Daylight Considerations for Offshore Wind Operations and Maintenance

Orla Donnelly, James Carroll

Department of Electrical and Electronic Engineering, 99 George Street, G1 1RD, Glasgow, Scotland

E-mail: orla.donnelly@strath.ac.uk

Abstract. The cost associated with operations and maintenance (O&M) for offshore wind is a cost that developers and operators are striving to reduce in order to reduce the overall Levelised Cost of Energy. Improving accessibility and increasing time based availability of wind turbines can guarantee these reductions. To increase time based availability , some wind farms utilise night shift work to reduce downtime for turbines. Previous studies revealed cost reductions using this method but are strictly based on North Sea wind farms. This paper investigates the impact daylight hours have on the O&M costs for an offshore wind farm depending on location. Using an O&M model, three maintenance strategies are simulated and their associated O&M costs are found: 'Daylight Limited', 'Daylight Not Limited' and 'Night Shift'. Three case studies are chosen: North Sea, USA and Australia. The operational costs for the North Sea were reduced by £32.74/MWhr with the introduction of the night shift. With increased daylight, the US site saw a smaller reduction in operational costs of £3.48/MWhr using the night shift. However, the Australian site was negatively impacted when adopting a night shift strategy as operational costs increased by £3.19/MWhr. The study considers, if there are reductions in cost through night shift, is it worth the trade-off the industry makes for health and safety of technicians who work at night.

1. Introduction

In the global offshore wind (OW) sector, Europe is a leading developer, while countries like China, the USA, and Australia have made progress in integrating OW into their energy mix [1]. As a result, much research in focused around European waters, particularly the North Sea. As a result, much research in focused around European waters, particularly the North Sea. The European Union have pledged to install 300GW of offshore wind energy by 2030, with 47% of this target planned in the North Sea [2]. Operations and maintenance (O&M) for these wind farms can account for up to 30% of the overall project cost [3].

Research has focused on reducing O&M costs through improved maintenance strategies, enhanced accessibility, and condition monitoring. Improved accessibility, defined here as successful crew transfer from port to wind farm for maintenance, can significantly reduce downtime. As wind farms move farther from shore and increase in size, addressing accessibility becomes more challenging, especially in areas with high wind speeds and rough sea conditions [4].

Alongside cost savings, strict implementation of health and safety regulations is crucial for wind farm developers to ensure the well-being of personnel and the general public. Balancing

Content from this work may be used under the terms of the Creative Commons Attribution 4.0 licence. Any further distribution of this work must maintain attribution to the author(s) and the title of the work, journal citation and DOI.
Published under licence by IOP Publishing Ltd

cost and safety is often described as a 'trade-off.' One proposed solution to increase time based availability is the implementation of night shifts at wind farm sites, allowing maintenance to continue after daylight hours.

Studies by Dalgic [5] and Anderson [6] have explored the impact of night shifts on O&M costs and time based availability . Dalgic used the Strathclyde OW Operations and Maintenance tool to simulate different configurations of Crew Transfer Vessels (CTVs) during day and night shifts, concluding that the lowest O&M cost was achieved with 4 CTVs in both shifts [5]. Anderson's study utilised a real operational database to train a Bayesian hierarchical model, determining that night shift work increases time based availability by 0.64% annually [6]. Both studies acknowledged potential safety risks but primarily focused on cost and time based availability , emphasising the lack of literature on health and safety considerations in OW compared to the oil and gas industry.

1.1. Health and Safety

This paper addresses safety concerns related to low visibility and technician welfare in OW operations. It should be noted that some studies refer simply to offshore work and are not specific to OW. G+ standards, applied to over 100 operational wind farms, emphasise precautions for restricted visibility in small offshore vessels [7]. Limited health and safety literature in OW suggests adopting practices from the more established oil and gas industry [8]. Proposed adaptations include providing accommodations on vessels for extended shifts, akin to oil and gas practices.

It is recommended that shift workers, who work at night, work the same shift pattern for at least 7 days in a row so as not to disrupt their circadian rhythm, as it is thought to cause health issues stemming from insufficient sleep [9]. Research has shown that it takes 5-6 days for a worker to adapt to working night shifts. A disruption to circadian rhythm along with working for over 48 hours a week for onshore workers leads to an increase risk in road accidents [10]. Another study compares risk aspects between oil and gas and OW, highlighting higher risk in OW due to personnel transfers via boats [11].

Technician welfare is considered in studies, like the SPOWTT project [12], optimising transit safety and productivity. Another study [13] employs machine learning to factor in technician welfare when making dispatch decisions based on sea sickness indicators. A physical demand study compares offshore and onshore technicians, concluding that OW work demands more physically but not excessively compared to other blue-collar jobs [14].

The literature emphasises the need for enhanced consideration of technician welfare in future operations and maintenance strategies. A regulatory framework addressing safety risks, especially during night shifts, is crucial. Longer rotations, such as 14 days on, 14 days off, may mitigate sleep disruption risks, but challenges persist during the initial adjustment period.

1.2. Motivation

This study explores the impact of daylight limitations on OW farm O&M costs, with a focus on varying site locations. Specifically, it investigates how O&M costs are affected by daylight duration differences, particularly between the North Sea and locations closer to the equator. Additionally, the study assesses whether the introduction of a night shift to the wind farm alleviates O&M costs and to what extent.

The motivation behind this research is twofold. Firstly, the expansion of OW energy has meant that new locations and sites in development have not yet had extensive research done on their operations and maintenance for the simple reason that the projects are still at early stages. Secondly, the study addresses a gap in existing literature by specifically examining daylight limitations in Australia and the East Coast of the USA. Previous research on night shift work has focused on the North Sea and oil and gas industry practices, but none have conducted a comparative study on daylight hours and visibility across sites. The rest of the paper is as follows: Section 2 outlines the methodology, Section 3 analyses and discusses results from the model, Section 4 concludes and suggests future work.

2. Methodology

The following section details the methodology utilised to determine the effects of daylight limitations. Firstly, the origin and nature of the data used will be discussed and then the site specifics for each of the locations. After which, the O&M model will be described in terms of it's functionality and then the inputs chosen for the simulations and the outputs that can be obtained from the simulations.

2.1. Climate data and site location

To model OW farm operations and maintenance, climate data, specifically wind speed and significant wave height, is crucial for simulations over the farm's lifetime. Wind speed data is used to create time series simulations at sea level and hub height, influencing vessel limitations and energy production calculations for overall O&M cost. Significant wave height determines vessel transfer limits to the wind farm. This study examined three case studies: the North Sea, East Coast USA, and Darwin, Australia. North Sea, known for high wind speeds and shallow waters, used FINO data spanning 6 years [15]. East Coast USA data, from Martha's Vineyard Coastal Observatory [16], covered 18 months. The choice of location is based on recent interest in developing the OW sector in the region. Lastly, the third choice is Darwin, Australia. Despite

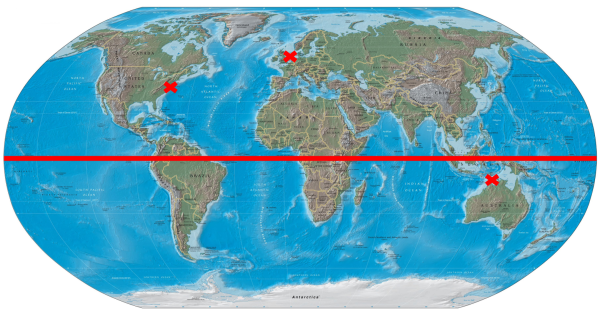


Figure 1: Diagram of the site locations selected across the globe, the red crosses represent the site location and the red line represents the equator.

not being a prominent site for OW development, Australia has shown significant interest in establishing projects in Victoria and New South Wales. Darwin was chosen for this study due to existing oil and gas port facilities, which can be repurposed for OW projects. The selection considers the similarity in requirements for large vessel ports between the oil and gas industry and OW. While other Australian regions also have suitable ports, Darwin's proximity to the equator is a distinguishing factor. The study's goal is to assess daylight limitations, making it crucial to choose sites at varying distances from the equator to understand the impact on O&M costs. Climate data for Darwin is sourced from the ERA5 reanalysis database [17], with the site located 50km from the shore for consistency with the other wind farm sites. The dataset includes hourly measurements of wind speeds at 10m and 100m heights, as well as significant wave heights, spanning four years. Figure 1 shows the site locations marked by the red crosses on the globe. The bold red line indicates the equator.

2.2. O&M Model

With site selection and climate data selected, the model can simulate the wind farm operations. The model used is the industrial bench-marked Strathclyde OW Operations and Maintenance tool. The function of the model is to simulate the operations of a wind farm over it's lifetime through the simulation of weather, wind turbine failure and maintenance schedules considering resources time based availability . The user must enter a range of required inputs including climate data, failure data, transportation information, costs, resources and wind farm specifics. The model uses Monte Carlo simulations to simulate failures in the wind farm which triggers maintenance to occur. Once the failure has occurred, the transport vessel which has been assigned to that specific failure mode is deployed. This is based on a number of conditions. Firstly, the number of required technicians for the repair must be available for the transfer, if they are occupied with another task then the turbine will remain down. If the weather exceeds the vessel limits for the vessel assigned to the task during the repair window then the vessel is not deployed and technicians will remain at port until a suitable weather time is available. Once the operations simulation is complete, several outputs are calculated for the wind farm, including power production, wind farm time based availability , vessel utilisation, repair specifics and cost breakdowns. Detailed information into the model can be found in [18, 19, 20]. The number of simulations is set to 100 resulting in 0.022% convergence of the output. The wind farm lifetime is set to 20 years, a conservative value based off the industry estimate that wind farm lifetime may be extended to 25-30 years [21]. Failure rates are taken from [22], the turbine used is a 3 MW direct drive wind turbine. The vessel that will be utilised for night shift is based on a CTV Catamaran boat that has the capacity for 6 technicians. The day shift will assume that there are 5 operational CTV's that can be utilised for maintenance. The night shift analysis assumes that the same number of CTV's in the day shift are available for night shift. A short sensitivity analysis will be completed surrounding this assumption. The transport inputs are displayed in Table 1. These values are based on the vessel specifications. Charter rates and mobilisation times are obtained from previous literature [23]. Note that the Jack Up also has a lifting capacity limit of 12 m/s.

The main outputs from the simulations are the total O&M costs in £/MWhr, power produced in MWhr, time based availability in % and direct O&M costs in £/MWhr. The difference between total and direct costs is that direct costs only looks at the staff (C_s), repair (C_r), fixed (C_f) and transport costs (C_t) whereas that total O&M costs considers lost revenue (C_{lr}) as well. The repair costs (C_r) are the sum of the costs for each component and associated failure mode. These are based on the average number of yearly failures simulated for each subsystem multiplied by the cost to repair the component multiplied by the lifetime of the wind farm and the number of turbines in the farm. The transport costs (C_t) are the sum of the costs for vessels used on the wind farm. These costs include charter rates, mobilisation rates, fuel consumption and hire costs based on the calculated utilisation of the vessel within the simulation. The lost revenue costs (C_{lr}) is the calculated wholesale value of lost electricity revenue as a result of turbine downtime over the wind farm lifetime. The staff costs (C_s) are the sum of technician costs based on the salary for permanent technicians and the total pool of technicians available throughout the lifetime of the windfarm. The fixed costs (C_f) are the sum of any port or insurance costs for the wind farm during it's lifetime.

The variables changed across the sites will be the climate data, coordinates of the wind farm, the port and the local offset, which is utilised to calculate the amount of daylight hours available throughout the year. Within the site case studies, the input that is varied is daylight limitation. The model has the functionality to simulate three different daylight scenarios: 'Daylight Not Limited', 'Daylight Limited' and 'Night Shift'. 'Daylight Limited' means that, regardless of how long is left of the 12 hour shift (8am-8pm), if it is dark then maintenance cannot be carried out. The measure of when daylight is limited and maintenance cannot be carried out is based on the model calculating the sunrise and sunset times of a specified location at a specific period in the year, it accounts for one extra hour of daylight to allow 30 minutes for sunset or 'dusk' and 30 minutes for sunrise or 'dawn'. The code also captures the +1 hour summer time between 'last Sunday of March 01:00:00' and 'last Sunday of October 01:00:00'. The maintenance decision also takes into account the length of the maintenance activity required, the time taken to reach the turbine and the time to transfer from the vessel to the turbine. If the sun sets before the full maintenance task can be completed then the task must wait until the next available weather window, daylight dependent. 'Daylight Not Limited' means that the 8am-8pm shift is carried out regardless of visibility but there is no night shift work. Finally, 'Night Shift' means the 8am-8pm shift is carried out followed by another 12 hour shift in which night technicians and night CTV's are used.

Table 1: Vessel inputs to the model

Input	CTV	SOV	Jack-up
Significant wave height limit (m)	1.5	3	4
Wind speed limit (m/s) at 10m	12	12	36
Fuel consumption (m^3/hr)	0.24	0.3	0.55
Charter rate (£/day)	1980	9500	360,000
Mobilisation time (days)	N/A	30	60

If either of the first two options are selected for the simulations then the vessel inputs required are all for day time vessels with associated technicians. If the last option is chosen then inputs must include the number of vessels on the night shift and how many technicians are available. All other inputs to the model are held constant across the different sites so the analysis will only focus on the impact daylight has on the O&M costs.

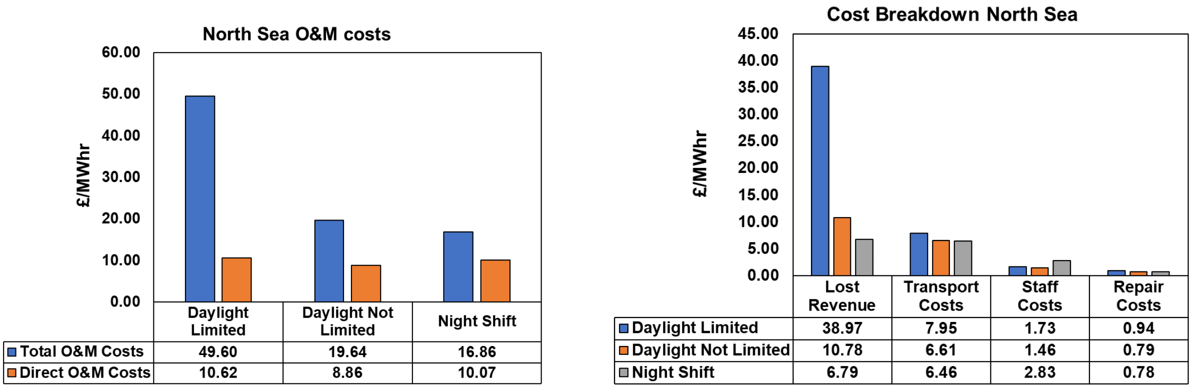
2.3. Assumptions and limitations in the model

The night shift workers are paid the same amount as the day shift workers. In reality, the pay for technicians will vary depending on the experience of the worker, the work that is being carried out and the time of day the work is being completed. The assumption to keep costs the same is seen as a conservative approach. For these simulations, the amount chosen was £40,000 per year based on industry estimates. The turbine used throughout simulations is the same and is not tailored to the climate of each site. For Australia and USA, it is likely turbines will be constructed to compliment the climate conditions of the site, so this could cause some under/overestimation in the total energy production by the turbines. To limit the variability of results, a fixed electricity price of £140/kWhr was utilised, when in reality each market is different and is dynamic over time. Limiting the scope of the study, is the lack of field data available for failure rates for larger turbines. The paper is restricted to using a smaller turbine of 3 MW as it has complete failure data. Finally, the metocean data for each site is different in order to capture the features of the different locations. While important for individualising the case studies, the different metocean conditions impact the results along with the daylight conditions of the site.

3. Results and discussion

3.1. North Sea

The North Sea data was simulated for three different scenarios, Figure 2a shows the direct and total O&M costs for each of these. Notably, the total O&M costs when daylight is a limiting factor are over double the total O&M costs of the two other scenarios. Looking at the direct costs across the three maintenance strategies, they are closer in range, indicating that lost revenue is contributing to the high total O&M costs for the limited by daylight scenario. This is highlighted in the breakdown of costs in Figure 2b. Aside from the lost revenue differences, it is noted that repair costs are similar, the staff costs are higher for night shift and the transport costs are highest for the limited daylight case. Higher transport costs for the limited by daylight scenario may be a result of maintenance not being completed during the day and extra charter costs incurred by having to go back and complete the maintenance the next day. Lost revenue



(a) (b)

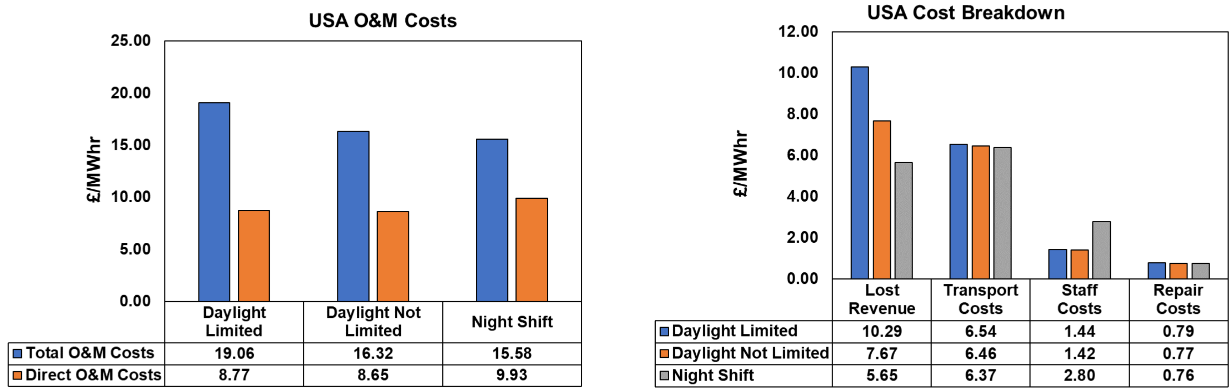
Figure 2: (a) Cost overview for the North Sea simulations (b) Breakdown of costs for the North Sea simulations

costs are driven by increased turbine downtime where maintenance has not been carried out to get turbines generating power again. For the limited daylight scenario, the available weather windows for crew transfers are reduced and accessibility is limited. Coupled with this, metocean conditions in the North Sea can reduce the amount of weather windows for maintenance to be carried out. These two factors result in high lost revenue costs. The night shift has the lowest total O&M costs as the opportunity to complete maintenance is higher so turbines will not experience as much downtime.

3.2. USA

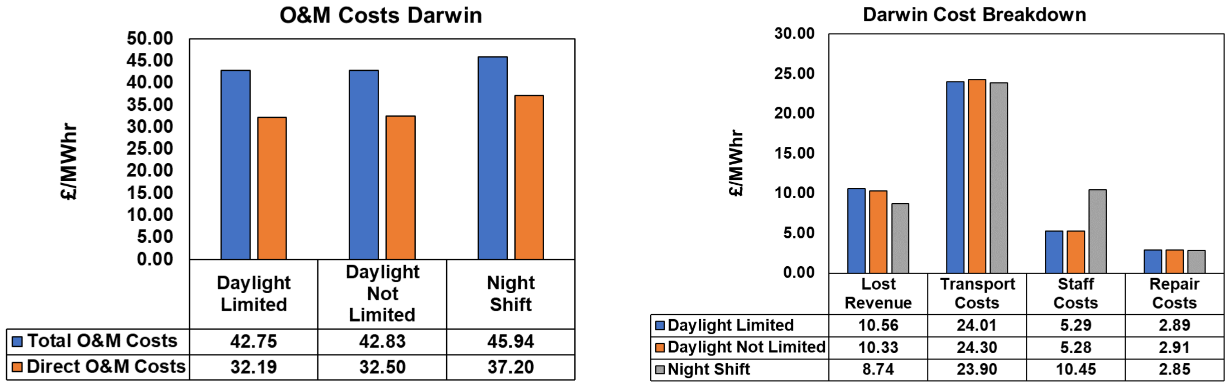
Using the same method, the US simulations were completed, the costs can be shown in Figure 3a. Similar to the North Sea, the highest total O&M cost is for the limited by daylight scenario but the difference between costs across the scenarios is a lot smaller. The night shift has the highest direct costs but not by a large margin. At this site, the difference in costs between the night shift strategy and the daylight not limited strategy is smaller than that seen in the North Sea. This means the US site has higher accessibility, due to met ocean conditions not breaching vessel limitations as frequently, resulting in larger weather windows for maintenance to be complete.

Figure 3b shows the breakdown of the costs for the US scenarios. The slightly higher direct costs for night shift are predominantly driven by the increase in staff costs. Despite the staff costs, for the total O&M costs, the night shift is the lowest as the lost revenue contribution is considerably lower due to the increase of available time to complete maintenance. The highest total O&M cost is when daylight is limited. Again, lost revenue is the prime driver of increased costs as the window of opportunity to complete maintenance is reduced. Although the difference in cost is high between the night shift scenario and the limited daylight scenario, it is important to note that the difference in cost is much lower than that what was simulated for the North Sea wind farm. As mentioned previously, this could be related to met ocean conditions being



(a) (b)

Figure 3: (a) Cost overview for East Coast US simulations (b) Breakdown of costs for East Coast USA simulations



(a) (b)

Figure 4: (a) Cost overview for Darwin Australia simulations (b) Breakdown of costs for Darwin Australia simulations

calmer, but for the daylight limited case, it could also be related to the fact that there are more daylight hours at this site so weather windows are increased.

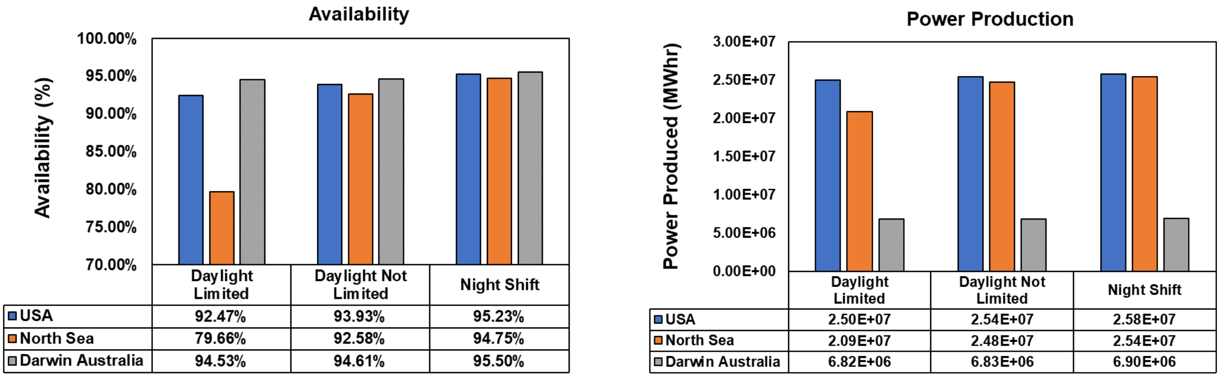
3.3. Australia

In Figure 4a and Figure 4b, the Australia case study results are presented. Total and direct O&M costs for Darwin are significantly higher than the North Sea and US, attributed to the lower wind resource with average speeds of around 4 m/s. Despite the absolute cost difference, the study focuses on the relative distinctions between scenarios. The night shift exhibits the highest total and direct costs, emphasising that lost revenue is not the primary cost driver at this site.

In Figure 4b, transport costs are notably higher than other contributing costs. While transport expenditures remain consistent across all sites, the elevated cost per MWh produced is attributed to lower power production in Darwin. Staff and fixed costs are affected by the lower power production but remain comparatively lower. Examining cost breakdowns, lost revenue costs are lowest for the night shift, indicating increased accessibility. Daylight limited has the highest lost revenue cost but the daylight not limited scenario is very similar in cost indicating that the site location has higher accessibility. This could be a combination of calmer metocean conditions, due to lower wind speeds in the area, but also the increase daylight hours. In fact, the two scenarios having almost the same cost indicates that daylight hours are increased to a point where an 8am-8pm shift is rarely limited by there being no daylight.

Transport and repair costs show minimal differences across scenarios. The most significant disparity arises from staff costs, doubling in the night shift compared to daylight scenarios due to the larger number of technicians. This increase is consistent across all site locations but has a more pronounced impact in Darwin.

3.4. Comparison



(a) (b)

Figure 5: Comparison of each wind farm location in terms of (a) Total time based availability (b) Power production.

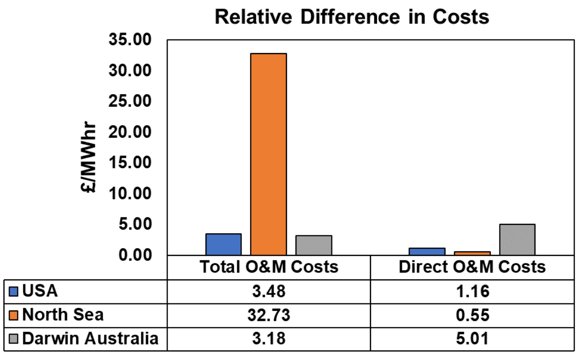
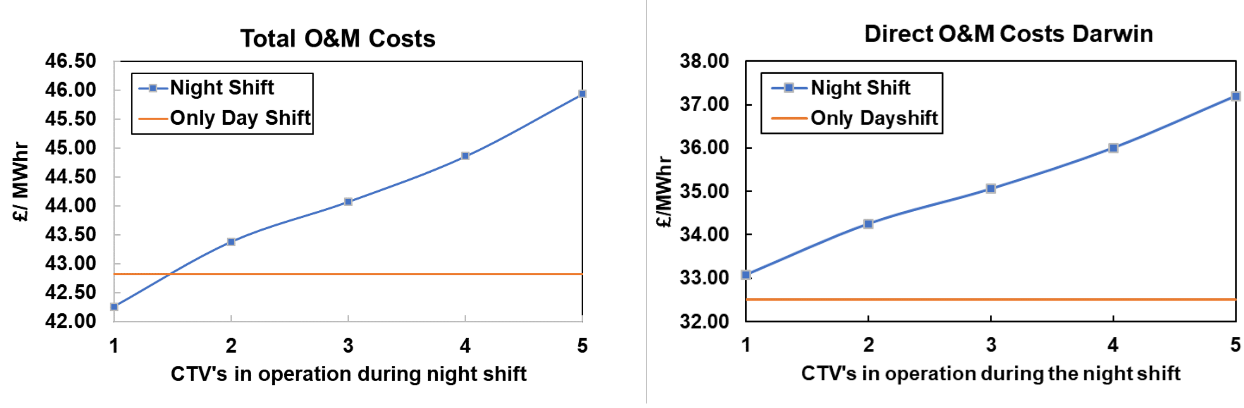


Figure 6: The relative difference in cost in £/MWhr between the night shift strategy and the daylight limited maintenance strategy is calculated for each site location.

To compare the three site locations, the study analyses the relative difference in cost across scenarios rather than determining the best overall site. Firstly, Figures 5a and 5b illustrate the time based availability and power production of each location. The North Sea wind farm has the lowest time based availability among the three sites, particularly in the daylight-limited scenario, where time based availability is only 79%, leading to high lost revenue costs. Overall, Darwin has higher time based availability but significantly lower power production due to its low wind resource and calmer climate compared to the US and North Sea.

Figure 6 depicts the overall relative difference in costs between different locations, calculated by determining the absolute difference in cost between the night shift and daylight-limited scenarios. The North Sea exhibits the largest relative difference in total O&M costs, around 10 times more than the US or Australia. However, in terms of direct costs, Darwin shows the greatest relative difference, primarily driven by high staff costs. The impact of changing the number of technicians during the night shift on total O&M costs is investigated in Subsection 3.5. One of the main conclusions that can be drawn from these results is that the night shift for Darwin would be a negative addition to the O&M strategy as the high staff costs incurred outweigh the reduction in the lost revenue costs.

3.5. Sensitivity around number of CTV's



(a) (b)

Figure 7: Sensitivity analysis of (a) Total O&M Costs and (b) Direct O&M Costs for Darwin Australia

In these simulations, the assumption is that the number of technicians remains constant between day and night shifts. Australia's results highlight that staff costs significantly contribute to higher night shift costs. A sensitivity analysis for the number of technicians during the night shift is performed, shown in Figure 7a and Figure 7b.

The orange line in both graphs represents the cost of the day shift at the Darwin wind farm with 5 CTVs and 6 technicians per CTV. For Darwin, total costs for only having a day shift are lower than having both a day and night shift costs when 2-5 CTVs operate during the night shift. The night shift becomes cost-effective only when one CTV is in operation at night. Direct O&M costs are consistently higher for night shift simulations.

4. Conclusion

This study delves into the influence of daylight limitations on OW O&M costs across three global wind farm sites. Employing three maintenance strategies— daylight limited, daylight not limited and night shift scenarios—the study evaluates their economic viability. Notably, the North Sea site exhibited a £32.74/MWhr reduction in costs under the night shift strategy compared to the daylight-limited scenario. Conversely, the US site saw a £3.48/MWhr reduction, while the Darwin site experienced a £3.19/MWhr increase in costs with the night shift. The variance in results highlights the critical role of location and daylight hours in determining the need for night shift maintenance. Furthermore, the study highlights possible health and safety risks associated with night shift work and its impact on technician welfare, a domain largely unexplored compared to the more extensively studied oil and gas industry. Quantifying and analysing these health and safety risks is a potential avenue for future work. The study emphasises the necessity of conducting a case-by-case cost-benefit analysis when considering the implementation of a night shift. O&M operators must carefully weigh the potential reduction in costs against the increased health and safety risks associated with night shift, including fatigue and reduced visibility. The decision-making process should involve evaluating mitigation strategies to address declining technician welfare and increased safety risks during night shifts. The industry's development depends on the well-being of its workforce, necessitating ongoing efforts to enhance safety measures and address welfare concerns for both day and night shift operations in OW.

References

[1] Díaz H, Guedes Soares C. Review of the current status, technology and future trends of offshore wind farms. Ocean Engineering. 2020;209:107381.
[2] Akhtar N, Geyer B, Schrum C. Impacts of accelerating deployment of offshore windfarms on near-surface climate. Scientific reports. 2022;12(1):18307.
[3] Tusar MIH, Sarker BR. Maintenance cost minimization models for offshore wind farms: A systematic and critical review. International Journal of Energy Research. 2022;46(4):3739-65. Available from: https://onlinelibrary.wiley.com/doi/abs/10.1002/er.7425.
[4] Martini M, Guanche R, Losada IJ, Vidal C. Accessibility assessment for operation and maintenance of offshore wind farms in the North Sea. Wind Energy. 2017;20(4):637-56.
[5] Dalgic Y, Dinwoodie I, Lazakis I, Mcmillan D, Revie M. The Influence of Multiple Working Shifts for Offshore Wind Farm OM Activities – Strathow-OM Tool; 2015. .
[6] Anderson F, McMillan D, Dawid R, Garcia Cava D. A Bayesian hierarchical assessment of night shift working for offshore wind farms. Wind Energy. 2023;26(4):402-21.
[7] G+. Good Practice Guidelines The safe management of small service vessels used in the offshore wind industry. 2022.
[8] offshoreWIND biz. Denmark: Wind Energy Update Releases Offshore Wind Health and Safety Information Pack. 2012.
[9] Gibbs M, Hampton S, Morgan L, Arendt J. Adaptation of the circadian rhythm of 6-sulphatoxymelatonin to a shift schedule of seven nights followed by seven days in offshore oil installation workers. Neuroscience Letters. 2002;325(2):91-4.
[10] Parkes KR. Shift schedules on North Sea oil/gas installations: A systematic review of their impact on performance, safety and health. Safety Science. 2012;50(7):1636-51.
[11] Wifa E, Hunter TS. Mitigating occupational health and safety risks in the proposed Australian offshore wind energy industry: lessons from the safety case regime. Journal of Energy & Natural Resources Law. 2022;40(1):83-104.
[12] Earle F, Huddlestone J, Williams T, Stock-Williams C, van der Mijle-Meijer H, de Vries L, et al. SPOWTT: Improving the safety and productivity of offshore wind technician transit. Wind Energy. 2022;25(1):34-51.
[13] Uzuegbunam TD, Forster R, Williams T. Assessing the Welfare of Technicians during Transits to Offshore Wind Farms. Vibration. 2023;6(2):434-48.
[14] Oestergaard AS, Gupta N, Smidt TF, Sandal LF, Søgaard K. The objectively measured physical work demands and physical capacity of offshore wind technicians: An observational field study. Applied Ergonomics. 2022;102:103716.
[15] Bundesamt für Seeschifffahrt und Hydrographie. FINO Database Information. Available at www.bsh.de/EN/TOPICS/Monitoring_systems/MARNET_monitoring_network/FINO/fino_node.html, accessed February 2023.
[16] Observatory MVC. Martha's Vineyard Coastal Observatory Data;. Available at https://mvco.whoi.edu/ accessed February 2023.
[17] Copernicus, European Commission, ECMWF. ERA5 Reanalysis Data for Darwin Australia;. Available at https://climate.copernicus.eu/climate-reanalysis, accessed May 2023.
[18] Dinwoodie I, McMillan D, Revie M, Lazakis I, Dalgic Y. Development of a Combined Operational and Strategic Decision Support Model for Offshore Wind. Energy Procedia. 2013;35:157-66. DeepWind'2013 – Selected papers from 10th Deep Sea Offshore Wind RD Conference, Trondheim, Norway, 24 – 25 January 2013.

[19] Dinwoodie I, Endrerud OE, Hofmann M, Martin R, Sperstad I. Reference cases for verification of operation and maintenance simulation models for offshore wind farms. Wind Engineering. 2015 Feb;39(1):1-14.

[20] Dinwoodie IA, McMillan D. Operational strategies for offshore wind turbines to mitigate failure rate uncertainty on operational costs and revenue. IET Renewable Power Generation. 2014 May;8(4):359-66.

[21] Li C, Mogollón JM, Tukker A, Dong J, von Terzi D, Zhang C, et al. Future material requirements for global sustainable offshore wind energy development. Renewable and Sustainable Energy Reviews. 2022;164:112603.

[22] Carroll J, McDonald A, McMillan D. Failure rate, repair time and unscheduled O&M cost analysis of offshore wind turbines. Wind Energy. 2016;19(6):1107-19.

[23] Dalgic Y, Lazakis I, Dinwoodie I, McMillan D, Revie M. Advanced logistics planning for offshore wind farm operation and maintenance activities. Ocean Engineering. 2015;101:211-26.