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Multi Rotor Wind Turbine Systems: An Exploration of Failure Rates and Failure Classification

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Abstract. The Multi-Rotor System (MRS) is a proposed solution to the increasing costs associated with the manufacture and maintenance of large single-rotor wind turbines. The MRS consists of many small rotors that can capture the same amount of energy as a large turbine but with the added benefits of standardization, reduced system loads, and improved reliability due to the redundancy of components and smaller size. However, modelling the operation and maintenance (O&M) of the MRS presents several challenges, including a lack of available failure data. This work aims to determine, what failure rate reduction, can MRS be competitive with equivalent single-rotor wind farms, using existing single-rotor turbine data as a baseline. The key failure components are identified through the use of a cost-based comparison parameter. Statistical and theoretical approaches are then used to analyse the impact of fatigue on failure rates for downscaled turbines, to determine if the required reduction in failure rate is feasible. Using a case study, the sensitivity of availability, operational expenditure, and lost revenue to failure rates is also determined.

1. Introduction

As the threat of climate emergency increases, there is a greater criticality in the need for the deployment of renewables. Offshore wind has proven not only to be feasible but also cost-effective. However, despite the success of offshore wind, the industry now faces a new set of challenges. As turbines increase in installed capacity, as does the size of components. At present, there is growing concern regarding the manufacturability, transportability and cost of materials of these growing assets [1]. The uptake of offshore wind has also placed additional demand on vessels, leading to an increase in charter costs [2]. One proposed solution for overcoming these challenges is the multi-rotor system (MRS) offshore wind turbine design [3] This concept aims to utilise the swept area of a single-rotor conventional turbine using multiple smaller rotors within the same structure. This concept design has several proposed advantages such as

- ***Logistical:*** the small scale of these components will increase the ease of transportation. The small scale of the components allows them to be transported by rail, road, or sea.
- ***Manufacturability:*** the smaller size also has manufacturability advantages as new facilities will not need to be created to deal with the increasing size of conventional turbine blades. Due to the volume of components required for a single system, it is expected that due to economies of

scale, the cost of individual components will decrease. In addition, an increase in components is expected to accelerate the learning curve process and potentially improve reliability.

- ***Scaling and Weight:*** MRS makes use of this disadvantage by exploiting rotors with a small volume to determine high energy yield over the same area, with a fraction of the weight [3].
- ***Vessel Utilisation:*** small component size would allow for all maintenance activities to be carried out by inexpensive crew transfer vessels (CTVs). The use of a permanent crane on site would also allow for the elimination of expensive jack-up vessels (JUVs).
- ***Environmental:*** material savings of the MRS design reduces waste. Smaller scale components also allow for more environmentally conscious materials to be used.

Operation and maintenance (O&M) can make up almost one-third of the total cost of energy for offshore wind [4], making it a key area for cost reduction. Therefore, it is important to consider the operability from the design stage for new concepts. Due to the unique design, the MRS allows for redundancy between rotors. Therefore, if a single rotor fails, only a percentage of the power output is lost, which decreases the criticality of repair as lost revenue is greatly decreased.

At present, specific failure data for MRS is unavailable. While the system will comprise, the same components used within a traditional single-rotor turbine, the number of components and the scale of the components will differ greatly. Previous work [5], supports the theory that individual components will have a reduced failure rate when compared to the equivalent single-rotor designs. The first part of this work utilises existing failure databases to determine at which failure rates MRS can become competitive with conventional single rotor. Section 2 introduces the ScotWind case study used within this work with details of failure rate classification and selected maintenance strategy. Section 3 uses a sensitivity analysis to determine the failure rates at which MRS will become competitive with equivalent single-rotor wind farms. This section also introduces the concepts of classification of the failure rates, due to the redundancy of the components

The second part of this work (Section 4) provides background as to why there is an expected decrease in failure rate in MRS components due to fatigue-related failure scaling, by, applying literature findings to the existing wind turbine failure databases. This is then compared against the baseline reduction in failure rates determined in Section 3. Finally, Section 5 concludes the work and makes recommendations for future research.

2. Case Study

ScotWind leasing zone E3, which was allocated 1GW in the 2022 leasing round, is selected as the location of the wind farm simulated within this study. This site is located 34 km off the coast of Aberdeen and will be maintained by a fleet of CTV's.

The full lifecycle of offshore wind farm maintenance operations is modelled using the Monte-Carlo-based simulation tool Strath-OW, which has been adapted to model MRS wind farms. The selected site was simulated at three increasing scales of deployment, 20MW, 500 MW and 1 GW. The design of the MRS used in this comparison is based on the work by Jamieson et al. [3], which consists of a 20 MW MRS design made up of 45 455 kW individual rotors. These turbines are used to make up the various scales of deployment stated above. The wind farms are then compared to an equivalent capacity wind farm consisting of single rotor 10 MW bottom fixed wind turbines. Power production and turbine design are based on the 10 MW NREL reference turbine [6].

2.1. Maintenance Strategy

This work models the impact of unscheduled failures and therefore does not consider a seasonal maintenance campaign. Due to the distance to shore, a crew transfer vessel (CTV) maintenance strategy is adopted for minor maintenance activities. Details of the vessel capabilities are defined in Table 2. This model adopts a fix-on-fail approach, where there is an immediate effort to repair a failed component as soon as a suitable weather window is available. The number of vessels within the maintenance fleet is optimised for each configuration, where the cost of transport is maximised to minimise the cost of lost revenue. This was performed through sensitivity analysis where vessel fleet size was gradually increased. The cost of transport never exceeds that of lost revenue due to downtime. It is assumed that spare parts are always available. Working hours are not daylight limited.

Table 1. Crew transfer vessel capabilities and model inputs

Vessel Speed (knots)	15
Hs Limit (m)	1.75
Charter Cost (£/day)	£3000

It is assumed that the MRS design has a dedicated crane at each structure for replacement operations, and therefore there is no requirement for an expensive JUV. It is expected that the baseline turbine will require a JUV for all major component replacement operations. For the selected components (Section 2.2), a proportion of all failures will be classed as major replacements. The proportion of major replacements is determined based on the failure rates and classifications from Carroll et al. [7].

2.2. Failure Baseline and Component Selection

The main issue surrounding MRS is the increase in the number of components required. An increase in components implies an increase in the overall number of failures. However, unlike with a conventional single-rotor machine, a failure does not mean the whole system is required to shut down. A single failure no longer has a detrimental impact on the downtime of the whole system. This approach removes the urgency of finding a suitable weather window and therefore could allow for a safer transfer.

A high number of components also means that OpEx simulations can be computationally expensive. Therefore, only a few key components are selected for this analysis. Using a component comparison parameter, the top six components were selected based on their total impact on wind farm operation, which considers both failure rate and total cost. The cost comparison parameter, inputs and methodology are given in Equation 1.

$$CCP = Failure\ rate \times \underbrace{Cost}_{Repair\ Cost\ +\ \underbrace{Lost\ Revenue}_{\frac{\pounds}{MWh} \times Power\ production \times \underbrace{Downtime}_{Waiting\ time\ +\ Time\ to\ Repair}}} \qquad \text{(Eq. 1)}$$

Dao et al. [8] presents an overview of relevant failure data for offshore wind. Using references [9-21] a distribution of the failure data for specific components can be determined. The third quartile (Q3) (see Dao et al. [8] for visualisation) of the failure data was selected as the baseline for this analysis, as this data point captures the majority of the existing datasets (75%). Q3 was selected to capture the majority of the dataset and still exclude outliers. The cost component consists of several parts:

- **Repair cost**: this was taken from Carroll et al. [7]. Due to the size of the components, it is assumed that the cost of MRS repair would equate to that of a minor repair in a single rotor system. For conventional turbines, the repair cost was a combination of major and minor repairs and replacements, based on contribution to the total failures.
- **Lost revenue**: the cost of lost revenue is determined based on the turbine's average hourly power output and the revenue. The revenue, in £/MWh, was selected as £50/MWh, in line with the UK Round 4 contract for the different strike price with adjustment for inflation.

- **Time to repair**: repair times for each failure type were taken from Carroll et al. [7] and adjusted for MRS based on the recommendations of McMorland et al. [5]

Due to a lack of downtime data in the literature, and its dependence on specific conditions at site, downtime is predicted using site-specific weather data using a statistical waiting time tool as used in Saeed et al. [22]. A summary of the waiting times for a range of weather window lengths from 4 hours to 60 hours is presented in Figure 1. Due to the distance to shore of 35 km, transfer time is assumed to be 2 hours. Weather data is taken from the centre point of the wind farm using ERA 5 dataset [23].

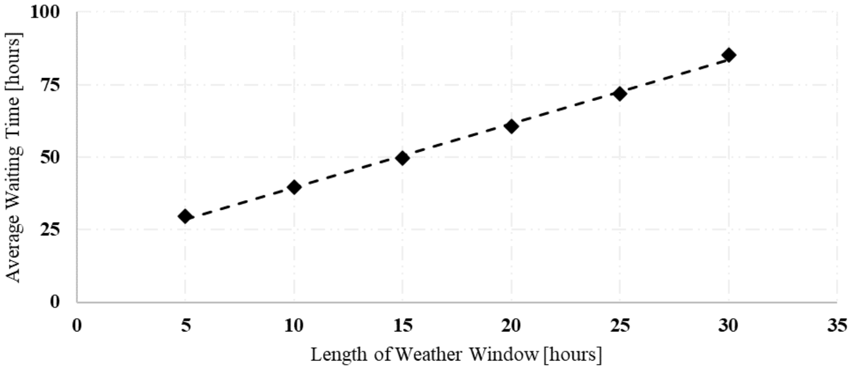

Figure 1. ScotWind Zone E3 average waiting time for suitable weather windows

Based on the results, blades and hub, pitch, generator, gearbox, electrical and control system were selected as the key components for this analysis. The failure rates are given in Table 2.

Table 2. Component failure rates

Blades & Hub	**Pitch**	**Generator**	**Gearbox**	**Electrical**	**Control**
0.15	0.42	0.24	0.18	0.252	0.72

3. Failure Sensitivity and Classification Baseline

The impact of failure rates is one of the key factors of determine the operational expenditure (OpEx) of an offshore wind farm. The reliability of each component is becoming increasingly significant as wind farm sites move further from shore and maintenance actions become more difficult to complete. There are not a lot of publicly available studies about the failure rates of wind turbines, mostly due to the competitive nature of the industry and the reluctance of manufacturers and wind farm operators to share operational data. As of 2019, only around 20 publicly available studies of wind farms in Europe, Asia and the U.S. are published [24].

While there has been some research into scaling failure rates [25-27], the MRS-specific challenges of downscaling failure rates go against the current upscaling trend. While, due to component size, it is expected that the failure rates will decrease, this is still a hypothesis.

This work utilises two techniques to determine failure rates for MRS using existing databases. The first uses sensitivity analysis to determine the failure rates at which MRS will become competitive with equivalent single-rotor wind farms (Section 3). This section also introduces the impact of redundancy and the concept of both global and local failures. The second technique (Section 4) examines failure strength fatigue scaling, by applying literature findings to the existing wind turbine failure databases.

3.1. Sensitivity Analysis

In order to determine the failure rates required for an MRS wind farm to become competitive with a single rotor equivalent, a sensitivity analysis was conducted to reduce the failure rates of the single components selected in Section 2.2

The total OpEx results as a factor of the single rotor comparative baseline simulations are given in Figure 2. The bars highlighted green indicate the point at which the MRS wind farm becomes competitive with the single rotor equivalent site, as shown subsequent Figures.

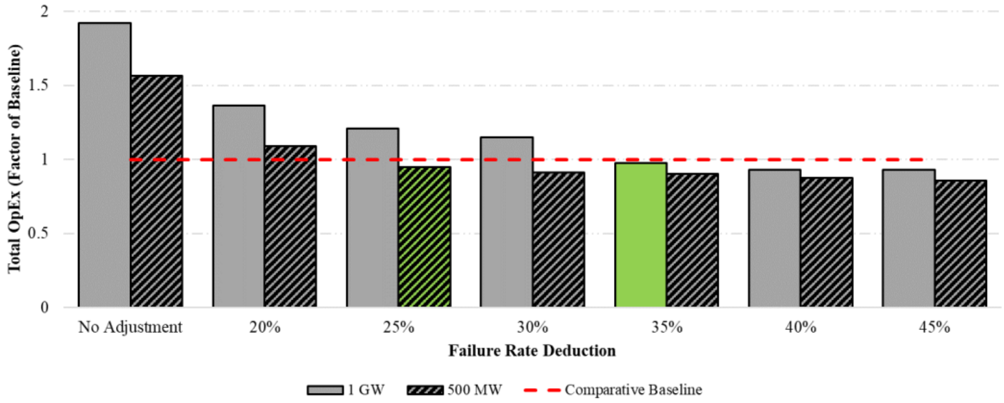

Figure 2. Failure rate reduction sensitivity analysis for 500MW and 1 GW scale wind farm

Within the sensitivity analysis, the 500 MW wind farm becomes cost-effective with a smaller reduction in failure rate, than that of the 1 GW scale site. The maintenance strategy for each simulation (500 MW and 1 GW with each set of failure rates), was optimised in terms of the number of vessels and technicians available to minimise lost revenue. However, increasing the number of vessels to reduce lost revenue, increased the total transportation cost.

Within this analysis, total annual OpEx is the summation of the cost of lost revenue, transportation, staff, repairs and fixed expenses such as port expenses and insurance. The reduction in failure rates saw a decrease in the cost of all expenses, apart from fixed costs. However, the reduction in lost revenue was most impacted, when compared against the baseline MRS lost revenue contribution. This reduction is displayed in Figure 3 for both the 500 MW and 1 GW MRS sites, comparing the reduction in non-fixed OpEx costs against failure rate reduction.

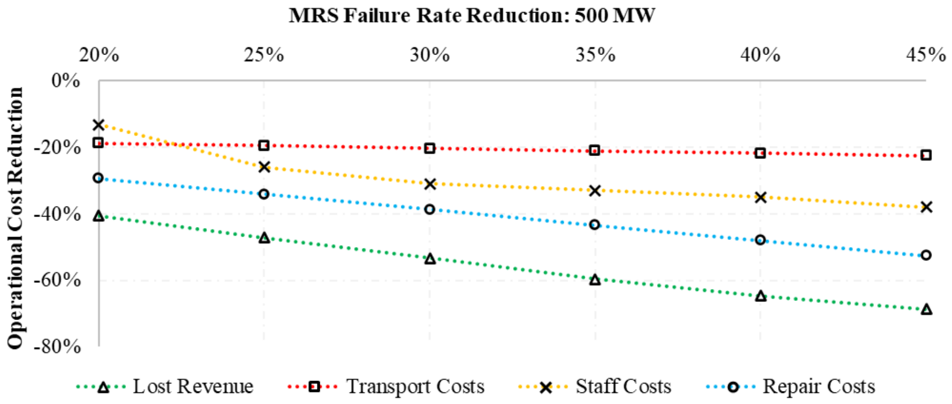

Figure 3. OpEx contributors' reduction in cost against reduction in failure rate

Lost revenue is increased due to increased downtime of the asset. While lost revenue had the highest reduction in total cost, across all simulations, the transport costs had the highest contribution to total OpEx. Vessel utilisation has a significant impact on both transport costs and lost revenue. Lost revenue is increased due to increased periods of downtime of the asset. This can be due to factors such as weather constraints, and resource availability. The CTV fleet contribution to downtime for the MRS 500 MW site at baseline, 20% reduction and 40% reduction in failure rates are provided in Figure 4. The 1 GW wind farm shows similar trends, with a total reduction in resource contribution of 5% for the 40% failure reduction scenario.

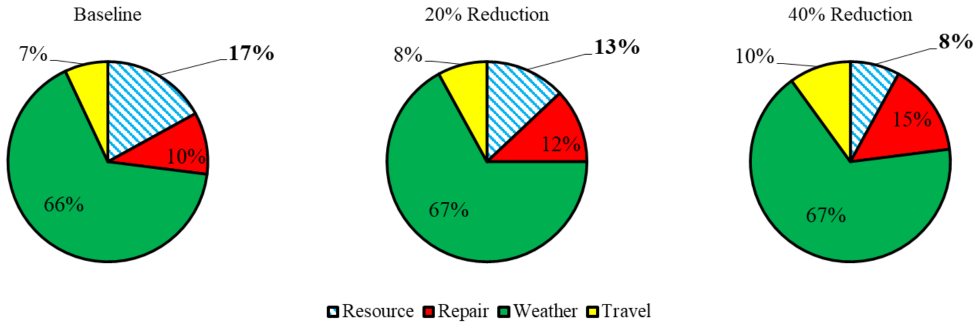

Figure 4. CTV contribution to downtime

Weather remains the key contributor, due to vessel limitations. Therefore, an increase in the significant wave height limit of the vessel would result in a decrease in total downtime. The reduction in the contribution of resources should also be noted. As explored in [28], overutilisation of vessels results in significant increases in OpEx. The reduction of transfers needed eases this pressure on the finite vessels available.

It should be noted that in terms of £/MWh, the 1 GW MRS site is more financially viable than the 500 MW MRS project. However, when comparing projects in terms of total annual OpEx (£), the cost of the 500 MW MRS is significantly less than that of the 1 GW MRS site.

3.2. Global and Local Failures

The failure of any component of the baseline turbine will result in a total loss of power output. The MRS has both global and local failure classifications of components as introduced in [28]. A global component will result in the loss of all power output from the system, and a local failure will see a loss of 1/45 of total power production (dependent on the number of rotors in the design). The failure rate of each component does not change based on the global/local classification of a component.

As shown in the original sensitivity analysis, high cost is the result of the volume of components failing. The determination of a global/local component will be determined in the design stage. A global component will have a reduced frequency of failure, but a higher impact on availability and downtime. In this analysis, the electrical system and the control system are selected as global components. Therefore, all rotors of a single MRS design share a single electrical system and a single control system. This work examines, first, the global control being the only global component, and then having both the electrical system and the control system being global components. All failure rates used in this analysis are the unaltered data from Dao et al. [8], as detailed in Section 2.2. Results comparing against the single rotor comparative baseline are given in Figure 5.

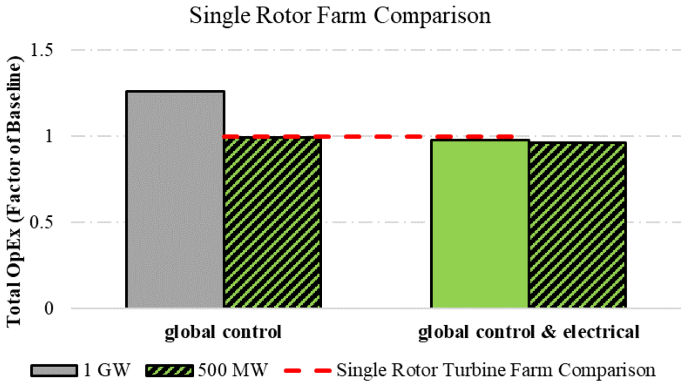

Figure 5. Impact of the implementation of global failures.

Results indicate that having both the control and electrical systems as global failures, the MRS becomes cost competitive with a single rotor equivalent wind farm for both the 500 MW and 1 GW scale. While the 1 GW is still more expensive than the comparative baseline, the true impact of the implementation of the single global control system for each MRS can be determined when compared against the MRS baseline comparison with local failures only and no failure adjustment (Figure 3). The comparison of the £/MWh determined in Figure 5 is compared against the baseline MRS system with no failure rate adjustment (Figure 1), this comparison is given in Figure 6.

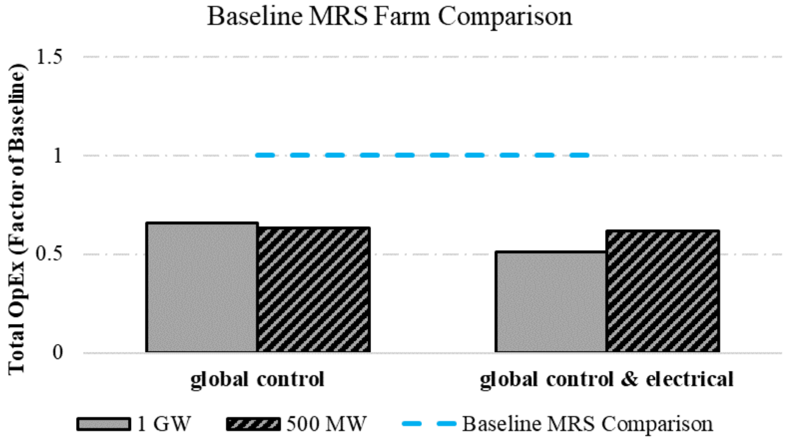

Figure 6. Global failure OpEx impact comparison with MRS using only local failure

Introducing global control and electrical systems has an increased advantage for the 1 GW wind farm over the 500 MW site. Despite the increase in the single impact of a global failure, versus a local failure, it is clear that this component classification can have significant OpEx savings. Therefore, when designing MRSs, great care should be taken to determine the balance between the number of global and local components.

4. Fatigue Strength Failure Scaling

This Section deals with the question, of how failure rates change with the size of a wind turbine. Assuming no technological changes and identical design, how will failure rates change with the geometric down- and upscaling of wind turbines?

Section 3 highlights that a significant reduction in failure rates is required for MRS wind farms to compete with single-rotor equivalents, in terms of OpEx. It is expected that failure rates will be reduced due to a number of factors including economies of scale and reduction in size. In this Section, fatigue strength fundamentals and the statistics therein are considered. Therefore, the following methods and ideas can only be applied to metallic components prone to fatigue failure.

[29] identifies four size effects, differentiated by their origin:

- **Technological size effect**: increasing component size makes it more difficult to achieve high-quality material textures. E.g. for a spheroidal graphite cast iron component, the graphite shape might deviate from its ideal spheroidal shape due to uncontrolled solidification of thick-walled, large components.
- **Stress-mechanical effect**: small notches experience a supporting effect by their neighbourhood.
- **Surface technological size effect:** becomes relevant for surface strengthening by introducing positive residual stresses (e.g., cold rolling)
- **Statistical size effect**: Comparing a small and a large specimen under fatigue load with identical stresses, the larger specimen will lead to premature failure due to the statistically higher amount of potential crack starters/ material imperfections. Therefore, components with a large hot spot surface or large hot spot volume show a reduced fatigue strength or a higher probability of failure.

In a thoroughly detailed design and certification process, size effects are considered for some of the above-mentioned effects, leading to additional wall thicknesses.

In [30] separate knockdown factors for the technological and stress-mechanical size effect on the material's ultimate strength are considered. The fatigue strength calculation is based on this static value and therefore based, among others, on the size effect knockdown factors. The calculation of the technological size factor is based on the material used and the so-called effective diameter $\mathrm{d_{eff}}$. In general, it is defined as $\mathrm{d_{eff}} = 4 * \frac{\mathrm{V}}{\mathrm{O}}$ for volume V and surface area O of the considered component part. Assuming the square-cube law for upscaling, this effective diameter increases in a linear fashion. For cast steel, construction steel, aluminium, etc. the effective diameter $\mathrm{d_{eff}}$ is defined as the wall thickness of the component part.

[31] uses a similar differentiation of size effects as [30], but states that it is challenging to differentiate these effects. Based on this assumption, no direct knockdown factors are used. Instead, so-called stress detail classes are defined that specify the S-N curves in the fatigue dimensioning process. These detail classes are differentiated based on component dimensions and component-similar specimens, to compensate for the technological and statistical size effect. The approaches used by [32] and the International Institute of Welding (IIW) lead to similar stress detail classes and classifications as [31] [33].

In contrast, many research activities, in particular multirotor research, are using geometric and other simple scaling rules for up- and downscaling a given turbine design. In such cases, the above-mentioned size effects and their knock-down factors are not inherent in the scaling laws. This paper, therefore, aims to consider the size effect in the operational phase, i.e., the effect it has on the failure rate of the wind turbine components. In the following, only the statistical size effect will be considered.

[29, page 538] compares a specimen with volume V_0 to a longer specimen with volume $V = n \cdot V_0$. For the distribution of defects with size a in a volume element [16] applies a two-parametric Weibull distribution as follows:

$$F(a) = exp\left\{-(\frac{a}{av})^{-b1}\right\} \qquad \text{(eq. 2)}$$

Where parameters av is a characteristic size and $b1$ the scatter of voids. $F(a)$ then describes the probability to find a void smaller than a in the volume V_0.
For the n-fold increased volume

$$\mathrm{V} = \mathrm{n} \cdot \mathrm{V_0} \qquad \text{(eq. 3)}$$

it is assumed that the n volumes are in series connection (i.e., a failure in one of the n volumes leads to failure of the specimen). Then the product of survival probabilities becomes the overall survival probability

$$F_V(a) = \prod_{i=1}^{n} \{F(a)\} = exp\left\{-n(\frac{a}{av})^{-b1}\right\} \qquad \text{(eq. 4)}$$

Since the material volume of the SR-RNA (rotor-nacelle-assembly) is much higher than the accumulated material volume of the MRS-RNAs, the failure rate of the SR would be substantially higher than that of the MRS, according to the above-mentioned theory. Since these equations are not easily applicable, a simplification is needed.

4.1. Simplified approach for consideration of statistical size effect

It is reasonable to assume, that an MRS with n RNAs has an n-fold higher failure rate related to one of its RNA. This is true for all components that do exist n-fold in an MRS. Other components, like a central converter and transformer or a central yaw bearing, must be treated differently.

A question being more difficult to answer is how failure rates of a large single rotor deviate from n small MRS rotors.

[29] states that fatigue cracks usually start from the component surface, since the highest mechanical stresses usually appear there. Instead of taking the material volume as the fatigue-relevant scaling parameter, [29] therefore alternatively considers the surface area.

Relating this to an MRS and SR, the outcome becomes simple. If one RNA of an MRS has a failure rate F, then the complete MRS will have an n-fold higher failure rate F_{MRS} =n x F.

Considering the square-cube law, the accumulated MRS surface is identical to the SR's surface. As such, the failure rate of the large SR is $F_{SR} = F_{MRS}$ =n x F.

- Failure rate of one RNA of the MRS: F
- Failure rate of the sum of all RNAs in an MRS F_{MRS} = n x F
- Failure rate of a large SR with equal rated power and surface area $F_{SR} = F_{MRS}$ = n x F

From a fatigue strength point of view, the authors see this as a reasonable approach. In comparison to historical data in [8], it can also be seen, that smaller turbines tend to have lower failure rates compared to their bigger counterparts. This effect should be more pronounced if the small (early stage) turbines were of a similar technological maturity as the big (latest stage) turbines. On the other hand, failure mechanisms are complex and individual for each component, which makes it difficult, if not impossible to precisely forecast failure rates and their scaling laws.

4.2. Simulation Results and Application

The RNA inputs are adjusted to reflect the findings using the above results. It is assumed that the failure rate of the component should be that of the total MRS system, e.g. the failure rate of each component is $1\,/\,number\ of\ rotors \times failure\ rate$. This methodology is applied to the components within the RNA of the turbine. All failures are assumed to be local only. The failure rates of non-RNA components (electrical system, control system and pitch) are based on the Q3 baseline failure rates (Section 3).

Figure 7 compares the percentage increase/decrease in total OpEx in comparison to the single rotor comparative wind farm and the MRS comparative baseline (Figure 2).

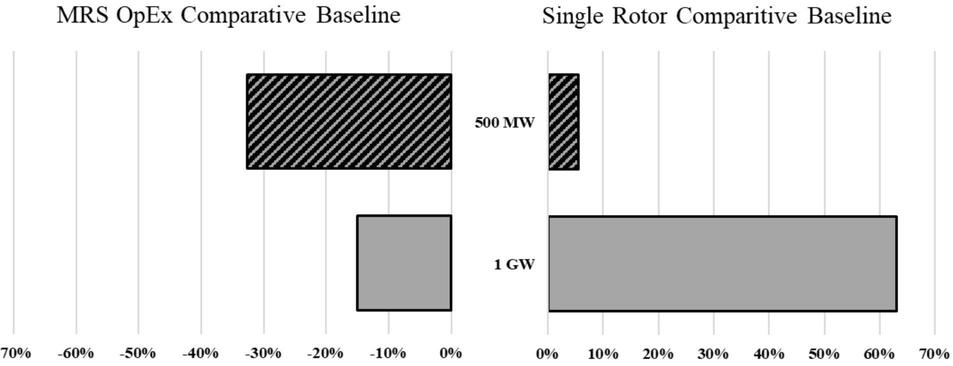

Figure 7. OpEx comparison after failure rate adjusted for RNA based on analysis of Section 3.1

When compared to the single-rotor farm baseline, OpEx is increased. However, when compared to the MRS baseline of local failures only, there is a significant decrease in total OpEx.

It was found that for the 500 MW wind farm, the combination of the RNA scaling law failure rate and the addition of a 20% decrease across the remaining components resulted in a cost-competitive wind farm, compared to the 25% decrease required without the assumption of the RNA scaling laws applied. For the 1 GW MRS wind farm, a reduction of ~27% of the pitch, electrical and control failure rates resulted in lower OpEx than that of the single rotor equivalent.

5. Conclusions and Future Recommendations

Results highlight that the 500 MW wind farm is more cost-effective in terms of OpEx in comparison to the 1 GW wind farm. This is due to the high number of vessels and technicians required to cope with the maintenance requirements of the 1 GW scenario. However, this work has highlighted that some of these challenges can be overcome by implementing some global component failures. While the risk and impact of these failures are heightened, the reduction of failure rates has a positive impact on total OpEx.

Due to the infancy of the technology, it is unlikely that upon initial deployment the MRS will be competing with single-rotor turbine equivalent sites for funding. Therefore, while it is favourable for the MRS to be more cost-effective than the single-rotor offshore turbine, for early deployment it is likely MRS projects will be subject to different funding mechanisms. It is also expected that as experience with the technology grows, savings across all aspects will increase.

Due to the expected savings in terms of the cost of materials and manufacture of the MRS components, it could be suggested that these savings be reinvested to increase the overall reliability of the components, particularly those with high failure rates such as pitch. Section 3 highlights the failure rate reduction required for OpEx to become cost competitive. Section 4 highlighted these reductions could be a reality, based on the theory behind fatigue strength and its relationship to component size.

One key question which must be considered in future work is "What proportion of failures across all components are fatigue based?". Other research surrounding RNA failure scaling should also be explored including analysis of design margins on RNA components with the potential to reduce failure probability as something to be explored in further work. Other scaling methods of other components should also be explored including length, weight, and volume-based approaches.

It is recommended that future work should further explore the allocation of global and local failures in order to determine the balance between a reduced number of failures and the increased impact of lost revenue. Due to the different configurations of the technology, compared to a single-rotor turbine, it may also be beneficial to explore different maintenance strategies such as batch repair. It is expected this will have a positive impact on OpEx due to the reduction of lost revenue for each failure.

References

[1] Williamson, R., 2023. Wind turbine failure rates are rising – has the industry gone too big, too fast? [online] RenewEconomy. Available at: https://reneweconomy.com.au/wind-turbine-failure-rates-are-rising-has-the-industry-gone-too-big-too-fast/ [Accessed 24 Feb. 2023].

[2] McMillan, D. and Dinwoodie, I.A., 2013. Forecasting long-term jack up vessel demand for offshore wind. ESREL 2013.

[3] Jamieson, P. and Branney, M., 2014, December. Structural considerations of a 20MW multi-rotor wind energy system. In Journal of Physics: Conference Series (Vol. 555, No. 1, p. 012013). IOP Publishing.

[4] Stehly, T., Beiter, P. and Duffy, P., 2020. 2019 cost of wind energy review (No. NREL/TP-5000-78471). National Renewable Energy Lab.(NREL), Golden, CO (United States).

[5] 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.

[6] Bortolotti, P., Tarres, H.C., Dykes, K.L., Merz, K., Sethuraman, L., Verelst, D. and Zahle, F., 2019. IEA Wind TCP Task 37: Systems engineering in wind energy-WP2. 1 Reference wind turbines (No. NREL/TP-5000-73492). National Renewable Energy Lab.(NREL), Golden, CO (United States).

[7] Carroll, J., McDonald, A. and McMillan, D., 2016. Failure rate, repair time and unscheduled O&M cost analysis of offshore wind turbines. Wind Energy, 19(6), pp.1107-1119.

[8] Dao, C., Kazemtabrizi, B. and Crabtree, C., 2019. Wind turbine reliability data review and impacts on levelised cost of energy. Wind Energy, 22(12), pp.1848-1871.

[9] Windstats newsletter. Wind Newsl. 1987-Present.

[10] Startseite—Landwirtschaftskammer Schleswig-Holstein. https://www.lksh.de/startseite/. Accessed April 10, 2018.

[11] Echavarria, E., Hahn, B., Van Bussel, G.J.W. and Tomiyama, T., 2008. Reliability of wind turbine technology through time. Journal of Solar Energy Engineering, 130(3).

[12] VTT Technical Research Centre of Finland Ltd Technology for business., 2018. [online] VTT Research. Available at: http://www.vttresearch.com/Pages/default.aspx. [Accessed April 18, 2018]

[13] Carlstedt, N.E., 2004. Driftuppföljning av vindkraftverk: årsrapport 2003. Energimyndigheten.
[14] Reder, M.D., Gonzalez, E. and Melero, J.J., 2016, September. Wind turbine failures-tackling current problems in failure data analysis. In Journal of Physics: Conference Series (Vol. 753, No. 7, p. 072027). IOP Publishing.
[15] Ogilvie, A.B. and Gershin, S., 2011. Continuous Reliability Enhancement for Wind (CREW) Database (No. SAND2011-8152P). Sandia National Lab.(SNL-NM), Albuquerque, NM (United States).
[16] DOWEC, 2003. Estimation of turbine maintenance figure within the DOWEC project. DOWEC project, (10086).
[17] Herbert, G.J., Iniyan, S. and Goic, R., 2010. Performance, reliability and failure analysis of wind farm in a developing country. Renewable energy, 35(12), pp.2739-2751.
[18] Lin, Y., Tu, L., Liu, H. and Li, W., 2016. Fault analysis of wind turbines in China. Renewable and Sustainable Energy Reviews, 55, pp.482-490.
[19] Ma, Z., An, G., Sun, X. and Chai, J., 2015. A study of fault statistical analysis and maintenance policy of wind turbine system.
[20] Su, C., Yang, Y., Wang, X. and Hu, Z., 2016, October. Failures analysis of wind turbines: Case study of a Chinese wind farm. In 2016 Prognostics and System Health Management Conference (PHM-Chengdu) (pp. 1-6). IEEE.
[21] Bi, R., Qian, K., Zhou, C., Hepburn, D.M. and Rong, J., 2014. A survey of failures in wind turbine generator systems with focus on a wind farm in China. Ran Bia and oth. International Journal of Smart Grid and Clean Energy.
[22] Saeed, K., McMorland, J., Collu, M., Coraddu, A., Carroll, J., 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.
[23] ERA 5 dataset, LAUTEC 2021. ESOX Map, https://esox.lautec.com/map/
[24] Artigao, E., Martin-Martinez, S., Ceña, A., Honrubia-Escribano, A. and Gomez-Lazaro, E., 2021. Failure rate and downtime survey of wind turbines located in Spain. IET Renewable Power Generation, 15(1), pp.225-236.
[25] Sieros, G., Chaviaropoulos, P., Sørensen, J.D., Bulder, B.H. and Jamieson, P., 2012. Upscaling wind turbines: theoretical and practical aspects and their impact on the cost of energy. Wind energy, 15(1), pp.3-17.
[26] Velarde, J., Kramhøft, C., Sørensen, J.D. and Zorzi, G., 2020. Fatigue reliability of large monopiles for offshore wind turbines. International journal of fatigue, 134, p.105487.
[27] Sergiienko, N.Y., da Silva, L.S.P., Bachynski-Polić, E.E., Cazzolato, B.S., Arjomandi, M. and Ding, B., 2022. Review of scaling laws applied to floating offshore wind turbines. Renewable and Sustainable Energy Reviews, 162, p.112477.
[28] McMorland, J., Pirrie, P., Collu, M., McMillan, D., Carroll, J., Coraddu, A. and Jamieson, P., 2022, May. Operation and maintenance modelling for multirotor systems: bottlenecks in operations. In Journal of Physics:Conference Series (Vol. 2265, No. 4,). IOP Publishing.
[29] Haibach, E. Betriebsfestigkeit, Springer-Verlag, third edition, 2005
[30] Kullig, E., Rennert, R., Vormwald, M., Esderts, A. and Luke, M., 2020. Rechnerischer Festigkeitsnachweis für Maschinenbauteile aus Stahl, Eisenguss-und Aluminiumwerkstoffen: FKM-Richtlinie.
[31] Deutsches Institut für Normung, 2009. Eurocode 3: Design of steel structures – Part 1-9: Fatigue", German version EN 1993-1-9:2005 + AC:2009
[32] DNV, 2014. RP-C203: Fatigue design of offshore steel structures.
[33] Götz, S., 2020. Betriebsfestigkeit, Springer-Verlag, 1st edition.