Operations expenditure modelling of the X-Rotor offshore wind turbine concept

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Abstract. O&M of an offshore wind farm is becoming increasingly challenging as farms are being commissioned further from shore. Weather windows are more difficult to navigate leading to longer downtime for turbines. The X-Rotor offshore wind turbine concept directly tackles these O&M challenges by, amongst other advantages, removing the requirements for components that have traditionally contributed high failure rates, repair times and downtimes, and by placing the heavy and expensive machinery closer to sea level. The turbine also benefits from having modular small rotors that can be quickly replaced and repaired onshore, and being able to operate at reduced capacity when there are failures in the modular rotors. This paper presents the StrathX-OM OpEx model. This model features changes to OpEx modelling that will allow for comprehensive analysis of the operations and maintenance costs for a wind farm made up of radical X-Rotor wind turbines with the flexibility to handle changing designs as the technology progresses. The calculation of lifetime O&M costs for a wind farm 100 km from shore showed that the X-Rotor has lower O&M costs than conventional HAWTs for an established design. A sensitivity study on the estimated failure rates of X-Rotor is also presented. This shows that even with significantly over-estimated failure rates the X-Rotor would still be competitive in today's market.

1. Introduction

The X-Rotor offshore wind turbine concept is the subject of a €4m EU H2020 project being conducted from 2021 to 2023. The X-Rotor is a radical rethink of a vertical axis wind turbine (VAWT) that directly addresses its disadvantages [1]. Figure 1 shows two versions of Artists impressions of what the turbine will look like. The VAWT rotor, referred to as the primary rotor, has blades with symmetric aerofoils angled both up and down in an 'X' shape from the ends of a short cross-arm. The role of the lower half of X-Rotor is to reduce overturning moment on the main vertical-axis bearing and house the secondary rotors, which are horizontal axis wind turbines (HAWT). The role of the secondary HAWTs is to provide power take-off. One of the fundamental issues with VAWTs is power take-off due to low rotational speed and high torque. This design removes the power take-off from the vertical rotor and in turn reduces the cost vs a conventional VAWT. The rotation round the vertical axis provides the secondary HAWT rotors with an increased wind speed - leading to increased energy capture for the size of rotor - and gives a rotational symmetry that removes the requirement for yawing the turbines. There is a large increase in the rotor speed of the secondary HAWT rotors with this arrangement; this allows the drivetrain to be a direct-drive system without the need for a multipole generator. The drivetrains in the X-Rotor are placed in a nacelle behind the secondary HAWT rotors which

Nomenclature/Definitions

HAWT	Horizontal-axis wind turbine
VAWT	Vertical-axis wind turbine
Secondary HAWT	Refers to the small horizontal turbine (rotor and drivetrain) fixed to the lower half of the vertical rotor for an X-Rotor turbine
Secondary HAWT rotor	refers exclusively to the rotor of the rotor portion of the turbine in the Secondary HAWT
Secondary HAWT module	A secondary HAWT (rotor and drivetrain together) that is designed as a detachable module
Conventional turbine or Conventional HAWT	3-bladed commercial HAWT
Primitive X-Rotor	Hypothetical design version of X-Rotor without HAWT modules or ability to operate with failed secondary HAWT
Established X-Rotor	Hypothetical design version of X-Rotor with HAWT modules or ability to operate with failed secondary HAWT

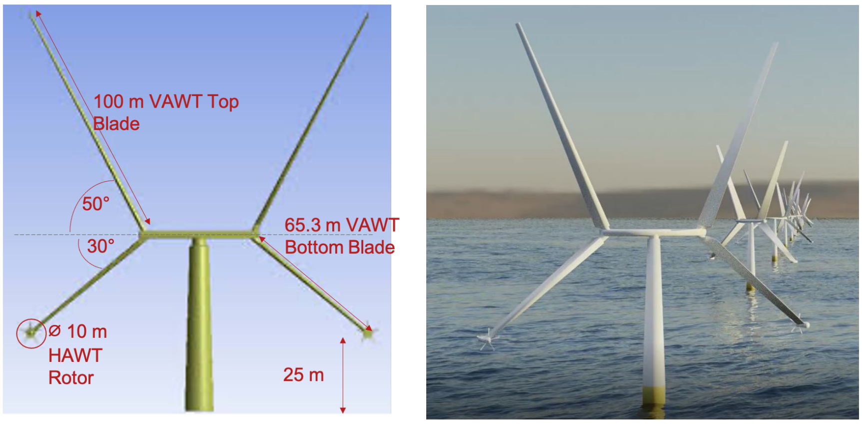

Figure 1: Artist's impressions of X-Rotor Offshore Wind Turbine Concept. Left figure is annotated with some dimensions of the X-Rotor turbine. The drivetrains are housed immediately behind the HAWT rotors. The HAWT rotor and drivetrain components make up the component referred to as a secondary HAWT. There is the option to design these secondary HAWTs as detachable modules that could be repaired onshore.

is housed on the bottom vertical-axis blades. Reference to a secondary HAWT as a component is inclusive of the rotor and the nacelle components.

The operations and maintenance (O&M) costs for this turbine are expected to be reduced due to the power take-off systems being situated closer to sea level. These are housed at the end of the bottom vertical-axis blades in the secondary HAWTs. The main benefit from this would be that almost all repair and maintenance could be completed without the need for a heavy-lift vessel, which accounts for half the vessel charter costs for conventional wind farms [2]. Only major pitch system and blade replacements on the vertical rotor would require a heavy-lift vessel. There is also the opportunity for the secondary HAWTs to be designed as detachable modules which can be quickly replaced and then repaired/maintained onshore; this module would consist of the rotor blades, the generator and the power converter. Onshore repair methodologies creates a safer environment for technicians and reduces needs for specialist training for offshore field work. The full weight of each secondary HAWT module is expected to be under 10 tonnes [3]. X-Rotor will also be able to operate with reduced capacity if one of the secondary HAWTs has failed. This can reduce the haste for repair as the capacity of the farm is reduced less significantly following a failure. The turbine would have to switch to a different operational strategy for

Table 1: Summary of O&M differences for X-Rotor compared to conventional HAWTs.

Consideration	X-Rotor	Horizontal Axis Wind Turbine
Power take-off System (PTO)	2 or more	1
Height of Nacelle	25 m	90 m
Weight of Nacelle	10 t	>200 t
Jack-up Vessel Use (Major Replacements)	Vertical-axis Blades, Pitch	Gearbox, Generator, Blades, Pitch, Yaw
Onshore Maintenance	Secondary HAWT module (consists of rotor, generator and power converter)	Not Possible
Redundancy	Operates with 1 2ndry Rotor	No Redundancy in PTO
Drivetrain type	No gearbox or multipole generator	Either gearbox or multipole generator
Yaw System	Not necessary due to rotaional symmetry	Yes
Scaling Solution	Add 2.5 MW 2ndry rotors	Increase size of all components

this but will lead to significantly less downtime associated with failures. Contrary to this, conventional turbines have very little redundancy in the power take-off system. Due to this, it is very unlikely to be cost-effective to batch fix failures that have resulted in a non-operational turbine. The ability to replace secondary HAWT modules to repair onshore and being able to capture the reduced capacity operation are essential for an X-Rotor OpEx model. X-Rotor also has an interesting scaling solution. It is proposed that, to increase rated power of this turbine, additional secondary HAWTs are added to the lower half of the X-shaped primary rotor, with each secondary HAWT having a rated power of 2.5 MW. This will lead to better standardisation of parts for both the primary and secondary rotors due to the size of all components remaining constant with increasing power rating. Finally, O&M cost advantages are expected from the X-Rotor due to the removal of high failure rate, repair time, and downtime components such as a gearbox and multi-pole generator. An additional benefit of the generator is that it requires less rare-earth material per MW than a conventional HAWT. Therefore, fluctuations in the commodities market will have less effect on installation or replacement costs. The key O&M differences between the X-Rotor and conventional wind turbines are outlined in table 1.

2. Methodology

The methodology required to model the lifetime O&M costs for the X-Rotor is two-fold: derivation of failure modes and their associated failure rates based on current wind turbine technology, and development of an OpEx model that has the capability to model the unique O&M features as well as the capability to test new O&M strategy options for the X-Rotor.

2.1. StrathX-OM Model

The model presented in this paper takes its basis from the StrathOW-OM model developed between 2012 and 2013 [4, 2, 5]. This OpEx model has been widely used in literature and industry for simulating proposed wind farms [6, 7, 8, 9]. The model has been reviewed in the context of offshore wind turbine operations modelling by Hoffman [10], Shafiee [11] and Seyr [12].

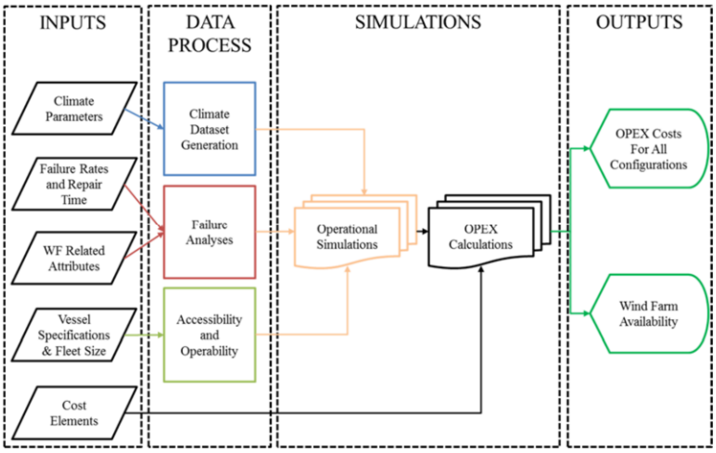

Figure 2: Schematic of methodology for the StrathOW-OM model [14]. The model presented in this work follows this overall methodology, with changes to the Operational Simulations block.

The primary algorithm for the work presented follows the same process as the StrathOW-OM model. The methodology is based on simulation of failures as a stochastic process based on failure rates. Time to repair is determined by using a representative time series for wave height and waiting for an adequate repair window for vessel access. Weather data and failure events are simulated within the model. The weather conditions are generated using a correlated, Multivariate Auto-Regressive approach (MAR) [13]. Wind speed, significant wave height and wave period are generated hourly for the lifetime of the farm. Failure events are simulated from a Weibull distribution of failures with the probability of occurrence of each failure mode an input. A Monte-Carlo method is used hourly to determine if failures occur. Strategic decisions such as number of technicians, crew transfer vessels (CTV), fast supply vessels (FSV), and use of a mothership vessel/offshore accommodation are inputs to the model. A schematic for the developed methodology for the StrathOW-OM model is shown in figure 2 [14].

The new functionality is realised through enhancing the flexibility of the simulations block. Vessels with adequate deck space and weight restrictions are used to transport X-Rotor HAWT modules to and from shore for onshore repair. FSVs are used in the model for this function. A predicted timeline for a repair task in the case of replaceable HAWT modules and fixed HAWTs are shown in figure 3. The time estimations for each part are based on discussions with a commercial CTV charter company and other researchers. The repair times in the right-hand side for minor/major/replacement are taken from Carroll et al. [9]. The "//" indicated the time axis is cut in this period. The yellow shaded areas indicated the time where the modular rotor will have influence on the repair time. The repair times range from 2-10 hours depending on the component. Therefore, there is clear value in having a quick replacement system even for minor repairs: shorter weather windows are required, less equipment to be transported, less downtime and safer working conditions for technicians.

Two new functions have been added to the operational simulations loop of the StrathOW-OM model that perform HAWT module replacement and onshore repair, respectively. The new repair functions are performed on a daily basis and run alongside the traditional repair schedule for failure modes that cannot be repaired by HAWT module removal. After identifying failed HAWT modules, the replacement tasks are allocated to vessels. The limiting factors are the max module capacity of the vessel, the weather window available, and the number of spare HAWT modules ready for deployment. The replacement of HAWT modules is not cumulative; this means that if the replacement cannot be fully completed, the replacement will not start

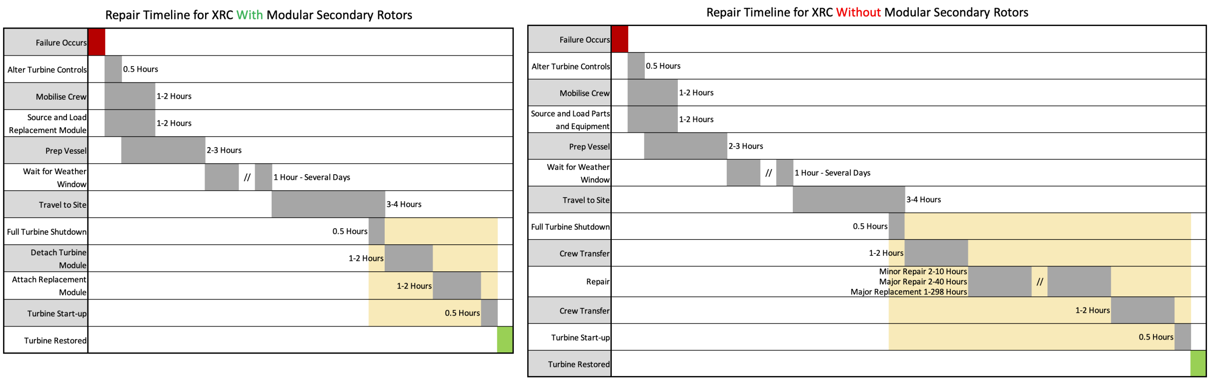

Figure 3: Diagram of timeline for a repair task for an X-Rotor turbine with a detachable HAWT design (left); and without (right). The time estimations for each part are based on discussions with a commercial CTV charter company and other researchers. The repair times in the right-hand side chart for minor/major/replacement are taken from Carroll et al. [9]. The "//" indicated the time axis is cut in this period. The yellow shaded areas indicated the time where the modular rotor will have influence on the repair time. Taken from Flannigan et al. [3]

until the next accessible day. The onshore repair function takes the failed modules delivered and uses inputs of repair time and number of technicians required to determine the time for the module to be ready for re-deployment. The onshore repairs are cumulative, this means if the repair cannot be completed within a single shift, the remaining part can be completed in the following day. The technicians required and repair time data are consistent with the offshore repair data used for other turbines [9]. If the strategy for onshore repairs is not well considered then there may be delays in replacement of HAWT modules due to no spare modules being ready for deployment. Important considerations for this is the number of spare HAWT modules available for use beyond the farm's capacity and the number of technicians hired for repairs.

2.2. Deriving Failure Modes For the X-Rotor

The failure modes for the X-Rotor are split into two categories: turbine level failures and secondary HAWT level failures. The components in which failures are considered secondary HAWT level are: generators, HAWT rotor blades, grease/oil/cooling liquid, sensors and HAWT rotor hubs.

Each component has broken down failure modes based on cost of repairs, consistent with [9]. Each of these failure modes are used as inputs to the model with an associated mean repair time, mean required technicians for repair, vessel type required and failure rate in failures/turbine/year. The failure categories from Carroll [9] are the start-point. The data from this paper was from turbines of 2-4 MW. The costs for each failure mode is extrapolated to 5 MW for turbine level failures and 2.5 MW for secondary HAWT level failures using equations from Fingersh et al. [15] which allows for masses and costs of components to be calculated from empirical equations. Component costs are calculated for both a 3 MW (generalisation of turbines with cost data available) and 5 MW turbine and the ratio of the minor repair, major repair, and major replacement to the max replacement cost is assumed to be equal for both ratings. This allowed the cost for the three categories of each component to be determined. The failure rate data was scaled linearly for blades with changes in quantity on a given rotor. As a conservative analysis, all failure rates for X-Rotor that it would be assumed to be less frequent than a conventional turbine are kept constant with Carroll and any that were assumed to be more frequent are increased by 15%. This 15% increase is a baseline and is later addressed in the sensitivity analysis in Section 4. Table 2 shows an example for the pitch system for a 3 MW

Table 2: Example of derived failure mode costs and failure rate for inputs into cost model for larger turbines and X-Rotor. This table shows this for the pitch system and generators for a 3-stage geared conventional HAWT and X-Rotor. The cost is calculated using Fingersh et al. [15], the 3 MW conventional turbine (HAWT) data was taken directly from Carroll [9]. The cost data for the 5 MW HAWT and the 5 MW X-Rotor are extrapolated from the 3 MW HAWT, keeping the ratios between the component cost and the failure brackets constant across the turbines. The failure rate is assumed to remain constant with increasing size of HAWT. The failure rate of the pitch system was increased by 15% for X-Rotor due to increased pitch activity for this turbine. The failure rate of the generator was kept constant as it would be assumed to have a higher reliability due to the lower torque generator. Note: there are 2x 2.5 MW generators in a 5 MW X-Rotor.

Turbine	Component Cost (€)	Repair Cost (€)			Failure Rate (fail/tub/year)		
		Minor Repair	Major Repair	Major Replacement	Minor Repair	Major Repair	Major Replacement
				Pitch System			
3 MW HAWT	70,000	210	1900	14,000	0.824	0.179	0.001
5 MW HAWT	154,000	463	4189	30,867	0.824	0.179	0.001
5 MW X-Rotor	350,000	1054	9538	70,281	0.9476	0.2059	0.0012
				Generator			
3 MW HAWT	222,000	160	3500	60,000	0.485	0.024	0.007
5 MW HAWT	371,000	178	3,898	66,825	0.485	0.024	0.007
5 MW X-Rotor	2x 156,000	89	1,949	33,412	0.437	0.024	0.007

conventional turbine, a 5 MW conventional turbine and a 5 MW X-Rotor. Similar analysis is completed for each turbine component. There is an increase in pitch activity in X-Rotor due to the proposed cyclic pitching through a vertical rotation. Therefore, there was an increase in failure rate by 15%. Note: the pitching discussed here is for the vertical-axis rotor blades. There is no pitching for the horizontal-axis rotor blades.

3. Case Study and Results

The OpEx model developed is used to calculate lifetime O&M costs (in €/MWhr) for a wind farm 100 km from shore, made up of 100 turbines. This was calculated for both a primitive and established X-Rotor design, and both a direct-drive and a 3-stage geared HAWT. The difference between the primitive and established X-Rotor designs are that the established design has detachable secondary HAWTs and has the ability to function at reduced capacity with one of the secondary HAWTs failed. This allows for smaller vessels to be used for most maintenance activities and reduces the use of the jack-up vessel (JUV). Both designs have two secondary HAWTs. Both X-Rotor designs and both HAWTs were analysed to show the flexibility in functionality of the model to handle turbines of different designs, and to show that the assumptions in design of the finalised X-Rotor need to be realised to set the turbine apart from conventional technologies in terms of O&M Costs.

The power curve used for modelling of the conventional HAWTs was the NREL 5 MW

Table 3: Summary of inputs into the model and strategies used for each turbine technology.

Turbine	3-stage Geared HAWT	Direct-drive HAWT	Primitive X-Rotor	Established X-Rotor
Farm to Port Distance (km)	100	100	100	100
Turbine Rating (MW)	5	5	2x 2.5	2x 2.5
Electricity Price (€/kWhr)	50	50	50	50
No. of CTVs	6	5	5	4
CTV Charter Cost (€/day)	3750	3750	3750	3750
Offshore Technicians	36	30	30	24
Onshore Technicians	0	0	0	6
JUV Charter Length (Days)	90	90	90	60
No. of FSVs	0	0	0	1
No. of Spare Rotors	0	0	0	2

reference turbine. The X-Rotor was modelled using the same power curve as a conventional HAWT but with two cumulative 2.5 MW power curves as opposed to one 5 MW power curve. The failure modes are split into two categories: turbine level failures and secondary HAWT level failures. In the established X-Rotor design, when one of the secondary HAWTs fails, it is assumed that the turbine continues to operate with one HAWT at 2.5 MW without any deviation from is normal operating production. In reality, there will be a change in operating strategy and the power curve for single rotor operation will not be exactly half of two rotor operation; it is expected to have increased power yield in below-rated operation [1].

The strategy used for the direct-drive HAWT and the primitive X-Rotor involved five readily available CTVs, each with a capacity of six technicians (total pool of 30 salaried technicians). The 3-stage geared HAWT used six CTVs and 36 salaried technicians. No FSVs were used for the maintenance of these three technologies and JUVs were used on a fixed-charter basis of 90 days for major component replacements. For the established X-Rotor, four CTVs, hence 24 salaried technicians were readily available. On the rare occasions JUVs were required, they were used on a fixed-charter basis of 60 days. Discussions with offshore vessel charter companies indicated that it would be difficult to charter a JUV for less than 60 days. There was one FSV used for maintenance for replacement of the secondary HAWTs. There was also six salaried technicians for onshore repairs with two spare rotors available. The strategies outlined above were chosen as they were found to be the most cost-effective for each technology in this hypothetical wind farm. A summary of the strategies for each simulation are outlined in table 3.

Figure 4 shows the operations and maintenance costs in €/MWhr for the calculations. The results are split into four categories: lost revenue, transport costs, staff costs and repair costs.

Table 4: Results from simulations of lifetime of wind farms made up of different turbine technologies. λ is the total turbine fail rate.

Turbine	3-stage Geared HAWT	Direct-drive HAWT	Primitive X-Rotor	Established X-Rotor
Availability (%)	91.54	91.24	91.36	92.57
Lost Revenue (€ m)	194.4	204.59	204.4	167.55
λ (fail/turb/year)	5.43	5.81	6.96	6.97
Jack-Up Required Failures	134	25	21	6

The transport is the major discrepancy in O&M cost breakdown for the four technologies. The transport cost is greatest for the 3-stage geared HAWT and lowest for the established X-Rotor. This is primarily due to JUV use as there are large mobilisation and daily charter costs for Jack-up hire. JUVs are required for major replacement of blades, generators and gearboxes for conventional HAWTs but just primary rotor blades for the established X-Rotor design. This can be seen directly from the number of failures that required a Jack-up for repair over the lifetime of the farm, shown in table 4. Using the FSVs to replace modules limits the number of Jack-up charters further to six in the lifetime of the farm and also allows for a reduction to four available CTVs without sacrificing on farm availability. The next major cost reduction is in the lost revenue which is accounted for by the continued operation of the turbine at reduced capacity with one of the secondary HAWTs failed. Comparing this to the other three technologies, there is an approximately 1% increase in availability which leads to approximately €30m extra revenue. For the repair costs, both of the X-Rotor designs show significant reduction in this area. X-Rotor generally has less expensive components, the only exceptions are the primary rotor's blades and pitch systems. Although the overall fail rate is larger for X-Rotor than a conventional HAWT due to the increase in number of components within the turbine, the average cost of each repair is less. This leads to lower repair cost overall. Finally, the reduction in staff costs is purely due to some of the technicians being onshore which in this study had a reduced salary. The staff cost for the 3-stage geared HAWT is increased further to accommodate the extra staff required for the six CTV strategy.

4. Sensitivity of Failure Rates

Sensitivity analysis was performed to verify the suitability of the assumptions made on the failure rates of the X-Rotor used in the case study above. The failure rates were varied from 0.9 to 1.3 of the values for corresponding components from Carroll et al. [9]. The same scenario and strategy as in the case study were used. Figure 5 shows how the availability and overall O&M costs for the primitive and established X-Rotors varies with increasing failure rate, along with the conventional HAWTs plotted as horizontal lines for comparison. The sensitivity analysis was carried out to see how much the failure rates for the X-Rotor could be increased before the availability and O&M costs would become lower than that found for the conventional HAWTs in the study above. It is clear that if the failure rates are the same for X-Rotor, there is

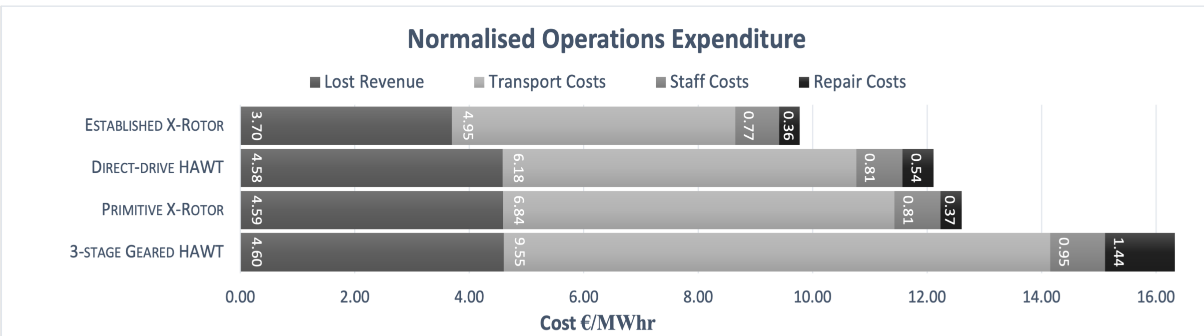

Figure 4: Operations and maintenance costs in €/MWhr for a wind farm 100 km from shore, made up of 100 turbines of different technologies: primitive X-Rotor, established X-Rotor, direct-drive HAWT and 3-stage geared HAWT. The results are split into four categories: lost revenue, transport costs, staff costs and repair costs. The established X-Rotor has detachable secondary HAWTs that are repaired onshore and has the ability to continue operating with reduced capacity after one of the secondary HAWTs has failed.

quite a significant increase in availability of the wind farm. The failure rates for the primitive X-Rotor have to be increased by 15% before the availability drops to a comparable value to conventional HAWTs. The failure rates need to be increased by nearly 30% for the availability of the established X-Rotor farm to drop below both the conventional HAWT technologies, and the O&M costs are still lowest for this technology at this point. The failure rates were also decreased to demonstrate the potential for further improvement in availability. It is usually assumed that smaller components have lower failure rates. Therefore, it is actually more likely that the failure rates for X-Rotor components are less than the equivalent components for conventional HAWTs. It can also be seen from the graph that the established X-Rotor design has a smaller divergence from equal failure rates than the primitive X-Rotor farm. This is due to the increased reliance on JUVs for the primitive X-Rotor design. Therefore, the impact of failure rates on the wind farm O&M cost and availability are smaller for the established X-Rotor.

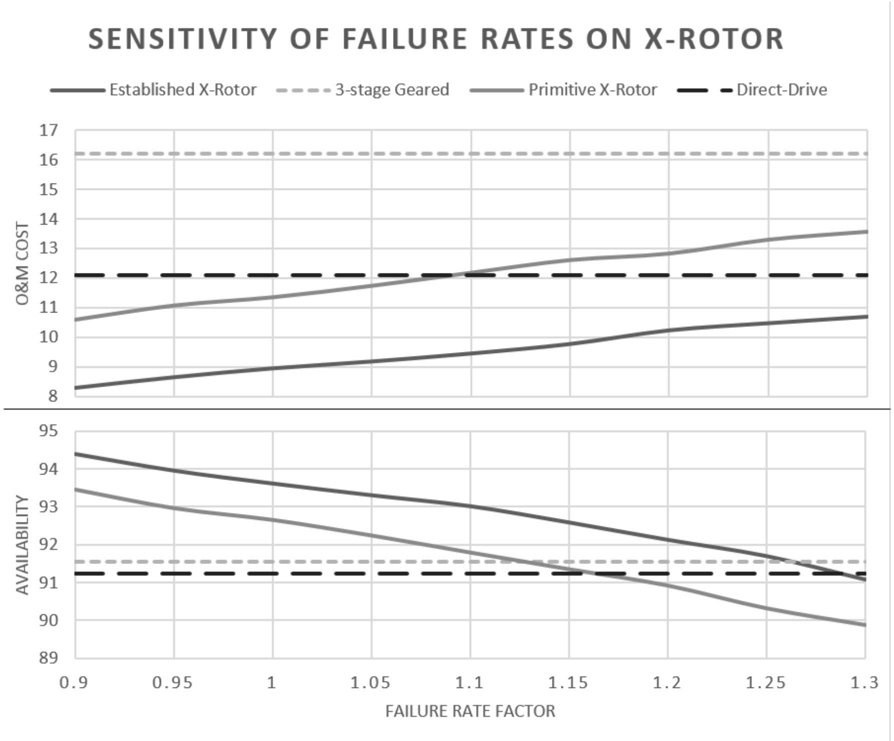

Figure 5: Sensitivity analysis on failure rates that are inputs to the model. The failure rates of all failure modes were varied from 0.9 to 1.3 of the values from Carroll et al. [9] used for conventional HAWTs. Plotted are the change in total O&M costs (top) and availability (bottom) for a farm of primitive X-Rotors and established X-Rotors. The O&M costs and availability of the direct-drive HAWT and the 3-stage geared HAWT are plotted as horizontal lines for comparison.

5. Discussion and Conclusions

The added flexibility in the StrathX-OM model compared to the StrathOW-OM model [2] allows for modelling of the innovation available to an X-Rotor turbine that is not possible for conventional HAWTs. The scope in variation from concept to commercial technology is large so the model produced needed to be able to handle this variation and capture the designs accurately. Both X-Rotor designs and both HAWTs were analysed to show the flexibility in functionality of the model to handle turbines of different designs, and to show that the assumptions in design of the finalised X-Rotor need to be realised to set the turbine apart from conventional technologies in terms of O&M Costs.

The FSVs used in the study could transport four HAWT modules at once and, on days without weather conditions limiting the length of the working day, four modules could be replaced per day. This opens up the option of batching the repairs. For this study, there were 200 secondary HAWTs across 100 turbines which lead to, on average, 325 secondary HAWT failures per year. However, only six of these required replacement of the HAWT module. Therefore, in this case batching was not a viable option due to the relative lack of frequency of replacements. For larger farms, or X-Rotors with more than two secondary HAWTs, this will become increasing valuable. Even without batching of the module replacements, the innovation lead to a decrease in transport costs and overall O&M costs.

There are significant reductions in O&M costs for the HAWTs compared with the results from previous literature [9]. The main difference for this is the electricity price used. In this case, €50/MWhr was chosen to reflect current market. The latest strike price in the UK was less than £40/MWhr, which is approximately €50/MWhr. Although the now widely used empirical data is from farms that had set electricity prices of nearly €150/MWhr, it was chosen to reduce this to current market value as the X-Rotor will be competing for market in the future when there is likely to be little financial support for wind energy. The three-fold reduction in electricity price leads directly to a three-fold reduction in lost revenue. This shifts the balance in favour of spending less on transport to reach the minimum total O&M cost. This can be seen in the results of the case study. The 3-stage geared HAWT had a higher availability then the direct-drive but had a greater O&M cost. This was due to using six CTVs in the strategy whereas there was only five used in the direct-drive farm. Adding an extra CTV to the strategy for the 3-stage geared farm increased the availability to beyond that of the 3-stage but the extra transport and staff costs made the total O&M cost greater. Similarly, as can be seen in the sensitivity study (figure 5), the availability of the established X-Rotor design drops below the availability of the conventional HAWTs between a 1.25 and 1.3 factor increase in failure rate, but the total O&M cost is still lower.

The results of this paper show that the X-Rotor has comparable availability and O&M costs to conventional HAWTs even when the design is primitive, that is, not making use of the potential to have detachable secondary HAWTs and operate at reduced capacity with one of the secondary HAWTs failed. The established design had higher availability and significantly reduced O&M costs. The reduced reliance on JUVs and the increased availability from reduced capacity operation following a failed secondary HAWT were the main factors in this. Similarly, the removal of high failure rate components with long down time also played a role in reducing O&M costs, even, as the sensitivity study showed, when the failure rates of other components were vastly over-estimated.

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