW adapted model only) • Vessel limitations (Hs, wind speed)
Waiting Time Model	Created for this thesis	Inverse of Weather Window model, where Outputs are reversed – e.g counts number of no access periods, instead of number of access periods.
FOW OPEX Model	Strathclyde O&M Model	Adapted OPEX model. Allowing for the impact of workability limitations to be determined on KPIs such as availability, lost production and OPEX
Wind Speed Threshold OPEX Model	Strathclyde O&M Model	Adapted OPEX model. Used to determine impact of additional constraints (low wind speed) on scheduled maintenance actions.
Curtailment OM OPEX Model	Strathclyde O&M Model	Adapted OPEX model. Addition pre-processing module for curtailment, curtailment level/periods pre-determined. Used to determine impact of performing scheduled maintenance during periods of curtailment only. **ADDITIONAL INPUTS** • Curtailment time series of equal length of the input met-ocean conditions (in hourly resolution)