



COMPARATIVE ANALYSIS OF WAVE WEATHER WINDOWS IN OPERATION AND MAINTENANCE OF OFFSHORE WIND FARMS AT HSINCHU AND CHANGHUA, TAIWAN

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Key words: weather window, operation and maintenance, offshore wind farm.

ABSTRACT

The exploitation of offshore wind farms is an inexorable trend in the development of wind power generation in Taiwan. The operation and maintenance (O&M) period at offshore wind farms depends on the wave conditions that allow vessels to safely access wind turbines. This study used well-calibrated simulation wave data for a 9-years period for the sea areas of Hsinchu and Changhua to analyze the weather windows and quantify the accessibility of offshore windfarms for O&M. Two factors, namely wave height limit and window length, were considered. The results revealed a higher wave distribution and lower percentage of access hours at a wave height below 1 m for each month at Changhua. In addition, higher levels of access were observed at Hsinchu than at Changhua. The annual number of windows decreased as the window length increased. November was more accessible than the adjacent months in winter for smaller wave height limits.

The inaccessibility analysis revealed that, for a wave height limit of 1 m and a window length of at least 6 h, the longest waiting time for access is 17.6 days at Hsinchu and 31.9 days at Changhua; if the wave height limit is up to 2.5 m, the longest waiting times are only 2.2 and 6.3 days, respectively. At Hsinchu, the highest possible number of waiting periods is less than 2 days, irrespective of wave height limits and window length. At Changhua, most waiting periods are also less than 2 days.

I. INTRODUCTION

The development and application of wind electricity have

been positively promoted in Taiwan since 2000 (MOEA, 2013). Through wind resource exploration, technology transfer, research and investigation, and publicity and promotion by the government, Taiwan Power Company (TPC) and other private companies have focused on successively developing onshore wind power. Until June 2015, 28 wind farms were built onshore, with a total of 321 wind turbines and a cumulative installed capacity of 637.15 MW.

Apart from onshore wind power, abundant wind resources are available in Taiwan's western sea. The area is estimated to have approximately 1200 MW of wind power capacity at depths from 5 to 20 m and 5000 MW at depths from 20 to 50 m. On July 4, 2012, the Ministry of Economic Affairs announced and launched the Offshore Demonstration Incentive Program (DIP). This was the turning point in the shift from onshore to offshore wind power generation in Taiwan. The Offshore DIP was formulated to encourage private companies to build demonstration offshore wind farms with a budget subsidy for both equipment and developing processes. Three cases were selected, and each case includes one wind mast and two offshore wind turbines that are required to be built by the end of 2017, except for the case involving TPC, the schedule of which could be postponed for reasons related to local industry. For three demonstration wind farms, 60 wind turbines with a total of 300 MW capacities are expected to have been built by the end of 2019. One of the three offshore wind farms is located near the Hsinchu sea area and the other two are located at the Changhua sea area. Subsequently, through zonal development at a commercial scale (e.g., at Changhua, Yunlin, and Chiayi open sea areas) and an installed capacity of 300 MW per year, offshore wind farms are expected to be promoted to gradually achieve an installed capacity of 4000 MW.

From the perspective of offshore wind farm setup costs, wind turbines account for approximately 30%-40% of total costs, whereas operation and maintenance (O&M) and ocean engineering (including installation and grid connection) account for approximately 55% (Chen et al., 2014). Therefore, O&M and ocean engineering costs substantially affect investment gains. Evidence from the development of offshore wind farms in Europe

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past years indicates the cost of offshore wind farms is still high because of problems such as limited weather windows for operation, the huge mobilization cost of installation vessels, harsh environmental damage to equipment (including wind turbines and submarine cables), unclear expectations regarding completion schedules, availability of equipment, and O&M costs at the design stage. Consequently, in Europe, cost reduction is currently the main target in attempts to improve aspects such as external conditions, wind turbine systems, grid integration, and offshore technology (European Wind Energy Technology Platform, 2014).

The biggest difference between offshore wind farms and onshore wind farms is the environment. The environment of offshore wind farms is substantially more challenging than that of onshore wind farms. The feasible maintenance period on offshore wind farms depends entirely on maritime wind and wave conditions. Therefore, more expensive, difficult, and time-consuming O&M activities are required in offshore engineering. The most important factor is the accessibility, which involves the ability of vessels to safely access a wind farm for a period sufficiently long to perform maintenance activities. The wave weather window denotes the period for which waves are smaller than the threshold, which is the limit at which wave height vessels can access to complete specific maintenance operations.

Availability and accessibility are two major concerns for offshore wind farms (O'Connor et al., 2013). Availability is defined as the period for which wind turbines can generate electricity. Wind farm availability is dependent on numerous factors, such as failure rates, downtimes for recovery after failure, inaccessibility, lack of spare parts, and logistics problems involving wind turbines. Accessibility is the percentage of time for which a wind turbine can be accessed, and it influences the failure rate and, ultimately, the availability of wind turbines. Turbines that are more accessible receive more regular maintenance and consequently tend to have a lower failure rate. In addition, accessibility affects downtimes after failure because of affecting the time required to perform repairs. Evidently, a detailed analysis on the accessibility of wind farms is necessary. Different O&M strategies were adopted for different weather windows to ensure the high availability of wind turbines. A further reason for using weather windows analysis is that of economics: Walker et al. (2011) concluded that the primary influencing factor for installation capital expenditure is the downtime due to weather windows; thus, understanding weather windows is essential in the planning of operations.

Salzman et al. (2007) stated that more than 90% of all maintenance actions require only the transfer of personnel and parts, which can be carried by man or lifted using a turbine's permanent internal crane. Therefore, the transportation of personnel to wind turbines becomes the main problem. Boat-to-ladder transfer is a more conventional access method and is commonly used. Each type of vessel has a specific ability under certain accessible wave conditions. The accessible significant wave height is approximately 1.5 m for ordinary vessels, approximately 2.0 m for passenger yachts, and up to 2.5 m for large-scale multifunction working ships. More advanced access vessel

systems, which enable people to walk stably to the ladder of wind turbines, are currently being developed. More expensive vehicles such as helicopters, which are not influenced by waves, could be used if the wind turbine includes a landing pad.

Unlike that of wind turbines with fixed foundations, the maintenance of floating wind turbines involves not only access problems but also their floating behavior. This challenge is similar to that of wave energy converters and is not considered here. The present study focused only on analyzing the wave weather window of on-site O&M excluding the trip to site. Although wind speed may also be an influencing factor when cranes are used, it was not investigated in this study. Moreover, the day and night cycle was not considered.

Conducting measurements in oceans is expensive, particularly in the development of offshore wind farms, which also requires wind measurements at the hub height. When sufficient metocean data are not available from wind farm sites, the use of numerical models is a feasible, cheap, and efficient means of simulating metocean conditions after validating the numerical model by using neighbor observations.

The main goal of this study was to quantify the levels of access of vessels to wind turbines for O&M activities and to analyze challenges related to O&M at the Hsinchu (Formosa) and Changhua (TPC and Fuhai) sea areas. Due to the lack of observation data at three demonstration sites, with only the Hsinchu buoy of Central Weather Bureau (CWB) close to the Hsinchu demonstration site, numerical wave model data was applied to the analysis after verification by using Hsinchu buoy observation.

The remainder of this paper is organized as follows: The numerical model and verifications are explained in Section 2; in Sections 3 and 4, the wave height analysis and weather window analyses are discussed separately; and discussions and conclusions are presented in Section 5.

II. NUMERICAL MODEL AND VERIFICATION

1. Numerical Model Setup

NWW3 wave model version 3.14, a third generation wind wave spectral model (Tolman, 2009), was used for simulation. The model solves the weakly nonlinear action balance equation by using the explicit numerical method. It employs the multigrid approach, featuring a two-way nesting with grids with various resolutions in a single wave model. This model could be efficiently applied to the parallel computing platform. Moreover, it is suitable for applications in trans-scale scopes, ranging from kilometers to thousands of kilometers.

The simulation comprised three grids (0.25°, 0.05°, and 0.002°) and used a higher resolution in the region near the Hsinchu sea area. The numerical water depth was implemented based on three sources. In the largest area, the depth was extracted from ETOPO1 of the National Geophysical Data Center, National Oceanic and Atmospheric Administration (NGDC, NOAA), which is a 1 arc-minute global relief model of the Earth's surface that integrates land topography and ocean bathymetry. The area close to Taiwan was replaced with 500-m resolution data

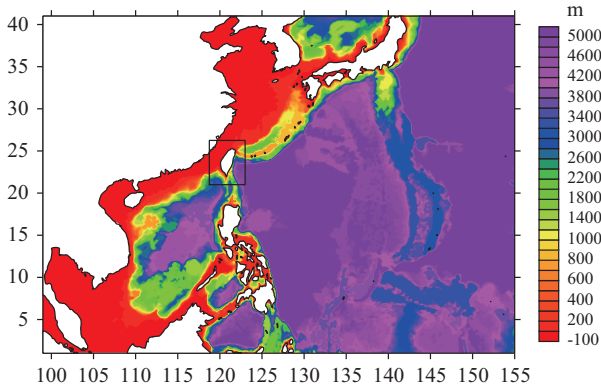


Fig. 1. Computation domains and water depth.



Fig. 2. Locations used in the weather window analysis.

from the Taiwan Ocean Research Institute. At the Hsinchu sea area, 2013 water depth measurements with approximately 50-m resolution were used. The computation domains of the wave model and water depth are presented in Fig. 1.

Wind forcing was obtained from hindcast wind of the CWB Nonhydrostatic Forecasting System (NFS) with two spatial grid resolutions, RC (45 km) and MC (15 km). This involves the objective analysis results being integrated with the observations (sounding reports, sounding wind reports, aircraft reports, satellite observations, surface synoptic observations, ship observations, bogus CWB Global Forecast System (GFS) data, and dropsonde).

Important parameters of numerical models contain 25 frequencies from the lowest frequency (0.04178 Hz), frequency increment factor 1.1, and 15° directional resolution. The built-in wind input source and dissipation term proposed by Tolman and Chalikov (Tolman, 2009) were used.

2. Methodology for Verification

For verification, the study used the CWB hourly, quality-controlled observed buoy data from Hsinchu for the January 2005 to December 2013 period, which was the only long-period observation available at both sites. Fig. 2 presents the locations of the Hsinchu buoy and Changhua Offshore DIP.

The study used the following conventional verification metrics to quantitatively assess the magnitude of errors, bias (*BIAS*), root mean square error (*RMS*), correlation (*CR*), scatter index (*SI*), and performance score (*Ps*), which are defined as follows (Chawla et al., 2009):

The nondirectional error metrics are given by

$$BIAS = \frac{1}{N} \sum (P_i - O_i) \quad (1)$$

$$RMS = \left\{ \frac{1}{N} \sum (P_i - O_i)^2 \right\}^{1/2} \quad (2)$$

$$CR = \frac{\sum [(P_i - \bar{P})(O_i - \bar{O})]}{\left\{ \sum (P_i - \bar{P})^2 \sum (O_i - \bar{O})^2 \right\}^{1/2}} \quad (3)$$

$$SI = \frac{\left\{ \frac{1}{N-1} \sum (P_i - O_i - BIAS)^2 \right\}^{1/2}}{\bar{O}} \quad (4)$$

where *P* and *O* refer to model and observation parameters (significant wave height, *H_s*; mean wave period, *T_{m02}*; and peak period, *T_p*). *N* is the number of data. To compute the performance score, error estimates must be normalized.

$$P_s = \frac{\hat{RMS} + \hat{b} + \hat{SI}}{3} \quad (5)$$

$$\hat{RMS} = \left(1 - \frac{RMS}{ORMS}\right) \quad \hat{b} = \left(1 - \frac{|BIAS|}{ORMS}\right) \quad \hat{SI} = (1 - SI) \quad (6)$$

where *ORMS* is the root mean square of the measurements.

For directional data, the angular bias and circular correlation are defined as follows:

$$\begin{aligned} BIAS &= \tan^{-1}\left(\frac{S}{C}\right) \quad \text{for } S > 0, C > 0s \\ &= \tan^{-1}\left(\frac{S}{C}\right) + \pi \quad \text{for } C < 0 \\ \infty &= \tan^{-1}\left(\frac{S}{C}\right) + 2\pi \quad \text{for } S < 0, C < 0 \end{aligned} \quad (7)$$

where $S = \sum \sin(\theta_p - \theta_o)$ $C = \sum \cos(\theta_p - \theta_o)$

$$CR = \frac{\sum [\sin(\theta_o - \bar{\theta}_o) \sin(\theta_p - \bar{\theta}_p)]}{\left\{ \sum \sin(\theta_o - \bar{\theta}_o)^2 \sum \sin(\theta_p - \bar{\theta}_p)^2 \right\}^{1/2}} \quad (8)$$

$$P_s = \frac{\hat{b}_a + CR}{2} \quad (9)$$

where $\hat{b}_a = \left(1 - \frac{|BIAS|}{180}\right)$

Table 1. Performance metrics of numerical wave model (Buoy Hsinchu, 2005.1-2013.12).

	Hs (m)	T _{m02} (sec)	T _p (sec)	Dir (°)
BIAS	-0.15	-0.22	-0.37	6.1
RMS	0.39	0.79	2.04	43.5
CR	0.78	0.53	0.43	0.67
SI	0.40	0.16	0.31	
Ps	0.70	0.87	0.78	0.81

The overall performance scores (Ps) are defined as the average of the normalized error estimate that the best value of Ps is 1 for the perfect model system, and the worst Ps is 0. Table 1 presents the verification metrics. The negative bias indicates that the model is relatively small compared with the observation. The score indicates that the model performs better in forecasting the wave period (T_p and T_{m02}) and wave direction than the wave height H_s .

The validation result of the NWW3 model conducted by NOAA (Chawla et al., 2009), which compared with buoy measurements, revealed that the performance scores averaged by regions (for Alaska, the US West Coast, and US East Coast) were 0.84-0.89 for H_s , 0.83-0.86 for T_p , and 0.80-0.88 for wave direction during 2007-2008. The scores also indicated that the model performs better in predicting the peak period T_p than the wave height H_s . An examination of the water depth and distance from the coast of buoys revealed that the nearest distance from the coast and minimum depth were 19 km and 135 m both at the US West Coast and Alaska. In general, the buoys in the two regions belong to deep water buoys. At the US East Coast, the water depths of buoys were between 28 and 47 m, and the nearest distance was 42 km, except for buoy 41035, which was located at a depth of 10 m and was 7.7 km from the coast.

No observations near Taiwan were used in the study by Chawla et al. (2009). Nevertheless, our model results for wave period and wave direction were close to their results; however, the wave height was slightly smaller. One reason for this finding may be that the Hsinchu buoy was located only 4.5 km from the coast, the wind was probably not very well represented (15-km resolution), and the downscaling effect accounting for land sea transitions was not resolved (Chawla et al., 2009). Another reason may be the use of different wind forcing. Chawla et al. (2009) used the analysis winds from the Global Data Assimilation System (GDAS), which is a system used by the National Center for Environmental Prediction (NCEP) Global Forecast System (GFS) model to place observations into a gridded model space for the purpose of starting or initializing weather forecasts with observed data. GDAS adds the following types of observations to a gridded, 3-D, model space: surface observations, balloon data, wind profiler data, aircraft reports, buoy observations, radar observations, and satellite observations. Huang (2006) compared the NFS with the wind measurement by using the satellite QuikSCAT from April 2004 to July 2005. He noted the negative bias of RC and MC. Chang (2011) compared the NFS with the wind data from 2005 to 2009 calculated using the Ku-band backscatter coefficient from the satellites JASON1 and

JASON2. The results revealed that the $BIAS$ was approximately 0.03 to -0.47 m/s, RMS was approximately 1.95-2.47 m/s, and CR was approximately 0.82-0.80. In addition, Chang compared the NFS with the wind data obtained from the European Center for Medium-range Weather Forecasting (ECMWF) from JASON1 and JASON2. The results indicated that the negative $BIAS$ was approximately -0.17 to -0.28 m/s, RMS was 1.62 m/s, and CR was 0.88. The results of NFS appeared to be close to ECMWF. Rasclé and Ardhuin (2013) concluded that the Climate Forecast System Reanalysis (CFSR) and NCEP analysis yielded systematically higher wind speed values than ECMWF analysis. Therefore, smaller wind growth parameters should be used for NCEP winds. CFSR, which employs GDAS, was designed and executed as a global, high-resolution, coupled atmosphere-ocean-land surface-sea ice system to provide the best estimate of the state.

We can infer that different winds resulted in the slightly smaller performance score in the study.

The data coverage rate at the Hsinchu buoy was only 88.8% over 9 years, indicating missing or unreliable data. If weather windows are to be analyzed on the basis of observations, the data should be amended and supplemented first. This is a huge task; moreover, data are still missing at the Changhua sea area. Therefore, instead of using only the observations at Hsinchu, the numerical model results at both sites were used for consistency in the following analysis.

III. SIGNIFICANT WAVE HEIGHT ANALYSIS

The analysis was conducted using the model output at the sites of the Hsinchu buoy (E120.84, N24.76) and Changhua Offshore DIP (E120.25, N24.03). The water depths were 25 and 28 m, respectively, whereas the offshore distances were 4.5 and 9.2 km, respectively. The data selection period was from January 2005 to December 2013.

Figs. 3 and 4 present the occurrence probability distribution and exceedance probability distribution of the significant wave height, respectively. A higher percentage of large wave heights were observed at Changhua when the wave height was larger than 1.2 m. This finding may be because the distance from the coast is long. At Hsinchu, 72.2% of the wave height was lower than 1 m and 98.16% was lower than 2 m. At Changhua, 55.6% of the wave height was lower than 1 m and 85% was lower than 2 m.

In the Taiwan Strait, the northeast monsoon prevails in winter with higher waves, whereas the southwest monsoon prevails in summer with smaller waves. June to October is the typhoon season, with an annual average hit frequency of 3 to 4 times (CWB, 2017). This type of weather pattern results in a prolonged period of calm seas in summer and a continuous period of high waves in winter. This indicates more frequent and easier access in summer that could last for a longer period. By contrast, the opportunity for wind turbine access in winter is limited, and a longer waiting time is required.

The annual average hours of occurrence during each month of wave height below the limits of 1, 1.5, 2, and 2.5 m are pre-

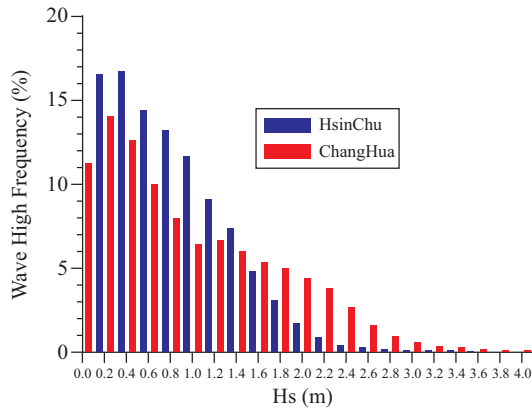


Fig. 3. Occurrence probability of indicative wave heights at Hsinchu and Changhua sea areas.

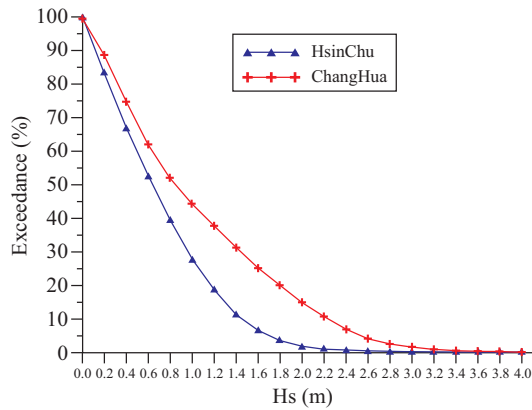


Fig. 4. Exceedance probability of wave heights at Hsinchu and Changhua sea areas.

sented in Figs. 5 and 6. The greatest potential for access could occur at higher wave height limits at Hsinchu for the entire year, but only from March to September at Changhua. In addition, low levels of access occurred during winter at low wave height limits. The occurrence hours of smaller wave height limits (1 and 1.5 m at Changhua and 1 m at Hsinchu) in November were evidently higher than those in the adjacent months (Fig. 5). Maintenance activities may be performed in this winter month. At a wave height limit of 1 m at the two sites, higher percentages of access hours were observed at each month at Hsinchu as a result of more chances of access for O&M tasks, particularly during winter (Fig. 7). This finding is consistent with the exceedance distribution in Fig. 4, which indicated the presence of lower wave heights at Hsinchu.

Fig. 8 presents the accessibility of the two sites. High accessibility was observed at Hsinchu at each wave height limit.

IV. WEATHER WINDOW ANALYSIS

The above analysis accounts only for the probability of occurrence without considering the time series of wave height, such as persistence of wave height relating to one another. However, the maintenance in offshore wind farms is time-consuming and

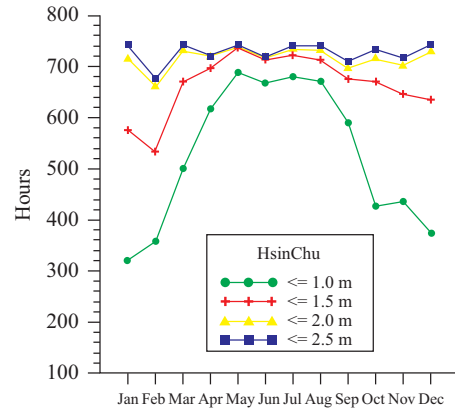


Fig. 5. Annual average hours for wave heights lower than various wave height limits in each month (Hsinchu).

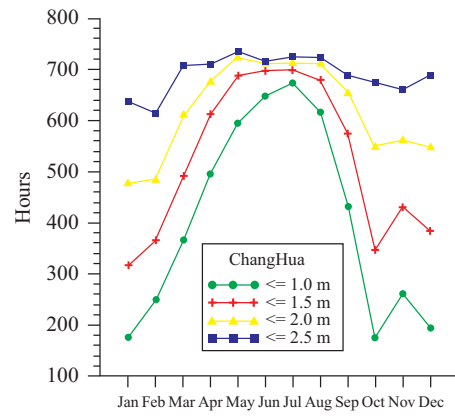


Fig. 6. Annual average hours for wave heights lower than various wave height limits in each month (Changhua).

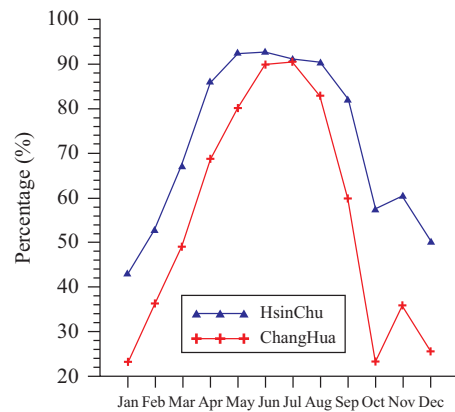


Fig. 7. Occurrence probability of wave heights below 1 m in each month at Hsinchu and Changhua sea areas.

might require several hours, days, or weeks. Various operating procedures have different requirements regarding weather conditions and durations. The duration required for maintenance is extremely important for O&M planning. If a longer duration is required and vessels can only access wind turbines at the conditions of smaller waves, the waiting time increases due to the

Table 2. Occurrence percentages of wave heights within specific window lengths and wave height limits from 2005 to 2013 for Hsinchu.

Hs (m)	Minimum Length of Windows (Hours)																% Occurrence
	2.5	99	99	99	99	99	99	99	99	99	99	99	99	99	99	99	
2	98	98	98	98	98	98	98	98	98	98	98	98	98	98	98	97	
1.5	90	90	90	90	90	89	89	89	89	88	88	88	87	87	86	85	
1	71	70	69	68	68	67	66	65	64	62	61	60	59	58	56	54	
	6	12	18	24	30	36	42	48	54	60	66	72	78	84	90	96	

Table 3. Occurrence percentages of wave heights within specific window lengths and wave height limits from 2005 to 2013 for Changhua.

Hs (m)	Minimum Length of Windows (Hours)																% Occurrence
	2.5	94	94	94	94	94	93	93	93	93	93	93	92	92	91	91	
2	84	84	83	83	82	82	81	80	79	79	78	77	76	75	74	74	
1.5	71	70	69	69	68	67	66	65	64	63	61	60	59	57	56	54	
1	55	54	53	52	51	50	48	47	46	45	44	42	41	39	38	37	
	6	12	18	24	30	36	42	48	54	60	66	72	78	84	90	96	

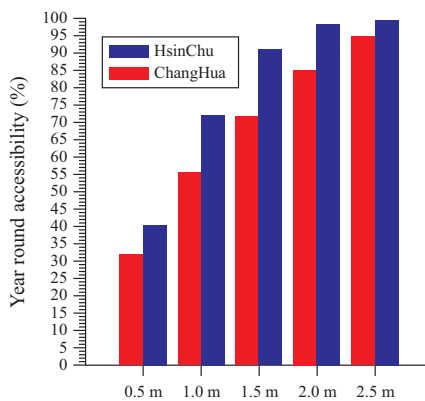


Fig. 8. Accessibility of Hsinchu and Changhua sites.

high probability of inaccessibility. Consequently, two parameters should first be set before analyzing weather windows, namely wave height limit and window length. The wave height limit is the limit within which vessels can access an offshore wind turbine, and the window length is the required operation period below the limit (Chen et al., 2008; O'Connor, 2012; O'Connor et al., 2013). Issues such as the longest waiting time, number of waiting period between weather windows, the probability of occurrence and annual number of weather windows at least a certain length at each wave height limit were analyzed.

1. Probability of Occurrence

Tables 2 and 3 present the occurrence percentages of wave height within specific window length and wave height limits of 1, 1.5, 2, and 2.5 m for Hsinchu and Changhua from 2005 to 2013. Occurrence probability indicates the levels of access to high probability indicates high accessibility. The probabilities of occurrence have been demonstrated to become low with small wave height limits and a long window length. For example, at Hsinchu, access to wind turbines is available for 71% of the year at a window length of at least longer than 6 h and the

Table 4. Minimum, mean, and maximum number of windows for at least 6, 12, 24, 48, and 96 h window lengths and at various wave height limits at Hsinchu and Changhua sea areas from 2005 to 2013.

Hsinchu	1.0 m			1.5 m			2.0 m			2.5 m		
	min	mean	max	min	mean	max	min	mean	max	min	mean	max
6 h	50	60	66	24	29	35	6	10	14	1	3	5
12 h	42	52	59	22	28	34	4	9	11	1	3	5
24 h	37	40	44	20	25	30	4	9	11	1	3	5
48 h	25	32	38	18	22	28	4	8	11	1	3	5
96 h	12	19	23	13	17	22	4	8	11	1	3	5

Changhua	1.0 m			1.5 m			2.0 m			2.5 m		
	min	mean	max	min	mean	max	min	mean	max	min	mean	max
6 h	43	56	69	46	54	66	28	43	52	13	24	31
12 h	40	47	54	40	47	58	27	39	47	12	22	29
24 h	31	38	47	34	38	42	24	33	36	12	19	23
48 h	18	26	32	24	29	32	22	27	31	10	18	21
96 h	10	13	16	12	15	19	16	18	22	10	15	17

strictest wave height limit of 1 m. If the window length becomes 96 h (4 days), the level of accessibility decreases to 54%. Nevertheless, at wave height limits of 2 and 2.5 m, the level of accessibility is almost higher than 98%, irrespective of the window lengths. This is consistent with the result presented in Fig. 5. At Changhua, the level of accessibility is 55% at a wave height limit of 1 m and a window length of at least 6 h and only 37% at a window length of at least 96 h. Evidently, higher levels of access were observed at Hsinchu than at Changhua.

At the North Sea offshore wind farm Col River Bar, 45 km off the Dutch coast, access to the device is achieved for only 5% of the year at a wave height limit of 1 m and window length of at least longer than 6 h and 62% at a wave height limit of 2.5 m at the same window length (O'Connor et al., 2013). In summary, the North Sea exhibited lower accessibility than the two sites in Taiwan, and Changhua exhibited a lower level of access than Hsinchu. Accessibility is one of the key factors for O&M activities. Therefore, vessels that can sustain high wave limits should be used at sites with low accessibility.

2. Annual Number of Weather Windows

Table 4 presents the statistical results of the annual number of weather windows within 9 years at wave height limits of 1, 1.5, 2, and 2.5m and window lengths of at least 6, 12, 24, 48, and 96 h, including the highest number (max), mean number (mean), and lowest number (min) over 9 years. The highest number is the highest number of windows observed in any of the 9 years, and the lowest number is the lowest number of windows observed over the 9 years. The mean number of windows is the average number of windows that occurred in 9 years. The number of windows decreased as the window length increased. The annual changes in number are also presented. Despite not including climate changes in the study, the annual change in the number of weather windows is an important factor influencing future O&M and power production of offshore wind farms.

Theoretically, when the wave height limit increases, the number of weather windows increases. That is, the probability or opportunity for O&M increases. However, this result is related to the distribution of wave heights. If 50% of wave heights is

Table 5. Longest waiting times (days) at wave height limits of 1, 1.5, 2, and 2.5 m and window lengths of at least 6, 12, 24, 48, 72, and 96 h.

Hsinchu							Changhua						
Wave Height Limits	Window Length (hours)						Wave Height Limits	Window Length (hours)					
	6 h	12 h	24 h	48 h	72 h	96 h		6 h	12 h	24 h	48 h	72 h	96 h
1.0 m	17.6	23.3	32.6	46.9	66.7	115.8	1.0m	31.9	40.4	63.8	75.3	114.6	207.7
1.5 m	6.9	6.9	6.9	14.4	32.0	45.9	1.5m	23.3	23.3	23.3	62.6	70.5	116.1
2.0 m	3.2	5.5	5.5	5.5	5.5	8.5	2.0m	8.3	8.3	14.5	21.8	46.1	46.1
2.5 m	2.1	2.2	2.2	2.2	2.2	2.2	2.5m	6.3	6.5	6.5	7.0	11.3	20.5

small (e.g., < 1 m), on the contrary, the number of weather windows decreases at a higher wave height limit because each window length is a very prolonged period of continuous access (> 96 h), as observed at Hsinchu. By contrast, because of the higher wave height distribution at Changhua, the number of weather windows increased when the wave height limit increased up to 1.5 m.

3. Waiting Time between Windows

The waiting time or period between windows represents the periods of inaccessibility. In the planning stage, the longest period of inaccessibility should be considered. The longer the waiting time is, the higher the cost becomes.

Table 5 presents the longest waiting times over 9 years at various wave height limits and least window length conditions. The waiting time becomes longer at a small wave height limit and long window length. Similarly, the shorter the waiting time is, the higher the wave limit is. In the winter season, the periods of inaccessibility tend to be more pronounced because winter represents the least favorable scenario in a year for most areas in the world.

For example, when the wave height limit is 1 m and the required window length is at least 4 days (96 h), the longest waiting time is up to 115.8 days at Hsinchu and 207.7 days at Changhua. This indicates that the waiting time are at most 4 months and over 6 months respectively, during which the sites are inaccessible. If only 6 h are required, the longest waiting time for access will be 17.6 and 31.9 days at Hsinchu and Changhua, respectively. If the wave height limit is up to 2.5 m, the longest waiting time becomes only 2.1 days at Hsinchu and 6.3 days at Changhua.

4. Number of Waiting Time between Windows

The highest possible number of waiting times after the weather window is another concern for O&M activities. The number of waiting times represents the possibility of the waiting times between weather windows. The higher the number is, the higher the potential waiting time is.

Table 6 presents the number of waiting times between windows of at least 6, 12, 24, 48, 72, and 96 h at wave height limits of 1, 1.5, 2, and 2.5 m. In addition, the waiting times are divided into three categories at each wave height limit: less than 2 days, between 2 days and a week, and longer than a week.

The number of waiting time decreased as the window length increased at each wave height and waiting time (Table 6). At

Table 6. Number of waiting periods within 9 years.

		Hsinchu						Changhua							
Wave Height Limits	Waiting Time (days)	Window Length (hours)						Wave Height Limits	Waiting Time (days)	Window Length (hours)					
		6 h	12 h	24 h	48 h	72 h	96 h			6 h	12 h	24 h	48 h	72 h	96 h
1.0 m	wt <= 2d	373	308	195	136	94	68	1.0 m	wt <= 2d	295	221	146	80	50	35
	2d < wt <= 7d	137	132	135	104	76	44		2d < wt <= 7d	158	144	141	86	55	40
	7d < wt	19	26	32	46	54	54		7d < wt	53	57	55	66	63	44
1.5 m	wt <= 2d	215	194	168	134	111	93	1.5 m	wt <= 2d	324	259	182	120	71	42
	2d < wt <= 7d	43	47	53	57	55	44		2d < wt <= 7d	141	139	117	93	66	42
	7d < wt	0	0	0	5	10	17		7d < wt	20	27	43	46	56	53
2.0 m	wt <= 2d	72	64	63	61	61	57	2.0 m	wt <= 2d	307	259	196	136	93	73
	2d < wt <= 7d	6	6	6	7	7	6		2d < wt <= 7d	74	85	87	81	72	59
	7d < wt	0	0	0	0	0	2		7d < wt	3	3	8	22	29	35
2.5 m	wt <= 2d	20	18	17	17	17	17	2.5 m	wt <= 2d	188	163	134	120	102	92
	2d < wt <= 7d	1	2	2	2	2	2		2d < wt <= 7d	18	23	30	34	37	33
	7d < wt	0	0	0	0	0	0		7d < wt	1	1	1	1	4	8

Hsinchu, irrespective of wave height limits and window lengths, the highest possible number of waiting times is observed for the less than 2 days category. Most situations occur at a window length of 6 h and a wave height limit of 1 m. At Changhua, the highest possible number of waiting times is also observed for the less than 2 days category; however, most situations occur at a window length of 6 h and a wave height limit of 1.5 m instead of 1 m due to the higher wave distribution.

5. Comprehensive Analysis

In conclusion, based on the wave height analysis and weather windows analysis, the accessibility at Hsinchu is evidently higher than that at Changhua. According to Salzman et al. (2007), the accessibility could be up to 50% with the wave height limit of 1 m for a typical offshore wind farm in the North Sea. When an access system can tolerate significant wave height of up to 2.5 m, it can be accessed for more than 90% of the year. The result reveals that accessibility at both Hsinchu (72%) and Changhua (55%) at a wave height limit of 1 m is higher than the typical wind farm in the North Sea.

Fig. 8 shows that the accessibility is very close (approximately 73%) with a wave height limit of 1.5 m at Changhua and 1 m at Hsinchu. O&M activities in offshore wind farms are still unavailable in Taiwan. The number of offshore O&M teams required in Taiwan remains unclear. Assuming that the O&M activities at both sites are performed by one company and an accessibility of 73% is the typical acceptance level, the minimum access level is at a wave height of 1.5 m. However, the longest waiting time is approximately 23-63 days at Changhua at a window length of at least of 6-48 h, whereas it is 7-14 days at Hsinchu. If the longest waiting time is acceptable at both sites, it could be used as the O&M strategy. If not, the wave height limit should be higher, which is inevitable by using vessels with higher seakeeping and advanced accessibility ability.

V. DISCUSSION AND CONCLUSION

Maintenance at offshore wind farms mainly depends on wave conditions, thereby increasing the costs, time, and difficulties

relative to onshore wind farms. Increased accessibility to wind turbines increases the chances of regular maintenance and consequently decreases the failure rate of wind turbines, as well as the downtime after wind turbine failure. This is a preliminary study to investigate the accessibility of offshore wind farms in Taiwan for O&M activities and with respect to both possibility of occurrence and persistence of wave height.

The study used results from well-verified high-resolution numerical simulations from 2005 to 2013, applying the NWW3 wave model to analyze significant wave heights and weather windows at the Hsinchu buoy location and Changhua Offshore DIP site. Significant wave height analyses reveal that the highest access occurs at higher wave limits. A higher wave distribution and lower percentage of access hours with a wave height below 1 m for each month was observed at Changhua. In addition, the seasonal variation of the probability of occurrence was below 2.5 m. For Hsinchu, wave heights below 1 m accounted for 72.2% and wave height below 2 m accounted for 98.2%. For wave heights below 1 and 1.5 m, the probability of occurrence presented obvious seasonal differences and a higher value in summer. November appears to be a monsoon transition period, and the site could be more accessible in the winter season.

The analysis of weather windows reveals that the probabilities of occurrence decrease with small wave height limits and long window lengths. Moreover, higher levels of access were evident at Hsinchu than at Changhua. The annual number of windows decreased as the window length increased. The features of annual change were also displayed. Due to the smaller wave height distribution at the two sites, the number of weather windows decreased at higher wave height limits because each window length is a very prolonged period of continuous access.

Inaccessibility or waiting time is another important concern. Waiting time between windows represents the periods of inaccessibility. If the wave height limit is 1 m and the required window length is at least 4 days (96 h), the longest waiting time is up to 115.8 days at Hsinchu and 207.7 days at Changhua. If only 6 h is required, the longest waiting time for access will be 17.6 and 31.9 days at Hsinchu and Changhua, respectively. If the wave height limit is up to 2.5 m, the longest waiting time becomes only 2.1 days at Hsinchu and 6.3 days at Changhua.

The number of waiting period represents the possible waiting time between weather windows. The higher the number is, the higher possibility of the waiting time is. At Hsinchu, irrespective of wave height limits and window lengths, the highest possible number of waiting period is less than 2 days. At Changhua, the most possible waiting period is also less than 2 days.

A thorough analysis of the access conditions of different vessels for O&M activities could provide suitable strategies for different weather windows. A more efficient plan could then be proposed to utilize the duration for maintenance. Good O&M strategy could thereby improve the availability of wind turbines and thus benefit the performance of offshore wind farms. However, the environment in offshore wind farms in Taiwan appears to be more favorable than that in the North Sea. The experience of Europe must not be only considered to determine a suitable

strategy in Taiwan.

This study focused only on the significant wave height. Apart from the significant wave height, other environmental factors that affect weather windows include wave period, wind speed, and ocean current. Among these, wind speed mainly affects the safety of crane operations, and ocean current affects cabling and diver activities. Further research should focus on the multivariate analysis of weather windows to consider more other environment factors. The advantage of studies based on numerical models is that continuous time series are obtained without any outliers or gaps in the data. However, the disadvantage of this approach is the uncertainty and error in the simulation, which makes assessing the impact difficult. In the future, we plan to collect the wind mast data at offshore windfarm sites and to calibrate the model to improve the simulation (including wind forcing and suitable empirical formula selection).

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