



## An economic assessment of tropical cyclone risk on offshore wind farms

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## **Risks of tropical cyclones on offshore wind farms in China**

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### **ABSTRACT**

Frequent tropical cyclones pose great risks and obstacles to the development of offshore wind farms in the coastal regions of China and other areas in the Pacific, where development of wind energy is gaining momentum. This paper aims to identify and evaluate the risks of tropical cyclones on offshore wind farms within the Economic Exclusive Zone (EEZ) of China and help improve decision-making for planners and investors. The risks of tropical cyclone impact in this paper are defined by the statistical extreme wind climate and the expected economic losses of offshore wind farms. A probabilistic tropical cyclone event model is applied to evaluate 20-year, 30-year, 50-year and 100-year recurrence of extreme wind speeds by geographical location. Combining a damage model derived from empirical loss data and an investment cost model within a Geographical Information System (GIS), the expected annual losses of offshore wind farms from tropical cyclones are evaluated and shown on a spatially continuous risk map. Results are given in terms of annual economic risks and damage losses based on occurrence of an average recurrence interval. Implications for identifying locations for offshore wind farms and resource potential and costs are then discussed. The impact of tropical cyclones on offshore wind farms likes a double-edged sword, which might be advantageous for some regions in terms of increasing full-loaded hours of turbines, but also disadvantageous for others due to its destructive effects. However, specific design standards and insurance of turbines would help reduce the risks and economic losses of offshore wind farms in tropical cyclone-prone areas and expand exploitable locations for future offshore wind farms.

### **INTRODUCTION**

An increasing energy demand, worries about energy security and climate change have compelled China to focus on developing renewable energy alternatives. At the 2009 United Nations Climate Change Conference (known as COP15), the Chinese government committed itself to reduce the CO<sub>2</sub> emissions per GDP by 40-45% in 2020 compared to its level in 2005.

In the medium and long term plan for renewable energy, the country established a goal of producing 15% of the primary energy it consumes via renewable sources. Offshore wind energy is deemed as a promising option to deal with the energy and climate dilemma, since the abundant, renewable and clean energy resources locate near the economic and population centers as shown in Figure 1.

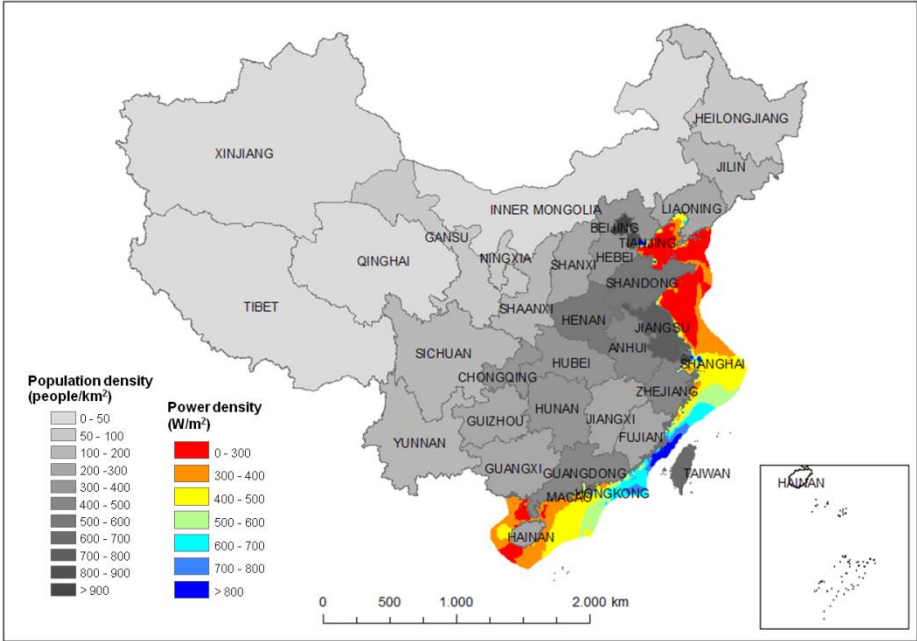


Figure 1 Population and offshore wind power density<sup>1</sup> in China

While the National Energy Administration of China has already proposed an ambitious plan of offshore wind energy development [1] (Figure 2), a lot of uncertainties still need to be further explored. One of the most concerning problems relates to the potential risks of tropical cyclones on offshore wind farms. China is one of the countries that suffer most from tropical cyclones in the world, with an average of nine tropical cyclones making landfall annually in 1951-2008[2]. Strong precipitation, extreme wind and storm surge brought by tropical cyclones would cause serious casualties and economic losses. Regarding wind farms, tropical cyclones might help increasing annual full-loaded hours and therefore electricity productions, but also leading to fatal damages sometimes. The focus so far has been on turbines intended for use in Europe, primarily in the North and Baltic Seas. One question that occasionally arises is how applicable offshore turbines designed for northern European conditions are to China, where tropical cyclones occur relatively frequently. In other words, what is the potential economic risk of developing offshore wind farms in tropical cyclone prone regions under current design standards for offshore turbines? In this paper, we strive to accomplish

<sup>1</sup> The boundary is gained from VLIZ (2009). As there are still a lot of disagreements on EEZ between countries worldwide, new treaties will be negotiated in the next years.

the following work: (1) describe the extreme wind speeds of tropical cyclones using a probability model and propose a rough turbine damage model; (2) reviewing current design standards for offshore turbines; (3) evaluate the potential economic risk of tropical cyclones on offshore turbines; (4) analyze its implications on site selection, offshore wind potential and costs; (5) further discuss the limitations of the model; and (6) conclusion.

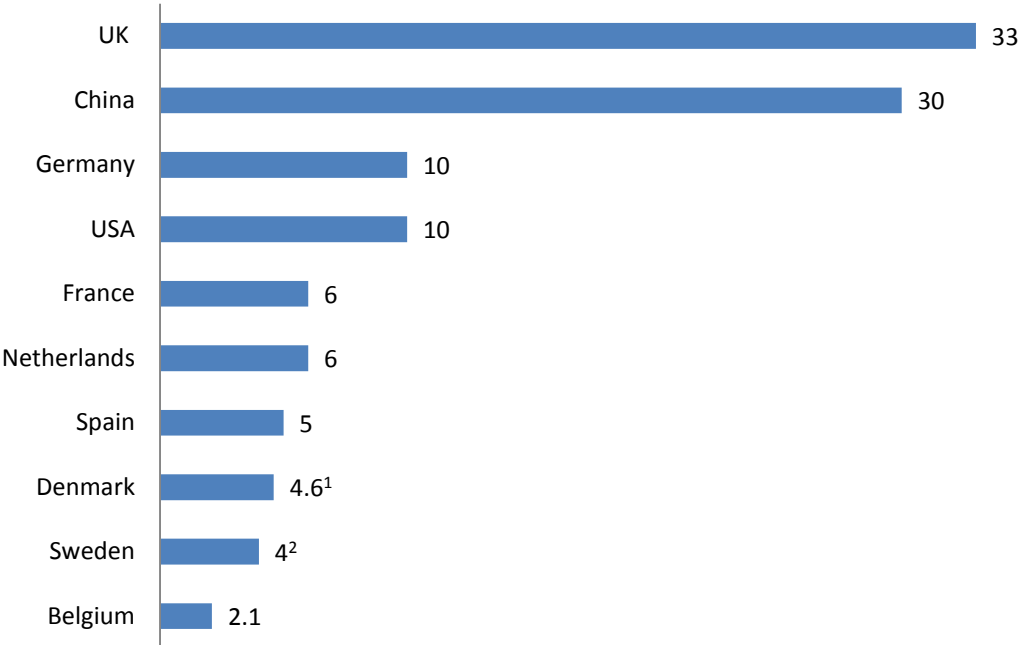


Figure 2 Targets for offshore wind energy in 2020(GW)

Note: 1 Until 2025. 2 Based on a capacity factor of 40 percent. [30][31]

**METHODOLOGY**

**Data source**

We use the CMA-STI Best Track Dataset for Tropical Cyclones in the Western North Pacific in this study, which is compiled by Shanghai Typhoon Institute (STI) of China Meteorological Administration (CMA) [3]. This dataset contains measurements of dates, intensities, latitudes, longitudes, minimum pressures at the storm center and 2-min mean maximum sustained wind speed near the storm center at 6-hour intervals for all tropical cyclones from 1949 to 2009 in the western north pacific (to the north of the equator and to the west of 180°E). The CMA-STI point dataset was converted into spatially continuous map layers for modeling using kernel density function of GIS. Since the mean size of tropical cyclone in the northwest Pacific Ocean is found to be 3.7 degrees of latitude [4], a scan radius of this figure is used in the study. All map layers in the GIS model have the unified spatial resolution of 1km<sup>2</sup> in a geographical reference framework of the Universal Transverse Mercator (UTM) system.

**Probability model of extreme wind speeds and waves**

A tropical cyclone is the generic term for a non-frontal synoptic scale low-pressure system over tropical or sub-tropical waters with organized convection (i.e. thunderstorm activity) and definite cyclonic surface wind circulation. While tropical cyclones can produce extremely powerful winds and torrential rain, they are also able to produce high waves and damaging storm surge as well as spawning tornadoes. Depending on its location and strength, a tropical

cyclone is referred to by names such as hurricane (in Northeast Pacific), typhoon (in Northwest Pacific and etc. In China, according to the Classification of Tropical Cyclones Standardization [GB/T19201-2006] published by CMA [5], tropical cyclones are classified in terms of maximum wind speeds near the center as Table 1.

Table 1 The classification of tropical cyclones standardization in China

Tropical Cyclone Classification	Maximum 10-minute mean wind near the centre(ms <sup>-1</sup> )	Wind scale <sup>2</sup>
Tropical depression, TD	10.8-17.1	6-7
Tropical storm, TS	17.2-24.4	8-9
Severe tropical storm, STS	24.5-32.6	10-11
Typhoon, TY	32.7-41.4	12-13
Severe typhoon, STY	41.5-50.9	14-15
Super typhoon, super TY	≥51.0	≥16

A number of possible distributions can be used to estimate the probabilities of tropical cyclones. The Poisson distribution is frequently used and its appropriateness has been well demonstrated [6]. A Poisson process should have the following characteristics: (1) the event can have only dichotomous outcomes: occurrence or nonoccurrence; (2) individual events are independent; (3) events occur randomly but at an approximately constant average rate, and (4) events should be rare enough so that the probability of two or more occurring simultaneously is very small. The annual occurrences of tropical cyclones in China meet the above characteristics and thus can be well represented by the Poisson process. Assume the probability that  $t$  tropical cyclones will occur in a location in one year be denoted by  $p_t$ :

$$p_t = \gamma^t \exp(-\gamma) / t! \quad (2.2.1)$$

where  $\gamma$  represents the average tropical cyclone occurrence rate per year in a location.

The return period of maximum wind speeds associated with tropical cyclones refers to the average period in which an event is expected to recur once. The probability of exceeding the  $N$ -year maximum wind-speed distribution in one year is  $1/N$ , i.e., a 50-year recurrence interval means the maximum wind speed having a 2% annual exceedance probability. Assuming independent annual maximum wind-speeds, the probability of exceeding the  $N$ -year maximum wind-speed distribution in  $m$  year is  $1 - (1 - (1/N))^m$ . A Gumbel distribution, one of the most frequently used extreme value distributions [7], is applied to get the maximum wind speeds at a certain recurrence interval. In the following description,  $G(x)$  denotes the cumulative distribution function (CDF):

$$G(x) = \exp\{-\exp[-\alpha(x - \delta)]\} \quad (2.2.2)$$

where  $\alpha = 1.28255/\sigma$ ,  $\delta = \bar{x} - 0.57722/\alpha$ [8],  $\alpha$  denotes the average wind speed of the sample and  $\sigma$  represents the standard deviation of the sample wind speed. The probability that the maximum wind speed on occurrence of an average recurrence interval event can be represented as:

$$F(x) = \sum_0^t p_t [G(x)]^t = \exp\{-\gamma[1 - G(x)]\} = P \quad (2.2.3)$$

<sup>2</sup> The Beaufort Wind Force Scale is an empirical measure for describing wind speed based on observed sea conditions (on land it is categorized by the physical effects it has on vegetation and structures). The initial scale of thirteen classes (zero to twelve) was extended in 1946, when Forces 13 to 17 were added. Forces 13 to 17 were intended to apply only to special cases, such as tropical cyclones.

and then,

$$v_p = \delta + \frac{-\ln[-\ln(1+\frac{1}{\gamma}\ln p)]}{\alpha} = \delta + \frac{-\ln\{-\ln[1-\frac{1}{\gamma}\ln(1-\frac{1}{N})]\}}{\alpha} \quad (2.2.4)$$

where  $V_p$  denotes the maximum wind speed and  $P$  denotes the probability of exceeding the  $N$ -year maximum wind-speed distribution in one year.

In order to verify the goodness-of-fit of the distribution model to wind speed data and occurrence interval observations, modified K-S test (Lilliefors test) is conducted. The absolute value of the largest difference  $D$  between the theoretical and empirical CDFs is,

$$D = \max_x |F_n(x) - F(x)| \quad (2.2.5)$$

where  $F(x)$  is the theoretical CDF as given by (2.2.5),  $F_n(x)$  is the empirical CDF as follows,

$$F_n(x) = \frac{k}{n} \quad (2.2.6)$$

where  $k = 1, 2, \dots, n-1$  denotes the cumulative frequency and  $n$  is the sample size. If a confidence level related parameter  $\beta$  is given, the critical value of  $D_\beta$  can be found in the critical value table of the modified K-S test according to the sample size  $n$  and the confidence level  $\beta$ . If  $D \leq D_\beta$ , then the distribution fitting is good, otherwise the fitting is not satisfactory. In this study,  $\beta$  is chosen as 0.1 and thus the confidence level is 90%.

### **Turbine damage model**

For offshore wind turbines the most important external conditions are wind and waves [9]. In the case of high wind speeds (above the cut out speed of 25m/s), the mechanical brake would stop the turbine from rotating in order to reduce the loads. Otherwise, the blades will reach over-speed, creating extreme loads that the structure cannot withstand, and eventually causing the blades to bend, get damaged or collapse. Also signals from wind vane and other components of the turbine would be sent to control system, which helps to reduce extreme and fatigue loads from over-speed and turbulence intensity. The yaw system uses electrical motors to turn the nacelle and typically rotor away from the prominent wind direction as to reduce the loads, whereas the pitch mechanism uses hydraulics to control the angle of the blades relative to the wind. Failure of the yaw system can be caused by various reasons: grid failure (in that case it would be dependent on back-up power supply), failure of wind vane that indicates the wind direction and failure in the electric motors controlling the system. Although offshore wind turbines in general are equipped with back-up power, these safety measures are not designed for use in a long time period, and it is impossible to replace back-up power or restore grid system timely in tropical cyclones. Therefore, wind turbines may become vulnerable due to their inability to react to external conditions. In general, once a tropical cyclone occurs, there could be a high risk of grid failure, which could imply that it is not possible to adjust and stop the turbine, and then over-speed could cause damage of the mechanical and electrical components. In more severe conditions, extreme high loads would cause the collapse of the turbine or breaking blade might hit and induce its tower to collapse.

A limited number of building damage models have been developed and utilized for economic assessment of hurricane or tropical cyclone damage, and one of the most comprehensive building vulnerability models has been developed by Huang et al [10]. The main idea of the building damage model is to reveal the relationship between wind speed and the damage ratio based on a large quantity of actual insurance loss data. Huang et al. [11] suggest that mean wind speed is a more comprehensive measure of wind conditions over a large spatial area and the severity of wind damage (over a large area) is more a function of the mean wind speed than a potentially isolate gust. However, experience from building constructions might not be able to be applied for wind turbines directly. Exceedance of designed extreme wind speed might cause structural problems for wind turbines within a very short time. Large random changes of aerodynamic force are very harmful to blades, gearboxes, bearings, yaw systems, control systems and generators [12]. Based on real cases (Table 2), the gust wind speed rather than the mean wind speed would be more appropriate to measure wind loads and thus the severity of wind damage for turbine components.

Table 2 Empirical data on tropical cyclone damage for wind farms

Tropical cyclone	Year	Wind farm	Size	3-s gust wind speed	Turbine	Damage description	Damage ratio	Source
03/A	1998	Gujarat, India	174MW	67m/s		260 of the 782 wind turbines. 40MW. \$50 million destroyed	40%	[32]
Dujuan	2003	Shanwei Honghai wan, China	16.5MW	57m/s	Vestas V47/660 kw	13 of 25 wind turbines stop operation; €1.15M loss	52%	[33]
Dujuan	2003	Single turbine	600kw	45m/s	Vestas V47/660 kw	One Blade damage	7.3%	[33]
Maemi	2003	Karimata, Japan	0.9MW	74.1m/s	Micon 400/100kw; Enercon 600kw	collapsed; Nacelle cover cracked and blades broken	100%	[34]
Maemi	2003	Nanamata, Japan	1.1MW	74.1m/s	Enercon 500kw; Vestas 600kw	collapsed; Nacelle cover cracked and blades broken	100%	[34]
Maemi	2003	Single turbine	100/600 kw	87.6m/s	Micon 400/100kw; Enercon 600kw	Collapsed	100%	[34]
Sangmei	2006	Cangnan, China		68m/s	Vestas/500kw	20 of 28 turbines damaged; 5 collapsed	71.4%	[8]

Since there is quite few empirical data on wind farm damage from tropical cyclones, the building of turbine damage model relies on a lot of assumptions. It is supposed that wind turbines can withstand tropical cyclones, when their wind speeds are lower than the cut-out speed of turbines (usually 25m/s). And damage ratios of turbines become 100%, when extreme wind speeds of tropical cyclones reach 75m/s. Within the range from 25m/s to 75m/s, damage ratios of wind turbines  $F_D$  was presented as a function of 3-s gust wind speed  $V_e$  at the hub height. And 3-s gust wind speed at 10m height can be calculated from extreme wind speed  $V_p$  referred in 2.2, based on a gust factor of 1.15[13]. Considering the 90m hub height of a 5MW turbine,  $V_e$  is 1.2 times of 3-s gust wind speed at 10m height according to the classic log formula. Therefore,

$$F_D = 0, V_e \leq 25m/s$$

$$F_D = 0.0002V_e^2 - 0.0031V_e - 0.0494, 25m/s < V_e < 75m/s \quad (2.3.1)$$

$$F_D = 1, V_e \geq 75m/s$$

It further assumes that tropical cyclones would not destroy submarine infrastructures (e.g. foundation) of offshore wind farms. Therefore, economic losses of offshore wind farms under the influence of tropical cyclones equal to that of offshore wind turbines and part of its grid system, which approximately take account 55% of the total investment costs [14]. And annual expected economic losses of offshore wind farms per ocean area unit  $E_c$  in €/km<sup>2</sup>/y are calculated as follows,

$$E_c = 1/N \cdot 0.55 \cdot F_D \cdot C_I \quad (2.3.2)$$

where N denotes the return period of tropical cyclones,  $C_I$  in €/km<sup>2</sup> denotes the investment cost per ocean area unit of offshore wind farms within the EEZ of China [15].

## CURRENT DESIGN STANDARDS

Design guidelines relevant to offshore wind turbines and other offshore structures have four main origins: international developments, classification societies, industry developments and governmental initiatives [16]. International Electrotechnical Commission (IEC) and International Organization for Standardization (ISO) are both international standards organizations for providing offshore wind turbine guidelines. Germanischer Lloyd (GL) and Det Norske Veritas (DNV) are two ship classification societies that have been active in developing designing guidelines specifically for offshore wind turbines. American Petroleum Institute (API) standards for the design of offshore platforms have been developed with support from industry. Government initiatives include a series of publications by the Department of Energy/Health and Safety Executive in the United Kingdom, Norwegian Petroleum Directorate (NMD) standards in Norway and the Danish Energy Authority (DEA) standards in Denmark.

IEC formalized design requirements for offshore wind turbines in IEC 61400-3[17]. It admits that the definition of onshore wind turbine classes illustrated in IEC 61400-1 in terms of wind speed and turbulence parameters remains appropriate as the basis of design of the rotor-nacelle assembly for an offshore wind turbine (Table 3). In addition to wind speed and turbulence intensity, IEC 61400-3 also requires other important parameters, notably marine conditions, to be used in the design of an offshore wind turbine. Unfortunately, the standard cannot meet the safety demands of offshore wind turbines in tropical cyclone prone areas such

as the southeast coast of China. For example, a Class I wind turbine has a reference wind speed ( $V_{ref}$ ) of 50m/s and a 50-year extreme mean wind speed ( $V_{e50}$ ) of 70m/s. But wind turbines usually breakdown prior to wind speed reaching the expected 70m/s in a strong tropical cyclone. In areas where strong tropical cyclones are common, wind turbines will most likely fall into the class S, which is defined for use when special wind or other external conditions or a special safety class, is required by the designer and/or the customer. However, IEC standard provides no guidelines for technical parameters of class S in the external condition of tropical cyclones.

Table 3 Basic parameters for WTGS classes

WTGS Class	I	II	III	S
$V_{ref}$ (m/s)	50	42.5	37.5	Values to be specified by the designer
$V_{ave}$ (m/s)	10	8.5	7.5	
A $I_{15}(-)$	0.16	0.16	0.16	
B $I_{15}(-)$	0.14	0.14	0.14	
C $I_{15}(-)$	0.12	0.12	0.12	

where:

- the values apply at hub height
- A designates the category for higher turbulence characteristics
- B designates the category for medium turbulence characteristics
- C designates the category for lower turbulence characteristics
- $I_{15}$  is the characteristic value of the turbulence intensity at 15m/s

GL offers a complete set of offshore guidelines for offshore wind turbines and offshore wind farms in one single document of Certification requirements, which covers requirements for the support structure, turbine, blades, and etc. The guidelines for offshore wind turbines have the same standards of wind speed as IEC 61400-1, but stricter standards of turbulence parameters [18]. DNV has some standards exclusively for wind turbines and some of their components, and have released a guideline on offshore transformer substations. Like the IEC standards, both the GL and DNV guidelines adopt the assumption of a 50-year return period of extreme external conditions for load cases.

The API recommended practice for offshore platforms (API RP-2A Working Stress Design), however, specifies a return period of 100 years for environmental conditions such as wind, wave, and current [16]. It has plenty of applications, which ranges from major multi-level platforms installed in very deep water to minimal structure located in shallow water for the development of marginal fields. Besides, structures API RP-2A provides a valuable experience base that can be used for the design of structures operating in harsh marine environments such as extreme storms, hurricanes, earthquakes, and ice. However, fixed platforms tend to be wave dominant whereas on-shore wind turbines are often wind dominant. Depending on the location, the offshore wind farms may be wave dominant or wind dominant: the forces of breaking waves may dominant even in shallow water. Fixed platforms are not often subject to dynamic behavior to the extent of offshore turbine structures [19]. The use of API RP-2A is directly applicable to transformer substations, but limited with application to turbine structures although it is a useful reference for them.

## **PREDICTION OF EXPECTED ECONOMIC LOSS**

According to the above-mentioned function, spatial distribution of annual expected economic loss for offshore wind farms conditional on occurrence of a 20-year, 30-year, 50-year and 100-year recurrence interval are showed in Figure 3. Here we assume that there is no temporal change in turbine vulnerability and thus the annual economic is time-invariant, considering the developer continuously replacing the wearing components of a turbine; in other words, it does not depend on operation period and so annual economic risk for year 1 is the same as the annual economic risk for year 20. Annual expected economic loss of a 20-year recurrence interval of tropical cyclones is much more severe than that of a longer recurrence interval due to its higher frequency. In regions of northern Yangtze estuary, annual expected economic loss of tropical cyclones are in the range of 0-3000€/km<sup>2</sup>/y. And Southern Zhejiang, Fujian, Guangdong and western Hainan provinces suffer from the most severe economic damages from tropical cyclones, with an annual expected economic loss of 6000-12000€/km<sup>2</sup>/y. Provinces locate in the southern coast of Yangtze estuary (including Shanghai, Zhejiang, Fujian, Guangdong and Hainan) suffer 2-7 times of higher annual economic risks from tropical cyclones than that of northern coast. Figure 4 shows the percentage of expected economic risks of offshore wind farms compared to their initial investment costs within the lifetime of 20 years. In general, regions locate in the northern Yangtze estuary suffers little risks from tropical cyclones, less than 1% of total investment costs within 20 years. However, risks increase sharply to more than 10-15% for most regions of southern Yangtze estuary.

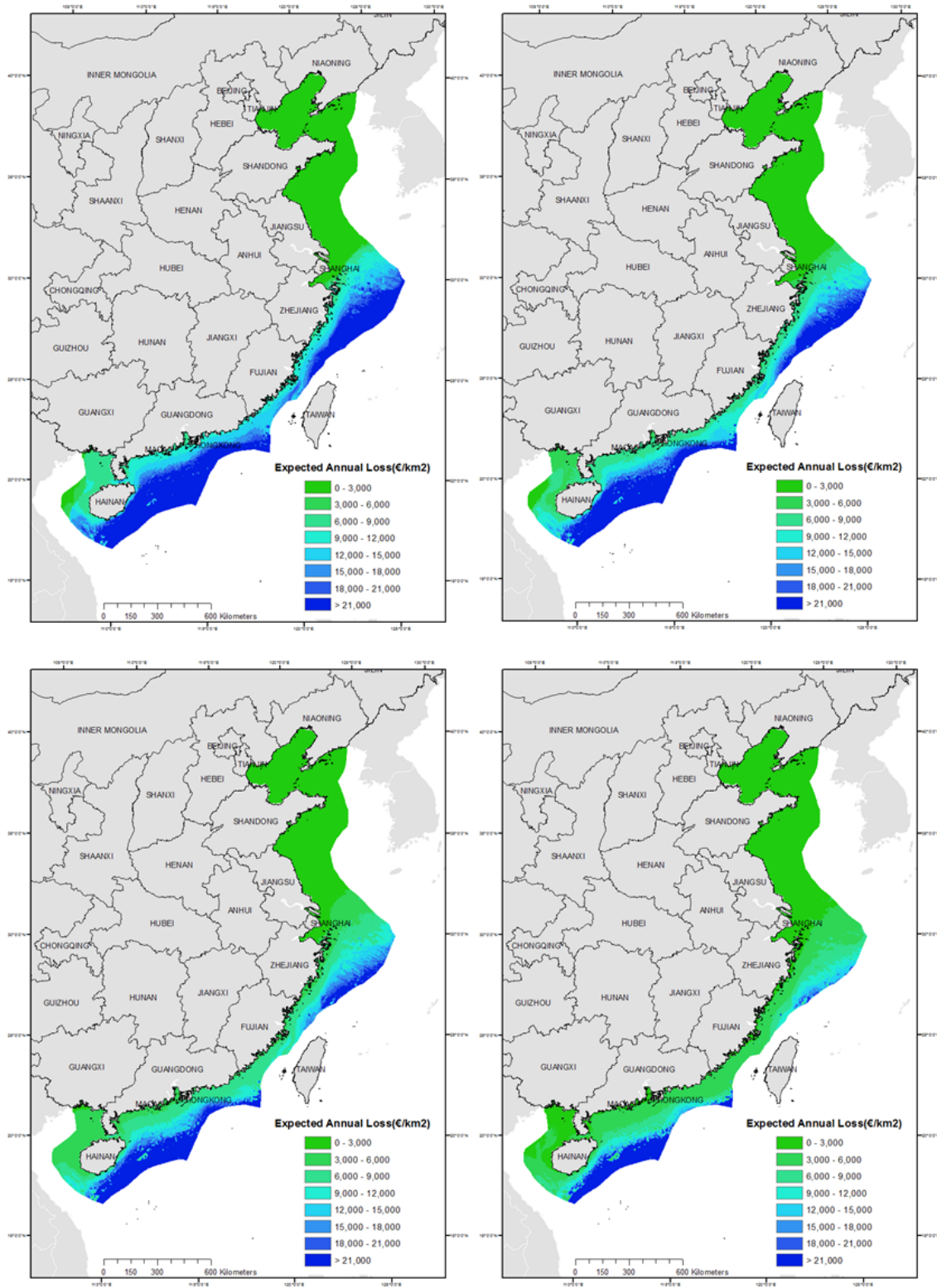


Figure 3 Spatial distribution of annual expected economic loss for offshore wind farms

(Top left: a 20-year recurrence interval; Top right: a 30-year recurrence interval; Bottom left: a 50-year recurrence interval; Bottom right: a 100-year recurrence interval)

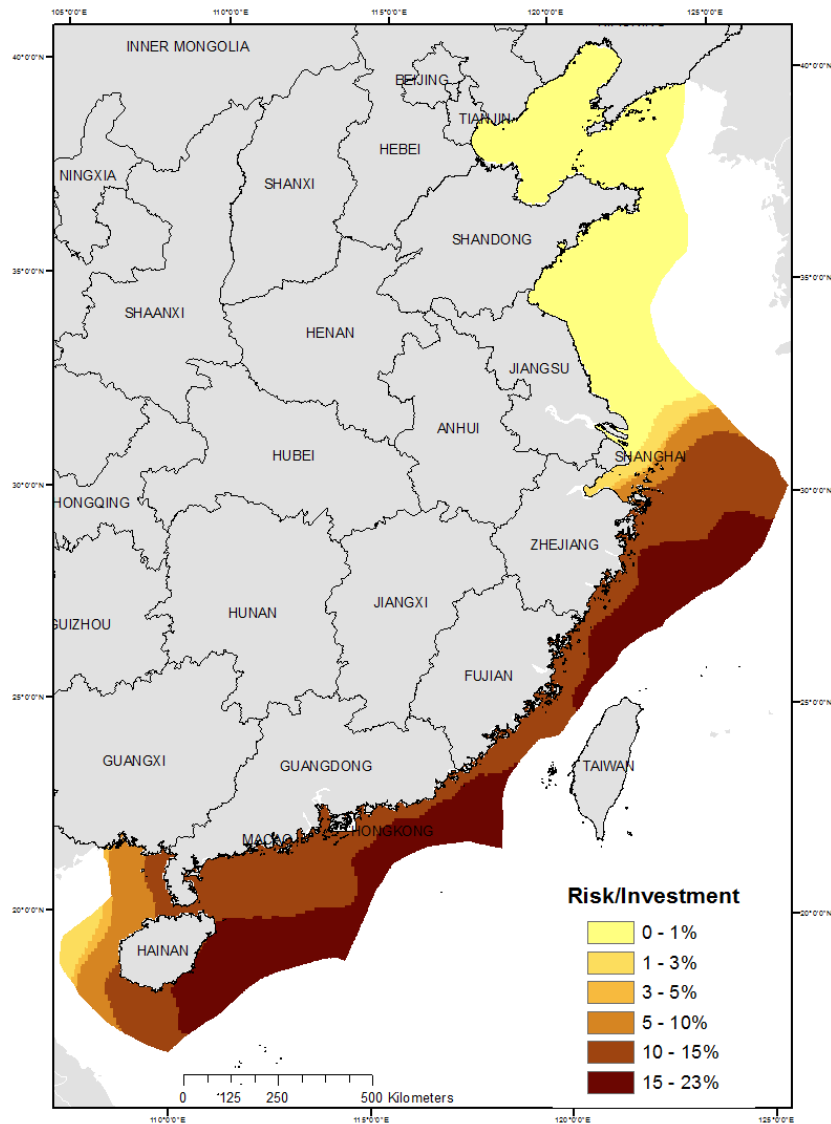


Figure 4 The percentage of economic risk in investment cost

On the other hand, regions suffering from higher risks of tropical cyclones are usually endowed with richer offshore wind potential. For example, the average wind power density in regions including Fujian, Northern Guangdong and Southern Zhejiang reaches as high as 600-800W/m<sup>2</sup> at the height of 90m, compared to that of 200-400W/m<sup>2</sup> in provinces locate in northern Yangtze estuary. Figure 5 shows the spatial distribution of levelised production cost (LPC) including economic losses of possible tropical cyclones and thus reduced wind power productions for offshore wind farms during their lifetime. The least cost sites for developing offshore wind energy are along the coasts of southern Jiangsu and Shanghai, with an average LPC of 47-80€/MWh. In 20-50m waters of Jiangsu, 0-20m waters of Bohai Rim, Zhejiang and Fujian, an average LPC is in the range of 80-100€/MWh. As the distance being far away from the coasts, the average LPC of developing offshore wind farms would reach as high as 200€/MWh.

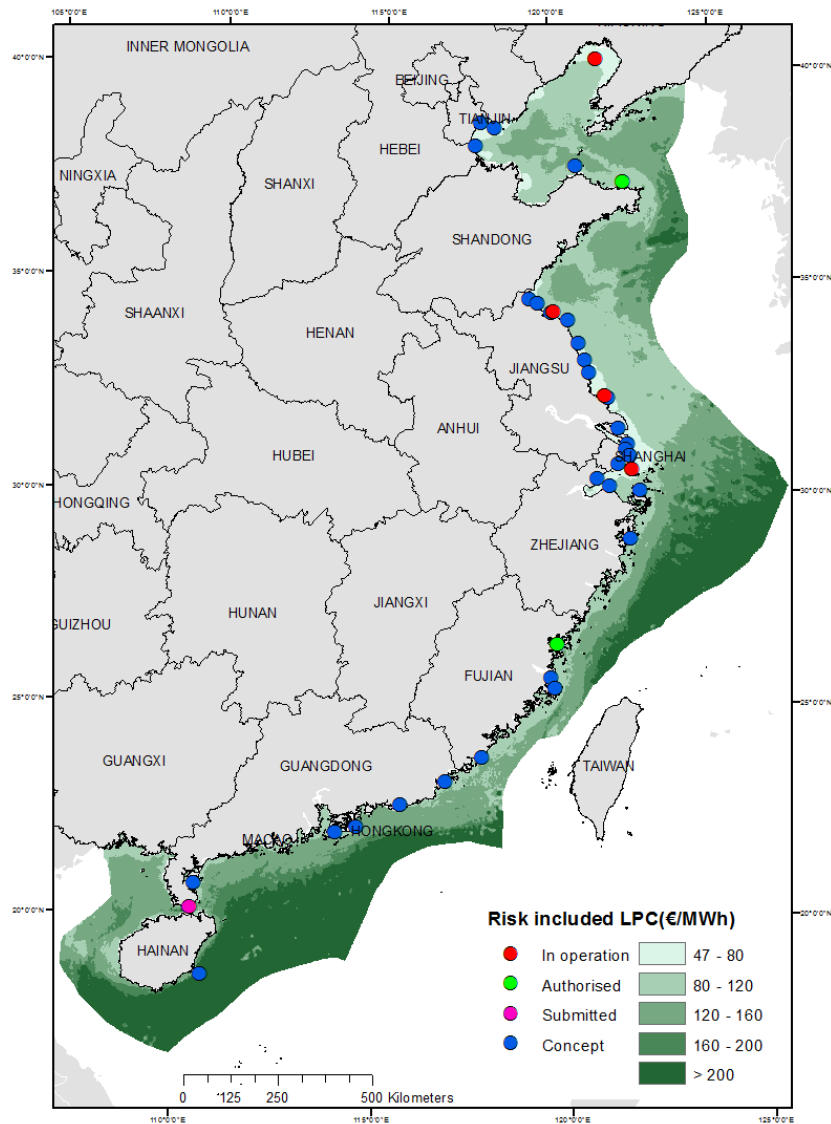


Figure 5 Spatial distribution of TC risks included LPC for offshore wind farms

## IMPLICATIONS FOR WIND POTENTIAL AND COST

Under current technological level, risks of tropical cyclones have a pronounced constraint on the total amount of exploitable wind potential<sup>3</sup> and their related production costs. Figure 6 indicates the amount of offshore wind power potential under 5% of economic risks based on a 20-year recurrence interval, a 30-year recurrence interval, a 50-year recurrence interval and a 100-year recurrence interval of tropical cyclones. For all four scenarios, at least 200TWh of offshore wind energy is free of risks from tropical cyclones, approximately 12% of the total offshore wind potential. There are about 556TWh of offshore wind energy can be developed under the economic risk of 5% in a 20 RI scenario, while the available amount decreased by 2%, 15% and 19% in 30 RI, 50RI and 100 RI scenario respectively.

<sup>3</sup> In this paper, it refers to technical potential on the basis of current technological levels of wind turbines and farm layout, without taking environmental constraints such as shipping lanes and submarine cables into consideration.

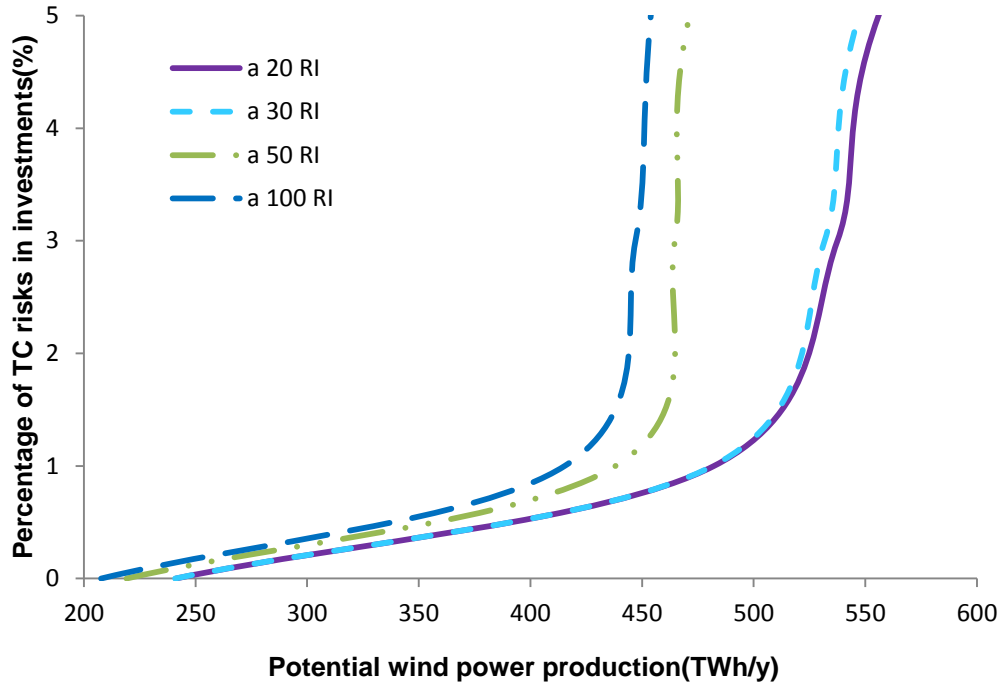


Figure 6 Potential wind power production under 5% of TC risks

In the long term, based on different scenarios, the TC risks of exploiting all the technical potential under current technological level are ranging from 22% to 39% (Figure 7). And 72% of the total offshore wind energy can be exploited under the economic risk of 15% in a 20 RI scenario, but the percentage decreased to 56%, 41% and 35% in 30 RI, 50RI and 100 RI scenarios respectively.

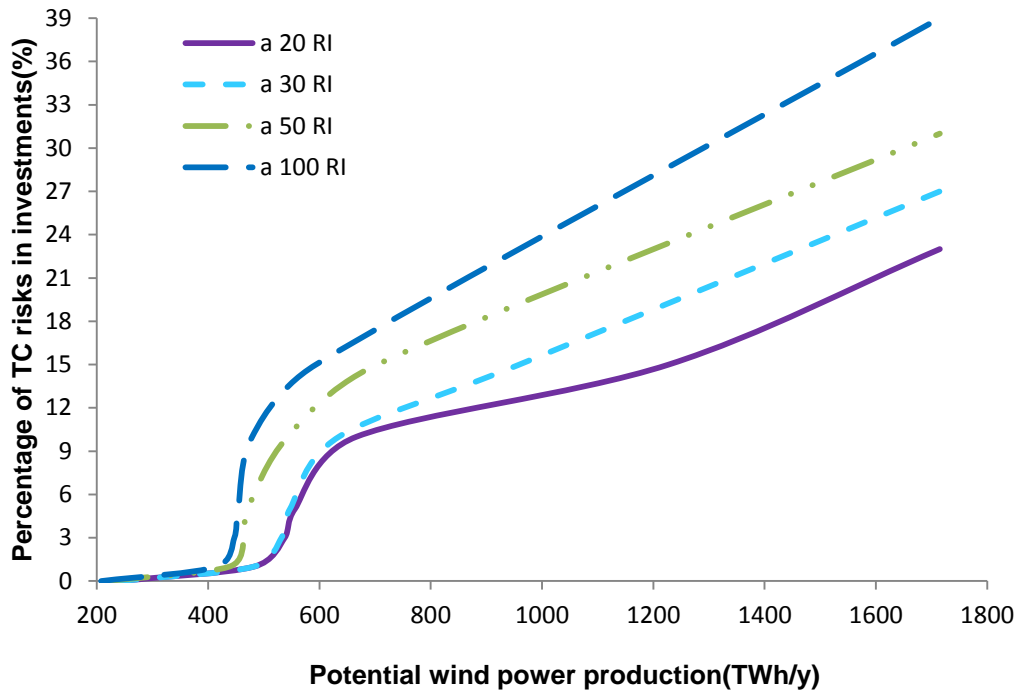


Figure 7 Potential wind power production under TC risks

Figure 8 compares the marginal production costs of offshore wind energy without risks of tropical cyclones and with different economic risks on the basis of a 20 RI, 30 RI, 50 RI and 100 RI of tropical cyclones. Without considering TC risks in coastal regions, about 360TWh of offshore wind energy can be produced at costs below 80€/MWh. Yet frequent occurring of tropical cyclones might decrease the available energy under 80€/MWh in a 20 RI scenario by 78%, and by 85% in a 100 RI scenario. Compared with risk free LPC, the increased marginal production costs of offshore wind energy caused by a 20 RI and 30 RI of tropical cyclones are around 40€/MWh in average, but being twice in the most risky regions. Tropical cyclone increase the marginal production costs of offshore wind energy by about 70€/MWh in a 50 RI scenario, and 80€/MWh in a 100 RI scenario averagely.

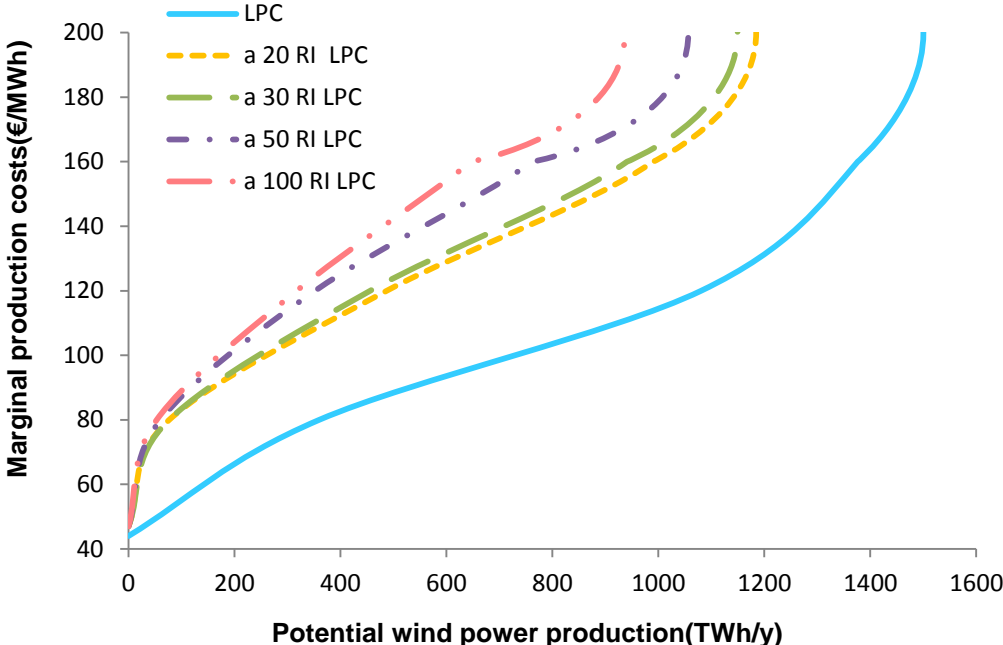


Figure 8 Marginal production costs under TC risks

From a practical point of view, Figure 9 would be more interesting for decision-makers. A 30GW target of offshore wind energy development by 2020 has been set recently, and thus the total amount would be 75TWh, considering the average full-loaded hours of 2500h in a typical offshore wind farm in China. As the feed-in-tariff (FIT) for the first Chinese offshore wind farm was around 106€/MWh, which could be assumed to be composed of an 80€/MWh LPC plus a 15% of internal return rate. Fig.10 suggests that offshore wind target by 2020 can be achieved in a 20RI and 30RI scenario under current standard of FIT, whereas approximately 73% and 83% of the target can be accomplished in a 50RI and 100 RI scenarios. Simultaneously, marginal production costs increased rapidly from 4 to 30€/MWh in a 20RI and 30RI scenario, as the offshore wind energy production gradually reach the development target.

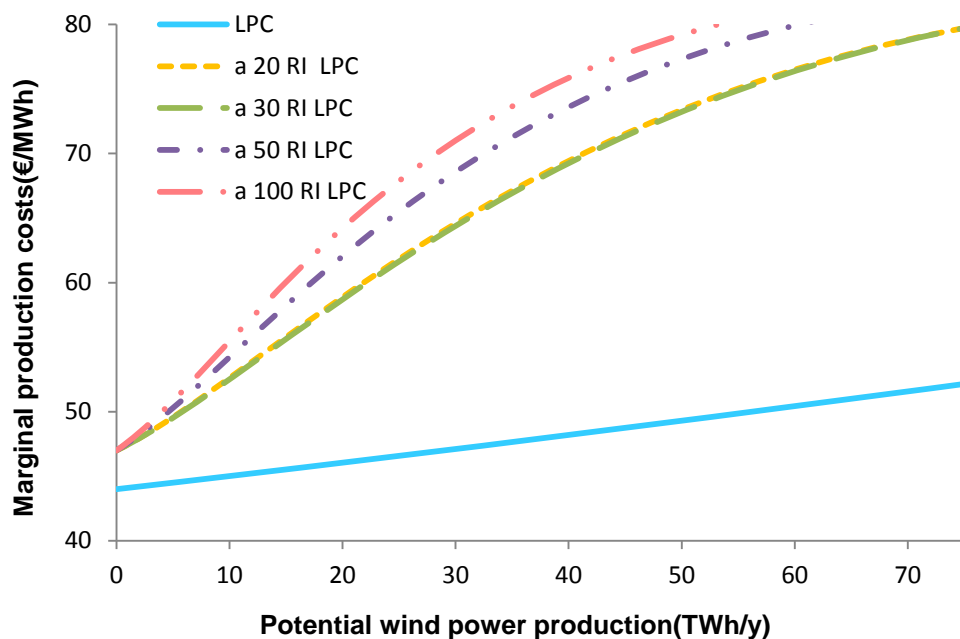


Figure 9 Marginal production costs under TC risks

## IMPLICATIONS FOR SITE SELECTION

In order to meet the total targets of 30GW, coastal provinces of China initiate their own plans for developing offshore wind energy in 2015 and 2020 as illustrated by Table 4. Main coastal provinces interested in developing offshore wind energy in near future include Shanghai, Jiangsu, Zhejiang, Shandong and Fujian, whose estimated total installed capacity of offshore wind energy will reach 10.1GW in 2015 (intertidal offshore<sup>4</sup> 4.2GW and near offshore<sup>5</sup> 5.9GW), and 22.8GW in 2020(intertidal offshore 5.1GW and near offshore 17.7GW). Offshore wind plans in various coastal provinces are at different stages, but generally speaking, Shanghai and Jiangsu are pioneers of developing offshore wind energy in China. The first offshore wind farm of China at Shanghai Donghai Bridge with an installed capacity of 34×3MW are already in operation, and plans for building another offshore wind farms in Shanghai has been approved by National Energy Administration. Four concessions of offshore wind farms with a total installed capacity of 1GW have finished public tendering procedures and are under construction in Jiangsu. Its master plan for developing offshore wind energy in 2015 and 2020 has been examined but still needs to be further revised. And other provincial plans basically cannot completely satisfy the requirements due to a great deal of uncertainties.

<sup>4</sup> Intertidal offshore is in the area between high- and low-water marks (especially off the provinces north of Yangtze estuary), with wind speeds at the height of 10m roughly estimated to be in the range of 6-7m/s (mostly along the coastal provinces of Shandong, Jiangsu and Shanghai).

<sup>5</sup> Near offshore is in the area with sea depth between 5-25m, where are supposed higher wind speeds than intertidal areas. But this assumption is based on very limited measurements in Fujian, Jiangsu, Guangdong, Shandong, Shanghai and Zhejiang.

Table 4 Provincial plans for offshore wind energy

Province	Capacity(GW)		Plan Stage
	2015	2020	
Shanghai	0.7	1.55	Approved
Jiangsu	4.6	9.45	Being examined
Zhejiang	1.5	3.7	Waiting for investigation
Shandong	3	7	Original draft
Fujian	0.3	1.1	Original draft
Other	5	10	Compiling plan
Total	15.1	32.8	

Table 5 compares the conditions of developing offshore wind energy in ambitious coastal provinces based on calculated wind resources, economic risks of tropical cyclones and TC risk included LPC. An interesting phenomenon is that higher risks from tropical cyclones correlate to higher wind density and thus higher wind productions, not necessarily higher risk included LPC like in Fujian province. On the contrary, lower risks of tropical cyclones do not associate with lower risk included LPC as illustrated by Shandong province. Yet the trade-off between risk and LPC is rather complicated. The economic advantages and disadvantages brought by tropical cyclones depend largely on their frequencies and intensities on a specific site. A rough conclusion might be that the near coast regions of Shanghai and Jiangsu provinces are relative safe and economic viable for developing offshore wind farms. The objectives of offshore wind energy development in Shandong and Zhejiang provinces seems a little bit optimistic under current technical level, both of which have a danger of suffering high economic costs. Though the calculated risk included LPC in some shallow water locations of Fujian province seems attractive, more precise evaluations based on site-specific data are needed before making an investment decision.

Table 5 Comparison of provincial resources, TC risks and costs

Province	Wind Density (W/m <sup>2</sup> )	Wind Potential (TWh)	Risk/Investment (%)	Risk included LPC (€/MWh)
Shandong	200-300	174	0	80-200
Jiangsu	200-400	169	1	47-160
Shanghai	400-500	7	1-3	47-200
Zhejiang	400-700	313	3-15	80-200
Fujian	600-1300	153	10-15	80-160
Guangdong	400-700	405	10-23	120-200

## DISCUSSIONS ON THE MODEL

There exist few empirical data on damage ratio and economic losses of wind farms suffered from tropical cyclones, not to mention offshore wind farms. Thus, the model and calculated results rely on plenty of assumptions. Simulation studies on the relationships between various levels of maximum wind speeds of tropical cyclones and corresponding damage ratios of offshore wind turbines would be helpful in verifying and correcting the results. Garciano et al. [20] simulated the probabilities of failure for anchor bolts and tower under different levels of typhoon loads, yet provided little information on the performance of turbine components. In addition to wind, wave is the other major source of loads which turbines and foundations must

be designed to withstand. How the interaction of wind and waves on offshore wind farms during cyclones is still a matter of investigation. Since a good empirical relation between significant wave height and extreme wind speed during tropical cyclones has been well illustrated in [21], it is not difficult to estimate wave characteristics and incorporate them into the GIS-model once the principle is clear.

Based on a 20-year recurrence interval, it might underestimate the risk of tropical cyclones on possible offshore wind farms locate in Fujian, Guangdong and Hainan provinces. As shown in Figure 10, these regions are highly prone to tropical cyclones, and in some locations the annual frequency of TC even reaches once every two year. Even though some TC may not necessarily cause any damage or interruption of operations, vibration is a major contributing factor to problems including failure to maintain tolerances, noisy operation, uncontrollability, material failure, premature fatigue and shortened product life [22]. Therefore, the sensitivity analysis on economically available potential and marginal production costs of wind energy based on four scenarios of TC risks, can supplement for the limitations of empirical data to some degree and provide useful implications for decision-makers.

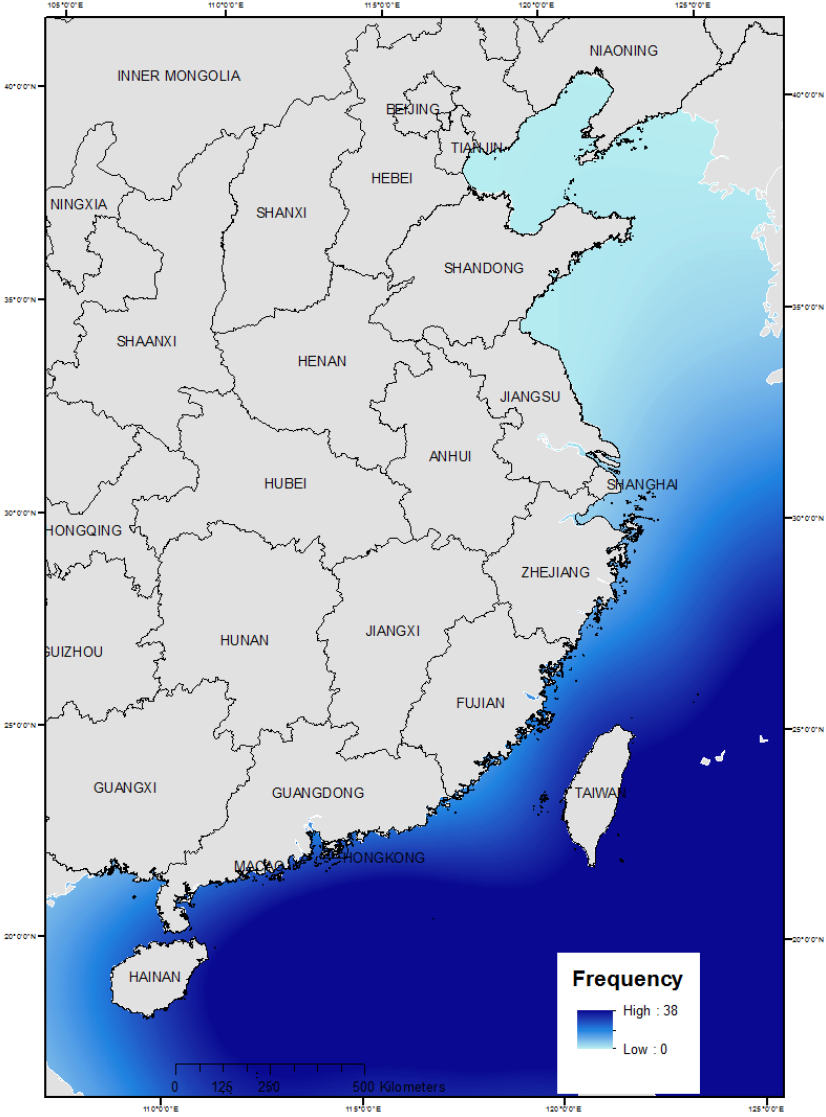


Figure 10 Frequency of TC in Northwest Pacific (1949-2009)

Moreover, the model is static, without taking time as a variable. Tropical cyclones are complicated meteorological phenomenon, which are influenced by multiple of factors such as global climate change. The frequency and intensity and even spatial influencing extent might change in different time periods. Figure 11 shows paths of super typhoon (with wind speeds higher than 51m/s), severe typhoon (with wind speeds in the range from 41.5m/s to 50.9m/s) and typhoon (with wind speeds in the range from 32.7m/s to 41.4m/s) in 1949-1963, 1964-1978, 1979-1993 and 1994-2009. The frequency of the above mentioned strong tropical cyclones are decreasing, especially in the south sea of China. Numerous recent studies have addressed the question of whether tropical cyclone numbers would increase in a warmer world, yet little consensus has emerged from these disparate methods [23]. In the western North Pacific, the number of storms and the number of storm days reach maximum in the mid-1990s, but that trend has recently reversed [24,25]. A comparison experiment based on a 20km high-resolution global atmospheric model suggests that the tropical cyclone frequency in future 10 years reduced by about 38% in western North Pacific Ocean, but the number of intense tropical cyclone would increase [26]. The potential impacts of global warming on TC tracks are assessed for the periods of 2000-29 and 2030-59 by [27]. It indicated that during the period of 2000-29, the numbers of TC affecting the regions of China experience a slight decrease, whereas a significant reduction in the frequency of TC would occur in the South and East China Sea during the period of 2030-59.

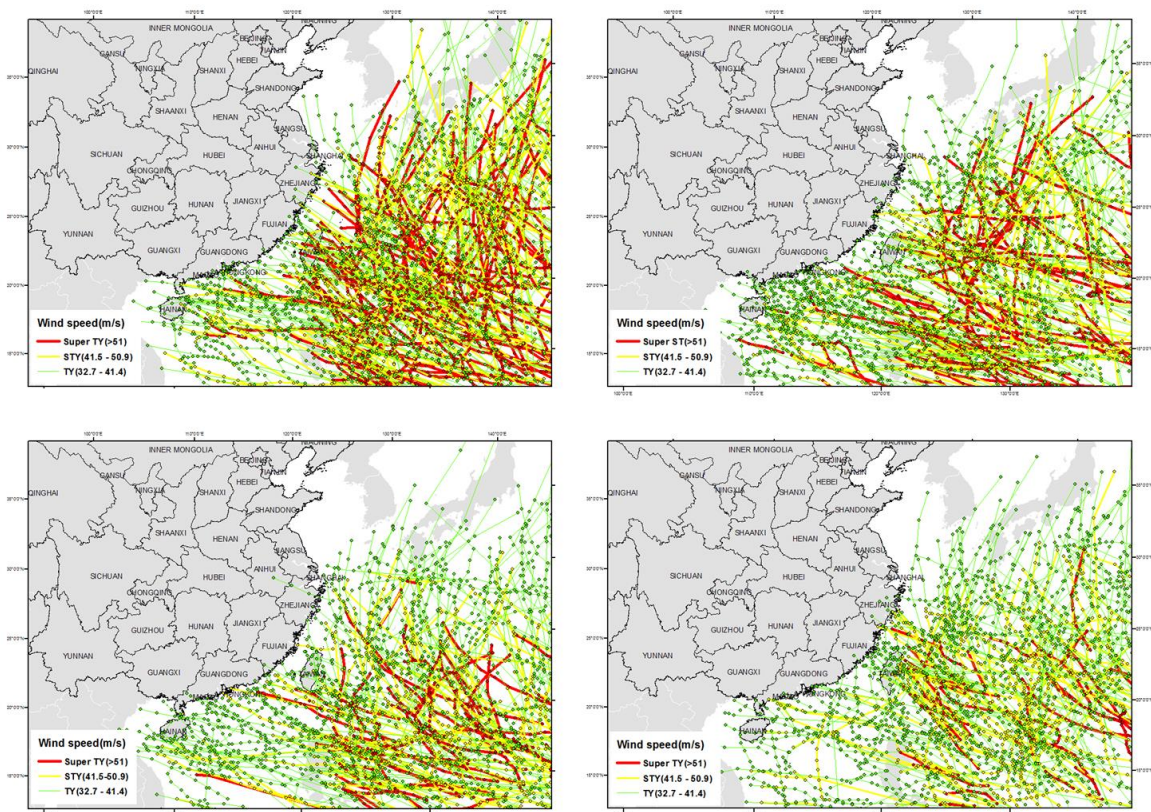


Figure 11 Changes of TC intensity in different periods (1949-2009)  
(Top left: 1949-1963; Top right: 1964-1978; Bottom left: 1979-1993; Bottom right: 1994-2009)

## CONCLUSIONS

This paper proposed a rough turbine damage model to evaluate the economic risks of tropical cyclone on offshore wind farms within the EEZ of China. Tropical cyclones would pose a great risk to offshore wind energy development in the southern of Yangtze estuary, especially along the southeast coastal regions of China, where are endowed with the highest offshore wind power density. Illustrated by TC risk included LPC, it seems that some locations around the shallow waters of Fujian province are still economically competitive for developing offshore wind farms even under the conditions of frequently occurring tropical cyclones. However, it requires prudent considerations as discussed above on the calculated results before making a conclusion. Offshore wind target by 2020 can be achieved in a 20RI and 30RI scenario under current standard of FID, whereas approximately 73% and 83% of the target can be accomplished in a 50RI and 100 RI scenarios. Therefore, a step-by-step strategy for offshore wind energy development ought to be taken in China, which means exploring offshore wind resources in both safe and cheap locations such as those in the inter-tidal and near-shore of Shanghai and southern Jiangsu provinces first, and then expand the horizons as gaining more experience and achieving technological progress. On the other hand, tropical cyclones also provide a severe constraint for the total amount of available offshore wind potential and more importantly for that of economically viable potential. Approximately 88% of the total offshore wind potential, which is around 1500TWh, needs to be exploited in TC risky locations. And risks of tropical cyclones would increase the marginal production costs of offshore wind energy by at least 30€/MWh within the EEZ of China.

From the point view of R&D on TC-resistant wind turbines, it would be highly cost-benefit of capital investments. Considering the total available offshore wind energy of roughly 1715TWh, the value of developing a TC-resistant offshore wind turbine would be at least 51 billion euro. The calculated value would even be much higher if incorporating onshore wind energy in TC-prone regions of China and wind energy in other Asia countries such as Japan and Philippines. Currently, Minyang Wind Power of China developed a TC-resistant wind turbine with a single capacity of 1.5MW. Thirty-three of this type of turbines have been installed in Yangqian wind farm and succeed in withstanding the attacks of 15 tropical cyclones, including one with the extreme wind speed of 50m/s. However, the quality of the turbine needs to be further tested in a longer time period and the safety standards of this kind of wind turbines needs to be further improved prior to their utilization in more risky regions. Clause et al. [28] proposed a design of wind turbines in TC-prone areas and estimated a 20-30% increase of turbine cost in an area with an estimated reference wind speed of 60m/s compared to a site with that of 50m/s. But for offshore wind turbines, they face new challenges from the harsh offshore environment, especially considering the influence of wave heights caused by tropical cyclones. Unfortunately, there is still little literature on the design of TC-resistant offshore wind turbines, which would be an urgent problem for further studies.

Moreover, there is no specific construction standard for offshore wind farms under the risks of tropical cyclones worldwide. Existing design standards such as IEC and API might provide some experience. Besides, much of the insurance for commercial wind energy projects, owned and developed by larger parent companies in the power sector, has been provided under the main property insurance package covering the parent companies' power assets [29]. The use of unspecialized parent company package did not provide adequate cover to the unique risk profile especially for offshore wind projects under the risks of tropical cyclones. The wind turbine manufacturers are responsible for maintenance costs during the first five

years of operation; however, damages caused by tropical cyclones are not included into this after-sale service. Considering merely 12% of offshore wind potential (approximately 200TWh) can be developed without TC risks in China and not all of them are economically competitive, there is a necessity of developing specific design standards and insurance for offshore wind turbines. It would be of great importance in helping reduce risks and economic losses of offshore wind farms in tropical cyclone-prone areas and expand exploitable locations for future offshore wind energy.

## REFERENCES

- [1] Wang, M., Introduction of China's offshore wind planning, Shanghai, China, 2010.
- [2] Xiao, F. J., Xiao, Z. N., Characteristics of tropical cyclones in China and their impacts analysis, *Natural Hazards*, Vol. 54, No. 3, pp 827-837, 2010.
- [3] CMA-STI Best Track Dataset for Tropical Cyclones in the Western North Pacific. Shanghai Typhoon Institute, China Meteorological Administration, 2010.
- [4] Liu, K.S., Chan, J.C.L., Size of tropical cyclones as inferred from ERS-1 and ERS-2 data. 2010.
- [5] China Meteorological Administration. Classification of tropical cyclones (GB/T19201-2006). Standardization Administration of the People's Republic of China, SAC, 2006.
- [6] Chu, P., Wang, J., Modeling return periods of tropical cyclone intensities in the vicinity of Hawaii. *Journal of applied meteorology*, Vol. 37, pp 951-961, 1998.
- [7] Xiao, Y.Q., Li, Q.S., Li, Z.N., Chow, Y.W., Li, G.Q., Probability distributions of extreme wind speed and its occurrence interval. *Eng.Struct.*, Vol. 28, No. 8, pp 1173-1181, 2006.
- [8] Feasibility study of the impact of typhoon on offshore wind farm operation in China, report no. EEP-PMU/CN/12607/RE003, 2009.
- [9] Manwell, J.F., Elkinton, C.N., Rogers, A.L., McGowan, J.G., Review of design conditions applicable to offshore wind energy systems in the United States. *Renewable and Sustainable Energy Reviews*, Vol. 11, No. 2, pp 210-234, 2007.
- [10] Stewart, M.G., Cyclone damage and temporal changes to building vulnerability and economic risks for residential construction. *J.Wind Eng.Ind.Aerodyn.*, Vol. 91, No. 5, pp 671-691, 2003.
- [11] Huang, Z., Rosowsky, D.V., Sparks, P.R., Long-term hurricane risk assessment and expected damage to residential structures. *Reliab.Eng.Syst.Saf.*, Vol. 74, No. 3, pp 239-249, 2001.
- [12] Ueda, Y., Suguro, Y., High Performance MW class Wind turbine for Asian Region. *Proceedings of the 3~(Rd) World Wind Energy Conference & Renewable Energy Exhibition the 2nd Wind Power Asia*, 2004.

- [13] Harper, B.A., Kepert D.J., Ginger, D.J., Guidelines for converting between various wind averaging periods in tropical cyclone. World Meteorological Organization, 2009.
- [14] International wind energy development: offshore report 2010. Ringkøbing, Denmark: BTM Consult ApS, November 2010.
- [15] Hong, L., Möller, B., Offshore wind energy potential in China: under technical, spatial and economic constraints. *Energy* (2011). doi:10.1016/j.energy.2011.03.071
- [16] Saigai, R.K., Dolan, D., Kiureghian, A.D., An assessment of structural design guidelines for offshore wind turbines. San Diego, California, USA.
- [17] Design requirements for offshore wind turbines, report no. IEC 61400-3. Geneva, Switzerland: IEC, 2009.
- [18] Guideline for the certification of offshore wind turbines. Hamburg, Germany: Germanischer Lloyd WindEnergie GmbH, 2005.
- [19] Sharples, M., Structure, equipment and systems for offshore wind farms on the OCS, report no. Project No. 633, Contract M09PC00015, December, 2009.
- [20] Garciano, L.E.O., Koike, T., Performance-based design of a wind turbine under typhoon and earthquake loads. Tokyo, Japan. London: Taylor & Francis Group, 2007.
- [21] Kumar, V.S., Mandal, S., Kumar, K.A., Estimation of wind speed and wave height during cyclones. *Ocean Eng.*, Vol. 30, No. 17, pp 2239-2253, 2003.
- [22] Meilan, A., Tsouroukdissian, A.R., Development and adaptation of wind turbines to typhoons and earthquakes conditions. Conference of electric power supply industry, Taipei, Taiwan, Oct 24-28, 2010.
- [23] Walsh, K., Tropical cyclones and climate change: unresolved issues. *Climate Research*, Vol. 27, No. 1, pp 77-83, 2004.
- [24] Chan, J.C.L., Liu, K.S., Global warming and western North Pacific typhoon activity from an observational perspective. 2010.
- [25] Webster, P.J., Holland, G.J., Curry, J.A., Chang, H.R., Changes in tropical cyclone number, duration, and intensity in a warming environment. *Science*, Vol. 309, No. 5742, pp 1844, 2005.
- [26] Oouchi, K., Yoshimura, J., Yoshimura, H., Mizuta, R., Kusunoki, S., Noda, A., Tropical cyclone climatology in a global-warming climate as simulated in a 20 km-mesh global atmospheric model: frequency and wind intensity analyses. *Journal of the Meteorological Society of Japan*, Vol. 84, No. 2, pp 259-276, 2006.
- [27] Wu, L., Wang, B., Assessing Impacts of Global Warming on Tropical Cyclone Tracks\*. *J.Clim.*, Vol. 17, No. 8, pp 1686-1698, 2004.

[28] Clausen, N.E., Ott, S., Tarp-Johansen, N.J., Design of Wind Turbines in an Area with Tropical Cyclones. *Proc. of European Wind Energy Conference*.

[29] Montes, G.M., Mart n, E.P., Profitability of wind energy: Short-term risk factors and possible improvements. *Renewable and Sustainable Energy Reviews*, Vol. 11, No. 9, pp 2191-2200, 2007.

[30] KPMG. Offshore wind in Europe 2010 market report, November 2010.

[31] Global Wind Energy Council. See also: <http://www.gwec.net/index.php?id=9>. Date Accessed: 04/04/2011.

[32] Offshore wind farms: risk and initial loss experience.

[33] Yu, W.M., Damage and concerns from typhoon dujuan. Damage and concerns from typhoon dujuan. Hainan, China, 2004. pp. 896-900.

[34] Ishihara, T., Yamaguchi, A., Takahara, K., An analysis of damaged wind turbines by typhoon maemi in 2003. An analysis of damaged wind turbines by typhoon maemi in 2003. Seoul, Korea, 2005. pp. 1413-1428.