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Wind Turbine Reliability Forecast: A Technical Review on the Research Milestone and Assessment of the Energy Cost Using Monte Carlo Simulation

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Abstract

Renewable energy, particularly wind energy, has begun to transform the global power structure, which was previously dominated by fossil fuels. The growth rate of wind energy installations reaches 30%, providing promising potential. However, wind turbines have the potential for failure in both offshore and onshore wind turbines. The failure rate of wind turbines needs to be considered to maximize the electrical energy they can generate, which may increase the levelized energy cost. This research aims to develop maintenance strategies, implement risk prevention measures, and enhance the operational efficiency of wind turbines to minimize negative impacts on energy production and costs. This research utilized variables such as failure probability, downtime, and maintenance cost, which were then simulated using the Monte Carlo method. The results showed that wind turbine failures had a significant impact on energy production and costs. The prolonged duration of downtime and increased maintenance costs will lead to a decrease in energy production and higher energy tariffs.

Keywords: Wind turbine; Component failure; Monte Carlo simulation; Energy production; Energy cost.

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1. Introduction

Energy is essential for industrial and transportation needs. Energy demand increases annually, as illustrated in Fig. 1, which presents data on energy demand from various sectors from 1990 to 2050.[1] Limited fossil fuels, the adverse effects of greenhouse gases, and high crude oil prices underscore the importance of renewable energy sources, such as geothermal, solar, and wind.[2] Using renewable energy has altered the global energy landscape, which was once dominated by fossil fuels. Among all sources of renewable energy, wind energy has the highest growth rate, increasing by 30%.[2] Wind energy has been used to produce electrical energy since the 1880s, with three wind turbines installed in the United States (1883), Scotland (1887), and Denmark (1887). Since then, both onshore and offshore wind turbine types have been used to explore wind energy.[3] Fig. 2 illustrates that the number of offshore wind turbines installed annually is increasing, with a total installed capacity of 57.6 GW in 2022.[4]

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In recent years, offshore wind turbines have emerged as an attractive and rapidly growing option due to their numerous advantages. They have more abundant, robust, and consistent wind sources.[5] In addition, the capacity factor, or the ratio of actual electrical energy to the maximum possible electrical energy output during that period, is usually higher in offshore wind turbines. The goal of wind energy is to reduce the price of electricity to a level comparable to that of fossil energy sources. Therefore, operational reliability, availability, and effectiveness of energy generation from the concept are required.[3]

Wind turbines have complex and intricate components that have a risk of failure. The costs associated with wind turbine operations are primarily driven by operating and maintenance

(O&M) costs, according to research by Shafiee *et al.*[6] conducted on 100 wind turbines of 5 MW or with a capacity of 500 MW, the cost required for O&M is 26%. From these results, downtime and O&M costs are the primary considerations in the wind energy sector to achieve lower Levelized Cost of Energy (LCOE) values.

Wind turbine cost estimation is crucial for several reasons, including investment planning, budgeting, site selection, and risk management. Investment planning is a reference for investors to determine the value of an investment in a wind turbine project. Budgeting aims to determine the budget required for the purchase, installation, and operation of wind turbines. Cost estimation is also crucial for selecting wind turbine sites based on wind speed, regional conditions, and accessibility.

Table 1 summarizes the methodological approaches and variables in several recent studies on wind turbine reliability and energy cost estimation. These studies show a variety of methods, ranging from empirical data analysis to probabilistic-based modeling,[7] such as Markov and Monte Carlo,[9] which are used to assess the effect of reliability on annual energy production. Several studies, such as by Shafiee & Dinmohammadi,[8] focus on risk-based Failure Mode and Effects Analysis (FMEA) approaches to assess potential failures of key turbine components. In contrast, others, such as Tavner, concentrate more on industrial and engineering data analysis to evaluate performance and downtime.[11]

This case study aims to analyze the optimization of wind energy as a renewable energy source, replacing fossil energy. The analysis calculated wind turbine failure rate, downtime, and maintenance costs. This aims to consider the risks associated with wind turbines, providing a reference for selecting components that are more resistant to failure. Additionally, the calculation includes Annual Downtime, Annual Maintenance Cost, Energy Production, and the Cost of Energy (COE).

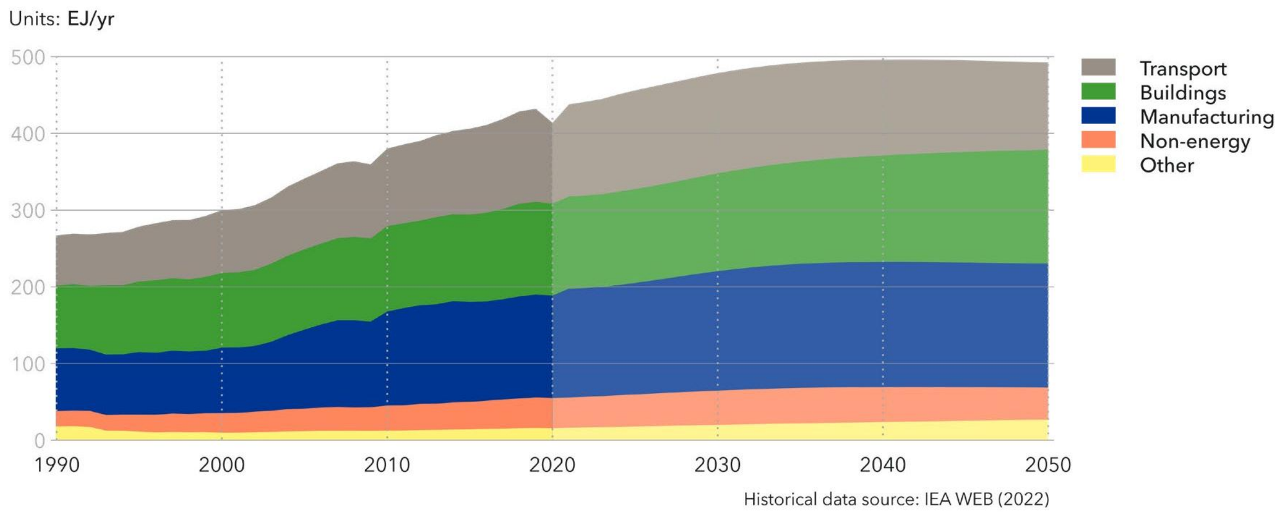


Fig. 1: World energy demand by sector.[1]

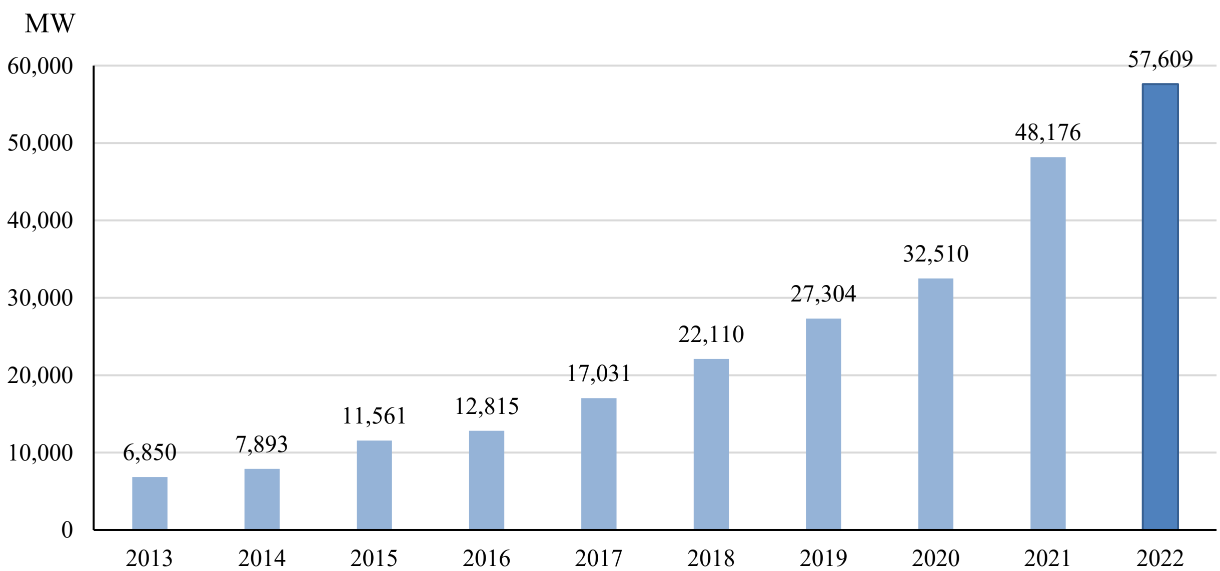


Fig. 2: Offshore wind turbine installed by capacity. The figure is produced based on the data in the reference.[4]

Table 1: Comparison of methods and variables used in recent studies on wind turbine reliability and energy cost analysis

Reference	Method	Turbin type	Capacity (MW)	Variables analyzed	COE analysis
Carroll *et al.*[7]	Empirical data analysis	Offshore	3.6	Failure rate, O&M cost, repair time	No
Shafiee & Dinmohammadi[8]	Risk-based FMEA	Onshore	2–5	Failure risk, ranking of components	No
Fan *et al.*[9]	Markov + Monte Carlo	Offshore	5	Reliability, AEP loss	No
Kaiser & Snyder.[10]	LCOE Modeling	Offshore	–	CapEx, OpEx, LCOE	Yes
Present study	Monte Carlo & Analytical	Offshore	5	Failure rate, Downtime, Maintenance cost AEP, COE	Yes

This case study aims to analyze the optimization of wind energy as a renewable energy source, replacing fossil energy. The analysis calculated wind turbine failure rate, downtime, and maintenance costs. This aims to consider the risks associated with wind turbines, providing a reference for selecting components that are more resistant to failure. Additionally, the calculation includes Annual Downtime, Annual Maintenance Cost, Energy Production, and the Cost of Energy (COE).

2. Failure tendency

Offshore Wind Turbines (OWTs) comprise a complex structure of interconnected and interdependent subsystems negatively impacted by harsh operational conditions.[12] OWTs are built to withstand extreme environmental conditions, including high winds, seawater waves, seawater corrosion, and storms. Failures in OWTs include structural foundation damage, blade damage, component wear, and electrical system failure.

In 2008, five wind turbines at Changhua Coastal Industrial Park in Taichung were damaged by the storm brought by Typhoon Jangmi. Seven blades were damaged; only one turbine blade could be repaired, while the other six were declared irreparable.[13] Fig. 3 shows data that in March 2012, there were 1208 WT failures, with blade damage accounting for 19.4% of the causes. The other highest category of WT failure cause was the "Unknown" category, which accounts for 19.4%. The data showed that blade damage was the most common cause of WT failures.

Table 2 shows WT's statistical data on the causes of blade failure. Based on the data, more than 30% of blade failures were caused by lightning, storms accounted for 28.21%, and strong winds accounted for 15.38%. If storms and strong winds were combined, the percentage increased to 43.59%. Both storms and strong winds occurred during Typhoon Jangmi. In addition to this data, it can be concluded that extreme weather factors dominated the cause of blade damage.

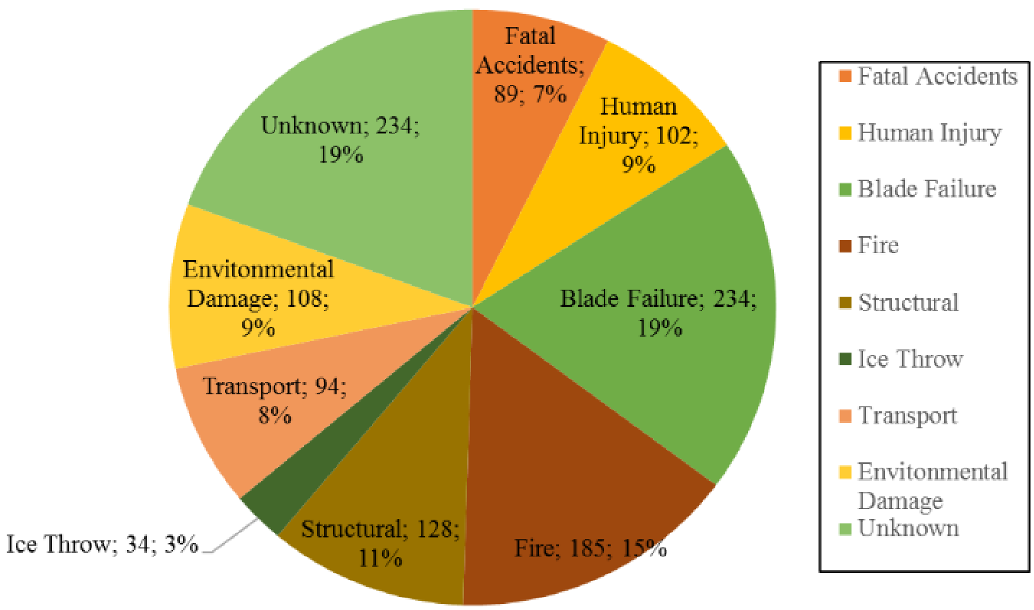


Fig. 3: Causes of wind turbine failure. The figure is produced based on the data in the reference.[13]

Table 2: Summary of wind turbine blade damage causes.[13]

Damage disaster	Number of times	Occurrence (%)
Lightning	38	32.479
Storm	33	28.205
Strong wind	18	15.385
Tornado	3	2.564
Resonance	3	2.564
Snowstorm	3	2.564
Human error	2	1.709
Hailstone	2	1.709
Defect	2	1.709
Self-destruct	2	1.709
Collapse	1	0.855
Blade fail	1	0.855
Technical defect	1	0.855
Transport	1	0.855
Bolt damage	1	0.855
Fire	1	0.855
Running out of control	1	0.855
Poorly designed	1	0.855
Strike	1	0.855
Mast damage	1	0.855
Explosion	1	0.855
Total	117	100

Fig. 4 shows a wind turbine blade used in ANSYS software. The results showed that most wind turbine failures occurred at the blade's tip. The causes of the failure incidents included blade material strength, wind frequency and resonance effects, and human error at the installation stage. Based on the tests, the WT blades are expected to fail at an average wind speed of 80 m/s.

Another study on the failure of WT blades by Rafiee and Hashemi-Taheri discussed the inability of WT blade adhesive joints.[14] As the dimensions of WTs increase, the length of the blades will also increase. Concerns about the strength of WT blades to failure at 20-25 years of use had increased. Damage was caused by delamination, complete buckling, global buckling, and separation of the adhesive joint. Adhesive joint failure occurred at the leading edge, spar cap, shear web, and trailing edge joints. Damage to the trailing edge was one of the primary causes of wind turbine blade failure and also contributed to the reduced aerodynamic performance of the blades.

Marín *et al*.[15] mentioned that the damage zone on a blade was found in the form of cracks. The cracks in the zone between the blade root and the aerofoil profile are shown in Fig. 5. Fatigue damage occurred due to delamination in the composite material and the lack of resin content in the material that makes up the blade. Additionally, the damage was caused by differences in thickness within the blade structure, particularly in the zone between the blade root and the aerofoil profile.

Lee *et al*.[17] conducted a turbine blade fatigue test on a 3 MW composite blade with a length of 56 m and a weight of 14.5 tons at full scale. The test aimed to identify the cause of wind turbine blade fatigue by simulating the deformation and stress distribution at the blade root. The test results showed the delamination failure at the blade root tip. The failure at the blade root tip was caused by the bumping motion of the blade, which caused the load distribution.

In addition to turbine blade failures, the tower was another wind turbine component with a high failure frequency. In 2016, six wind turbine towers at the 2 MW Taichung Port wind farm collapsed due to Typhoon Soudelor. In addition, in 2008, Typhoon Jangmi also caused the first collapse of a turbine tower in Taiwan at the same place. Statistics from 1980 to 2017 revealed a total of 2,089 wind turbine accidents. Fig. 6 shows that data from 2007 to 2017 were used as a reference, with 1,479 accidents occurring, indicating that blade failure was the leading cause of wind turbine accidents. However, most wind turbine collapses were caused by wind turbine tower fatigue and failure of bolts that were either under-strength or in short supply.[16] The failure of wind turbine towers causes considerable economic losses.

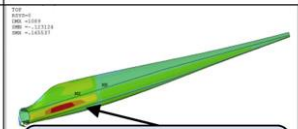
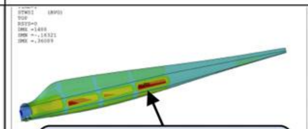
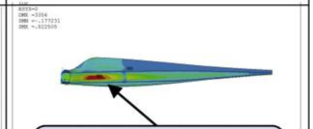
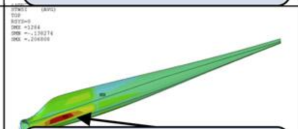
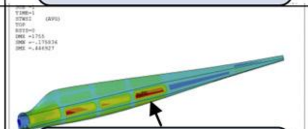
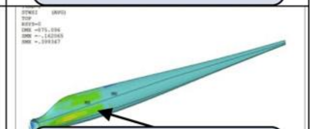
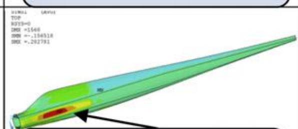
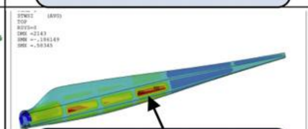
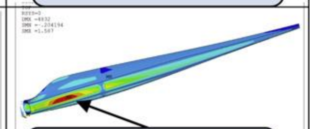
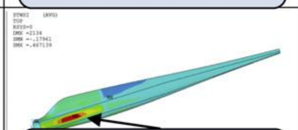
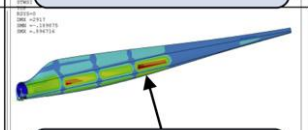
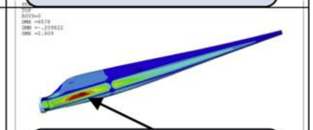
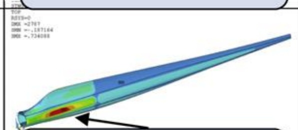
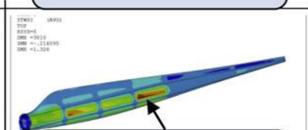
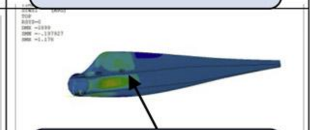
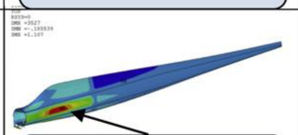
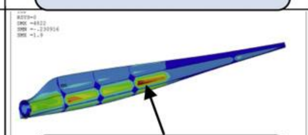
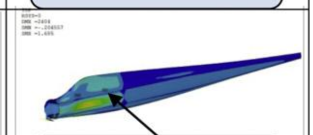
Wind speed (m/sec)	Model constructed according to the parameters recommended in [26]	Model constructed according to the parameters recommended in [29]	Model constructed according to this study's parameters
50	 Tsai-wu failure criterion: 0.165537	 Tsai-wu failure criterion: 0.36089	 Tsai-wu failure criterion: 0.323
53.4	 Tsai-wu failure criterion: 0.206808	 Tsai-wu failure criterion: 0.44693	 Tsai-wu failure criterion: 0.399
60	 Tsai-wu failure criterion: 0.282781	 Tsai-wu failure criterion: 0.58345	 Tsai-wu failure criterion: 0.521
70	 Tsai-wu failure criterion: 0.467039	 Tsai-wu failure criterion: 0.89672	 Tsai-wu failure criterion: 0.798
80	 Tsai-wu failure criterion: 0.734088	 Tsai-wu failure criterion: 1.32600	 Tsai-wu failure criterion: 1.178
90	 Tsai-wu failure criterion: 1.10700	 Tsai-wu failure criterion: 1.90000	 Tsai-wu failure criterion: 1.685

Fig. 4: Wind turbine ANSYS simulation.[13]

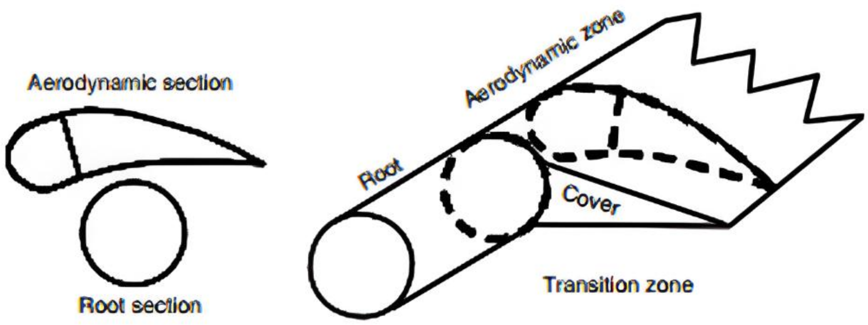


Fig. 5: Zone between the blade root and aerofoil profile.[15]

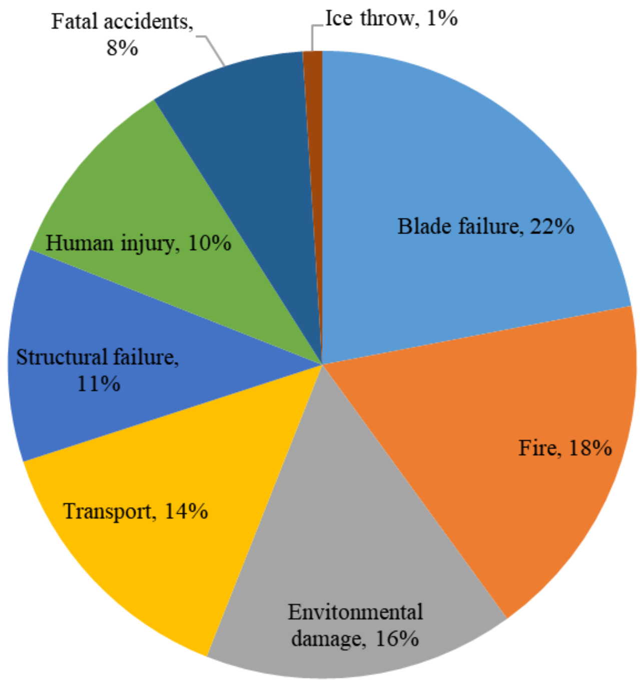


Fig. 6: Distribution of causes of wind turbine failure.[16]

Chou and Tu discussed the causes of Floating Offshore Wind Turbine (FOWT) tower collapses, identifying several contributing factors, with the highest percentage attributed to storms at 34.1% in 15 cases, as shown in Table 3.[18] The following include strong winds, fire, ice storms, material fatigue, etc. The failure of a wind turbine tower is crucial because wind turbine towers are unlike other components that can be easily replaced when damaged.

Gearboxes are a vital component in a wind turbine, and failures can result in various losses, including downtime and increased operational costs. Gearboxes in offshore wind turbines present numerous challenges during operation. Challenges to gearbox components in offshore wind turbines include design, manufacturing development, installation, maintenance, and operation. Gearboxes in offshore wind turbines must withstand a range of weather conditions, including varying temperatures, wind speeds, and loads.[19] Gearbox components are susceptible to unique environments, including corrosion, high temperatures, high pressures, high speeds, and vacuum. In offshore conditions, wind turbines often experience extreme weather conditions with wind speeds exceeding 25 m/s.

The gearbox comprises several components, including gears, bearings, lubricating systems, shafts, housing, and pipes. The failures of the gear section are gear tooth failure and gear slippage. The causes of these failures include corrosion, fatigue, misalignment, and deformation. Failures in the gears can cause the gearbox to stop and reduce its efficiency. Shaft components experience failures in fatigue and fracture, bending, and misalignment. These failures are caused by irregular grooving, high torque, high speed, weld defects, and fretting corrosion. The effects of shaft damage are the cessation of energy transmission, reduced efficiency, and the onset of vibration in the gearbox.

Table 3: Significant causes of tower collapse.[18]

Cause of Failure	Case	Occurrence
Strom	15	34.1
Strong winds	8	18.1
Fire	5	11.3
Ice storm	4	9.1
Material fatigue	3	6.8
Being struck by blade	3	6.8
Lightning strike	2	4.6
Faulty welding	2	4.6
The braking system failed	2	4.6

Other studies categorize types of gear failures into seven parts: wear, abrasion, plastic deformation, contact fatigue, cracks, fractures, and bending fatigue. In the gear, tooth fracture occurs due to extreme loads or overloads, which cause cracks that become root-bending fatigue cracks. The result of this damage can cause broken gear particles to damage other gears, and also cause noise and vibration. The pitch system, in particular, is one of the critical subsystems of a wind turbine, supporting its effective control to maximize wind capture while protecting its integrity in the event of overload. The pitching mechanism is also responsible for operational downtime, so its reliability performance needs to be carefully evaluated to ensure operational availability. Results confirm high failure rates in pitch systems of both types. With 0.54 failures per WT and year, the overall failure rate of the hydraulic pitch system is slightly lower than that of the electric pitch system, with 0.56 failures per WT per year shown in Figs. 7 and 8.[20]

The component categories ‘‘Battery Pack, ‘‘Control/ Rectifier/ Inverter/Thyristor, and ‘‘Motor Protection Relay/Multifunction Relay’’ were identified as most critical for the electrical pitch system. The hydraulic pitch system showed the highest failure rates in the component categories ‘‘Hydraulic Accumulator Unit/ Oil Tank’’, ‘‘Pitch Cylinder’’ and ‘‘Hydraulic Valve’’. This highlighted that the main concerns of the hydraulic pitch system were related to the system itself.

3. Failure probability

Failure means the inability of a system or component to perform the required function according to its specifications. Carroll *et al*.[7] defined failure as an unscheduled visit to a wind turbine where a component or element allows the wind turbine to function. The probability of failure is defined as the probability of failure of a system or component within a specific period.[21] Probability of failure (PoF) is the calculated value of the chance of a possible failure of a piece of equipment. While failure probability is significant, it has troublesome properties that raise several theoretical, practical, and computational issues. In particular, these problems arise when failure probabilities are used in structural design optimization.

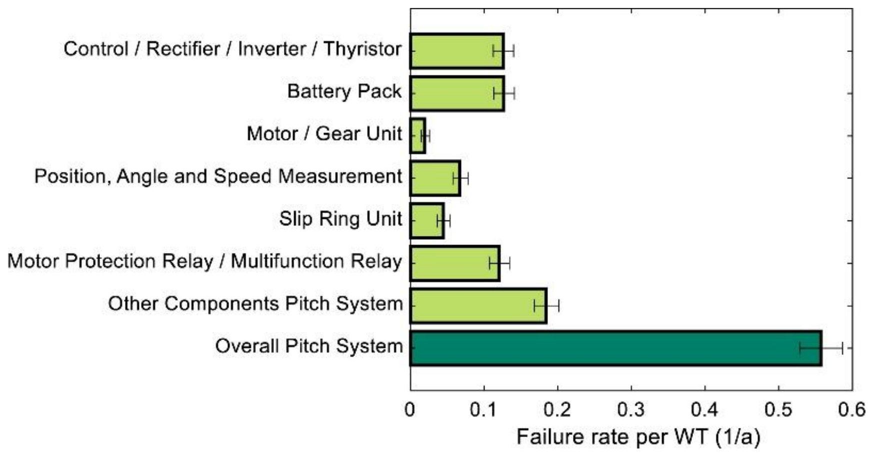


Fig. 7: Failure rate of the hydraulic pitch system.[20]

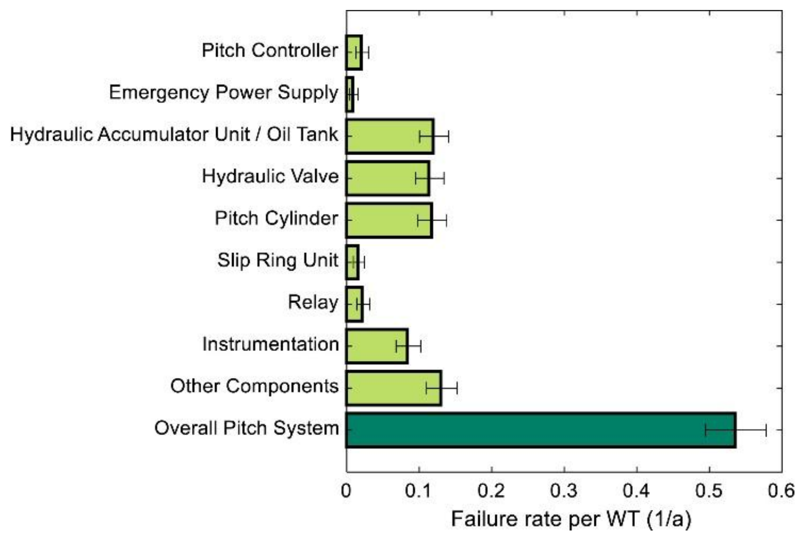


Fig. 8: Failure rate of the electric pitch system.[20]

In the case of wind turbine failure, the bathtub graph in Fig. 9 shows that the failure rate is high at the beginning of the installation period. However, initially, a relatively rapid period of decline occurs, and a rapid decline due to product failures and defects can be quickly and easily recognized. Then, it has a low and constant failure value in the use period phase. This period is the life span of a product. Then, the last period is the wear-out period, also known as the end of life. During this period, the failure rate was relatively high, as it exceeded the design calculation for the product.[22]

The complex system in a wind turbine allows failures to occur. Failure analysis and failure behavior are indispensable for the performance of floating offshore wind turbines. They form the basis for determining economic maintenance strategies, robust designs to reduce potential failures, and the expected return on investment. However, the structures on offshore wind turbines are still relatively new, so information regarding their failures is not yet available. Li *et al.*[3] Conducted research for Failure Mode and Effect Analysis (FMEA), which was applied in OWT's comprehensive failure analysis based on extensive expert data collection. FMEA is a systematic process that identifies and ranks failure items using a bottom-up approach. Risk Priority Number (RPN) is an index of the level of risk in each failure item/cause of failure. The equation for calculating RPN, based on severity, occurrence, and detection, is given in Eq. (1).

$$RPN = S \times O \times D \quad (1)$$

where RPN represents the Risk Priority Number, S is the severity score, O is the occurrence score, and D is the detection score.

Table 4 presents the severity rating parameters, event descriptions, and their corresponding probability values, providing a reference for further calculations.

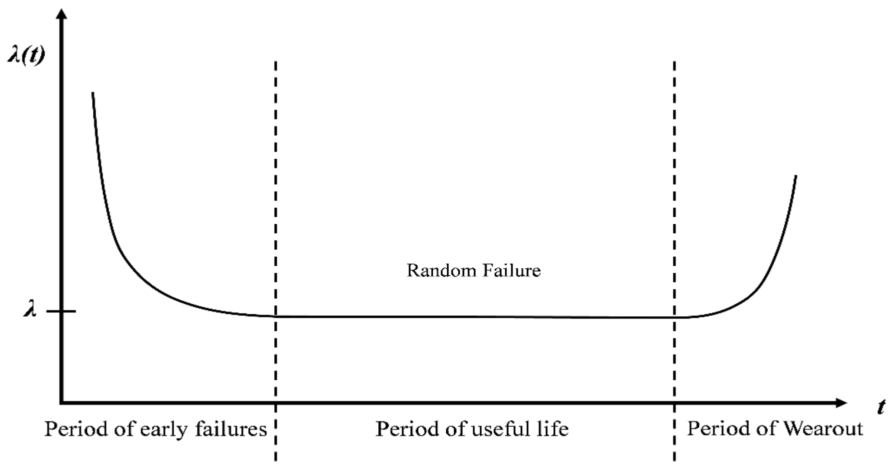


Fig. 9: The bathtub curve.[22]

Table 4: The rating guidance of severity, occurrence, and detection.[23]

Rating	Severity	Occurrence		Detection
		Probability	Description	
1	The effect is not noticed	$P < 10^{-5}$	Extremely less	Certain
2	Very slight effect noticed	$P = 10^{-5}$	Remote	Very high
3	Slight effect causing annoyance	$P = 10^{-5}$	Very slight	High
4	Slight effect causing return of product	$10^{-5} < P < 4 \times 10^{-4}$	Slight	Moderate
5	Moderate effect causing return of product	$4 \times 10^{-4} < P < 2 \times 10^{-3}$	Occasional	Medium
6	Significant effect	$2 \times 10^{-3} < P < 1 \times 10^{-2}$	Moderate	Low chance
7	Major effect	$10^{-2} < P < 4 \times 10^{-2}$	Frequent	Slight
8	Extreme effect, system inoperable, safety issue	$4 \times 10^{-3} < P < 0.2$	High	Remote
9	Critical effect, system shutdown, safety risk	$0.2 < P < 0.33$	Very high	Very remote
10	Hazardous, without warning, life-threatening	$P > 0.33$	Extremely high	No chance, no inspection

Overall, the results of 15 components, 42 failure modes, and 104 causes of offshore wind turbine failure were considered according to their criticality ranking (see Fig. 10). The results showed that energy-generating components and supporting structures had a higher risk level. Additionally, components with complex functions, such as gearboxes and generators, are more prone to failure.[24]

Li *et al*.[24] defined the failure rate as the probability of failure in a unit of time. This demonstrated the innate ability of wind turbines to resist failure under the influence of a coupling of internal excitation, such as strength degradation, and external excitation, such as environmental conditions. The study also revealed the failure rate of wind turbine components and sub-components in 76 wind turbines, resulting in a total of 2.57 failures/turbine/year, as summarized in Table 5.

The study conducted by Pinar Pérez *et al*.[22] showed the value of the average failure rate of wind turbine components, including hubs, blades, generators, electric systems, control systems, *etc*. Fig. 11 presents the highest failure rates for the blades, electric system, and control system, while the components with the smallest failure rates were the hub, drive train, and structure. The presented data in Fig. 11 shows the wind turbine failure analysis value based on its components.

The same study also compared the failure rates of wind turbine components based on their type and power output. The wind turbine had three blades and was capable of producing 600 kW. The types of wind turbines were A0 (constant speed with passive stall control), A1 (constant speed with active stall control), Direct Current (DC) Damper Enhancement (DDE - variable speed direct drive with an electrically excited synchronous generator), and B (limited variable speed). Table 6 shows that the DDE type had the highest failure rates, followed by types A1, B, and A0. In general, the blade and electric components had a failure rate that was large enough.

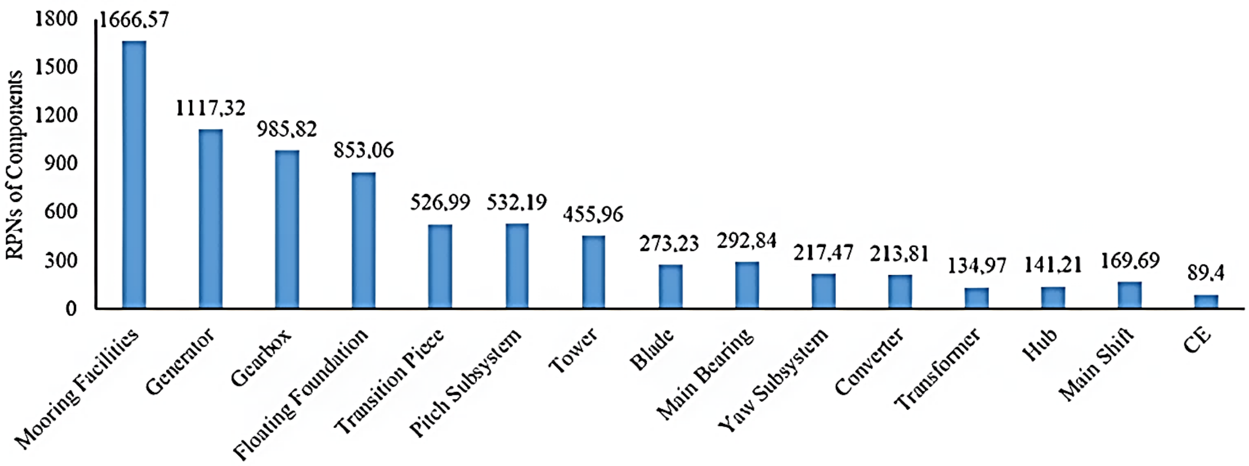


Fig. 10: RPN of components in failure analysis of floating offshore wind turbine systems and components.[24]

Table 5: Failure rate of the components.[24]

Components	Subcomponents	Failure Rate/Year
Rotor	Blade	0.1732
	Hub	0.0693
	Main Bearing	0.0116
	Main Shift	0.0116
Generator	Generator	0.8778
Gearbox	Gearbox	0.335
Electrical Facilities	Converter	0.693
	Monitoring and SCADA	0.3003
	Weather Unit	0.1271
Pitch and Yaw	Pitch System	0.4158
	Yaw System	0.0924
Cooling and Hydraulics	Cooling System	0.8085
	Hydraulic	0.8431
Auxiliary	Crane	0.0116
	Climbing Aid	0.0116
	Brake	0.0346
	Nacelle	0.104

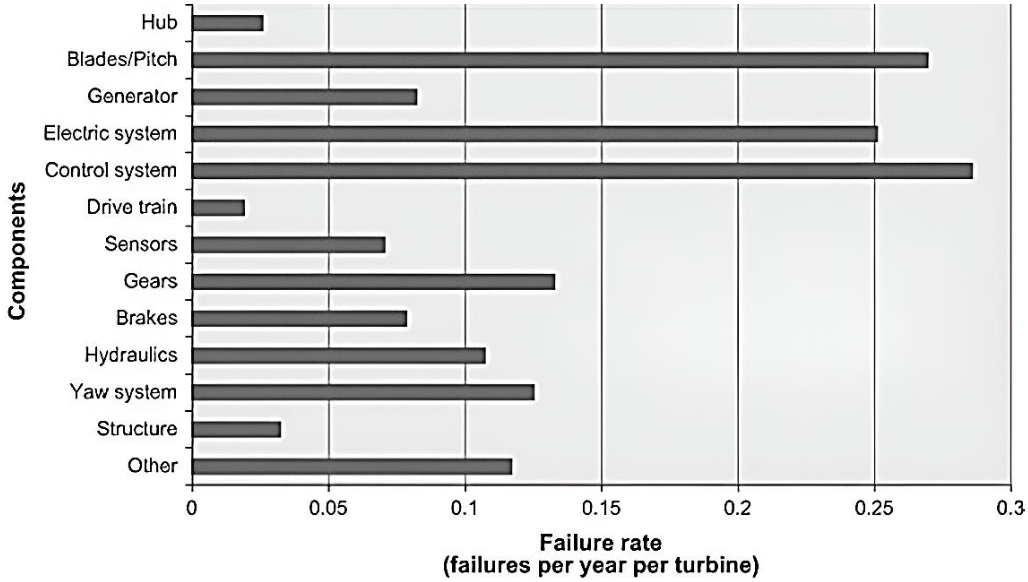


Fig. 11: Average rate of failure vs. wind component.[22]

Table 6: The failure rate of components for type A0, A1, DDE, and B.[22]

Components	Type and Model			
	A0	A1	DDE	B
Blades	0.22	0.38	0.24	0.17
Pitch	0	0	0.3	0.1
Generator	0.18	0.18	0.35	0.09
Electric	0.27	0.28	0.54	0.34
Inverter and electronics	0.2	0.14	0.31	0.27
Shaft/bearing	0.06	0.02	0.08	0
Sensor	0.12	0.07	0.12	0.08
Gearbox	0.1	0.2	0	0.18
Brake	0.05	0.18	0	0.01
Aerodynamic brake	0.1	0	0	0
Hydraulics	0.07	0.18	0.02	0.26
Yaw	0.06	0.18	0.11	0.1
Anemometry	0.02	0.04	0.08	0.06
Other	0.25	0.3	0.24	0.2

4. Downtime estimation

Wind turbine failures have another impact: the downtime required to repair turbine failures. Downtime is a crucial aspect of the wind turbine lifecycle, yet very little scientific literature has been published on this topic. Downtime in wind turbines can occur due to several factors, including machine failure, routine maintenance, adverse weather conditions, energy availability, and operational errors. In reality, downtime can occur due to a combination of these factors.

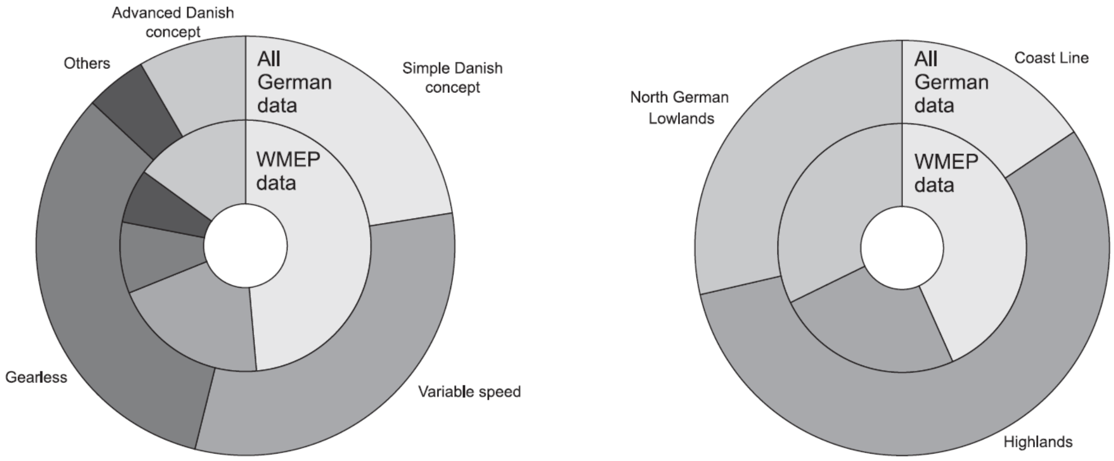
In addition to wind turbine failures, downtime occurs due to routine maintenance processes. Wind turbines require regular maintenance to operate correctly, which involves stopping the turbine's operation. Weather factors also cause the wind turbine to stop operating. Extreme weather requires the wind turbine to be shut down to prevent severe damage to its components.

In the study conducted by Faulstich *et al*.[25] a survey was completed by collecting 64000 maintenance and repair reports from 1500 wind turbines. However, the database still lacks sufficient information to accurately assess the severity of the damage. The representativeness of wind turbines is evident in Fig. 12, which illustrates both the technical concept and the turbine's location. Fig. 12(a) shows stall or pitch control, constant or variable speed, gearbox, or direct drive. In contrast, Fig. 12(b) illustrates the distribution of wind turbine locations in Germany, specifically in the North German Plain, along the

German coast, and on the German plateau. Based on this distribution, the survey conducted represented the wind turbine population in Germany.

The survey results revealed the failure rate and downtime data for wind turbines of various subassemblies, as illustrated in Fig. 13. The results highlighted the importance of downtime data, not just the value of the failure rate. The results showed the value of the annual wind turbine downtime. The wind industry focuses strongly on improving the reliability of rotor blades, gearboxes, and other mechanical subassembly systems using appropriate condition monitoring systems (CMS). However, these results showed that electrical and electronic subassemblies also caused significant downtimes, which will be extended in offshore applications.

In another study, the average downtime was the expected downtime after a system fails and stops operating. Downtime is defined as the total time between the stop and resumption of unit operation, considered when the unit is in a down state.[26] This period encompasses all subcategories, including waiting time, administrative delays, transportation time, failure detection, and repair time. Failure and related downtime are often assigned to the causative system or component to obtain detailed results for further use. The study of Pfaffel *et al*.[27] informed of the wind turbine downtime per failure of seven wind turbines. The results shown in Table 7 indicate that the downtime per failure varied from 0.18 to 7.29 days. The data showed that the drive train system had the most significant downtime compared to other components.



a. Technical Concept b. Turbine Location

Fig. 12: Representativeness of WTs in the WMEP program to WTs installed throughout Germany.[25]

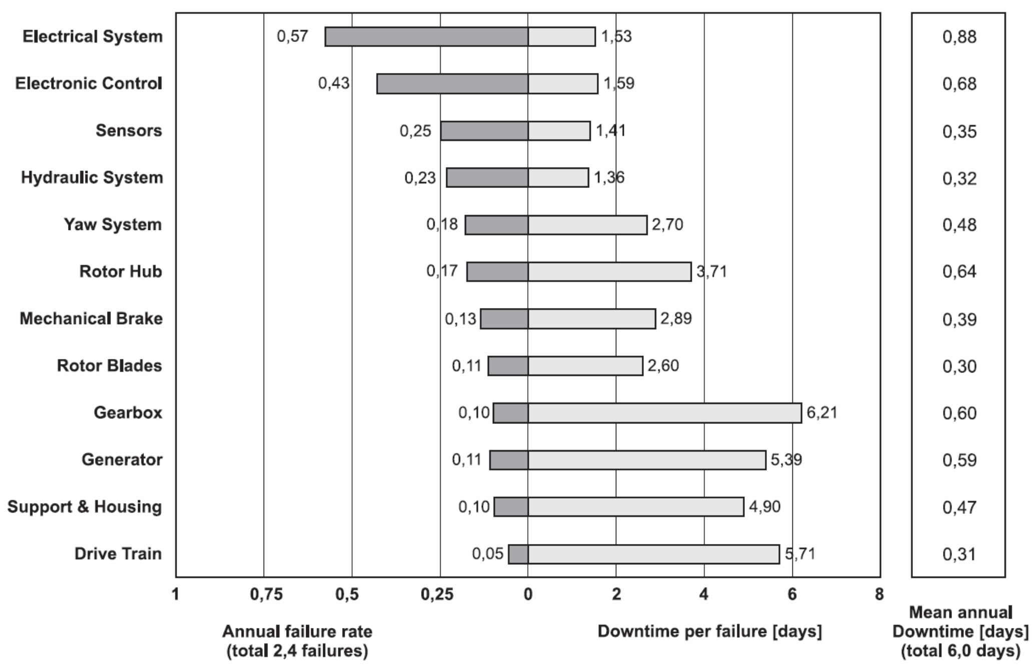


Fig. 13: Reliability characteristics for different subassemblies in the WMEP program.[25]

Table 7: Average failure rate per WT as published by different initiatives.[27]

System/Subsystem	CIRCE	Elforsk/ Vindstat	Hudian	LWK	University Nanjing	VTT	WMEP
	Mean Down Time per Failure (days)						
Rotor System	6.4	3.75	4.27	1.62	0.17	10.2	3.07
Rotor Blades	8.3	3.82	7.58	1.76	-	10.67	3.42
Rotor Hub Unit	6.76	0.52	-	-	0.14	0.83	4.13
Rotor Brake System	5.54	-	-	2.25	-	-	-
Pitch System	4.17	-	3.5	1.05	-	-	2.14
Drive Train System	8.24	10.3	6.82	4.15	0.25	21.08	4.63
Speed Conversion System	8.26	10.7	6.5	5.27	0.3	25.08	6.69
Brake System Drive Train	4.29	5.23	8.53	0.74	0.06	6.08	2.71
Yaw System	6.35	10.81	9.48	1.31	0.21	6.38	2.56
Central Hydraulic System	2.05	1.8	-	1.04	0.16	3.58	1.15
Control System	1.81	7.69	4.74	0.99	0.16	1.75	1.88
Power Generation System	13.65	8.78	7.02	3.1	0.24	5.13	7.45
Transmission	3.17	4.44	6.03	1.44	0.18	5.96	1.51
Converter System	3.2	-	6.34	1.24	-	-	-
Generator Transformer System	10.68	-	11.37	-	-	-	-
Nacelle	13.98	-	-	-	-	-	3.31
Common Cooling System	1.55	-	-	-	-	-	-
Meteorological Measurement	0.83	-	-	0.74	-	-	-
Tower System	1.88	4.34	-	-	-	7.42	-
Tower System	0.45	4.34	-	-	-	-	-
Foundation System	4.69	-	-	-	-	-	-
Other	2.02	2.27	2.27	0.92	0.14	2.8	1.57
Wind Turbine (Total)	5.18	5.42	5.75	1.72	0.18	7.29	2.57

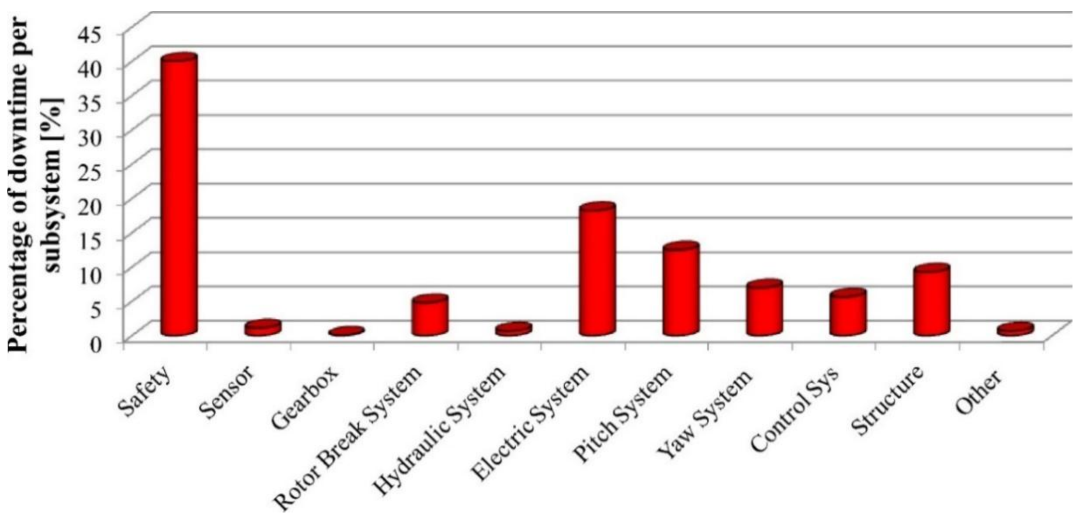


Fig. 14: Distribution of downtime per subsystem for the cluster of analysed wind turbines.[28]

As presented in Fig. 14, the study of Sarma *et al*.[28] showed the contribution of WT subsystems to the total amount of downtime. It can be seen from the data that the highest downtime value was "safety," which accounted for 40% of the total downtime events in the wind turbine farm. The "safety" alarm can be related to all existing WT components, such as alarms triggered when the wind speed exceeds the parameter limit, when extreme wind gusts cause high rotor speeds, and when the generator and rotor speeds experience speed differences exceeding the maximum allowable difference. Then, when the angle of the nacelle and the direction of the wind exceed reasonable limits, when the fire alarm system makes an error, and so on. However, the "safety" alarm can reset when the parameters are shown below the allowable limit.

Then, after "safety," the subsystem with the highest downtime when the WT fails is the "electric system." Thus, based on the data, it can be said that the problematic subsystem was in the electrical system. Examples of events resulting from electrical system failures include measurement system errors, battery issues, converter system malfunctions, switch failures, and transformer malfunctions. The electrical system is a critical component of the wind turbine. After the electrical system, the components contributing to downtime are followed by pitch, yaw, control, rotor break, and structural issues. At the same time, the WT subsystem components with the least downtime contribution are sensors, the hydraulic system, the gearbox, and others.

5. Maintenance cost

Wind turbine failures have another impact: the downtime required to repair turbine failures. Downtime is a crucial aspect of the wind turbine lifecycle, yet very little scientific literature has been published on this topic. Downtime in wind turbines can occur due to several factors, including machine failure, routine maintenance, adverse weather conditions, energy availability, and operational errors. In reality, downtime can occur due to a combination of these factors.

Maintenance is necessary to maintain or restore an item to a particular condition. In their study, Carroll *et al*.[7] stated that the gearbox had the highest average cost per failure, which reached an average of €230,000 for significant replacement costs. This value was based on the gearbox's high failure rate and high downtime. Thus, the gearbox significantly contributed to the overall operational and maintenance (O&M) cost of the wind turbine. In addition to the gearbox, the components with high repair costs were the hub and the blade, which amounted to €95,000. A further €90,000 was used for significant replacement costs. However, the fact that these components had a very low significant replacement failure rate means that the annual O&M costs were relatively low compared to the gearbox and generator, which had a high failure rate (Fig. 15).

Mishnaevsky and Thomsen explained that the repair cost of a single wind blade is $30,000, and the price of a new blade averages $200,000.[29] The blade, hub, and gearbox had the highest repair times, repair costs, and required the most technicians for repair compared to other components. A turbine that stops working can cost $800-$1600 per day, and the average repair time required is between 1 and 3 days.

Martin-Tretton *et al*.[30] provided an analysis of the component cost of repair, which showed that for a 1.5 to 2 MW wind turbine, the crane cost was $44,000, the labor cost for structural repair was $23,000, and for nonstructural repair, $4,000. The average component cost for structural repair was $88,000, and for nonstructural repair, it was $13,000.

In the study of Pinar Pérez *et al*.[22] Fig. 16 shows the distribution of component costs for a 2 MW wind turbine. The highest cost was for the tower and blades, indicating the

	Gearbox	Hub	Blades	Transformer	Generator	Power Supply/Converter	Contractor/Circuit?Breaker/Relay	Pitch/Hyd	Yaw System	Controls	Electrical Components	Other Components	Sensor	Safety	Pumps/Motors	Grease/Oil/Cooling Liq.	Heaters/Cooler	Services Item	Tower/Foundation
Minor Repair	125	160	170	95	160	240	260	210	140	200	100	110	150	130	330	160	465	80	140
Major Repair	2500	1500	1500	2300	3500	5300	2300	1900	3000	2000	2000	2400	2500	2400	2000	2000	1300	1200	1100
Major Replacement	230000	95000	90000	70000	60000	13000	13500	14000	12500	13000	12000	10000	0	0	0	0	0	0	0

Fig. 15: Failure rate Pareto chart for subassembly and cost category.[7]

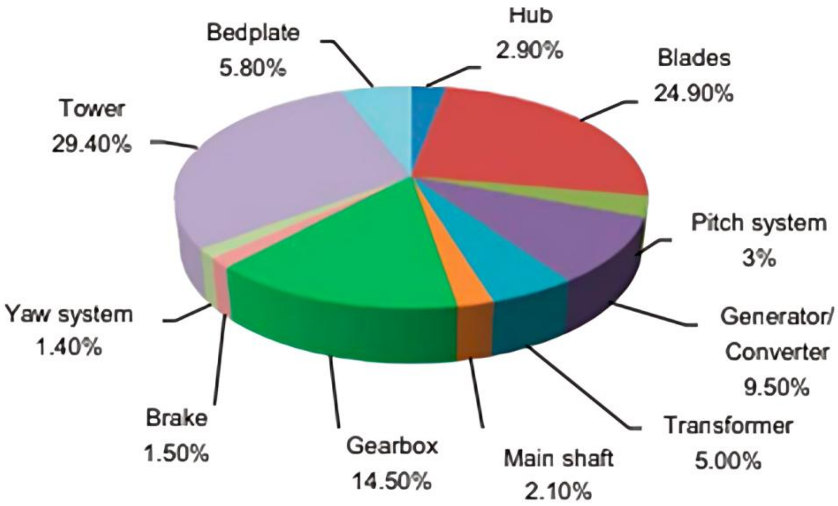


Fig. 16: Distribution of installed capacity by the leading manufacturers in 2010.[22]

highest cost of structural components in the wind turbine. The gearbox, which reached 14.5%, was the next component with a high cost. From these results, it can be concluded that the cost required when a component fails is higher the greater the percentage.

The study conducted by Kahrobaee and Asgarpoor showed the Annual Failure Cost of wind turbine components. The component with the highest cost was the generator, which cost around \$30,000, followed by the electrical system and the blade, each of which cost around \$5,000. Based on the data, the total AFC of the wind turbine reached \$55,500 with a total failure rate of 2.17 per year for the wind turbine.[31]

In the study by Tazi *et al*.[32] the generated failure costs on 2-3 MW wind turbine systems resulted in the data in the table above. The results in Table 8 show that the highest cost when the wind turbine failed was in the structure component, which reached €628,983.92. From the data, although the structural component failure rate was at the bottom compared to other components, the cost of the required components was expensive, and the repair cost was the highest. The second- and third-highest cost components were gearboxes and rotor blades, which cost €493,561.76 and €266,863.02, respectively. Meanwhile, the component with the highest failure rate, the electrical system, had a cost failure value of only around €24,057.88.

6. Case study

6.1 Site selection

The location used in this study was in Papua in the waters around the coast, located in the easternmost part of Indonesia (see Fig. 17). The exact location is in the Arafura Sea at a distance of 10 km from the coast, with the water depth of the selected location still less than 5 meters. The selected location had a wind speed of > 6 m/s at 100 meters. The wind speed was obtained from the National Aeronautics and Space Administration (NASA) Prediction of Worldwide Energy Resource (POWER) data access viewer. The meteorological parameters used were those from the NASA Global Modeling and Assimilation Office (GMAO) Modern-Era Retrospective analysis for Research and Applications Version 2 (MERRA-2). The wind data used were hourly data for 1 year, from January 10, 2021, to January 10, 2022. The data was given at

Table 8: Expected costs of failure for wind turbine sub-system.[32]

Subsystem	Failure Rate (N/Year)	Cost of Failure (€)
Structure	0.09	628983.92
Gearbox	0.1	493561.76
Rotor Blade	0.17	266863.02
Main Shaft	0.05	200589.32
Generator	0.1	179434.03
Yaw System	0.18	171169.55
Converter	0.24	69414.79
Electrical System	0.55	24057.88
Control System	0.41	22216.04
Hydraulic System	0.23	21060.4
Mechanical System	0.13	11550.08
Others	0.11	10969.4

10 m and 50 m above the ground, so calculations were needed first to get the wind speed value at a height of 100 m. The equation of the law of wind power that connects two different heights with wind speed is presented in Eq. (2) as follows:[33]

$$\frac{v_2}{v_1} = \left(\frac{h_2}{h_1}\right)^{\alpha} \quad (2)$$

where v is the wind speed, h is the height where the wind speed is recorded, and α is the wind shear exponent. For offshore wind shear, the exponent values range from 0.07 to 0.15.

From Eq. (2), the average wind speed data from the selected location at a height of 100 meters is 6.94 m/s, so the potential for energy generation is also excellent. Details of the locations used in this study are presented in Table 9.

6.2 Wind turbine configuration

The wind turbine selected for this study was a commercial model with a capacity of 5 MW. Wind turbine specification data was obtained from the wind turbine, which included cut-in wind speed, cut-off wind speed, rated wind speed, rated power, rotor diameter, and hub height. The specifications of the wind turbine are presented in Table 10. The wind turbine's power curve is shown in Fig. 18, which shows all the cut-in speed, rated speed, and cut-off speed.

6.3 Failure rate, downtime, and maintenance cost

This study utilized annual data on failure rates, downtime, and maintenance costs sourced from various literature sources, as presented in Table 11. The data obtained was the failure rate

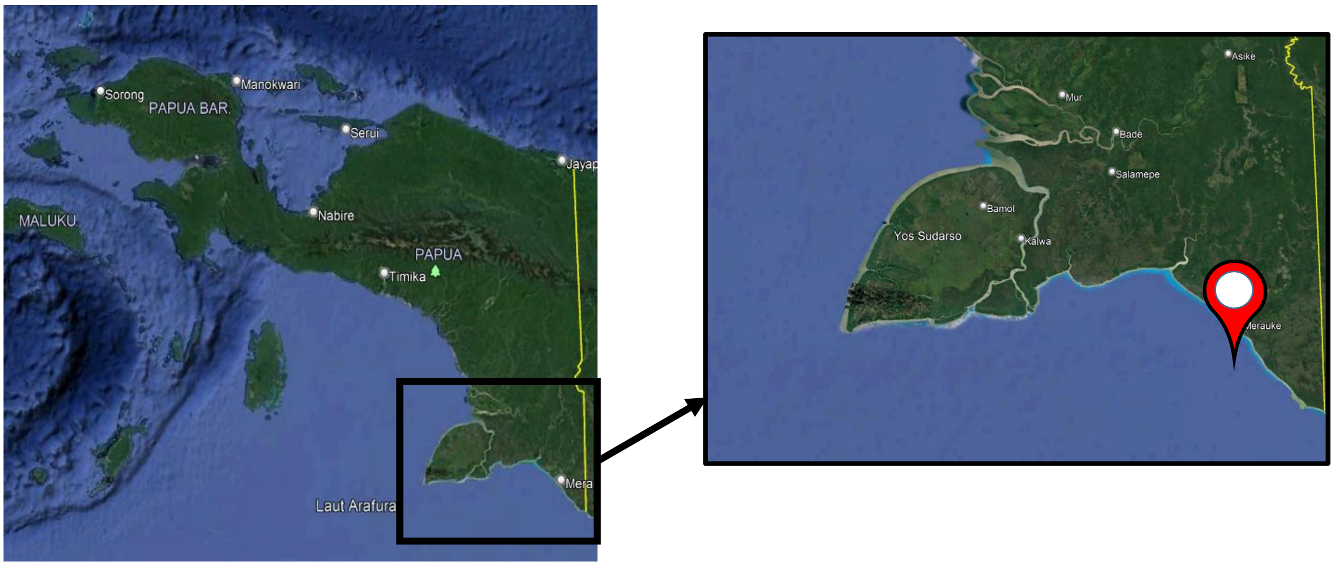


Fig. 17: Map of the site location in Papua. The image is taken from the open website Google Maps (https://www.google.com/maps).

Table 9: Site selection details.

Variable	Value
Coordinates	8°54'24.8"S 140°34'56.3"E
Water depth	<5 m
Distance to shore	10 km
Annual average wind speed	6.94 m/s
Elevation	100 m

Table 10: Wind turbine specification.

Specifications	5 MW Wind Turbine
Power Rated	5 MW
Cut in wind speed	4 m/s
Rated wind speed	11.5 m/s
Cut off wind speed	25 m/s
Rotor diameter	128 m
Hub height	120 m

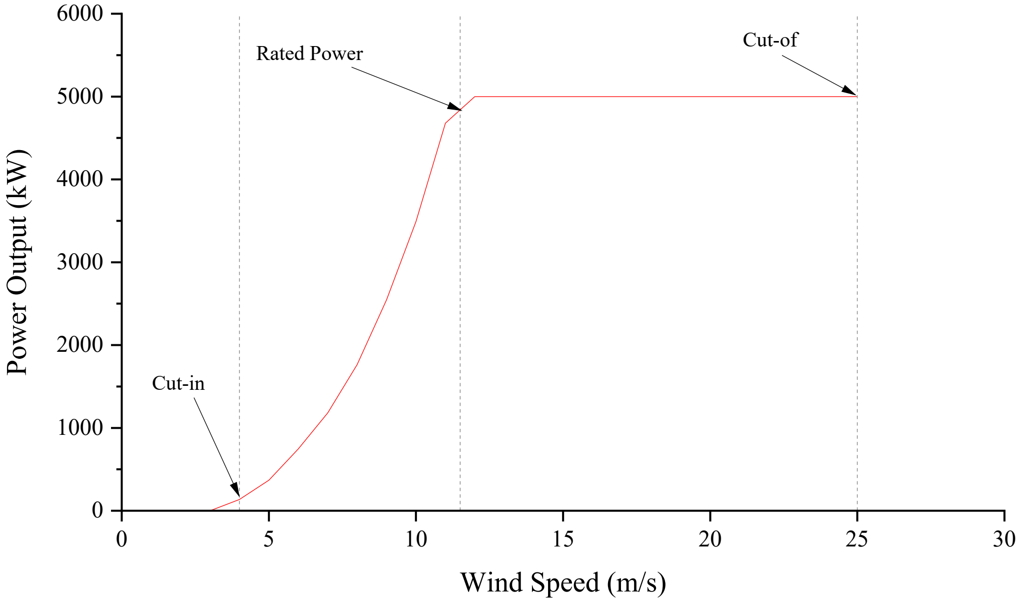


Fig. 18: Power curve of the wind turbine.

Table 11: Data failure rate, downtime, and maintenance cost.[7,31,32]

Component	Failure rate	Downtime	Maintenance cost
Generator	0.183	143.710	$124,222.53
Gearbox	0.150	264.250	$268,689.10
Brake system	0.073	105.200	$14,033.91
Power converter	0.121	75.333	$38,876.60
Blades	0.135	196.177	$151,460.23
Yaw system	0.076	68.643	$72,915.83
Electrical system	0.296	72.310	$22,106.62
Auxiliary System	0.206	51.400	$17,335.51

of each wind turbine component over one year. The downtime value represented the downtime of the wind turbine when it failed, accumulated over one year. While maintenance costs were incurred when the wind turbine failed, they consisted of repair costs, component replacement, labor costs, and towing costs.

The Monte Carlo Simulation is a widely used technique for estimating uncertainty and failure probabilities in engineering.[34] The Monte Carlo Simulation generates random samples based on input variable distributions and evaluates the system's response to each sample to determine the likelihood of failure. The failure probability is the ratio of failure-inducing samples to the total number of samples, where an indicator function is used to classify points as either failed or safe.[35] Monte Carlo simulation is slightly inefficient for computations involving minimal probability values, as it requires many simulation iterations to obtain reliable results.[36] Despite this, it remains a fundamental approach in reliability and uncertainty analysis, often serving as the foundation for more advanced methods. Monte Carlo simulation used on the probability of failure can be shown in Eq. (3) as follows:[37]

$$Pf = \frac{1}{N}\sum_{i=N}^{N} I(x_i) \quad (3)$$

where the value of N is the total number of iterations, and x_i is the i-th random sample, $I(x_i)$ is defined as Eq. (4):

$$I(x_i) = \begin{cases} 0 \; g(x_i) > 0 \\ 1 \; g(x_i) \leq 0 \end{cases} \quad (4)$$

This study uses the Monte Carlo method to simulate the probability of component failure in wind turbines. The component failure rate data is used as the basis for determining whether a component will fail or continue to function normally. Simulations were conducted to estimate two essential aspects of wind turbine operations, downtime and maintenance costs, through 2000 iterations representing various possible failure scenarios.

The Monte Carlo simulation was implemented using MATLAB software, where the Random function was used to generate a random number between 0 and 1. The random number was compared to the component's failure rate value to determine if a failure occurred. If the random number is smaller than the failure rate value, the component is considered to function normally; if it is greater, the component is declared to have failed. Simulation results are calculated for downtime and maintenance costs at each iteration. Downtime refers to the period when the turbine is out of operation due to component failure, while maintenance cost encompasses the expenses required to repair or replace a failed component. The simulation was performed in 2000 iterations to produce a more accurate distribution of both parameters under normal and extreme conditions.

Several essential input parameters are used in this simulation, including failure rate, downtime, maintenance cost, random number, and number of iterations. The failure rate describes a component's failure probability over a given period and is compared to a randomly generated number to determine whether a failure has occurred. Downtime and maintenance costs are calculated based on whether or not a failure occurs in each iteration. In addition, the number of iterations used is as many as 2000 times, aiming to obtain results representative of the possible failure results. Component failure data also serves as the basis for determining the failure rate used in the simulation. The flowchart of the Monte Carlo process is presented in Fig. 19.

A pseudocode can be used to describe the logic flow of this Monte Carlo simulation. Pseudocode represents algorithm steps in a clear, easy-to-understand form before being implemented in a specific programming language. The form of the pseudocode is shown below Algorithm 1.

The simulation produces two primary conditions: normal conditions and extreme conditions. The normal condition is the average result of 2000 iterations, describing the performance of the wind turbine under expected daily operational conditions. The extreme condition is the maximum downtime and maintenance cost value calculated from the simulation iterations, describing worst-case scenarios such as extreme weather or significant disruptions. Extreme conditions are situations that pose significant threats and can lead to extreme experiences, such as strong winds, storms, and other severe weather events. Table 12 is the result of the Monte Carlo simulation that was obtained.

From a study conducted by Faulstich *et al.*[25] analyzed the failure of wind turbine components using field data with the WMEP (the Scientific Measurement and Evaluation Program) program in Germany. The method used is real-time data collection from the turbine monitoring system, and its failure is attributed to component-level issues. The study's results indicate that several components are susceptible to damage, resulting in downtime. The downtime values from the survey ranged from 400 to 900 hours per year. The study highlights the importance of preventive maintenance, particularly for components with high failure rates, in enhancing the system's reliability more efficiently.

The study by Carrol *et al.*[7] It also showed an annual average downtime of between 500 and 800 hours, with maintenance costs ranging from $100,000 to $15,000. It

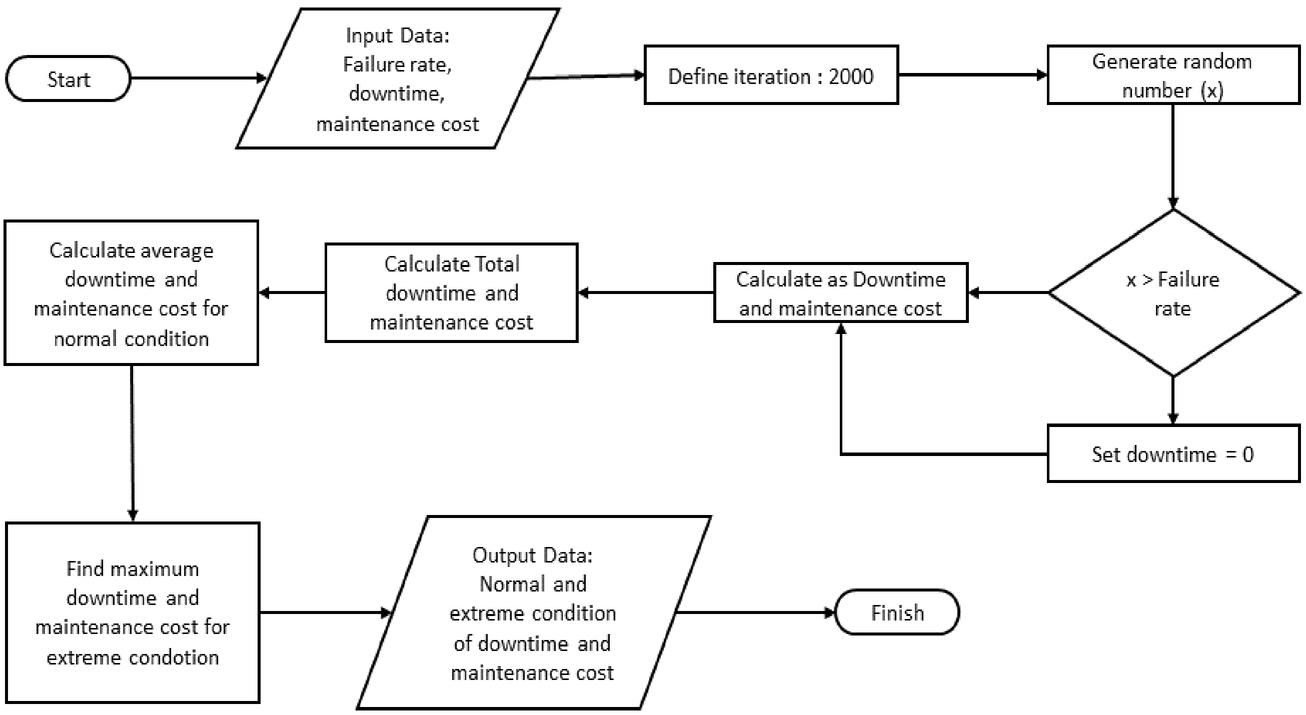


Fig. 19: Flow chart of the Monte Carlo simulation.

Algorithm 1: A pseudocode can be used to describe the logic flow of this Monte Carlo simulation.

```
START
  - Load input data from Excel file into variable `input`
  - Extract columns for failure rate, downtime, maintenance cost, and other necessary data
  - Define number of iterations (2000) for Monte Carlo simulation
  - FOR each component (index a) in failure rate data:
    - FOR each iteration (index b) from 1 to 2000:
      - Generate random number N1 using RAND()
      - IF N1 < failure rate (component a):
         - Component does not fail, set downtime to 0
      - ELSE:
         - Component fails, calculate downtime (DT) as downtime of component a
      - Generate another random number N2 using RAND()
      - IF N2 < failure rate (component a):
         - Component does not fail, set cost to 0
      - ELSE:
         - Component fails, calculate maintenance cost (CT) as cost of component a
      - Store downtime and cost in arrays DT(a, b) and CT(a, b)
    END FOR
  END FOR
  - FOR each iteration (index b) from 1 to 2000:
    - Calculate total downtime for iteration Dall
    - Calculate total maintenance cost for iteration Call
  END FOR
  - Calculate average downtime and maintenance cost for normal conditions:
    - Normal downtime = average of Dall array
    - Normal maintenance cost = average of Call array
  - Find maximum downtime and maintenance cost for extreme conditions:
    - Extreme downtime = maximum of Dall array
    - Extreme maintenance cost = maximum of Call array
  - Output the results for normal and extreme conditions
END
```

analyzed the reliability and operational costs of 5 MW offshore wind turbines in the European region. The study found that the maintenance strategy and site selection are fundamental and also affect the turbine's total operating cost. Shafiee *et al.*[6] conducted an evaluation using a dynamic programming model approach that simulated the impact of each strategy on operational costs, downtime, and failure rates. The results showed that the annual maintenance cost reached \$139,754.50/MW or \$698,772.50 for a 5 MW capacity.

6.4 Annual energy production and capacity factor

Annual energy production (AEP) is the amount of energy a wind turbine produces in one year. AEP is one of the key parameters used to evaluate the efficiency and profitability of a wind turbine. Several factors, including wind speed, size, mast height, efficiency, and other environmental factors, influence AEP. AEP is often a key criterion in wind turbine site selection and operation planning. Annual energy production can be calculated by Eq. (5).

$$AEP = \sum_{k=1}^{m}[p(V_k) \times f(V_k) \times n] \tag{5}$$

where AEP is the annual energy production in MWh, $p(Vk)$ is the power curve in MW, $f(Vk)$ is the relative frequency of wind, n is the number of hours in a year, and m is the number of bins (usually 1 m/s as the bin width).

Due to fluctuating wind speeds, wind turbines cannot run at maximum capacity continuously. The capacity factor is the ratio of the total electrical energy generated to the maximum electrical energy that could have been generated in a given period. The higher the capacity factor of a wind turbine, the more efficient and productive it is. Eq. (6) formulates the capacity factor of a wind turbine.[38]

$$CF\% = \frac{AEP}{Power\ Rated \times n} \tag{6}$$

The AEP estimation results for the wind turbine with site selection in Papua were 14577.06 MWh/year under normal conditions and 13423.96 MWh/year under extreme conditions (see Table 13). The CF of the same turbine was 33.76% for

Table 12: Result of the Monte Carlo simulation.

Parameter	Normal condition	Extreme condition
Downtime (h)	150.36	833.31
Maintenance Cost ($)	104813.11	583813.99

Table 13: Result of the AEP and CF calculations.

Parameter	Normal condition	Extreme condition	Without downtime
AEP (MWh/years)	14577.06	13423.96	14830.91
CF	33.76%	30.56%	33.77%

Table 14: Result of the COE calculations.

Parameter	Normal condition	Extreme condition	Local cost tariffs for Papua
COE ($¢/kWh)	10.39	14.86	15.02

normal conditions, and the CF of extreme conditions was 30.56%. These results utilize the number of hours in a year from the wind data of the wind turbine, which reduces downtime compared to the Monte Carlo simulation. The AEP estimation result when working continuously for a year without experiencing downtime was 14830.91 MWh/year; for the CF result, it was 33.77%. The value of CF was still quite good under both normal and extreme conditions, as the CF for offshore wind turbines was 30-40%.[39]

6.5 Cost estimation

The cost estimation in this paper was based on the scaling model of Fingersh *et al*.[40] at the National Renewable Energy Laboratory (NREL). The cost of energy (COE) encompasses the costs of energy production, including initial capital expenditures, operational and maintenance expenses, operating time, and the capacity factor level. The mathematical expression for the cost of energy is given by Eq. (7).

$$COE = \frac{(FCR \times ICC)}{AEP_{net}} + AOE \quad (7)$$

where COE is the cost of energy in $/kWh, *FCR* is the fixed cost rate 1/y (constant $), *ICC* is the initial capital cost in $, AEP_{net} is net annual energy production in kWh/y, and *AOE* is the annual operating costs in $. *AOE* is calculated using Eq. (8).

$$AOE = LCC + \frac{(O\&M + LRC)}{AEP_{net}} \quad (8)$$

where *LCC* is the land lease cost in dollars, O&M is the levelized operating and maintenance cost in dollars, and LRC is the levelized replacement/overhaul cost in dollars. For *O&M* and *LRC*, this calculation uses the maintenance cost value previously calculated by the Monte Carlo simulation.

The results of the cost of energy calculation in this study (see Table 14) indicate that under normal conditions, the COE value was 10.39 $¢/kWh, while under extreme conditions, it was 14.86 $¢/kWh. This difference was significant, reaching 42.92% from normal to extreme conditions. However, the cost was still below the maximum local electricity tariff from the Papua region. Electricity tariffs in Indonesia are regulated by the Cost of Supply (BPP), as stipulated in the Decree of the Minister of Energy and Mineral Resources no. 169.K/HK.02/MEM.M/2021.[41] The local cost tariff for Papua is 15.02 $¢/kWh. The current methodology may be extended to other energy harvesting infrastructures, such as those introduced by pioneering researchers.[42-52] Nevertheless, the scale and distribution must be considered to ensure compliance with both regulatory and economic aspects of the proposed technology.

7. Conclusions

The failure rate of wind turbine components must be considered in the design, especially in OWTs. Offshore wind turbines have a higher risk of failure than onshore wind turbines. This study examined the impact of wind turbine failure rates on energy production and the associated energy costs in a wind turbine installation in Papua, Indonesia. The wind turbine considered in this study had a capacity of 5 MW with a cut-in speed of 4 m/s and a rated speed of 11.5 m/s. The average annual wind speed in Papua was 6.94 m/s at a height of 100 m.

In this study, the wind turbine experienced a downtime difference between standard and extreme conditions for 682.95 hours per year. The difference in maintenance costs between normal and extreme conditions reached $479,000.88. The maintenance costs were incurred to repair wind turbine component failures, including component repair, replacement, labor, and other associated expenses. Wind turbines experienced a decrease in annual energy production of 1,153.10 MWh/year when operating under extreme conditions. Therefore, the percentage of the reduction in annual energy production reached 7.91%. This showed that wind turbine failure considerably influenced wind turbine energy production.

The percentage increase in COE from normal to extreme conditions was 42.92%. This increase was significant and will have a substantial impact on the energy tariff for wind turbine energy generation. With a maximum energy tariff in the Papua region of 15.02 $¢/kWh, extreme conditions will result in a smaller profit than when the wind turbine is under normal conditions. Therefore, paying attention to each component and preventing wind turbine failure is essential to maximize the benefits of installing wind turbines, especially offshore ones.

This research can be utilized in future studies to inform wind turbine design, maintenance planning, risk prevention strategies, and enhance wind turbine operational efficiency. Additionally, it is essential to inspect each component of the wind turbine to minimize the risk of failure rates that can occur in wind turbines. The selection of locations with a lower risk of failure must also be considered to maximize the benefits of installing wind turbines.

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Conflict of Interest

There is no conflict of interest.

Supporting Information

Not applicable.

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