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Operational strategies for offshore wind turbines to mitigate failure rate uncertainty on operational costs and revenue.

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Abstract: Several operational strategies for offshore wind farms have been established and explored in order to improve understanding of operational costs with a focus on heavy lift vessel strategies. Additionally, an investigation into the uncertainty surrounding failure behaviour has been performed identifying the robustness of different strategies. Four operational strategies were considered; fix on fail, batch repair, annual charter and purchase. A range of failure rates have been explored identifying the key cost drivers and under which circumstances an operator would choose to adopt them. When failures are low, the fix on fail and batch strategies perform best and allow flexibility of operating strategy. When failures are high purchase becomes optimal and is least sensitive to increasing failure rate. Late life failure distributions based on mechanical and electrical component behaviour have been explored. Increased operating costs due to wear out failures have been quantified. An increase in minor failures principally increase lost revenue costs and can be mitigated by deploying increased maintenance resources. An increase in larger failures primarily increases vessel and repair costs. Adopting a purchase strategy can negate the vessel cost increase, however, significant cost increases are still observed. Maintenance actions requiring the use of heavy lift vessels, currently drive train components and blades are identified as critical for proactive maintenance to minimise overall maintenance costs.

1. Introduction

Worldwide offshore wind power has reached an installed capacity of 5GW, with a further 40GW in the construction, consenting or planning stages, primarily concentrated in the North Sea area [1]. This has been driven by a desire to capture the vast high wind speed offshore resource, the advent of multi-megawatt turbine designs and the remaining number of undeveloped locations suitable for commercial scale onshore wind farms decreasing. These benefits are offset by the current higher cost of offshore wind compared to onshore wind and conventional power generation sources [2]. A particular area of increased costs is the higher operating expenditure (OPEX) due to the remote location of sites, the greater dependency on wind and wave climate for any maintenance action and the dependency on expensive, specialist vessels to perform major component repair and replacement [3].

The majority of wind farms in operation or under construction are located within 10km of shore in water depths less than 20m and can be considered ‘near shore’[1]. This has allowed their operation to be carried out in a similar manner to onshore wind farms with 1-2 annual planned maintenance trips and corrective maintenance. Future sites will be further from shore, in deeper waters and more extreme climates resulting in this approach no longer being cost effective, there will therefore be a requirement to adopt alternative operational strategies. Additionally, there is a drive towards using next generation turbines in the 6-7MW range for many of the larger planned offshore wind farms in order to reduce capital expenditure (CAPEX), in particular foundation costs. If the failure performance of larger machines is consistent with smaller machines; there will be a corresponding reduction in OPEX due to the lower number of assets and associated maintenance actions for the same power production.

One of the key influences on OPEX and corresponding operational strategies is the failure behaviour of the wind turbine population in a wind farm. The direct use of historic onshore failure data is one solution to this lack of information but is problematic when considering offshore wind turbines. There is a lack of suitable onshore data with which to infer offshore performance due to the fundamental design difference between more modern machines and early wind turbines. There are a relatively low number of offshore turbines in operation and the commercial sensitivity surrounding their performance also limits data. This problem is heightened by the drive towards using a new generation of larger machines to reduce CAPEX. The result is a high degree of uncertainty in the middle to late life performance of the initial turbine population. The offshore operating climate is harsher therefore similar turbine designs onshore may behave significantly differently to those offshore. Finally, due to the access constraints and the associated costs, maintenance regimes for offshore wind turbines will be required to differ from the onshore case which will also contributes to different failure performance of offshore turbines.

Understanding OPEX costs is critical in both the planning stage and throughout the life cycle of the wind farm in order to minimise cost of energy (COE). During operation, information from condition monitoring and operating experience can be used to optimize maintenance actions. In addition, improved understanding of the root cause of failures and improved maintenance practice will potentially reduce the failure rate of turbines. However, several operational decisions such as resource procurement as well as critical project finance depend on accurately predicting the OPEX costs of a project as well as understanding how to best to control costs when there are inherent uncertainties. Modelling is therefore required to explore different future operational scenarios and provide this understanding.

A particular OPEX driver is the high costs and potential delays associated with the use of specialist vessels which are required for repair and replacement of major components, principally the blade, generator, gear box and main bearings. Major repairs and replacement of these subsystems requires the use of specialist vessels with high CAPEX and day rate costs. An example of such a vessel is shown in Figure 1.

Figure 1: Example of a jack-up vessel being used for offshore wind turbine maintenance [4].

Due to the high vessel costs associated with failures of this type it is necessary to explore various potential operating strategies. This allows the identification of strategies that minimise cost, uncertainty and exposure to external cost influences or a combination of all these criteria. This study builds on previous analysis [5] of offshore heavy lift vessel strategies in order to provide greater understanding of the circumstances under which different strategies are optimum and the key cost drivers associated with each approach.

The secondary focus of this study is to explore the different failure scenarios that are likely to be observed in the offshore wind industry and understand the impact these scenarios will have on OPEX costs and lost revenue. Operational strategies for different failure scenarios that mitigate the increase in operational costs are also evaluated along with the financial case for proactive maintenance strategies that avoid increasing failure behaviour.

2. Methodology

Several models related to the field focussing on different aspects of offshore wind O&M with varying degrees of complexity have been developed and are summarised in [6]. Previous academic models in the field have principally adopted two approaches. Simplified simulation approaches and direct analytical methods [7-13] are more computationally efficient but do not allow interactions from complex operational decisions such as maintenance strategies to be modelled. For this study a more complex simulation approach is applied in order to explore the different operational strategies and uncertain behaviour under future scenarios where higher late life failures are observed. This approach requires a wind and wave climate time series with which to determine power produced and the ability to perform maintenance actions. This can be performed using historical climate data at a site however due to the high cost and time required to obtain a sufficiently long time series, a climate model has been used to produce synthetic time series that preserve key site characteristics.

2.1 Climate Model

The synthetic wind speed and significant wave height time series are generated using a Multivariate Auto-Regressive (MAR) model, shown in (1) normalized by the mean of the data μ where X_t is the simulated data at time step t, φ is the auto-regressive co-efficient, p is the model order and E is a random noise covariance matrix [14].

$$X_t = \mu + \mathrm{E} + \sum_{i=1}^{p} \varphi_i (X_{t-i} - \mu) \qquad (1)$$

In order to apply (1) to a wind and wave climate a transformation must be applied in order that, the data set mean and variance are stationary and approximate a Gaussian distribution. For wind speed, removal of seasonality and diurnal variation has been shown to be appropriate [15]. For a significant wave height time series, Hs_t, it is necessary to apply the Box-Cox transformation described in (2) and (3) where the transformed data time series is Y_t, $\hat{\mu}$ represents a Fourier series fit of the seasonality observed in the transformed data [16].

$$Y_t = \ln(Hs_t) - \hat{\mu}_{\ln(Hs_t)}, \text{for } \Lambda = 0 \qquad (2)$$

$$Y_t = \frac{Hs_t^{\Lambda-1}}{\Lambda} - \hat{\mu}_{\frac{Hs_t^{\Lambda-1}}{\Lambda}}, \text{for } \Lambda > 0 \qquad (3)$$

Having transformed the data, (1) can be applied to both wind and wave climate data. The determination of AR coefficients and model generation is implemented using the arfit algorithm in MATLAB [17]. Order is chosen by optimizing Schwarz's Bayesian Criterion and coefficients are estimated using a stepwise least squares estimation process, both standard methodologies. Determination of appropriate Box-Cox transfer coefficient was determined using an iterative approach, minimising the error observed between data and simulation mean, variance and probability distribution. Seasonality is preserved by re-trending simulated wind time series directly and adding the seasonal component of (2) and (3) to simulated wave time series.

2.2 Operational models

The wind turbine system failure process is implemented using the methodology developed in [18]. The complete wind turbine is represented as a series of subsystems that can each exist in a discrete state at each simulation time step. The probability of moving from an operating state to a failed or reduced operating state is governed by the hazard rate h(t) which is defined as the probability of observing a failure in a specified time interval Δt. The hazard rate through the life cycle can be represented by (4) where the shape parameter β determines the gradient of the hazard rate and scale parameter ρ corresponds to the frequency of observed failures:

$$h(t) = \rho\beta t^{\beta-1}, \text{for } t \geq 0 \qquad (4)$$

At each time step a random number, R, in the interval 0 to 1 is generated and used to determine if a failure has occurred using the criteria in (5). There is a failure transition if:

$$R > (1 - h(t)) \cdot \frac{\Delta t}{8760} \quad (5)$$

Repair is then simulated based on the climate time series. If a turbine is in a failed state it will return to a working state when sufficient access time has been observed or when a series of repair actions have been performed corresponding to a completed maintenance action. In this study only complete failures and maintenance actions are considered, representing the ideal case.

Maintenance is carried out only when operating strategy supports it, there are sufficient resources available and the site is accessible based on the simulated climate. In the case of major repairs the entire repair action must be complete in a single window whereas routine maintenance and minor repairs can be performed cumulatively. Scheduled maintenance is performed in a specified time period of the year when resources are available but precedence is given to corrective maintenance. The state of each turbine is recorded in order to determine overall availability of the wind farm and tracked throughout the simulated life time.

2.3 Cost and availability calculations

Using the described climate and operation models lifetime O&M costs can be predicted. Total O&M (OPEX) costs are considered to comprise of lost revenue (LR), repair cost (RC), staff cost (SC) and vessel cost (VC) in (6) – (13).

$$OPEX = LR + RC + SC + VC \quad (6)$$

Lost revenue is determined from (7) where P(t) represents the power produced at each simulated wind speed time step, U(t) based on a 5MW wind turbine power curve p(t) with cut in speeds and cut out speeds U_{in} and U_{out}. Losses associated with electrical transmission and wind farm arrays are represented by efficiency coefficients, η_{farm} representing losses within the wind farm due to wakes and η_{elec} corresponding to export and inter array losses. The value of power produced, EP(t) defined in (8) is a combination of the market price (MP_{elec}) of electricity and value of current UK support mechanism (MP_{sup}).

$$P(t) = U(t) \cdot p(t) \cdot \eta_{farm} \cdot \eta_{elec}$$
$$\text{for } U_{in} < U(t) < U_{out}, \text{ else } P(t) = 0 \quad (7)$$

$$EP(t) = MP_{elec} \cdot P(t) + MP_{sup} \cdot P(t) \quad (8)$$

The lost revenue cost due to maintenance is calculated using availability, A(t) of the wind farm. This is defined as the number of operational turbines T_{on} divided by the total number of turbines, T_{total}, shown in (9). Lost revenue (LR) can therefore be calculated from (10).

$$A(t) = \frac{T_{on}(t)}{T_{total}} \quad (9)$$

$$LR = \sum (1 - A(t)) \cdot EP(t) \cdot T_{total} \quad (10)$$

Repair costs are calculated from (11) and are equal to the number of subsystem failures, F_n, multiplied by the cost of repair or replacement of the subsystem, FC_n, where n is the number of subsystems simulated.

$$RC = \sum_n F_n \cdot FC_n \quad (11)$$

Staff costs are calculated from the number of staff available and, S and annual salary of staff C_{staff} shown in (12).

Vessel costs are described in (13). Any vessels purchased or leased for the duration of the wind farm life are represented as one off CAPEX costs. In addition, an annual fixed charge, V_{fixed} associated with vessels that covers costs such as fleet maintenance and docking fees is specified. The variable vessel costs are calculated based on the duration of repair, R_n for each subsystem and the associated vessel day rate, D_{vess} and mobilization, M cost required.

$$VC = V_{CAPEX} + V_{fixed} + \sum_n (R_n \cdot D_{vess} + M) \quad (12)$$

2.4 Operational strategies

Discussion with operators established 4 initial operational strategies that were investigated over a range of wind farm sizes and major component failure rates. Four operational strategies were established:

- Fix on fail (FoF) - Charter vessel when fault is predicted or observed. Only pay for duration of the vessel charter however exposure to long mobilisation periods where the turbine will not be generating electricity.
- Batch repair - As FoF but operator does not go to spot market until a threshold number of failures have occurred. Reducing total number of charters but increasing exposure to lost revenue,
- Annual Charter - Short term (1-12) month yearly charter each year, failures falling outside the charter period do not receive maintenance until the start of the next charter period.
- Purchase - Purchase a vessel for the duration of the wind farm life

The advantages, weaknesses and critical cost influences associated with these strategies have been investigated in detail in order to provide greater clarity to developers and operators in the early stages of wind farm development and operation.

To model vessel costs under different contractual arrangements, expert knowledge has been applied to vessels currently operating in the North Sea that are suitable for offshore wind to estimate day rates depending on charter length. These are primarily derived from operational knowledge of the North Sea [4, 19] and values in [20, 21]. Figure 2 identifies the cost for vessels with varying capability under different operating contracts [22].

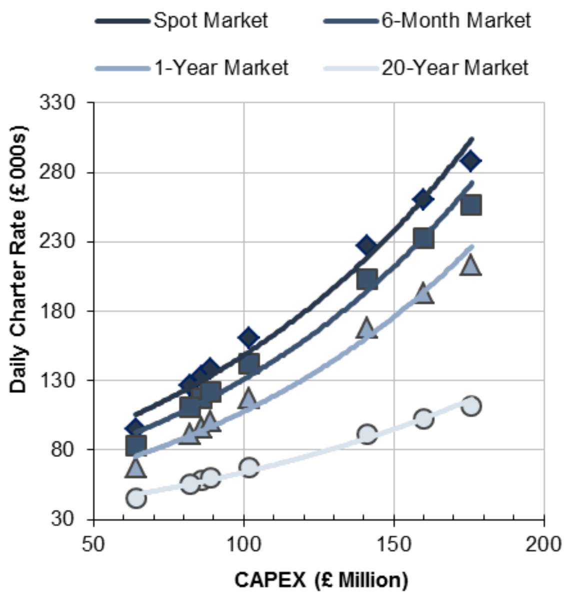

Figure 2: Vessel Day Rates under Different Operational Regimes

3. Failure behaviour of wind turbines

The failure behaviour of onshore turbines has been explored in detail and investigations into identifying the properties of the early life hazard rate in (4) have been performed [23]. However, due to the relative immaturity of the industry there is a lack of data from wind turbines in the later stages of design life; in the case of the offshore wind industry the data has not yet been generated. This is a particular concern for developers and operators of offshore wind farms as unlike early life, this region of the wind farm operation is not covered by warranty period. There is therefore a critical need to explore the consequences of increased late life failure and this can be done by simulation. The expected late life performance of wind turbines can be informed by the failure characteristics of classical electrical and mechanical components. Figure 3 shows classical late life failures for electrical and mechanical systems which exhibit differing late life trends [24].

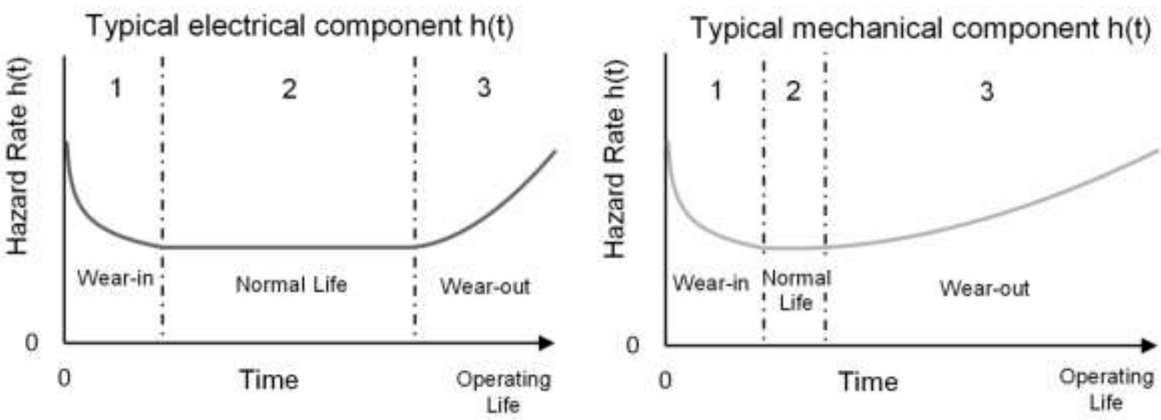

Figure 3: Hazard rate profiles of electrical and mechanical components

In both cases, the late life failure rate is typically observed to double or treble from the normal life failure rate. In electrical components the wear out period follows an extended normal life period before a wear out period with a sharply increasing hazard rate observed in the last third to quarter of the design life. In contrast the normal life observed in mechanical components is typically very short and a more prolonged, gradually increasing hazard rate wear out period is observed. In the case where the final observed failure rate has been reached following the two alternative profiles, the total observed failures over the lifetime duration following the mechanical failure behaviour will be greater.

Wind turbines have been assumed to follow the electrical component bathtub curve [20, 23]. However, the complex nature of the modern wind turbine means that this is unlikely to be observed for several of the large mechanical components such as the gear box, bearing and blades. These components have been observed onshore to fail rarely but with a large associated downtime. This problem is increased offshore where complex logistical operations are more complex, subject to harsher environments and require the use of specialist vessels.

An aspect of the bathtub not considered in detail in this study is the influence of maintenance actions on the population failure rate. In particular, major retrofits, addition of improved monitoring or more rigorous scheduled maintenance regimes may delay or remove the occurrence of wear-out. All of these actions have an associated cost to implement; the modelling approach and analysis in this study can determine the financial case for such maintenance actions. As a greater understanding of the lifetime failure behaviour is observed in operational offshore wind farms this will allow the optimal operating decisions to be made.

4. Baseline analysis of heavy lift strategies

The optimum strategy is driven principally by the number of wind turbines in a wind farm as well as the number of failures that require the use of specialist vessels. Using the failure charectristics and costs in Table I a series of cases were simulated under different charter regimes, the results are shown in Figure 4 [5].

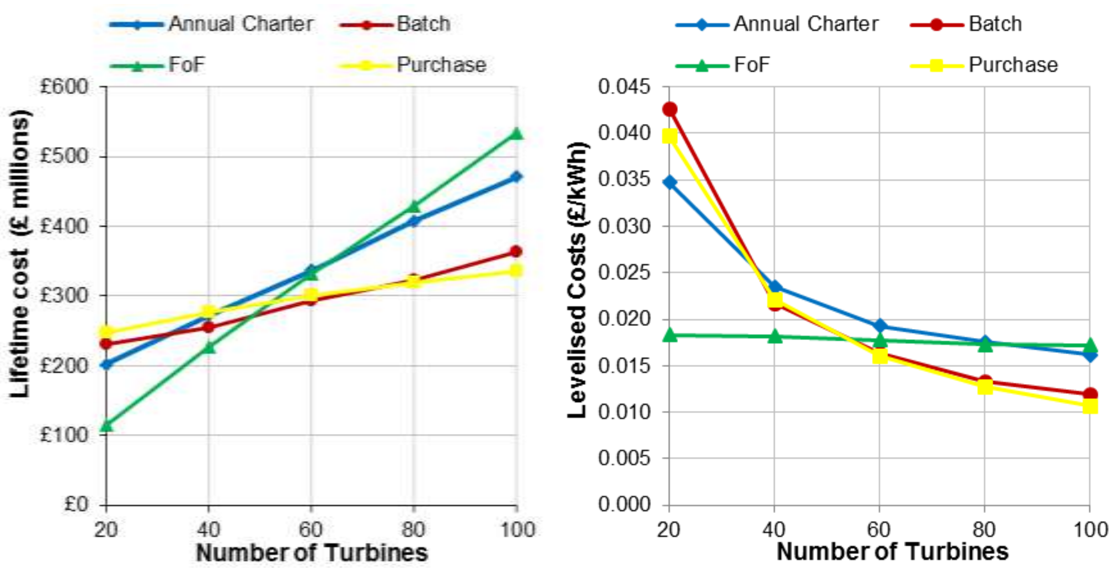

Figure 4: Absolute costs of strategies over a range of wind farm sizes and levelised Cost of Energy

Error! Reference source not found.shows how the sensitivity of strategies to wind farm size by absolute cost and costs per kWh power produced. Costs in this figure consider only direct vessel procurement costs and lost revenue due to downtime associated with chosen strategy. When failure rates requiring specialist vessels are equal to the major failure rate observed onshore of 0.2 per year [25] and wind farms have more than 60 turbines, a purchase strategy becomes optimum. Using a batch repair strategy can achieve similar costs but with greater variability and exposure to the future price of electricity. This result identifies that with current market conditions and historic onshore failure performance there is a strong economic case for purchasing a dedicated heavy lift vessel or adopting a batch repair approach. In order to determine if this result holds for a wider configuration of failure behaviour the sensitivity and key cost drivers associated with each strategy have been explored.

The failure values for the analysis in Figure 4 are derived from historic onshore failure behaviour and consider only two failure types, major and minor. More recent projects [26] and discussion with operators has identified that although the overall observed offshore failure rates have been higher than historic onshore failure rates, the number of failures requiring the use of heavy lift vessels is lower than the major failure rate observed offshore and improved design aims to reduce this value further for next generation turbines. It is necessary to consider various categories of failure depending on the repair consequence rate to accurately predict OPEX costs. Based on the performance of Egmond aan Zee Wind farm where the number of vessel operations in the first three years averaged 8 per turbine [27] and the analysis from [26] the following failure rates and corresponding repair action were defined for further analysis. Component costs were estimated based on weighted average of observed failures and costs from [28].

Table I: Failure characteristics

Failure type	**Scheduled Maintenance**	**Manual repair**	**Minor repair**	**Major repair**	**Major replacement**
Failure rate	1	5	2	0.25	0.067
Repair duration (hrs)	48	3	8	25	52
Vessel requirement	Crew Transfer (or Helicopter)	Crew Transfer (or Helicopter)	Crew Transfer (or Helicopter)	FSV (or large Helicopter)	Jack-Up
Day rate/ OPEX		£2500		£10 000	£150000 / £24000
CAPEX		N/A		N/A	£112.5 m
Number Available		5		1	1
Component Cost	£18500	£0	£2000	£75000	£450000

Each of the proposed strategies was investigated for a 75 turbine wind farm of 5MW machines [29] using climate data typical of the North Sea from [30]. The breakdown of cost contributions and the sensitivity to major replacement failure rates are shown in Figure 5 for each of the four strategies. Lost revenue values are based on 2013 UK offshore market conditions, staff wages are based on a cost of £80000 per maintenance personnel and wind farm efficiency of 81 % based on array losses and transmission losses.

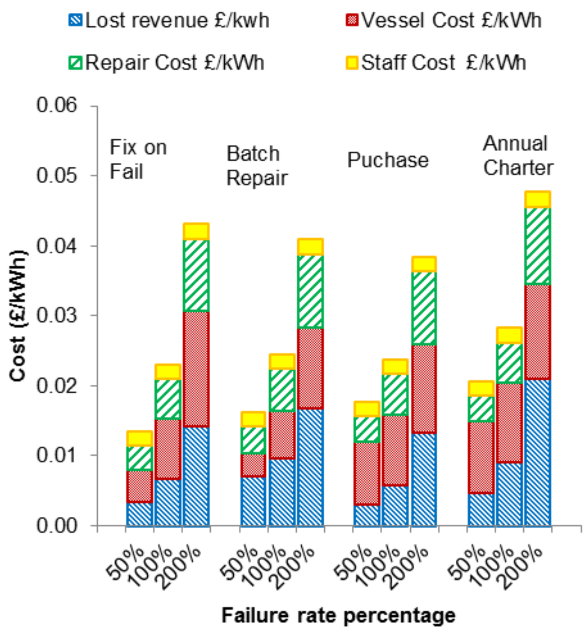

Figure 5: Breakdown of cost component and sensitivity to failures of operating strategies

For the expected failure performance, the reactive fix on fail and batch strategies as well as purchase strategy are within 5% of each other with the fix on fail OPEX costs marginally lowest. The fix on fail approach is most favourable when failure rates are lower than currently predicted with the batch and purchase strategies costing 17% and 24% more respectively. Scrutinising the reduced failure rate scenario it can be observed that the batch repair approach costs are driven by lost revenue whereas purchase costs principally comprise of vessel costs, the costs are shared with the fix on fail approach. These results may influence the operational strategy an operator would adopt as there may be preference to minimise risk to a particular external cost driver during operation. When the failure rate is greater than predicted the order of preference is reversed with purchase becoming optimum followed by batch repair and fix on fail which are 6% and 11% more expensive. The principal cost driver for the increase in fix on fail OPEX are vessel costs identifying the high cost associated with repeatedly chartering specialist vessels from the spot market. The annual charter strategy is 20%-30% more expensive under all scenarios and on a cost optimal approach would not be considered.

The strengths, weakness and key cost drivers for different strategies have been identified. The fix on fail strategy is demonstrated to be a cost effective approach when failure rates are low. In addition, this approach is highly flexible with no up-front costs and the ability to move to a different strategy with no penalty. If the vessel market becomes saturated and vessel day rates fall then adopting a fix on fail approach will allow an operator to take advantage of this situation. If there is scarcity of vessels and day rates increase it remains possible to adopt an annual charter type approach or commission a vessel for the remainder of the wind farm life. Finally, the approach benefits from spreading costs evenly between direct vessel costs and lost revenue. However, when failure rates are observed to be high the vessel costs associated with this strategy increase rapidly. Relying on the spot market for chartering vessels also exposes operators to volatile mobilisation times and costs which introduce a higher degree of uncertainty than other strategies.

The benefits of the batch repair strategy are consistent with the fix on fail approach with the added benefit of reducing exposure to the fluctuations of vessel market price and in particular the high costs associated with vessel mobilisation. Countering this is the added complexity of determining the optimum batch number to adopt and risk of adopting the wrong value which may change dynamically and requires operational experience. Also there is a potential for individual turbines remaining in a failed state for an unacceptable duration. In addition, if a strict batch approach is adopted then opportunities to perform maintenance in spring and summer months when accessibility is increased may be missed resulting in poorer overall availability. If the electricity price increases then this approach becomes less favourable.

Purchasing a heavy lift vessel adds a significant capital investment cost at the early stages of a project and may require the establishment of a vessel operations division which is outside the existing structure of a wind farm developer and operator. In addition if the failures observed are significantly lower than those predicted the purchase strategy is more expensive than others and cannot readily be changed. Countering these drawbacks the purchase approach is the most robust strategy to minimising OPEX when failure rates are high and allow the highest availability to be achieved, minimising lost revenue. It should also be noted that the financial penalty from overestimating failure rate and adopting a purchase strategy is less than that from underestimating failures and relying on the spot market. This makes the purchase strategy the most risk averse strategy if the initial financial cost can be tolerated. There is also the possibility of sub leasing the vessel if it is under used which mitigates some of the previously identified risk but this is not considered in this study. Alternatively, a lifetime charter with an external vessel operator will provide the protection from increased failures without the high CAPEX and infrastructure cost although the total lifetime vessel costs will increase under this scenario.

Annual charter strategy does display some favourable characteristics; principally the consistent vessel costs irrespective of failure behaviour allow accurate vessel cost estimation. A guaranteed contractual price covering the life of the wind farm would also be favourable as it offers protection from increases in the spot market and the length of the contract may allow reduction in the day rate currently assumed. In addition, as offshore maintenance practice improves, the required duration of repairs will decrease while accessibility will improve with future vessel designs. This will reduce the lost revenue, particularly if failure rate increases.

5. Late life failure scenarios and mitigation strategies

The late life failure behaviour has been investigated under several scenarios to explore the overall impact on OPEX cost and potential mitigation strategies. The scenarios and associated assumptions are described in Table II. In all cases the early life wear in failures are not considered as these have previously been the subject of previous studies and fall under the warranty period and therefore will not affect the long term OPEX costs for developers and operators.

Table II: Late life failure scenarios

Scenario (Number)	Scenario description
Baseline (1)	Baseline scenario where no late life failure is observed. This is the previously assumed failure scenario and provides a benchmark with which to determine the impact of late life failures and the financial benefit of mitigation strategies
Electrical wear-out x2 (2) and x3 (3)	Electrical bathtub curve wear out behaviour takes place over the final quarter of the wind farm life time. This is investigated at a final hazard rate equal to double and triple the normal hazard rate.
Mechanical wear-out x2 (4) and x3 (5)	Mechanical bathtub curve wear out behaviour takes place from one third of the wind farm life time. This is investigated at a final hazard rate equal to double and triple the normal hazard rate.
Electrical x3, minor failures only without	The failure behaviour associated with electrical failures principally relates to minor wind turbine failures that can be performed without the need for

(6) and with mitigation strategy (7)	specialist heavy lift vessel. Therefore the increased late life failure is applied only to crew transfer failures, in order to mitigate this failure behaviour increased vessel and maintenance staff are available at all times.
Mechanical x3, major failures only without (8) and with mitigation strategy (9)	The failure behaviour associated with mechanical failures principally relates to major wind turbine failures that require a heavy lift vessel. Therefore the increased late life failure is applied only to major failures, in order to mitigate this failure behaviour a heavy lift vessel is purchased and available throughout the duration of the wind farm life.

The resulting £/kWh lifetime OPEX costs of the described scenarios and the corresponding availabilities are shown in Figure 6. The breakdowns of lifetime costs are shown in Figure 7.

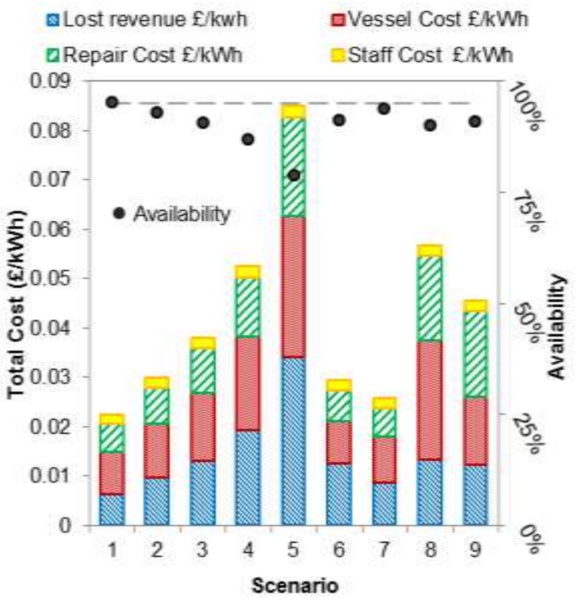

Figure 6: Lifetime cost and availability under different failure scenarios

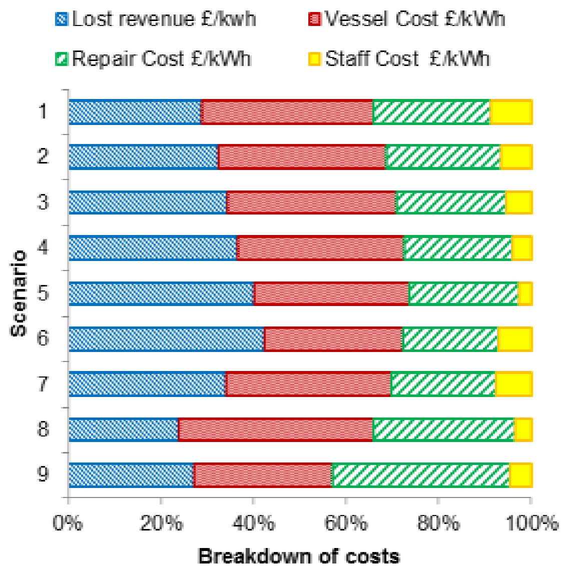

Figure 7: Lifetime cost breakdown under different scenarios

From Figure 6 and Figure 7 it can be observed that increased late life failure rates have the potential to significantly increase the lifetime OPEX costs for offshore wind farms as well as influence the key cost drivers that need to be controlled. The most severe scenario is represented by the mechanical failure behaviour in scenarios 4 and 5 leading to OPEX costs increases of 150% and 325% with large increases in lost revenue, vessel and repair costs. The increased costs under electrical bathtub failure behaviour results are principally driven by an increase in lost revenue as the total increase in failure occurrences are less despite reaching the same final hazard rate.

The influence of minor and major failures driving lost revenue can be identified by comparing scenarios 3 and 6 and also 5 and 8 which represent the extreme failure scenarios applied to both failure types and minor only (6) and major only (8). Large number of small failures increase lost revenue and critically reduce availability leading to a dramatic increase in £/kWh costs. Major failures have a lower impact on lost revenue and availability but high direct vessel and failure costs. Mitigating the impact of increased minor failures can be cost effectively achieved by increasing the number of vessels and maintenance staff available shown in scenarios 6 and 7 where the reduction in lost revenue and increased availability is greater than the additional costs incurred. Considering scenarios 8 and 9 the adoption of a purchase strategy reduces the impact of increased major failures. Increased lost revenue and vessel costs are limited but remain significant and the large cost associated with repairs become unacceptable. Therefore understanding the state of components and failure mechanisms that result in major repair and replacements are vital to controlling lifetime maintenance costs. There is a strong business case for active condition monitoring, inspection and preventative maintenance on these components. The specific value of such action and acceptable expenditure will depend on the configuration of the wind farm involved and can be determined using the prescribed modelling approach.

6. Conclusion and further work

The importance of considering the future costs of major maintenance actions for future offshore wind farms has been highlighted and a number of potential operating strategies identified and examined under a range of scenarios. A modelling framework to allow the sensitivity of operating strategies to be investigated has been developed and demonstrated, identifying where different strategies are optimal. The developed modelling methodology provides a clear insight into the strengths and weaknesses of different operational strategies as well as identifying where different strategies will be favourable. Minor failure rate principally drives lost revenue costs, high failure rates can be mitigated by deploying increased maintenance resources. Larger failures primarily increases vessel and repair costs, adopting a purchase strategy can negate the vessel cost increase and minimise lost revenue however significant cost increases are still observed. There is a strong business case for proactive maintenance of these subsystems in order to minimise overall maintenance costs.

Several areas of additional analysis have been identified for future work using the modelling approach described. The impact of turbine size and configuration, discounting rates and external price drivers have the potential to impact on optimum vessel strategy and will be considered in future work. Further quantification of the implementation and integration of asset management techniques and condition monitoring to perform predictive maintenance is also necessary.

Over the course of a wind farm life cycle, different operational strategies may present the optimal solution. A decision making support model allowing operators to determine the preferable strategy at different points throughout the project life cycle is therefore desirable to complement this modelling approach.

Very large future wind farms may require non-conventional operational strategies. The so called floating island concept where a permanently manned operations vessel may become cost effective under certain conditions such as when distances to port are sufficiently large or lost revenue costs overcome associated costs and downtime must be minimised. There is difficulty in accurately quantifying the costs associated of this approach as no such permanent maintenance vessel exists. In addition, how such a configuration would operate in practice and the degree to which downtime for both minor and major failures would be decreased is unknown but is an area requiring further research.

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