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UPTEC ES 25035
Examensarbete 30 hp
December 2025

Resilience of Offshore Renewable Energy Technologies to Extreme Weather Scenarios

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Abstract

In this study, extreme weather scenarios and their prospective damage to offshore wind and wave farms are investigated. The objective of the study is to answer when failures are more prominent. A qualitative risk assessment is carried out to identify which extreme weather events could pose as hazards to offshore wind turbines (OWT) and wave energy converters (WEC), the results are presented in a risk matrix. Then building upon the risk assessment, a quantitative risk analysis is constructed based on the risk of failure due to wind and waves respectively during a year of operation. A model is built to estimate the number of failures of a park with 100 units and a total of 20 yearly simulations is carried out. The results are then analyzed with the intent to show during what timeframe OWTs and WECs are more prone to failures and why. This study will show that most of the failures will occur during the later parts and beginning of the year, from October through February results show that up to 40 % of wind turbines and 30 % of wave energy converters could be lost due to significant weather events.

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Populärvetenskaplig sammanfattning

Världens hav innehåller otroliga mängder energi och i omställningen till en mer hållbar och grön framtid behöver denna energi utvinnas för att minimera världens kol och oljeberoende. Det finns idag ett par tankar på hur denna energi bäst nyttjas, det främsta och mest mogna exemplet är vindkraft som man har fäst i havsbotten. Det medför att man kan utvinna mer och framförallt stabilare effekt i jämförelse med på land. Dock har vindkraftparkerna en tendens att störa den visuella miljön, sjötrafik och fiskerinäring. Det är något som man skulle kunna minimera med hjälp av flytande vindkraftsparker och vågkraft då man kan placera dessa parker längre ut till havs.

Flytande vindkraft och vågkraft är idag två tekniker som har relativt låg mognadsgrad men stor potential. Flytande vindkraftverk har kommit något längre i utvecklingen där en park i Norge har installerats med endast flytande verk. Däremot råder det inte samma konsensus inom vågkraftsindustrin och det finns ett antal olika designconcept för hur man bäst utvinner vågornas energi.

Att placera kraftparker längre ut till havs kommer dock inte bara med fördelar utan även utmaningar såsom höga installationskostnader, svårigheter att utföra underhåll och kraftverkens överlevnad i havets klimat. De väderförhållanden som råder långt ute till havs medför inte bara mer energi utan även större påfrestningar på material och konstruktion. Då extremväder blir allt vanligare och vanligare behöver dessa vind- och vågkraftverk vara tillräckligt tåliga för att överleva kraftiga stormar och vändande väder.

I denna studie utforskas flytande vind- och vågkraftverks överlevnad i havets extrema väderförhållanden vidare. Fokus ligger på att finna de risker som extrema väderfenomen kan utgöra, samt undersöka hur stor påverkan kraftiga vindar och höga vågor kan ha på två potentiella vind- och vågkraftsparker.

Resultatet visar på att det finns tydliga risker med att placera kraftparker i områden där extrema väderförhållanden förekommer. Stormar och orkaner riskerar att slå ut stora delar av parkerna. Upp till 30% av de flytande vindkraftverken i en park kan under en kort period förloras pågrund av allt för starka vindar. Resultatet visar också på att vågkraftverken överlag är väldigt känsliga för våghöjder över en viss nivå.

Det är därför viktigt att ha extremväder i åtanke för platser där parker förslås installeras. Förekomsten av orkaner är låg men dem kan ha förödande konsekvenser för kraftparkens överlevnad.

Executive Summary

In this report weather dependent risks to offshore wind and wave energy parks are analyzed, both qualitatively and quantitatively. The results indicate that risks due to extreme weather events are significant and must be mitigated carefully. The qualitative risk assessment initially show that both hurricanes and tornadoes pose the greatest risk to the parks survival. Verified by the quantitative risk assessment, which show that at an instant 30 % of the operational wind turbines could be lost due to a hurricane or tornado. Wave energy converters are also lost at a great rate during the year due to very high wave heights.

The ocean energy market is growing and the need for diversification is large but until offshore wind turbines and wave energy converters are more robust and can withstand more extreme weather the parks themselves are at a great risk of being a lost investment and time.

Contents

1 Introduction

In an era defined by environmental concerns and the urgent need to transition to sustainable energy sources, renewable energies have emerged as a solution to mitigate climate change and secure a cleaner, more sustainable future. Offshore renewables such as offshore wind, wave and tidal energy, are an option in the future but there are hurdles to overcome for offshore wind and wave energy technologies. There is potential for offshore energy production in general as the ocean offers abundant energy. In some cases ocean waves at particular sites can feature less intermittency and be more predictable, useful traits in power generation. The technology on the other hand is not as mature as onshore energy generation. Offshore wind turbine parks have been installed at a rapid rate in the last decade, with the majority placed in shallow waters which allows for foundations fixed to the seabed. Floating offshore wind turbines have been a concept for long time but have not yet reached full commercial scale.

Wave energy converters mostly exist in the model stage and in small pilot studies. The diversity among the different wave energy technologies is huge, and none of the technologies have been found superior to the others for installations, some types may fit specific conditions (water depth, distance from shore, wave conditions, etc.) better than others. Produced power, maintenance and installation costs and survivability are topics which can be discussed for both wind and wave energy as the ocean offers a harsh but rewarding environment.

Survivability is a major concern for the technologies to reach a commercial maturity. A major issue is the harsh nature of the ocean climate, strong winds and bigger waves produce more energy but also necessitates more robust construction and materials. The resilience of wind turbines onshore are studied but far fewer studies have been made for offshore floating foundations, and there are even less for wave energy converters. As offshore energy projects entails larger costs, one needs to ensure that maintenance and repair costs are kept at a feasible level.

1.1 Scope

The goal of this project is to investigate the resilience of offshore renewable energy technologies in the event of extreme weather conditions. The renewable technologies include floating offshore wind turbines (OWTs) and wave energy converters (WECs) and they will be studied in regards to the survivability in extreme weather scenarios. In the end the project will aim to discuss the following questions.

- When are failures expected for the different technologies?
- In what weather scenarios is the power production expected to be severely reduced?

1.2 Background

The offshore renewable energy sector faces unique challenges due to their increased vulnerability to environmental forces. Although research on offshore energy sources is growing, there remain significant knowledge gaps that need to be addressed to encourage further investment in these technologies.

Currently, energy producers are investing in offshore wind energy farms. However, floating wind farms have yet to be fully developed. Floating offshore wind turbines and wave energy converters could provide greater flexibility in the placement of energy generation parks. They allow for installation in deeper waters, helping to address the limited space available in shallower waters, which are often reserved for other uses such as tourism and shipping or reserved for military use. Additionally, floating systems would reduce the visual impact on coastlines.

Despite their potential, floating offshore energy systems face challenges, including, a lack of data on their long-term performance, the harsh and unpredictable ocean environment and difficulties in installation and maintenance.

While the number of research papers on this topic is steadily increasing, there are still significant gaps in our understanding that must be filled to fully unlock the potential of floating offshore energy technologies. This thesis is an attempt to fill those knowledge gaps as it is an important and growing area in the renewable energy field.

The remainder of this thesis is organized as follows. In section 1.3, an introduction to offshore renewable energy systems is given, focusing on the technologies, how they operate, and the issues they face. Theory and methods are detailed in chapter 2. This section is divided in two parts, the qualitative risk assessment and the quantitative risk assessment. The qualitative risk assessment introduces a literature review as well as a hazard identification. The second part then builds upon the identification of the hazard and introduces a Matlab scripts in an attempt to quantify the hazards arising from wind speeds and wave heights. In this chapter the script is explained in detail.

Furthermore the results are presented in chapter 3, where figures and tables produced from both the qualitative and quantitative assessments are shown. This chapter introduces tables presenting the hazards for both offshore wind farms and wave farms, specifically in section 3.1. Moreover in section 3.2 figures from the Matlab script and the quantitative risk assessment are presented.

Lastly in chapter 4, the results and their validity are discussed, followed by the conclusion in chapter 5. The Matlab scripts are available in the appendix.

1.3 Offshore Renewable Energy Systems

1.3.1 Wind Energy

Wind turbines placed on land is a fairly mature technology with its history going back as far as windmills producing mechanical power. The modern day horizontal axis turbines share structural similarities with the original windmills with their blades and large tower but now produce electriciy instead of mechanical power. During the course of wind turbine development, several designs have been proposed such as the vertical axis turbine, diffuser and drag-driven rotors, although none have proven to be as successful as the lift-driven horizontal-axis rotor (Manwell et al. 2009) commonly seen in wind parks worldwide. As the available land with favorable wind resource decreases, governments and market actors push the development of wind power further out at sea with floating foundations. This facilitates the convenient placement of large projects near major load areas.

Offshore wind parks are also attractive thanks to other beneficial factors, such as higher wind speeds and less wind shear which is improved with distance from the shore. This will directly lead to greater power production and allows for a lowered tower height to be used. The lowered tower height will allow for support structures to be smaller. The decreased wind shear results from the low surface roughness of the ocean surface (Manwell et al. 2009). This issue is more prevalent onshore, where factors like trees, hills, and buildings raise surface roughness, leading to a greater decrease in wind speeds at lower elevations.

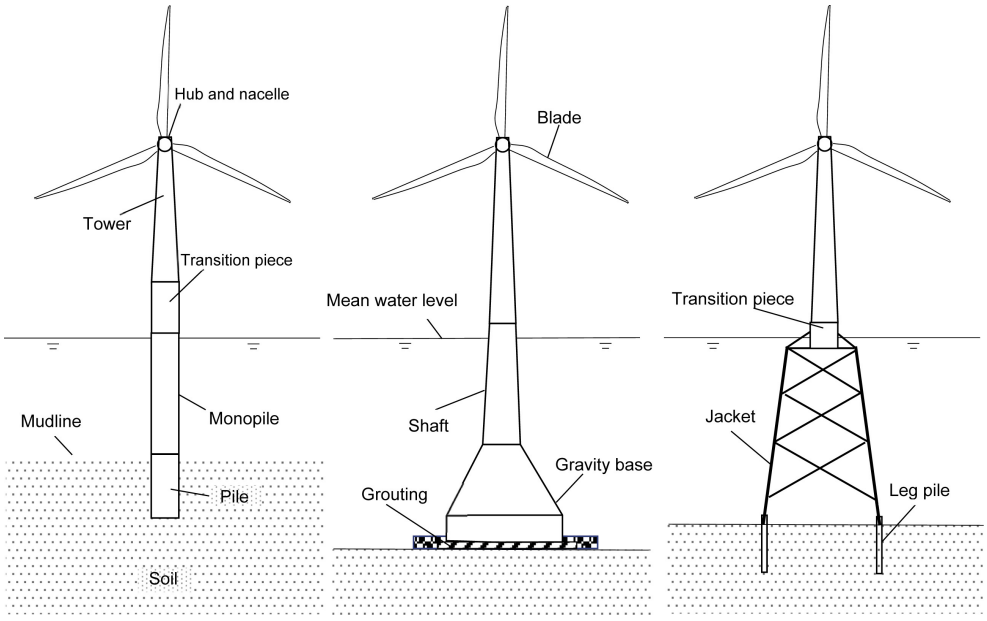

Figure 1: Three different methods of attaching the offshore wind turbine to the seabed (Jiang, Z 2021)

Most offshore wind turbine parks in operation today utilize a fixed foundation in relatively

shallow waters. In figure 1, three different foundations are shown. These are the most common types with the most straightforward structure being the monopile, on the left side in figure 1. The monopile is made from steel and in the shape of a cylinder with a diameter ranging from 3-8 m. It is used at depths of 20-40 m where the monopile can be driven into a solid seabed. In shallower waters, with depths below 10 m, gravity based foundations can be used, shown in the centre of figure 1. The base is most commonly made out of concrete and transported to the location to be submerged. The foundation can be applied to seabeds consisting of clay, sandy soil or rocks after some initial site preparation has been carried out. Lastly on the right side of figure 1 a jacket structure is featured with steel frames welded together to reach installation depths of 50-70 m (Jiang, Z 2021).

In figure 2, floating offshore wind turbine (OWT) concepts are illustrated. One option is the spar platform shown on the left side of figure 2, a cylindrical foundation which can be towed in a horizontal position, then submerged and rotated 90° at the location. The wind turbine can thereafter be installed on top of the spar. This method was used to install the first floating OWT park, Hywind Scotland following the demo spar tested in 2009. Another type of floating foundation is the semi-submerged one, which usually consists of three or four columns in parallel, as seen in the centre of figure 2. This type features more stiffness and stability compared to the spar. It can also be towed as a single unit which simplifies both installation and maintenance operations as it can be towed to and out of shore. The tension leg platform is the third type of structure seen on the right side of figure 2, which comes in a variety of designs. Even though it has a long history of use in floating oil platforms it is not commonly proposed for wind energy purposes. However the first offshore floating wind turbine was built upon a tension leg structure in 2007 (Jiang, Z 2021).

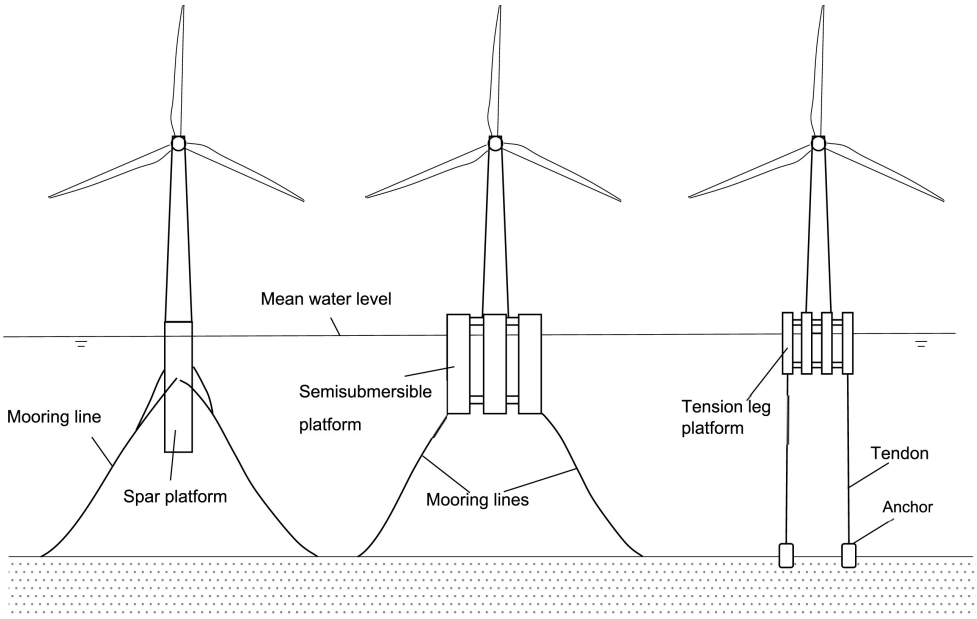

Figure 2: Three proposed methods for floating offshore wind turbine foundations (Jiang, Z 2021)

In 2023 the total installed capacity for wind power in Europe totaled 272 GW out of which 34 GW came from offshore wind. Most of the offshore wind power is due to fixed offshore wind farms, but recently Norway installed the until then largest floating offshore wind farm, Hywind Tampen totaling an installed capacity of 95 MW (Costanzo & Brindley 2023). That is a very small part of the offshore wind power capacity, but the amount of new installations is expected to grow, with for example France and the UK in the development phase of two new floating wind farms. (IEA 2023)

1.3.2 Wave Energy

Wave energy converters (WECs) are devices used to convert the energy from ocean waves into electricity. Wave energy is a renewable form of energy as it is derived from wind blowing at the surface of the ocean. It has the advantage of being more constant and predictable over time compared to other renewable sources such as wind and solar energy, since the waves will still propagate as the wind dies down. The ocean waves also have a high energy density which makes it an attractive source of reliable energy.

There exist no full-scale operation wave farms to date, only small prototype devices in different parts of the world. In general, they have in total a very small amount of power capacity in the range of hundreds of kilowatts up to a couple megawatts. For example, the Ada Foah wave farm in Ghana commissioned in 2016, where the company Seabased installed devices reaching 400 kW, or the Pelamis devices of the coast of Portugal which had an installed capacity of 2.25 MW but was closed down a couple months after installations

due to technical issues in 2008 (Ning & Ding 2023). The devices were based on different working principles, where the Seabased device is a so called point absorber and the Pelamis device an attenuator. This suggest that there is no main category of converter design such as is the case for wind energy extraction with mainly horizontal turbines. Categorization of WEC designs can be done by multiple methods. For example, by their working principle, their direction to the waves and their method of energy absorption. They can also be further categorized by their location, either nearshore, offshore or onshore as well as by their structure if it is a floating, submerged or fixed device. As it is not possible to investigate every unique design, this study will base the failure simulation on a singular type of WEC, the point absorber.

The point absorber is one of the simpler WEC designs, operating as an oscillating buoy on the surface of the ocean or submerged. In this study the focus will be on a floating buoy in an offshore environment, with depths above 30 m. The power take off (PTO) system can be placed at various points in the structure. It can either be coupled with the buoy itself where the floating buoy is connected by a spring and a damper to another semisubmerged body and the relative motion between them drives the generator, or have its PTO system placed directly at the ocean floor connected to the buoy only by a line which in turn drives the generator (Ning & Ding 2023). A depiction of the point absorber can be seen at the top left of figure 3.

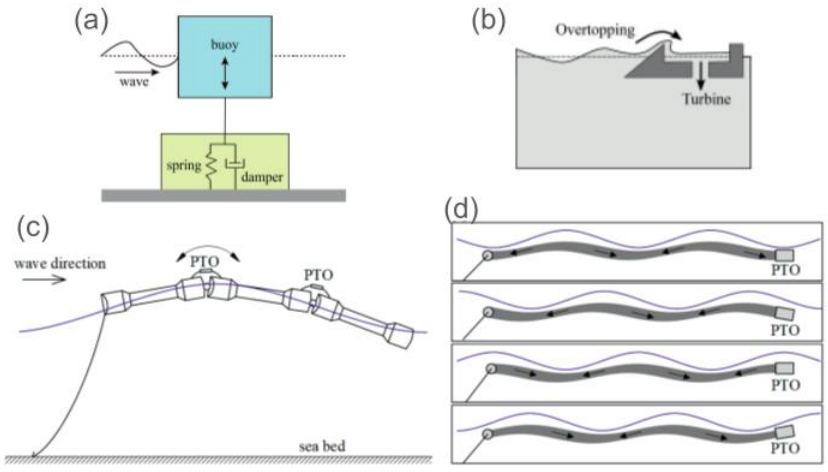

Figure 3: Wave energy converter design options, (a) Point absorber (b) Overtopping device (c) Attenuator sectioned (d) Attenuator flexible tube (Ning & Ding 2023).

Other devices include the attenuator, such as Pelamis, or a terminator, for example the

wave dragon device, though there are many more. The attenuator, see figure 3(c) and (d), is placed in the direction of the wave and on the surface. It can either consist of several sections connected by hinges, 3(c), or a longer flexible tube, 3(d), which allows the attenuator to bend or rotate with the wave. In the flexible tube, water will pass through a turbine which in turn generate electricity, or in the case for the Pelamis device, the motion difference of the section hinges will drive a liquid (oil) through hydraulic motors which then drives the electrical generator. The terminator works perpendicular to the wave direction, as for example an overtopping device or oscillating water column (OWC). The overtopping device is rather simple in concept using principles from traditional hydropower, seen in 3(b). It works by waves entering a reservoir, which can be designed onshore or offshore, and further into a turbine inlet where the downward flowing water drives the turbine. An example of this is the wave dragon floating device, where the largest one is proposed to deliver up to 12 MW. The OWC also uses a turbine but with flowing air instead. This is acquired by trapping a column of air between the water surface and a chamber. When the waves roll in and out of the WEC, the water level in the chamber increases and decreases, which pushes the trapped air through a turbine. The turbine is activated by the air flowing out of the chamber but can also operate when the air flows in the opposite direction inward to the chamber, though this necessitates the use of a directional independent turbine, such as the Wells turbine. A well known example of the OWC device is the Mutriku breakwater power plant, which started its operation in 2011 with a capacity of 296 kW. A drawback for OWC devices is its relatively low capture efficiency and power output (Ning & Ding 2023).

The future for the wave energy sector sees both opportunities and challenges. Even though there have been multiple successful test phases of wave energy project such as the ones stated above, Mutriku, Pelamis and from Seabased, the industry as a whole is still in a pre-commercial state. The commercial step is limited by several technical issues such as low efficiency, fluctuating power output and site specific factors such as demand, regulations and environmental problems. As a way to overcome these challenges, research into integration with infrastructure and other renewable energy sources is an opportunity unique to the wave energy sector, for example implementing WEC devices at other marine structures such as harbors and breakwater points, combining wave energy with wind and solar projects (Ning & Ding 2023). Research into this concept is limited but necessary as an integrated wind, solar and wave farm could increase the total power output as well as providing a more stable output.

2 Theory and Method

2.1 Qualitative Risk Assessment

The qualitative risk assessment is structured as a smaller literature review with some limitations. The purpose of the literature review was to identify risks in the offshore environment, specifically related to extreme weather. Furthermore, the review was done as it would provide a foundation for the quantitative risk assessment. Simply put, the literature review would try to answer to what elements of the quantitative risk assessment could reasonably be quantified and used in a more thorough analysis.

The literature used in the review was mainly found by using Google Scholar and the university library search function. The search began by identifying possible hazards to energy systems in general, as sources detailed on specifically extreme weather hazards affecting offshore energy systems were limited. For example search terms included "hazards" "threats" in conjunction with "power/energy system".

As hazards were identified, further literature searches were then broadened by including the hazardous event as a search term together with terms such as "floating offshore wind farm" or "wave energy converters". The literature search was early on expanded to include similar fields as useful sources were infrequent. Related fields introduced looking into onshore wind farms, and in the case of wave energy converters looking into specific components such as the power take off system or mooring systems to better understand the effects of the hazardous event.

Moreover the review was structured in two parts, one corresponding to the threats to offshore wind turbines and the other to wave energy converters. Hazardous weather events were then systematically categorized with the effect it had on the OWTs or the WECs. The quantitative review will concentrate on direct impacts of extreme weather events, it will not focus on indirect effects, such as increased energy demand due to heat waves or severe winds reducing the possibility of carrying out maintenance.

Additionally by using the results of the literature review, a risk assessment was constructed by analyzing the aforementioned hazards and estimating their potential impact on the system. The hazards were attributed a likelihood and severity score. The scores were based on the likelihood of the weather event to occur in the energy park and the severity is based on the amount of damage the event would generate. The hazardous weather events could then be summarized in risk matrices which can be seen in section 3.1.1 and 3.1.2.

2.1.1 Classification of Weather Events

Weather related threats to power systems can be categorized into different events based on their types and attributes. Bompard et al. (2013) attempts to classify and describe those, the categorization which are directly related to OWTs and WECs are presented in table

1.

Table 1: Extreme Weather Events (Bompard et al 2013)

Category	**Description**
Windstorm	Storm with strong wind with low or no amount of precipitation, a smaller scale of cyclonic storm
Cyclonic storm (Hurricane)	A very large rotating system with a low-pressure center
Tornado	Vortex of wind, an intense rotating column of air, smaller in diameter compared to storms and hurricanes
Lightning	High voltage electrical discharge, often accompanied by a thunderstorm
Hailstorm	Weather event that produces hail
Rain- or thunderstorm	A storm characterized by lightning and thunder with some occasions of rain, hail and snow
Cold wave	Rapid fall in temperature
Heat wave	Long period of very warm weather, with a chance of high humidity
Heavy rain	Longer period with a substantial amount of precipitation

Hurricanes can be further categorized ranging from a category 1 hurricane to a category 5 hurricane. The categorization is dependent on a hurricane's sustained 1 minute average wind speed. A category 3 or above may be called a "major" hurricane but even on the scale 1 and 2 will produce damage to energy infrastructure (National Weather Service, USA (n.d.)). The wind speed of a category 1 through 5 hurricane can be seen in table 2.

Table 2: Saffir-Simpson scale (National Weather Service, USA (n.d.))

Category	1	2	3	4	5
[m/s]	32-42	43-49	50-58	58-70	≥ 70

2.2 Quantitative Risk Assessment

2.2.1 Theory

Building upon the qualitative risk assessment, a more detailed look into the risk due to specific weather phenomena such as wind speed and wave heights will be taken. In the case of wind power, risk assessments and fragility analysis due to wind and wave loadings have been made with different methods and scopes. Three studies have in this case been identified in literature to be relatable to this work.

According to the paper by Zuo et al. 2020 wind turbines are subjected to both aerodynamic and sea wave loadings, the behavior of the turbine due to the simultaneous loadings has been investigated for two different cases, a parked and operating condition. Separate fragility curves for the blades and tower are produced in the mentioned work. The OWT system of focus is the NREL (National Renewable Energy Laboratory, USA) 5 MW reference turbine, which is commonly used as it has redundant properties and definitions listed to support these kinds of studies (Jonkman et al. 2009). Zuo et al. used FE modeling, a computational method typically used in structural analysis, to simulate the results. The model simplifies the connection between the blades and the tower as they lump the hub and nacelle masses together as a point at the top of the tower. The precision of the model is in part verified by calculating natural frequencies and mode shapes from an eigenvalue analysis in the FEM and comparing it to the NREL 5 MW reference document. The study identified certain uncertainties which can increase the variability of the behavior of the tower, monopile and blades. The uncertainties lay in the structural stiffness, masses and damping ratios. The results of the mentioned study will in the end show that the uncertainties in general affect the blades more than the tower itself.

To examine the responses of the wind turbine, both aerodynamic and sea wave loads need to be applied. In the study by Zuo et al, to estimate the load from aerodynamic forces, the tower and blades are separated. The forces act differently due to the factors such as rotational speed, pitch angle and the geometric shape. The tower itself is separated into segments, nine segments, a compensation between computational time and accuracy. The aerodynamic load on the tower in this study is defined with an average and fluctuating component and the local forces acting on the blades can be described by equations (2) and (1).

$$F_{lift}(r) = \frac{1}{2}\rho U(r)^2 l(r) C_l \tag{1}$$

$$F_{drag}(r) = \frac{1}{2}\rho U(r)^2 l(r) C_d \tag{2}$$

where r is the radial distance, U wind speed at distance r, ρ the air density, l the chord length and C_l and C_d lift and drag coefficients respectively, which are dependent on the angle of attack. The addition of lift and drag forces are due to the properties of the blades acting as an airfoil.

On the other hand, the loading due to ocean waves only occur at the monopile structure. To estimate those forces, the JONSWAP spectrum is used to simulate the elevation of the ocean waves. The Morison equation can be applied to evaluate the sum of the inertia and drag forces, to calculate the transverse load from the ocean waves,

$$F_w = \rho_w C_m A a + \frac{1}{2}\rho_w C_{dp} d|v|\ v \tag{3}$$

where ρ_w is the density, A and d the cross-sectional area and diameter of the monopile, v and a the velocity and acceleration of the water. C_m and C_{dp} the inertia and drag coefficient, which in this case are $C_m = 2.0$ $C_{dp} = 1.2$.

After the aerodynamic and ocean wave loads can be determined, Zuo et al. (2020) took a closer look at the structural fragility. To be able to produce a fragility curve of the tower and blades, the displacement response based on the acting load can be explored. The authors discuss two different methods for obtaining the fragility curve, the IDA (incremental dynamic analysis) method and the PSDA (probability seismic demand analysis). As IDA requires an substantial amount of iterations, the computational time increases, PSDA is therefore used as it produces an accurate enough result. With the method of estimating the displacement of structural elements in the turbine, one can compare it to damage limit states. Zuo et al. (2020) entered four limit states, ranging from a critical displacement of 0.524 m to 1.049 m. The combined wind and wave load are approximated as $D_w = m(U)^n$ where $m = 0.0643$ and $n = 0.7350$ was parameters based on displacement simulations in the operating condition and U mean wind speed at hubheight. The fragility curve is then defined as equation 4,

$$P_d(U) = \phi((\frac{ln(D_w) - ln(D_s)}{\beta})) \tag{4}$$

where ϕ is the normal cumulative distribution function, D_s the displacement limit state and β also a parameter based on the displacement simulations.

Furthermore, the study by Rose et al (2013) also investigated the fragility of a wind turbine. The study aimed to estimate the risk of catastrophic damage to offshore wind farms during intense weather. As records of hurricane occurances only streches so far, they used simulated hurricanes over a longer time period to make the risk calculations more accurate. The simulated hurricanes were generated by a model produced by Emanuel et al (2006). The simulated hurricanes ranged in intensity, out of 9900 storms, 3285 could identified as of hurricane intensity. Those 3285 storms are used to generate a long time series of hurricane activity, in total 5000 years. Assuming reparation took place during this period, the hurricane activity and its damage was simulated over 50 iterations. The study highlighted turbines offline due to damage in different return periods and regions. For example a proposed wind farm on the east coast of Texas (U.S.) could suffer 10% of its wind turbines offline simultaneously with a return period of 100-years.

As similarly done in Zuo et al. (2020) estimations of damage probability is created in the study by Rose et al (2013) as well, where the basis for the damage probability function was the maximum 10-minute wind speed experienced at hub height. The probability of failure is based on a log-logistic distribution with normally distributed scatter. The study proposes a damage function for yawing and non-yawing wind turbines, the non-yawing turbines will hit the wind in the broadside direction. The parameters of the log-logistic function are found by simulating bending moments of the 5MW NREL turbine using the

TurbSim software and the design parameters of the 5MW reference turbine found in the definition by Jonkman et al (2009). The method is built upon an earlier iteration described in a study by Rose et al (2012), where the addition is the normally distributed scatter in the log-logistic fitted damage function.

The simulations are done without incorporating ocean wave loads which will give a lower maximum bending moment on the tower. Wind speed loads are simulated from $40m/s$ to $110m/s$. As wind loads across the turbine structure is derived, buckling probability is calculated by comparing the bending moment to the resistance of buckling incorporated with a random variable. This is repeated for over 5000 total samples for each load case. The results of the samples are then fit to a log-logistic function, which can be seen in equation 5, where $a = 139.6$ and $b = 18.5$ are shape parameters and U the wind speed. Furthermore in figure 4, the fragility curve from Rose et al. (2013) is show, where equation 5 is plotted from $U = 20$ m/s to $U = 140$ m/s

$$D(U) = \frac{(U/a)^b}{1 + (U/a)^b} \tag{5}$$

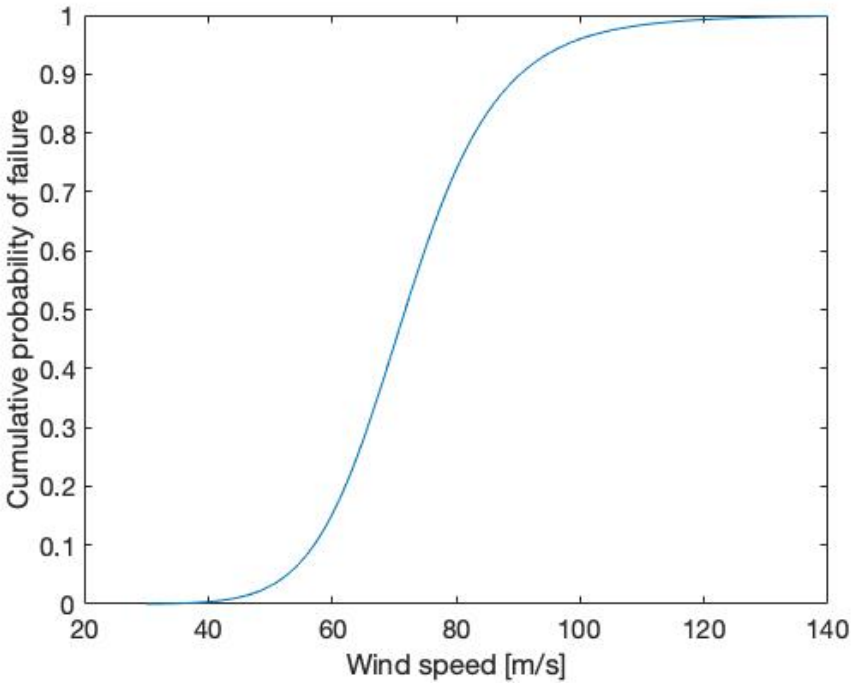

Figure 4: Fragility curve of an OWT showing the probability of failure based on the wind speed (Rose et al. 2013)

In the case for wave energy converters there is sparse information regarding their failures in operating conditions. In general there is also no common technology used in the industry

which may add to the limited information of failures and failure probabilities. Göteman et al (2023) approached the issue by estimating a cumulative probability of failure based on failure rates reported in the literature. There exist studies which derive failure rates for wave energy converters by the failure rates of the individual components and through a fault tree analysis estimate the total failure rate. However this method is equipped with uncertainties and difficulties in verifying the results. Failures of WECs have both been studied in simulations and with experimental methods. The failures in extreme weather conditions are for this study especially interesting though the results are rarely expressed in terms of failure rates or fragility curves. This makes the study by Göteman et al (2023) compelling as they express the fragility curve in different ocean states by determining it as a function of the significant wave height, which is plotted in figure 5.

Based on the results of Göteman et al. (2023), the fragility curve is based on results of the failure rates in the literature as shown in fig 5. The function follows the shape of the fragility curve for wind turbines, and present fragility with both lower wave heights in a calm ocean to a more violent ocean state with higher significant wave heights.

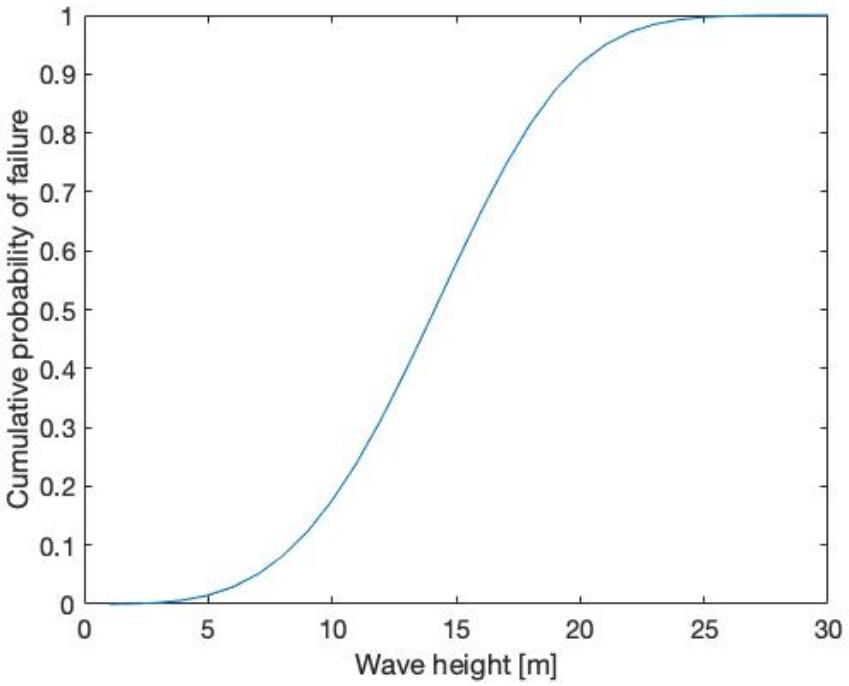

Figure 5: Fragility curve of a WEC where probability of failure is based on wave height (Göteman et al. 2023)

2.2.2 Weather Data

Weather data, wind speed and wave height, is collected from the National Data Buoy Center (NDBC), USA, from buoy station 41008. The buoy is located off the coast of

Georgia in the United States, an area where hurricanes and storms are fairly active during the third and fourth quarter of the year, for example hurricane Ian in late September 2022 which caused great damage along its track (National Weather Service 2022).

The data is presented hourly for both wind speed and significant wave height, in the units m/s and m respectively. The model explained further below will use data from 2022 as a whole. In figures 6 and 7 wind speed and wave height measurements from 2022 are presented.

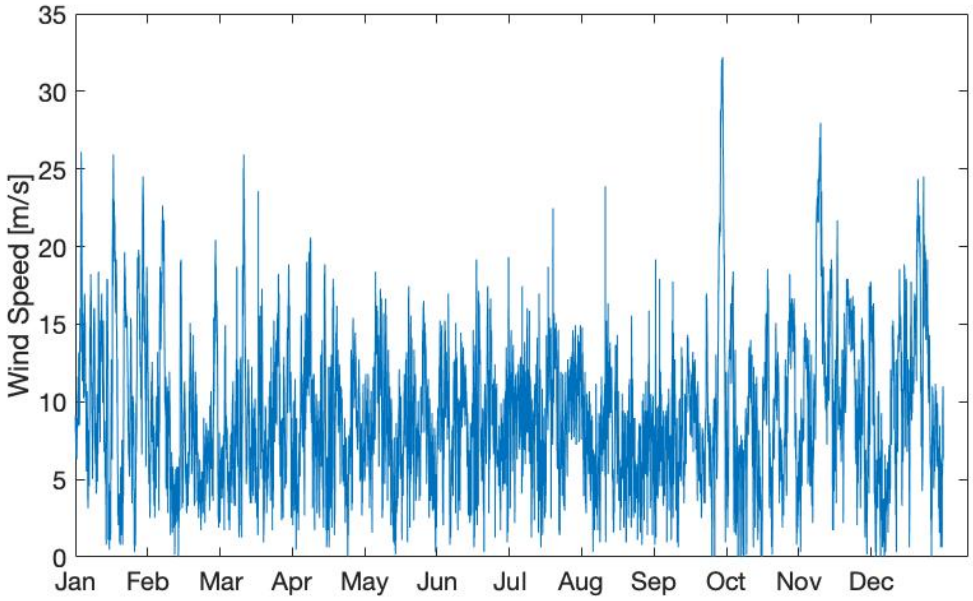

Figure 6: Wind speed during 2022 measured of the coast of Georgia, USA. (National Weather Service 2022)

The greatest wind speed measured is 32.22 m/s and the greatest wave height 3.98 m both occurring in late September.

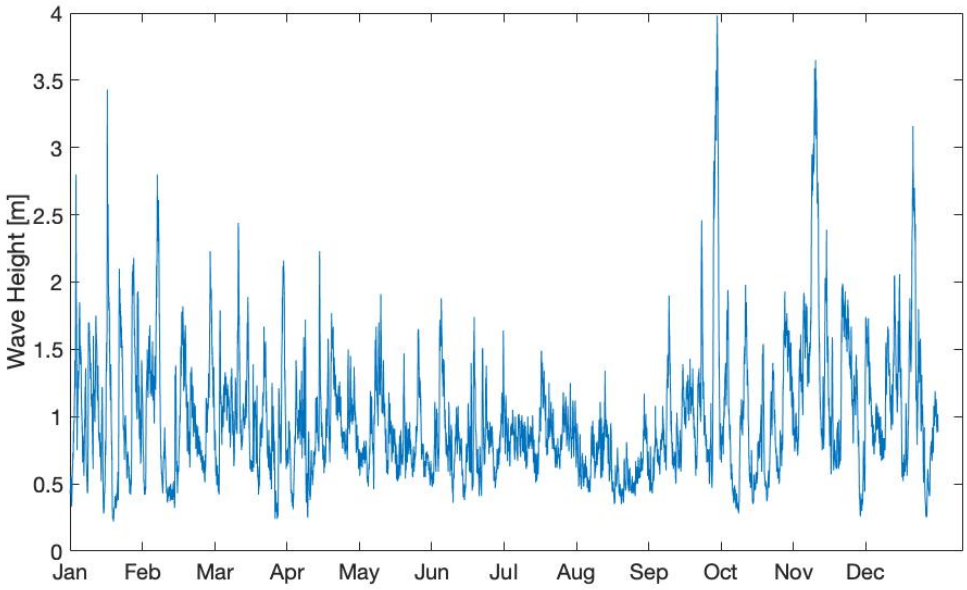

Figure 7: Wave height during 2022 measured of the coast of Georgia, USA. (National Weather Service 2022)

2.2.3 Method

This section presents the MATLAB script used in this study to produce the results for the qualitative risk assessment. The script begins by importing wind speed and wave height data from the standard meteorological data set from buoy 41008 from NDBC,

$$U_{\text{speed},3.8}(t), \quad H_s(t) \tag{6}$$

where $U_{\text{speed},3.8}(t)$ is the wind speed and $H_s(t)$ the significant wave height, both measured each hour. A few data points are missing in the wave height data set, and in those cases, the data is adjusted by replacing the missing values with the average of the adjacent data points. Wind speed measurements are initially taken at a height of 3.8 meters (as per buoy parameters), and they are scaled up to a hub height of 90 meters, corresponding to the reference turbine,

$$U_{\text{speed},90}(t) = \left(\frac{z}{z_r}\right)^a U_{\text{speed},3.8}(t) \tag{7}$$

where z_r=3.8 m, z=90 m and a=1/7. The wind shear exponent a is set to 1/7 as it is commonly used in wind resource estimations.

Additionally, the wind speed peaks are amplified by a factor of 1.5, as the focus is on understanding failures during extreme conditions. The wind speed does not cause significant damage to the wind farm during low speed periods i.e. before hurricane Ian in late September, but the extremes are of interest. For the wave data, no scaling is applied to the peaks, as wave-related failures are already frequent. In order to only scale up the peaks but leave the troughs untouched, we first shift the minimum wind speed to zero, scale the resulting values by 1.5, and then add the minimum wind speed again. The following equation is used,

$$U_{\text{speed, scaled,90}}(t) = 1.5[U_{\text{speed,90}}(t) - \min\big(U_{\text{speed,90}}(t)\big)] + \min\big(U_{\text{speed,90}}(t)\big) \tag{8}$$

Next, the failure curves for both the OWTs and WECs are defined. These curves describe the likelihood of failure based on wind speed and wave height, respectively. The failure curve equation of the wind turbines is shown in equation 9. In this case $\alpha = 139.9$ and $\beta = 18.6$ which are dimensionless parameters determined in Rose et al (2013),

$$pf_{wind} = \frac{(U_{speed}/\alpha)^{\beta}}{1 + (U_{speed}/\alpha)^{\beta}} \tag{9}$$

The failure curve equation for the wave energy converters can be seen in equation 10. In this case $\alpha = 15.61$, $\beta = 1.16 \cdot 10^{-16}$ and $k = 3.69$ are the shape parameters and H_{wave} is the significant wave height. The shape parameters and pf_{wave} equation are given in the paper by Göteman et al (2023).

$$pf_{wave} = 1 - e^{-(\frac{H_{wave}-\beta}{\alpha})^{k}} \tag{10}$$

Furthermore, the following section simulates the survivability of an energy park. Both *simlength* and *numUnits* are changeable variables that determine the number of simulations and the size of the park respectively. In this study the *simlength* is set to 20 and the size of the park *numUnits* is set to 100. In the MATLAB-code seen below the simulations is done for the wind turbines, and a similar one is carried out for the wave energy converter simulation where the difference lies with equation 9 where it is changed to equation 10 and the following subscripts changed to *wave* instead of *wind*.

```
for k=1:simlength
    for i=1:length(WSPD)
        pf_WIND=((WSPD(i)./a_a).^b_a)./(1+((WSPD(i)./a_a).^b_a));
        for j=1:numUnits
            if sum(failureMatrix_WIND(j,:)) == 0
                rn2(j,i) = rand;
                if rn2(j,i) < pf_WIND
                   failureMatrix_WIND(j,i)=1;
```

```
                end
            end
        end
        WIND_fail_res{h} = failureMatrix_WIND;
        remainingWINDs(i) = numUnits-sum(sum(failureMatrix_WIND(:,1:i)));
    end
    h=h+1;
end
```

The MATLAB - code starts in simulation $k = 1$ and continues on to $k = simlength$ and then loops through each element in the input vector $WIND$ or $WAVE$ on line 2 of the code. The code then calculates the respective probability for failure pf_{WIND} value for the wind speed at the current time step, $WSPD(i)$. With the momentary pf_{WIND} value, the code then loops through each wind turbine unit from $j = 1$ to $j = numUnits$ to evaluate if the unit has failed or not, a failure is counted as a 1 in the result vector named $failureMatrix$. Line 5 is created to ensure that the code does not count unit failures more than once. The failure evaluation is done by attributing a uniformly distributed random value between 0 and 1 to each unit according to the MATLAB function **rand**. The random variable *rn2(j,i)* is then compared to pf_{WIND} on line 7. And if $rn2(i, j)$ is lower than the instantaneous pf_{WIND} value a failure has occurred which in the code is signified by adding a 1 to the failure matrix. As it loops through $numUnits$ each time, the number of operational units at timestep i are calculated and saved in the vector $remainingWinds$ which in the end is used to plot the results.

3 Qualitative risk assessment

This section introduces findings from the qualitative literary review. It is further divided into two parts, one for offshore wind turbines and the other wave energy converters. The main focus will be on the direct impact from the extreme weather threats.

3.1 Extreme Weather Impact on OWTs

For land based turbines there are many examples of failures. A total loss of a wind turbine may occur by bending/buckling of the tower or in the blades. Though blades are costly to repair and will incapacitate the wind turbine, a blade failure may also result in a collision with and collapse of the tower (Patil et al. 2023). A failure could also appear as a deformation of the tower, blades or a complete loss of one or more blades (Rose et al. 2012). The impact of the extreme wind speed is set by the design limitations of the wind turbine, in most cases hurricane winds exceed the maximum operational conditions for wind turbines (Wang et al. 2022). There is limited data related to the operation and performance of offshore wind turbines during extreme weather events, though looking onshore there are examples of failures. In 2008, typhoon Jangmi hit Taiwan and caused one turbine to collapse, the lower parts of the tower had buckled and a later investigation suggested that the likely cause was strong high-velocity winds in combination with inadequate construction (Chou & Tu 2011). There are also other examples of turbine failures such as, typhoon Maemi, a category 4 hurricane where wind speeds exceeded 60 m/s and caused the failure of 7 turbines and typhoon Dujuan which also damaged multiple turbines (Wang et al. 2022). Hallowell et al (2018) highlighted that typhoon Jangmi in Taiwan is the exception of the norm, most failures occur not only due to strong winds but in conjunction with error in control systems which prohibits the nacelle the ability to yaw. Rose et al (2012) demonstrated that the ability to yaw is critical to ensure the survivability during a hurricane as the probability for buckling is lower. Hallowell et al. (2018) also showed that the failure probability is lower with a functional yaw control system. In the case of hurricanes the direction of the wind can change 180°in a timespan of 30-90 min (Worsnop et al. 2017).

A significant difference with onshore and offshore wind energy is the interaction with loads from ocean waves. The industry currently relies on design standards to estimate wave loads. In general extreme waves are nonconstant, nonsymmetric and the largest loads may not always be followed by the largest wave, smaller waves can in some cases result in higher loads due to breaking and slamming into the monopile structure (Pierella et al 2021). In the case of both floating and fixed offshore wind turbines, there are no or very few documented instances of failure due to wave loading.

Lightning

As both the tower and blades of the wind turbine grow larger and taller there is an increasing concern about their sensitivity to lightning damage. Lightning damage can cause

severe damage to structural elements of the wind turbine which are costly to repair and come with considerable downtime. Lightning strikes does not necessarily mean damage will occur as wind turbines are equipped with lightning protection systems. The protection system are most often installed in the blades which allows the current to safely path through the blade and tower to the base and dissipate over the sea (Sun et al. 2022). Damage will therefore be dependent on the condition of the protection system. Garolera et al. (2016) points out from observations in the U.S. that a wind turbine on average will experience a significant number of lightning strikes during its lifetime, the most common point of damage occurs in the rotor blades. However the risk of lightning strikes in a wind farm is highly susceptible to seasonal and regional variations (Patil et al. 2023).

Cold weather

Snow, hail and ice are examples of cold events which will directly affect a wind turbine. In low temperatures other threats may also occur in the components of the wind turbine, due to lowered viscosity of hydraulic fluids and lubricants. This might lead to a decrease in performance as gearbox, dampers and couplers may not be functioning properly (Wang et al. 2022). As temperatures decrease icing will become a problem for the performance of the turbine. Ice accumulation on the blades will negatively affect their aerodynamic properties, an effect that is not only limited to extreme icing events but can also occur with small amounts of ice accretion (Lamraoui et al. 2014). As the aerodynamic function of the blades are reduced a loss of produced power is expected. There are ways to mitigate the losses for example by introducing heating systems in the blades (ibid.). Lamroauoui et al. (2014) suggests that shutting down the turbine during severe icing events is the best way to reduce ice accumulation, as the severe icing events mostly occur for short periods of time.

Hailstorms

The occurrence of hail is a rare cold event and its contributed losses to the annual production is barely measurable (Battisti 2015). Though it can lead to structural damage of the blades, tower and the nacelle. The damage level is determined by impact velocity and the frequency of impact. Parallels can be draw to the threat of rain drops as their collision damage is based on the same parameters. Impact velocity will increase as turbine blades are rotating during operation, therefore blades are the most vulnerable to damage. As hail and rain may be considered frequent during the lifetime of a wind turbine, blades are designed to minimize the damage caused by the particles (Verma et al. 2023). In combinations of heavy rain or hail with heavy winds impact damage may surpass design limitations.

Heat wave

Increased temperatures in events such as heat wave can also negatively affect the technical workings of power system equipment. There are instances of said equipment failing during

heatwaves which have directly lead to blackouts (Bompard 2013). There is little information on the direct effects of a heat wave related to wind turbines. A study by Reder et al. (2018) investigated failure frequency of onshore wind turbines based on different weather parameters such as temperature, there one can see that failure frequency is higher in cold ($5 - 10$°C) to mild ($15 - 20$°C) temperatures compared to warm ($25 - 30$ °C) to very hot ($35 - 40$ °) temperatures.

3.1.1 Offshore Wind Turbine Results

Table 3: Likelihood and Severity Scores for Offshore Wind Turbines

Risk		Likelihood				
		Rare	Unlikely	Possible	Likely	Almost certain
Severity	Catastrophic		Tornado Cyclonic storm			
	Major			Thunderstorm		
	Moderate			Windstorm		
	Minor		Cold wave	Rainstorm Lightning		
	Insignificant				Heat wave	Hailstorm Heavy rain

Based on the conducted literature review above, in Table 3 an estimation of the severity and likelihood of a certain weather event is presented. The matrix is a common method used to visualize the risk of different outcomes, where in this case the colors represent the risk of a turbine failure. A green color indicate a low risk of failure and red a high risk of failure, the yellow and orange colors lay somewhere in between. Each weather event presented in section 2.1.1 is given a severity and likelihood score, the severity score is based on the damage the event could cause and the likelihood score based on the chance that the extreme weather will hit the wind park. The severity of each event is based on contributing factors such as, wind speed, gust, precipitation, area of effect, occasions of lightning and temperature. The likelihood that a wind turbine will be struck by a certain weather event is difficult to estimate exactly, therefore it is approximated based on the region of the weather data presented earlier in the qualitative risk assessment.

On the likelihood scale, tornado is placed as unlikely, the same as for cyclonic storm even though there are more tornado reports than cyclonic storms in some regions. For example in USA, there are roughly 1000 tornado reports each year while there are only a handful cyclonic storms reported (NOAA 2023). The risk of a singular tornado hitting a wind turbine or wind farm is significantly lower as its size also is significantly smaller. The severity would be catastrophic as the air is rotating and the generated winds may not always hit the turbine in a favorable direction. Typically a cyclonic storm sees a gradient

of increasing wind speed closer to the eye, therefore its severity is based on the distance, from moderate to catastrophic.

Continuing with smaller and weaker storms, below the hurricane scale, with heavy rainfall or lightning. Generally they occur more often but the potential damage to wind turbines can still be major due to lightning. Even though a turbine is equipped with lightning protection, such as lightning rods and grounding systems, a direct strike to the blades or tower could cause severe mechanical failure. Subsequent strikes could also be dangerous as the protection gets worn out or damaged.

3.2 Extreme Weather Impact impact on WECs

As most wave energy converters (WECs) have a low profile on the surface of the ocean, direct wind damage can be assumed to be very low. On the other hand extreme winds will give rise to larger waves and rougher sea conditions which more directly affects the wave buoy. Extreme waves can pose a risk to wave energy converters (WECs) in several ways. Primarily, they can lead to mechanical damage to the WEC structure, including the mooring system and power take-off (PTO) system, which can reduce the WEC's performance or even cause it to fully fail (Ning & Ding 2023).

The design of the wave energy converter may vary and so will the effects of extreme waves hitting the device. For instance there is a large difference between near-shore, offshore and shoreline placed WECs and how the waves affect them. Larger structures that work on the principle oscillating water column (OWC) may encounter problems as waves reaches the air turbine or station room housing the generator and power electronics. As an example in 1995, a nearshore OWC plant named OSPREY was lost following a storm on the north Scottish coast (Falcão, A 2010).

On the other hand offshore placed free floating bodies require mooring to the ocean floor by anchor, chains and ropes. The mooring system is the main vulnerability of ocean waves and need to withstand the cyclic, nonlinear loading of ocean waves and currents. There are systems that are more suitable to specific types of energy converters, with one or more anchor points. As with wave energy as a whole there is no one solution that has been proven to be better, it therefore requires further investigation, mooring is a critical part in ensuring the survivability of the WEC during extreme waves. (Titah-Benbouzid 2015)

Lightning

Lightning interaction with wave energy converters have been simulated by Hettiarachchi et al (2018). The study investigates the injected current of both a direct lightning strike and on the surface surrounding the wave energy converter. In both cases the injected current was low enough to not cause significant damage. Though the study was limited in that it did not take into account the inner components of the wave buoy which potentially could

breakdown due to large injected currents. This is proposed as a worst-case scenario as there is a certain probability for arcing or flashovers to occur which could damage vital and costly equipment such as the generator. (Hettiarachchi et al. 2018)

Temperature

Temperature related extreme weather events such cold or heat waves have not been studied to any great extent in the case of wave energy converters. Though one can expect to see the same effects in specific components as for a wind turbines, for example lowered hydraulic efficiency and performance in cold weather. In general, increased ambient temperature will improve the efficiency of PTO system in wave energy converters as shown in the study by Niu et al (2022). However the study only investigated a mild temperature range ($6-18°C$), and the results might not be the same for even higher temperatures during longer periods of time. It is therefore difficult to estimate the vulnerability in heat waves.

3.2.1 Wave Energy Converter Results

Table 4: Likelihood and Severity Score for Wave Energy Converters

Risk		Likelihood				
		Rare	Unlikely	Possible	Likely	Almost certain
Severity	Catastrophic		Tornado Cyclonic sto			
	Major	Lightning		Windstorm		
	Moderate			Thunderstorm		
	Minor		Cold wave	Rainstorm		
	Insignificant				Heat wave	Hailstorm Heavy rain

As one can see in Table 4, the vulnerability of wave energy converters is similar to that of the wind turbines, seen in Table 3, and the arguments of the severity and likelihood scores stay mostly the same. As mentioned before, a green color indicate the lowest risk of WEC failure, yellow a low risk, orange a higher risk and red the highest risk of failure. Tornados and cyclonic storms are still great threats if they are to pass over a wave energy farm, as the wind will produce large chaotic waves in these weather events. However lightning has been downgraded on the likelihood scale due to not having a tall tower structure above the sea level.

4 Quantitative Risk Assessment

In the following chapter, the results from the quantitative risk assessment are presented. In figure 8 the wind resource with its peaks scaled by 1.5 according to equation 8 is presented. The greatest wind speed registered is $48.23 m/s$.

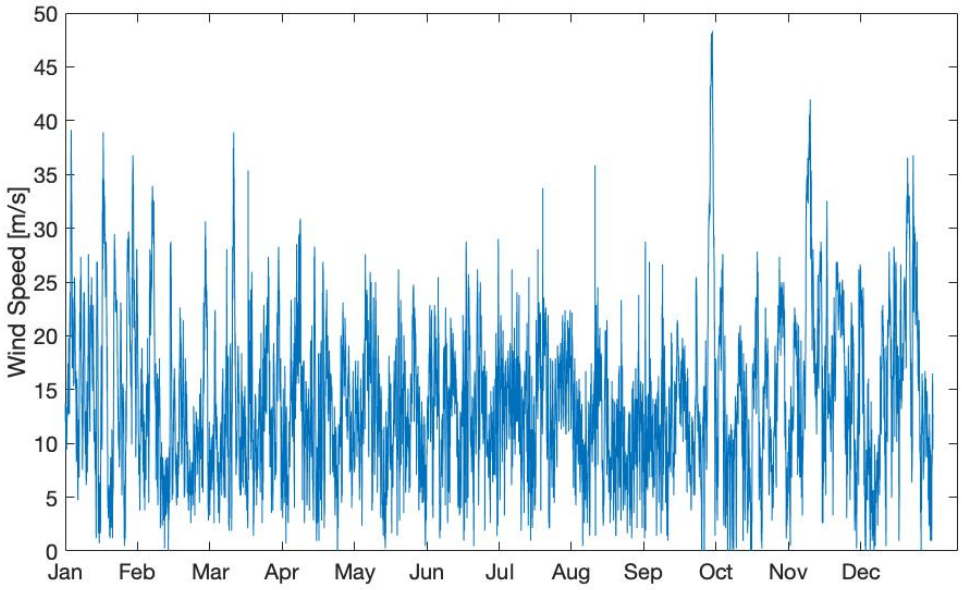

Figure 8: Wind speed during 2022 scaled by a factor of 1.5 according to equation 8

By applying the fragility curves presented in figure 4 and 5 in section 2.2.1, in conjunction with respective weather data in figures 7 and 8, results are simulated. In total there are 20 simulations for OWTs and WECs each and they are represented by blue dotted lines in figures 9 and 10. Each simulation event produces a unique result according to the attributed random variable explained in chapter 2. The average number of units left at a certain hour is represented by the black line.

The number of wind turbines lost due to failure during the year 2022 can be seen in figure 9. At the end of the year the average number of turbine units left in the park is 48 while the maximum units is 64 and the minimum 48.

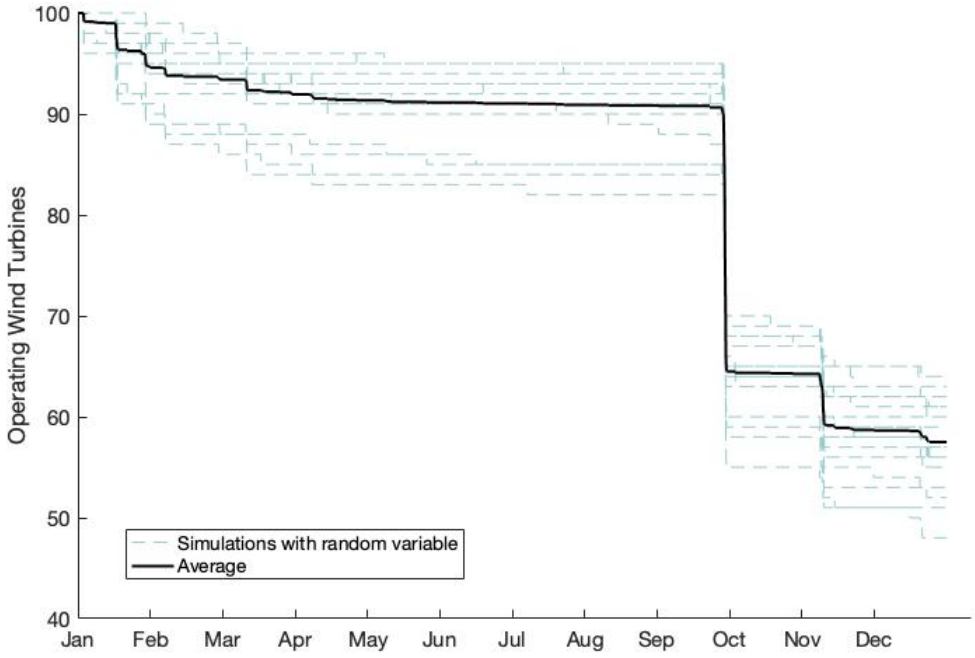

Figure 9: Number of operating wind turbines during 2022

Furthermore the number of WECs lost during 2022 can be seen in figure 10. The average number of WECs which survive till the end of the year is 42, while the maximum number is 52 and the minimum 32.

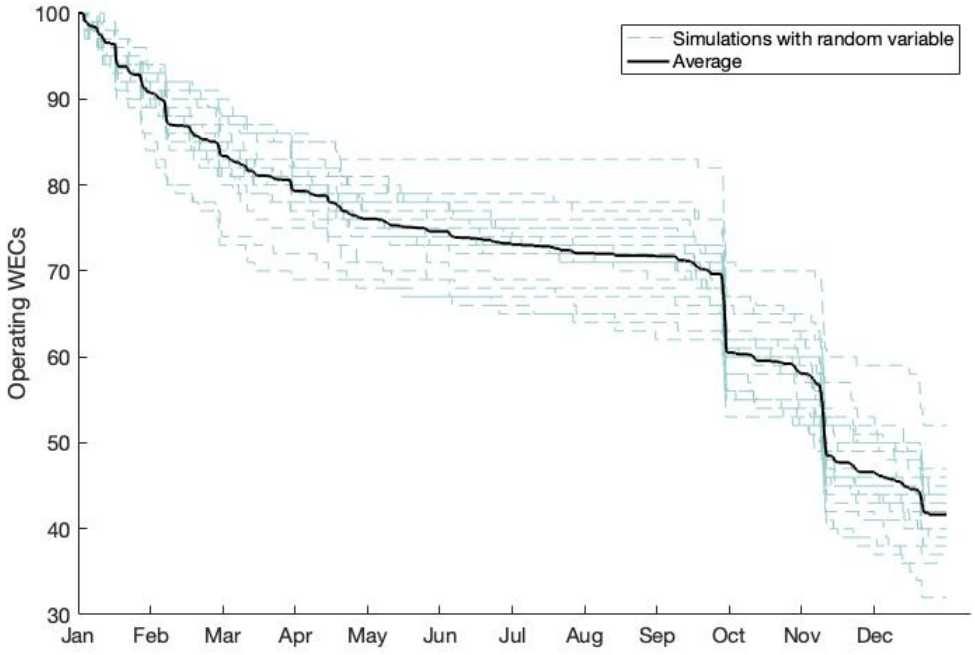

Figure 10: Number of operating WECs during 2022

5 Discussion

What we can read from the qualitative analysis is that wind related weather events, such as tornadoes and storms, constitute the most ultimate risks to both the OWTs and WECs and the lowest risk comes from temperature related events. This can be attributed to the fact that the devices' share some vulnerabilities. Though they both operate and look different wind is a direct threat to the OWT structure and indirect threat to a WEC due to waves being created by the wind, therefore extreme wind is given the high risk score. On the other hand threats from both cold and warm weather can be more easily mitigated by ceasing operation during critical temperatures or installing heaters and coolers on sensitive equipment. To mitigate the threat from wind and waves significantly, more robust changes would be necessary, for example changing the material of the structure.

In general, the worst threat to wave energy converters are the ocean waves themselves as the vulnerable parts are relatively protected either inside the structure or enclosed below the surface of the ocean. Particles such as hail, snow or rain are therefore not as harmful. Protection from lightning strikes can also be installed to mitigate the effects from surges. It should also be noted that other major threats, which have not been mentioned due to not being direct weather events are also prevalent, such as leakage, fatigue or corrosion due to seawater constantly breaking down the material.

Furthermore from the quantitative risk assessment we can see that the simulated OWT and WEC parks will see losses of units. Looking specifically at the wind turbines the first couple months of the year, January through April there is an average loss of almost 10 units, with a maximum loss of 15 units out of the 20 simulations. The following months up until the end of September sees a very low amount of turbine failures. At the end of September there is a great increase in wind speed during hurricane Ian, which lasted in the area for about 30 hours. During this time there is a sharp decline in the number of operating wind turbines. 26 turbines will go offline during this period, an instantaneous loss of almost 30% of the operational units before the hurricane. The same pattern can also be seen in the end of November even if to a lesser extent, where the relative loss is about 8%. In figure 11 the correlation between a large increase in wind speed and failures of the OWTs can easily be seen.

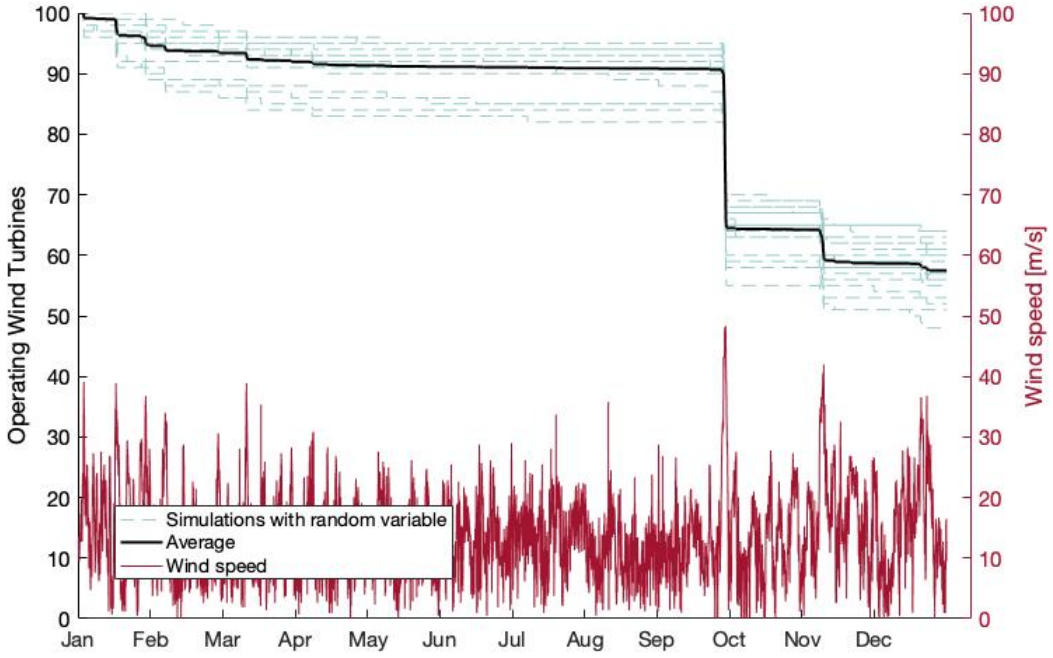

Figure 11: Number of operating OWTs plotted together with the wind speed during 2022

From figure 10 we see a continuous decline in operating WECs from the beginning of the year until about May and June where the decline slows down but not to the extent of the OWTs. However we still see a sharp decline in the same way at the end of September and in November. Though the relative loss in September is less, with a decrease of 13% units and in November 16%. In 12 we can see that the decrease in operational WECs follow the peaks in wave height deep blue line, even early on in the year and when the average wave height lowers from May to September the failures over time lessens.

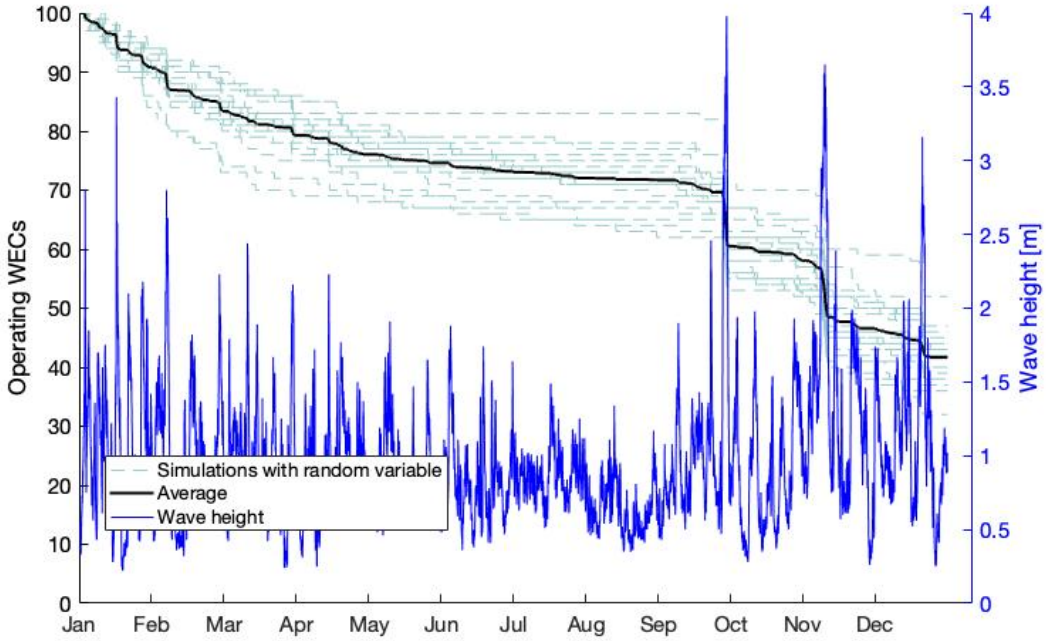

Figure 12: Number of operating WECs plotted together with the wave height during 2022

This can in turn be used to give an answer to question proposed earlier on in the work, when failures are expected. For OWTs failures are more prevalent when wind speeds reach a higher threshold above 35 m/s, as seen in figure 11. WEC failures are to be expected to occur fairly often during the year, even at lower wave heights. One can also see that failures for both energy sources are more common during the winter months, October through February. Which consequently means that we will see a great reduction in power produced, due to the loss of almost half of the wind and wave park during the latter part of the year.

Additionally, the results from the wind farm simulation can be compared to the study by Rose et al (2013), which was the source of the fragility curve in 4, though the study specifically looked in to hurricanes, where it simulates a large number of hurricanes in the area and their track, as well as its damage to a potential wind farm. The most significant result shows that 10 % of a wind farm could be simultaneously offline due a hurricane with 100 year return period. This is lower than what is seen in figure 11 where there is a maximum instantaneous loss of 30 %. A reason for this could result from different methods but also from the amount of simulations. The study by Rose et al. (2013) uses 50 5000 year periods during which the median amount offline is 10 % and also incorporates repair of turbines during this period. This makes it difficult to compare the results directly but a preceding study by Rose et al. 2012, *Quantifying the hurricane risk to offshore wind turbines* with a similar but slightly different method showed that a category 3 hurricane

could damage up to 46 % turbines, which is closer to what can be seen in the present study.

With the wave farm, some comparisons can be drawn from a more recent study by Göteman et al. (2023). Though it is more in depth and covers more the repair of damaged WECs, they use similar input data, with it being a year of weather data although at a different location. Even though repair is included a similar pattern emerges with a large number of units fails in an instant when the wave height significantly increases. The maximum amount of units lost in a short time period is 30% compared to 16 % in the present study. In this case the difference may be due to the wave being notably higher, above 7 m. Another interesting point can also be seen in that most failures occur during the first and last months of the year, which is due to the more violent nature of the ocean during this time interval.

6 Conclusions

Looking back at the questions posed in the scope of the work, when are failures expected for the different technologies? and in what weather scenarios is the power production expected to be severely reduced? The first one can be answered by taking a closer look at figures 11 and 12 where the number of operating devices are plotted against the weather data. There one can see that failures should be expected during the whole year but most damaging is the peaks in both wind speed and wave heights. Looking into the bottom red and blue line of the graph, major peaks are mostly concentrated toward the end and in small parts the beginning of the year, which is a timespan where failures in this study are guaranteed to happen. And lastly the specific weather scenarios which will limit the wave and wind park to operate at full capacity are the tornadoes and cyclonic storms which has been given a severity score of 'catastrophic' as if they would pass over the park would destroy a significant part of the devices.

In summary, the conclusions we can draw form this study is that extreme wind pose a significant risk to both wind and wave energy farms offshore. During the year, both farms will see losses of multiple units, especially during October through February. It is therefore necessary for both OWTs and WECs to be built with extreme wind and waves in mind, and allow for repairs and maintenance to be carried out should an eventual failure occur.

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Appendix:

```
clear all;
close all;
```

```
%Set length of mc sim
simlength=1;
nSimulations = 100;
numUnits = 100;
remainingWECsAll = [];
remainingWINDsAll = [];

%Importing weather parameters
data=readtable('41008_2022_copy.txt');
%Wave height
WVHT=(data.WVHT)';%[m]
%Wind speed
WSPD=data.WSPD'; %[m/s]

%Replace erroneous values of WSPD
for i = 1:length(WVHT)
    if WVHT(i) > 70
        WVHT(i) = mean([WVHT(i-1) WVHT(i+1)]);
    end
end

%power law wind profile
z=90;
z_r=3.8;
a=1/7;
WSPD=WSPD*(z/z_r)^a;

%Scale the peaks of weather resource
scaleWindPeaks = 1.5;
WSPD=WSPD*scaleWindPeaks-min(WSPD*scaleWindPeaks)+min(WSPD);
scaleWavePeaks=1;
WVHT=WVHT*scaleWavePeaks-min(WVHT*scaleWavePeaks)+min(WVHT);

%Fragility curve wind parameters(rose et al 2013)
a_a=139.6*0.5144;
b_a=18.6*0.5144;

%Fragility curve wave
k_b=3.69;
a_b=15.61;
b_b=-1.16*10^-16;
```

```
%Specify dimensions of failure matrix
numUnits = 100;
numCols = length(WSPD);
failureMatrix = zeros(numUnits,numCols);
pf=zeros(numUnits,numCols);
pfrnd=zeros(numUnits,numCols);

%Parameters for lognormal distribution
sigma = 0.25;
variance = sigma^2;

for simInd = 1:nSimulations

%Looping through each WindTurbine
failureMatrix_WIND=zeros(numUnits,length(WSPD));
remainingWINDs = 100-zeros(1,length(WSPD));
wind_fail_res = cell(1,simlength);
rn2 = NaN(numUnits,length(WSPD));
h=1;
    for i=1:length(WSPD)
        newpf_wind=((WSPD(i)./a_a).^b_a)./(1+((WSPD(i)./a_a).^b_a));
        pf_wind(i)=newpf_wind;
        for j=1:numUnits
            if sum(failureMatrix_WIND(j,:)) == 0
                rn2(j,i) = rand;
                if rn2(j,i) < newpf_wind
                   failureMatrix_WIND(j,i)=1;
                end
            end
        end
        wind_fail_res{h} = failureMatrix_WIND;
        remainingWINDs(i) = 100-sum(sum(failureMatrix_WIND(:,1:i)));
    end
    h=h+1;


remainingWINDsAll(simInd,:) = remainingWINDs;


%Looping through each WEC
failureMatrix_wave=zeros(numUnits,length(WVHT));
remainingWECs = 100-zeros(1,length(WVHT));
wave_fail_res = cell(1,simlength);
```

```
rn = NaN(numUnits,length(WVHT));
h=1;
    for i=1:length(WVHT)
        newpf_wave=1-exp(-((WVHT(i)-b_b)/a_b).^k_b);
        pf_wave(i)=newpf_wave;
        for j=1:numUnits
            if sum(failureMatrix_wave(j,:)) == 0
                rn(j,i) = rand;
                if rn(j,i) < newpf_wave
                   failureMatrix_wave(j,i)=1;
                end
            end
        end
        wave_fail_res{h} = failureMatrix_wave;
        remainingWECs(i) = 100-sum(sum(failureMatrix_wave(:,1:i)));
    end
    h=h+1;


remainingWECsAll(simInd,:) = remainingWECs;

end

names={'Jan','Feb','Mar','Apr','May','Jun','Jul','Aug','Sep','Oct','Nov','Dec'};


%Waveplot
remainingWECsAverage = mean(remainingWECsAll,1);

figure; hold on;
h1 = plot(remainingWECsAll(1,:),'--','Color',[0.6 0.8 0.8]);
for simInd = 2:nSimulations
    plot(remainingWECsAll(simInd,:),'--','Color',[0.6 0.8 0.8]);
end
h2 = plot(remainingWECsAverage,'k','LineWidth',2);
set(gca,'xtick',[0:729:8747],'xticklabel',names, 'Fontsize', 15)
ylabel('Operating WECs')
legend([h1,h2],'Simulations with random variable','Average')



%Windplot
remainingWINDsAverage = mean(remainingWINDsAll,1);
```

```
figure; hold on;
h1 = plot(remainingWINDsAll(1,:),'--','Color',[0.6 0.8 0.8]);
for simInd = 2:nSimulations
    plot(remainingWINDsAll(simInd,:),'--','Color',[0.6 0.8 0.8]);
end
h2 = plot(remainingWINDsAverage,'k','LineWidth',2);
set(gca,'xtick',[0:729:8747],'xticklabel',names, 'Fontsize', 15)
ylabel('Operating Wind Turbines')
legend([h1,h2],'Simulations with random variable','Average')
```