

An economic assessment of tropical cyclone risk on offshore wind farms

Lixuan Hong*, Bernd Möller

Department of Development and Planning, Aalborg University, Fibigerstræde 13, 9220 Aalborg, Denmark

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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 economic 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 annual 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 annual expected economic 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 on identifying offshore wind potential and cost and setting design parameters for offshore wind turbines are then discussed. The impact of tropical cyclones on offshore wind farms like 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 risks and economic losses of offshore wind farms in tropical cyclone prone areas and expand exploitable locations for future offshore wind farms.

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1. 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 CO₂ emissions per GDP by 40–45% in 2020 compared to its level in 2005 [1]. In the medium and long term development plan for renewable energy, the country established a goal of producing 15% of the primary energy it consumes via renewable sources [2]. Regarding the development of wind and solar energy, China has large potential but significant challenges of long-distance electricity transmission from resource regions to consumption centers [3]. The best onshore resources cover the northeast, north and northwest of China and the best regions for solar radiation resources locates in western provinces such as Tibet, Xinjiang and Qinghai [4], where are sparsely populated regions.

Offshore wind energy is deemed as a promising supplementary option to deal with the energy and climate dilemma, since the abundant, renewable and clean energy resources locate near the economic and population centers in eastern coastal regions as shown in Fig. 1.

Although the National Energy Administration of China has already proposed a 30 GW ambitious plan for offshore wind energy development [5], many uncertainties remain to be addressed. 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 [6]. Strong precipitation, extreme wind and storm surge brought by tropical cyclones would cause serious casualties and economic losses. Regarding offshore 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 offshore wind turbines intended for use in Europe, primarily in the North and Baltic Seas. One question that occasionally arises is how applicable offshore wind turbines designed for northern European conditions are to China, where tropical cyclones occur frequently. The aim of this

* Corresponding author. Tel.: +45 99403658; fax: +45 98153788.

E-mail addresses: lixuan@plan.aau.dk (L. Hong), berndm@plan.aau.dk (B. Möller).

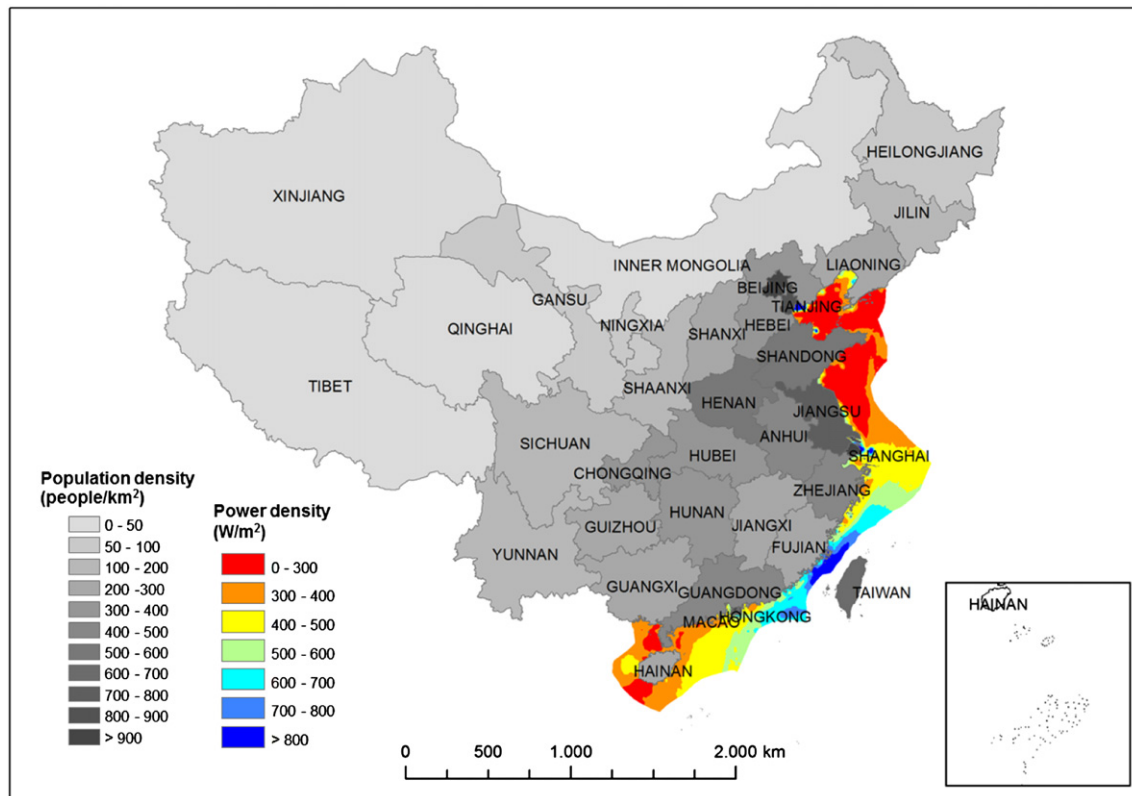


Fig. 1. Population and offshore wind power density in China. (The boundary is gained from VLIZ (2009). As there are still a lot of disagreements on EEZ between countries worldwide, new treaties will be negotiated in the next years.)

paper is to study the potential economic risks of developing offshore wind farms in tropical cyclone prone regions under current design standards for offshore turbines. The structure of this paper is organized as follows: firstly the methodology employed to model the extreme wind speeds of tropical cyclones under different probabilities is described and a preliminary turbine damage model is proposed in Section 2; secondly reviews on current design standards for offshore wind turbines are summarized in Section 3; and then the potential economic risks of tropical cyclones on offshore farms are evaluated in Section 4; the implications of tropical cyclones on offshore wind potential and cost are further revealed in Section 5; possible limitations of the model and future improvements are discussed in Section 6; and finally several conclusions are drawn in Section 7.

2. Methodology

2.1. 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) [7]. 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 h 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 is 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° of latitude [8], a scan radius of this figure is used in the study. All map layers in the GIS-

model have the unified spatial resolution of 1 km² in a geographical reference framework of the Universal Transverse Mercator (UTM) system.

2.2. Probability model of extreme wind speeds

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 so on. In China, according to the Classification of Tropical Cyclones Standardization [GB/T19201-2006] published by CMA [9], tropical cyclones are classified in terms of maximum wind speeds near the center as shown in Table 1.

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 [10]. A Poisson process should have the following characteristics [10]: (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 [11]. Assume the probability that t tropical cyclones will occur in a location in one year be denoted by p_t :

Table 1
The classification of tropical cyclones standardization in China.

Tropical cyclone classification	Maximum 10 min mean wind near the center (ms ⁻¹)	Wind scale ^a
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 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.

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

where γ 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 $1/N$, for instance, 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 [12], 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 $\alpha = 1.28255/\sigma$, $\delta = \bar{x} - 0.57722/\alpha$ [11], α denotes the average wind speed of the sample and σ 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:

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

and then,

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

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 β is given,

the critical value of D_β can be found in the critical value table of the modified K-S test according to the sample size n and the confidence level β . If $D \leq D_\beta$, then the distribution fitting is good, otherwise the fitting is not satisfactory. In this study, β is chosen as 0.1 and thus the confidence level is 90%.

2.3. Turbine damage model

For offshore wind turbines the most important external conditions are wind and waves [13]. In the case of high wind speeds (above the cut-out speed of offshore wind turbines), 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 which 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 imply that it is impossible 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. [14]. 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. [15] 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 unable to be applied for wind turbines directly. Exceedance of designed extreme wind speed is expected to 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 [16]. 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. 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 25 m/s). Damage ratios of turbines become 100%, when gust wind speeds of tropical cyclones reach 75 m/s [17]. Within the range from 25 to 75 m/s, damage ratios of wind turbines F_D is presented as a function of 3 s gust wind speed V_e at the hub height. And 3 s gust

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	174 MW	67 m/s		260 of the 782 wind turbines. 40 MW \$50 million destroyed	40%	[34]
Erica	2003	Plum, France	4.5 MW	55.6 m/s	Vestas V27/225 kw	5 tubines completely demolished; 12 turbines partially damaged; 3 turbines with light damages	50%	[35]
Dujuan	2003	Shanwei Honghaiwan, China	16.5 MW	57 m/s	Vestas V47/660 kw	13 of 25 wind turbines stop operation; €1.15 M loss	52%	[36]
Dujuan	2003	Single turbine	600 kw	45 m/s	Vestas V47/660 kw	One blade damage	7.3%	[36]
Maemi	2003	Karimata, Japan	0.9 MW	74.1 m/s	Micon 400/100 kw; Enercon 600 kw	Collapsed; Nacelle cover cracked and blades broken	100%	[17]
Maemi	2003	Nanamata, Japan	1.1 MW	74.1 m/s	Enercon 500 kw; Vestas 600 kw	Collapsed; Nacelle cover cracked and blades broken	100%	[17]
Maemi	2003	Single turbine	100/600 kw	87.6 m/s	Micon 400/100 kw; Enercon 600 kw	Collapsed	100%	[17]
Sangmei	2006	Cangnan, China		68 m/s	Vestas/500 kw	20 of 28 turbines damaged; 5 collapsed	71.4%	[11]

wind speed at 10 m height can be calculated from extreme wind speed V_p referred in equation (2.2.4), based on a gust factor of 1.15 [18]. Considering the 90 m hub height of a 5 MW turbine, V_e is 1.2 times of 3 s gust wind speed at 10 m height according to the classic log formula. Therefore,

$$\begin{aligned} F_D &= 0, \quad V_e \leq 25 \text{ m/s} \\ F_D &= 0.0002V_e^2 - 0.0031V_e - 0.0494, \quad 25 \text{ m/s} < V_e < 75 \text{ m/s} \\ F_D &= 1, \quad V_e \geq 75 \text{ m/s} \end{aligned} \quad (2.3.1)$$

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 [19]. And annual expected economic losses of offshore wind farms per ocean area unit E_c in €/km²/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 €/km² denotes the investment cost per ocean area unit of offshore wind farms within the EEZ of China [20].

3. Current design standards for offshore wind construction

Design guidelines relevant to offshore wind turbines and other offshore structures have four main origins: international developments, classification societies, industry developments and governmental initiatives [21]. 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 [22]. 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. However, the standard cannot meet the safety demands of offshore wind turbines in tropical cyclone prone areas such as the southeast coast of China. A Class I wind turbine has a reference wind speed (V_{ref}) of 50 m/s and a 50-year extreme gust wind speed (V_{e50}) of 70 m/s, which is usually lower than the maximum gust of a typhoon at the turbine sites. For instance, the maximum gust of typhoon Maemi in 2003 is estimated to be 87.3–90.7 m/s at Karimata and Nanamata wind power plants [17]. Besides, the extreme turbulence intensity at the wind speed range of 15–25 m/s during tropical cyclones is observed to be more than the IEC level of 0.16 [11]. The intense turbulence with a strong wind speed is unfavorable to the existence of the wind turbine designed in accordance with the existing IEC standards. This is the reason why a wind turbine sometimes breakdown prior to a gust wind speed reaching the expected 70 m/s in a typhoon. 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.

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 so on. The guidelines for offshore wind turbines have the same standards of wind speed as IEC 61400-1, but stricter standards of turbulence parameters [23].

Table 3
Basic parameters for wind turbine classes.

Wind turbine class	I	II	III	S
V_{ref} (m/s)	50	42.5	37.5	Values to be specified by the designer
A I_{ref} (–)		0.16		
B I_{ref} (–)		0.14		
C I_{ref} (–)		0.12		

The parameter 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_{ref} is the expected value of the turbulence intensity at 15 m/s.

V_{ref} is the reference wind speed average over 10 min.

DNV has some standards exclusively for wind turbines and some of their components, and have released a guideline on offshore transformer substations. Similar to 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 [21]. It has plenty of applications, which ranges from major multi-level platforms installed in very deep water to minimal

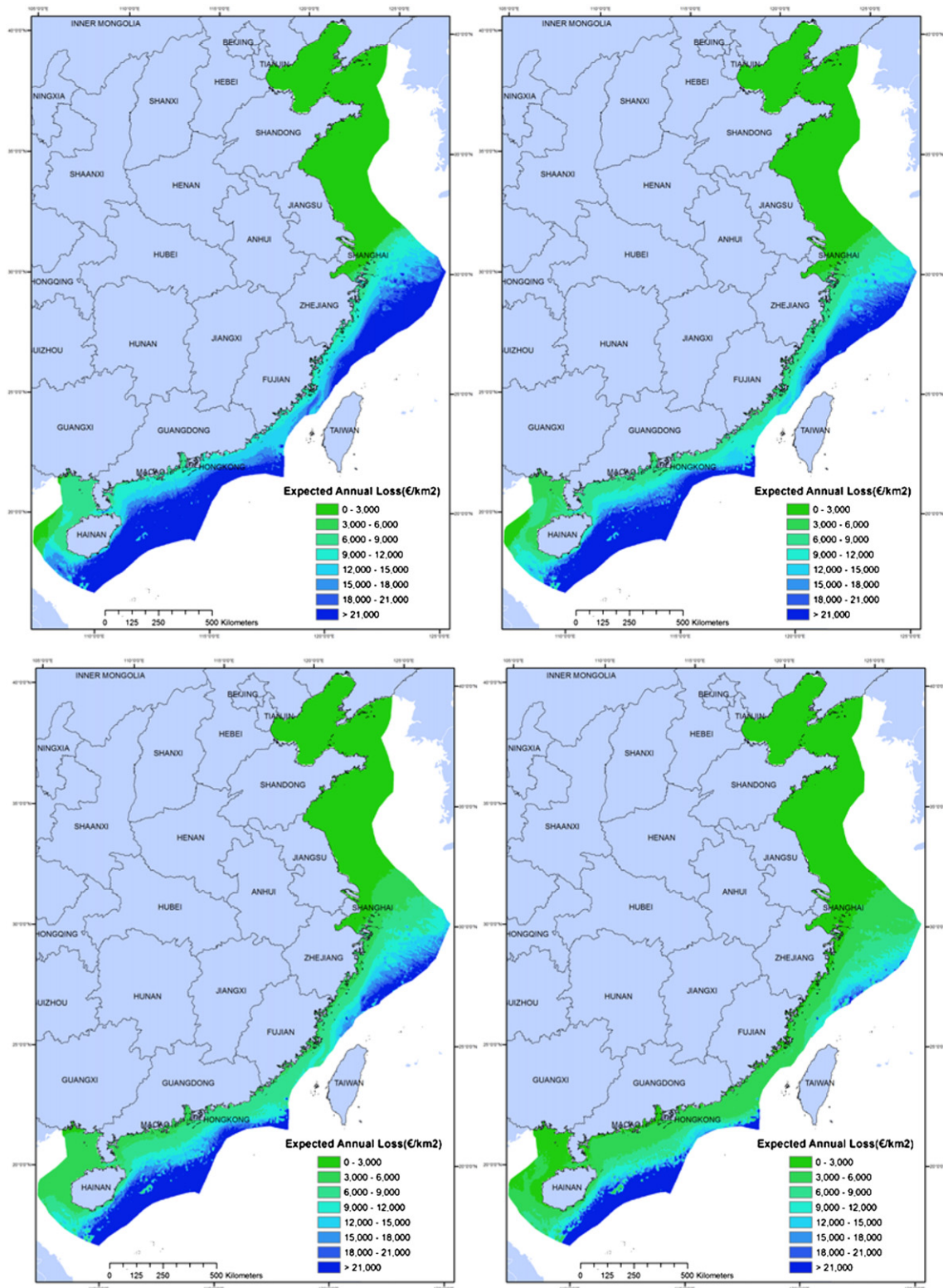


Fig. 2. Spatial distribution of annual expected economic loss for offshore wind farms. (Top left: a 20-year recurrence interval; Top right: a 30-year recurrence interval; Bottom left: a 50-year recurrence interval; Bottom right: a 100-year recurrence interval).

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 onshore 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 [24]. 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.

4. 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 Fig. 2. Here we assume that

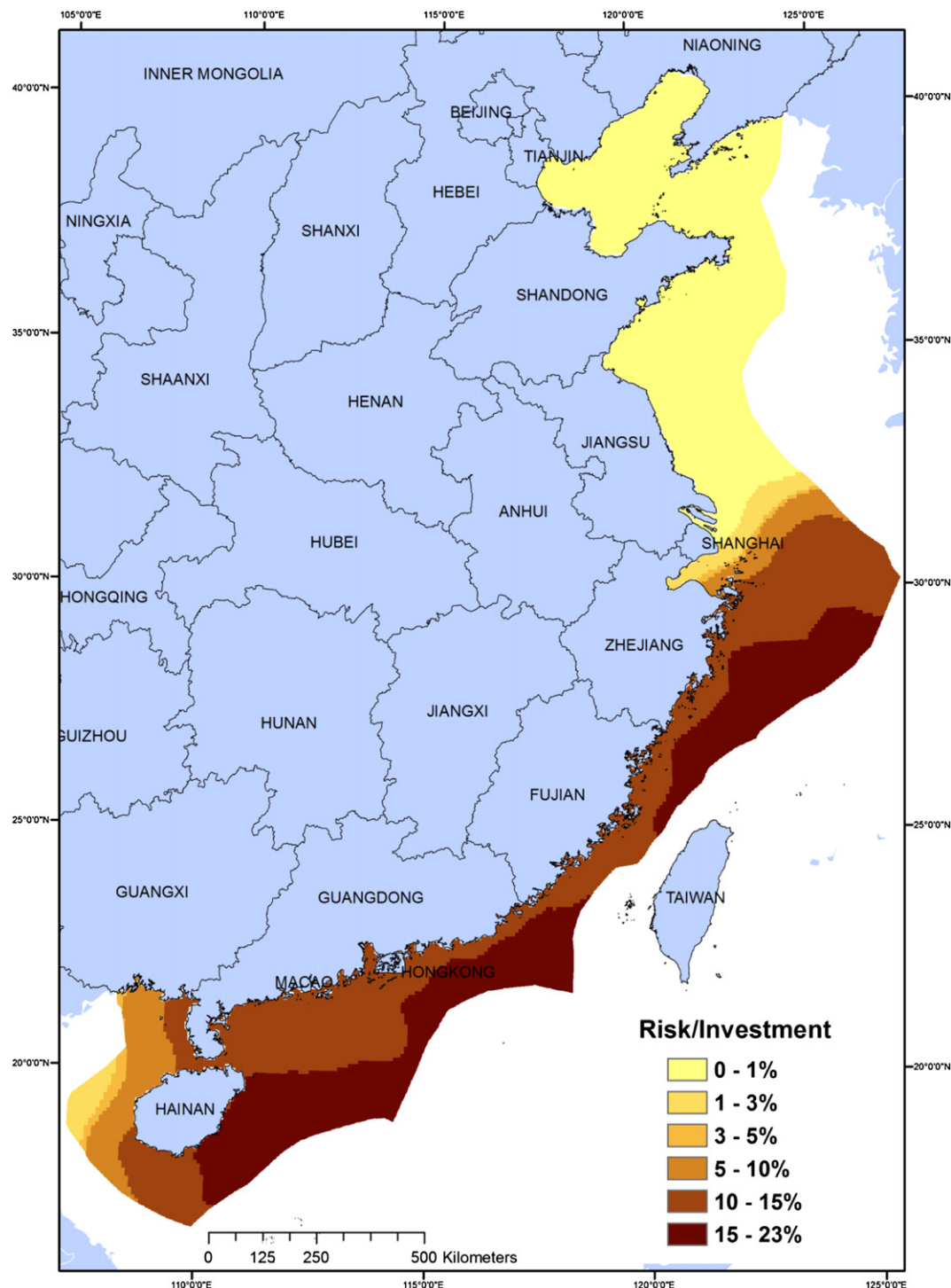


Fig. 3. The percentage of economic risk in investment cost.

there is no temporal change in turbine vulnerability and thus the annual expected economic loss 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, the annual

expected economic loss of tropical cyclones are in the range of 0–3000 €/km²/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 6000–12,000 €/km²/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. Fig. 3 shows the percentage of expected economic risks of offshore wind farms

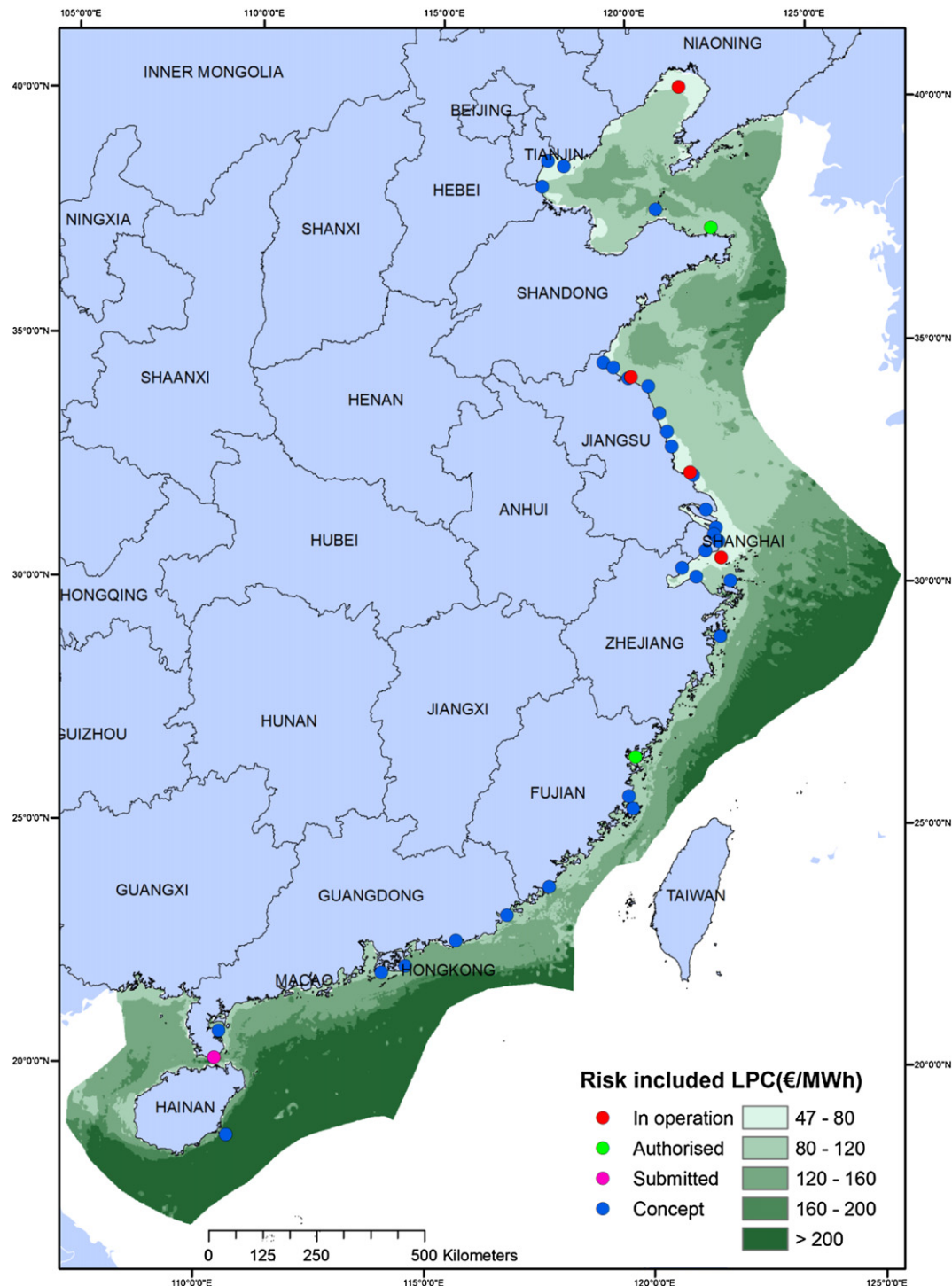


Fig. 4. Spatial distribution of tropical cyclone risk included LPC for offshore wind farms.

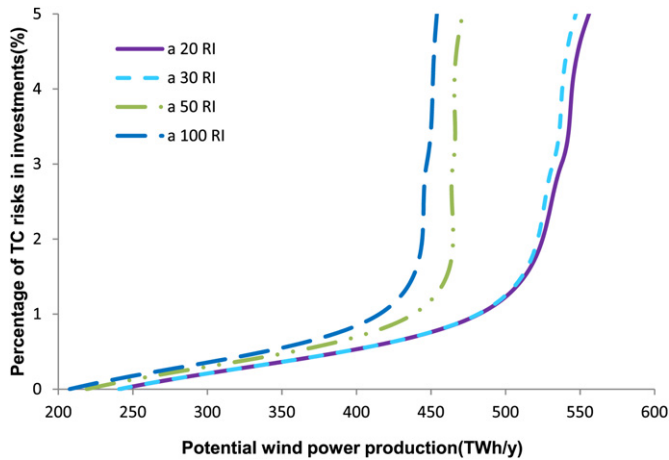


Fig. 5. Potential wind power production under 5% of tropical cyclone risk.

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.

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 600–800 W/m² at the height of 90 m, compared to that of 200–400 W/m² in provinces locate in northern Yangtze estuary. Fig. 4 shows the spatial distribution of levelised production cost (LPC) including economic losses of possible tropical cyclones and also 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 20–50 m waters of Shandong, 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.

5. 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 potential¹ and their related production costs. Fig. 5 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 200 TWh of offshore wind energy is free of risks from tropical cyclones, approximately 12% of the total offshore wind potential. There are about 556 TWh 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, 50 RI and 100 RI scenario respectively.

In the long term, based on different scenarios, the tropical cyclone risk of exploiting all the technical potential under current technological level is ranging from 22% to 39% (Fig. 6). And 72% of

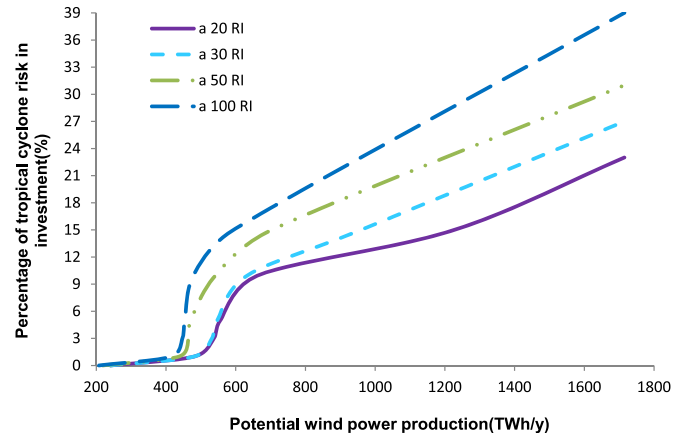


Fig. 6. Potential wind power production under tropical cyclone risks.

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, 50 RI and 100 RI scenarios respectively.

Fig. 7 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 tropical cyclone risk in

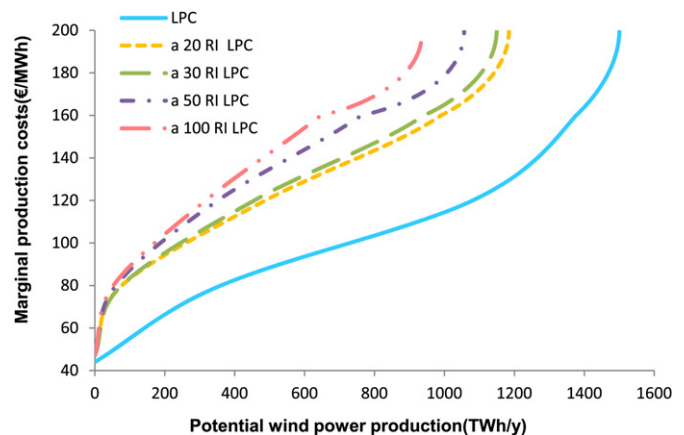


Fig. 7. Marginal production costs under tropical cyclone risks.

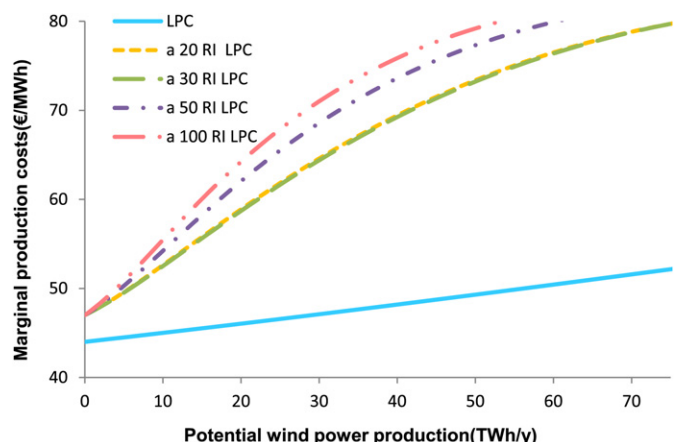


Fig. 8. Marginal production costs under tropical cyclone risks.

¹ 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.

coastal regions, about 360 TWh 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.

From a practical point of view, Fig. 8 would be more interesting for decision-makers. A 30 GW target of offshore wind energy development by 2020 has been set recently, and thus the total amount would be 75 TWh, considering the average full-loaded hours of 2500 h 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. 8 suggests that offshore wind target by 2020 can be achieved in a 20 RI and 30 RI scenario under current standard of FIT, whereas approximately

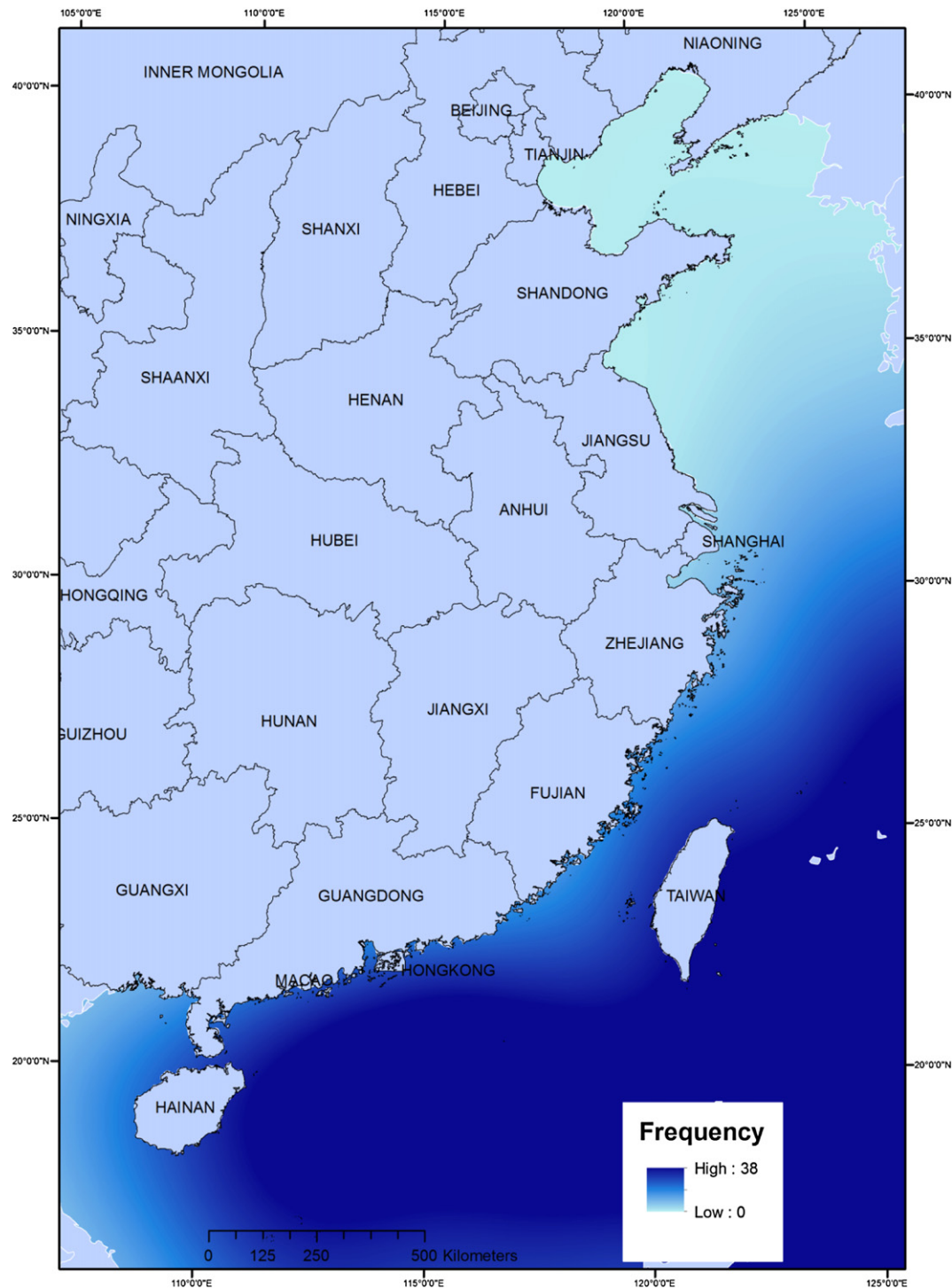


Fig. 9. Frequency of tropical cyclones in Northwest Pacific (1949–2009).

73% and 83% of the target can be accomplished in a 50 RI and 100 RI scenarios. Simultaneously, marginal production costs increased rapidly from 4 to 30 €/MWh in a 20 RI and 30 RI scenario, as the offshore wind energy production gradually reach the development target.

6. Discussions on the model

There exist few empirical data on damage ratios 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 gust wind speeds of tropical cyclones and corresponding damage ratios of offshore wind turbines would be helpful in verifying and improving the accuracy of the results. Garciano et al. [25] 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 conditions such as gust wind speed and wind turbulence intensity, wave is the other major source of loads

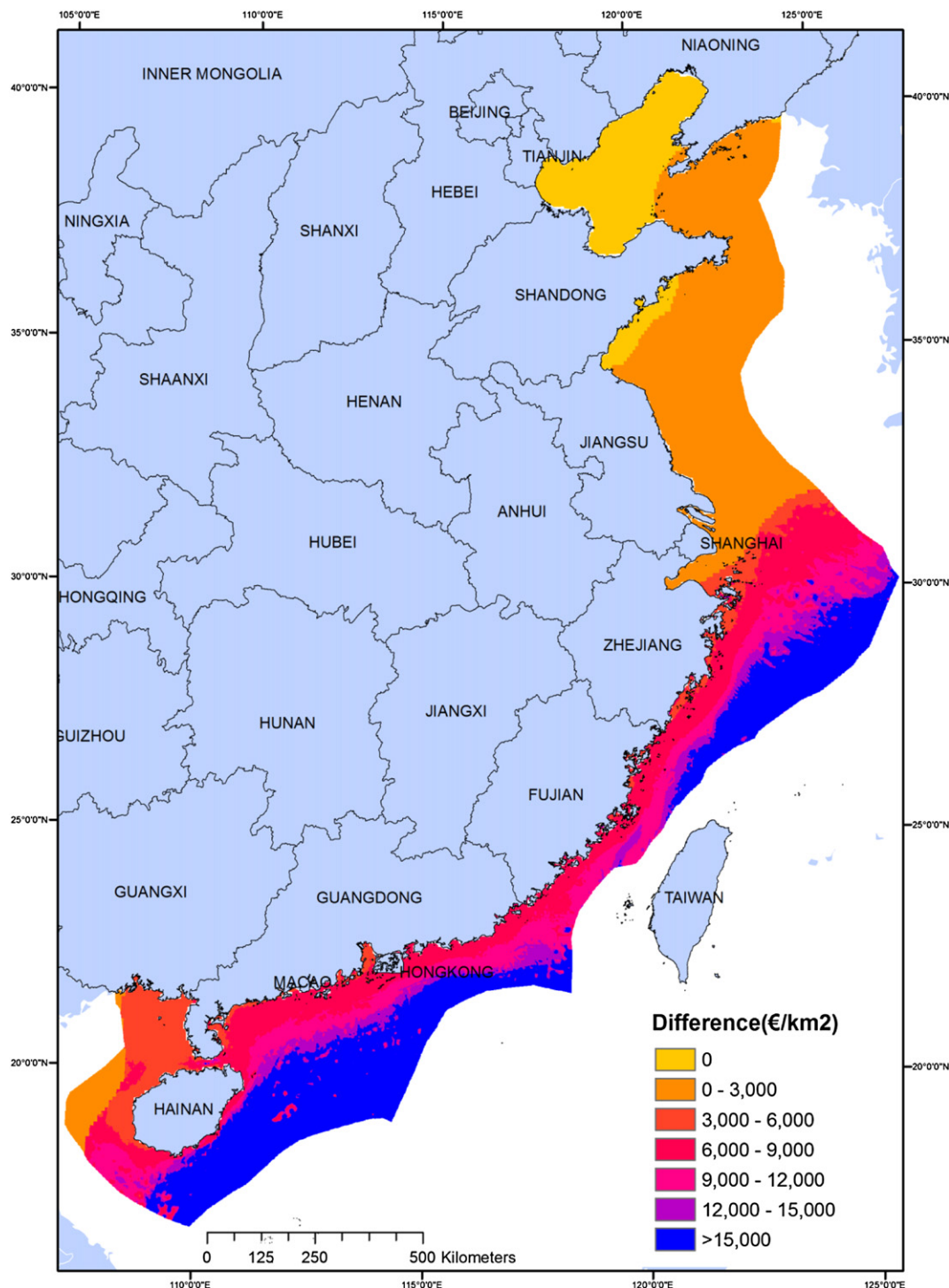


Fig. 10. Difference of annual expected economic loss between a 20 RI and 100 RI scenario.

which turbines and foundations must be designed to withstand. How the interaction of wind and waves on offshore wind farms during cyclones remains 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 [26], it is not difficult to estimate wave characteristics and incorporate them into the GIS-model once the principle is clear.

Nevertheless, the sensitivity analysis on economically available potential and marginal production costs of wind energy based on four scenarios of tropical cyclone risk can supplement for the limitations of empirical data and provide useful implications for decision-makers. The spatial distribution of tropical cyclone frequency in 1949–2009 is shown in Fig. 9, which reveals great difference from location to location. Even though some tropical cyclones 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 [27]. Therefore, incorporation of a wide range of probability assumptions from a 20 RI to 100 RI scenario as displayed in Fig. 10 has improved the accuracy of the model.

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. Fig. 11 shows paths

of super typhoon (with wind speeds higher than 51 m/s), severe typhoon (with wind speeds in the range from 41.5 to 50.9 m/s) and typhoon (with wind speeds in the range from 32.7 to 41.4 m/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 [27]. 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 [28,29]. A comparison experiment based on a 20 km 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 [30]. The potential impacts of global warming on tropical cyclone tracks are assessed for the periods of 2000–29 and 2030–59 by [31]. It indicated that during the period of 2000–29, the numbers of tropical cyclones affecting the regions of China experience a slight decrease, whereas a significant reduction in the frequency of tropical cyclone would occur in the South and East China Sea during the period of 2030–59.

In general, the economic risk model of tropical cyclones on offshore wind farms can be continuously improved by incorporating new empirical or simulation data on gust wind speeds and corresponding turbine damage ratios. Wind turbulence intensity

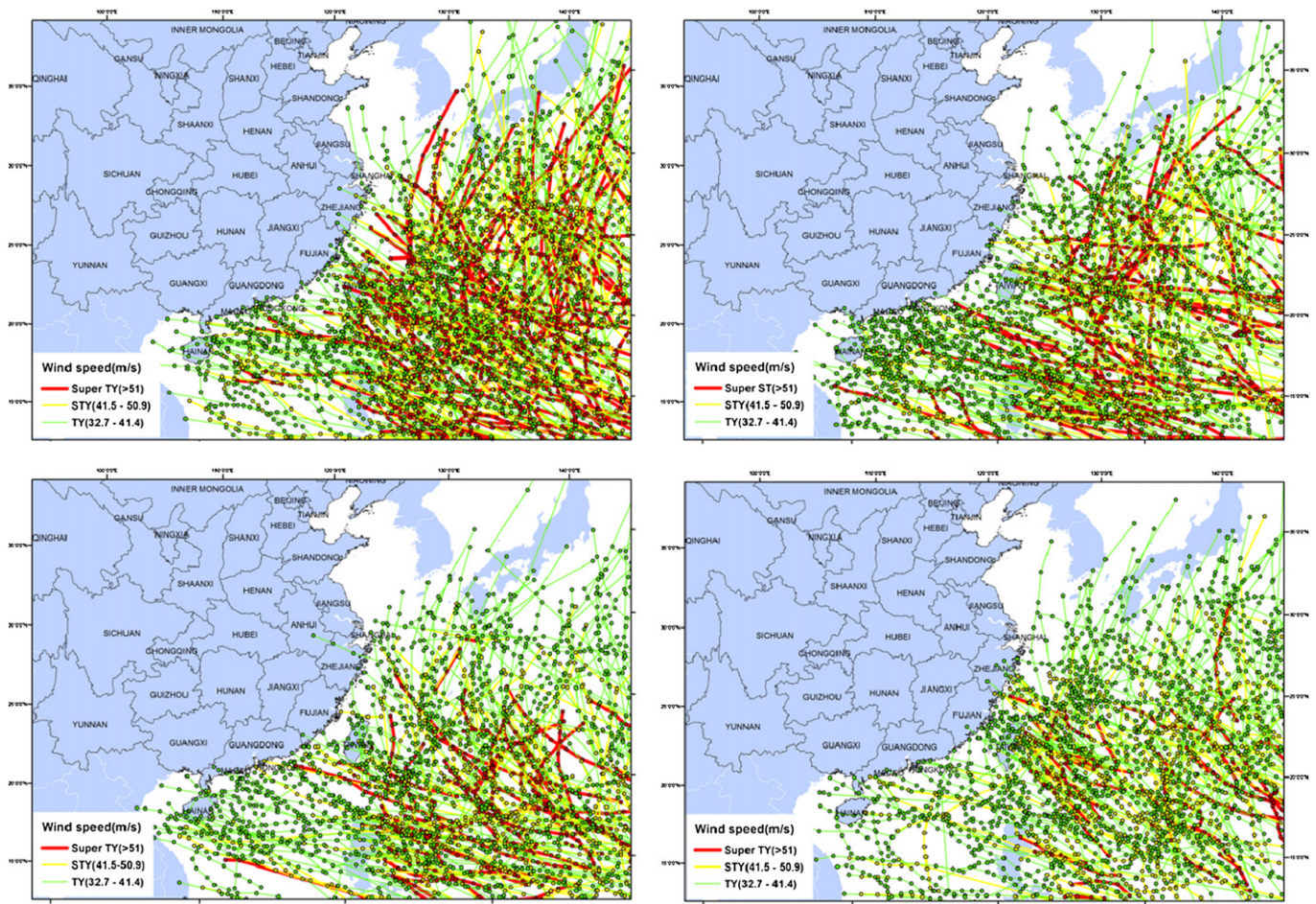


Fig. 11. Changes of tropical cyclone intensity in different periods (1949–2009). (Top left: 1949–1963; top right: 1964–1978; bottom left: 1979–1993; bottom right: 1994–2009.)

and wave height are two important parameters that might be considered for future model extension. Since the GIS-model is composed of various layers, it is easily to add layers on the effects of wind turbulence intensity and wave height to the existing model once the behind principles are studied. Nevertheless, scenarios analysis based on different probability assumptions in this study is useful to compensate for the limitation of data and thus reduce the uncertainty of the model. Besides, how to incorporate the time variable into the model might be a challenge for future study.

7. Conclusions

This paper proposed a preliminary GIS-based turbine damage model to evaluate the economic risks of tropical cyclones on offshore wind farms within the EEZ of China. Four scenarios based on a 20-year, 30-year, 50-year and 100-year recurrence of extreme wind speeds under tropical cyclones are developed, and their annual expected economic losses and implications to wind potential and cost are compared. In conclusion, tropical cyclones provide a pronounced constraint for the total amount of available offshore wind potential in China and more importantly for that of economically viable potential. Approximately 88% of the total offshore wind potential, which is around 1500 TWh, needs to be exploited in tropical cyclone risky locations. The marginal production costs of offshore wind energy are increased by at least 30 €/MWh within the EEZ of China taking the impact of tropical cyclones into consideration. The tropical cyclone prone regions generally locate 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 tropical cyclone risk included LPC, it seems that some locations around the shallow waters of Fujian province remain to be 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 decision. Offshore wind target by 2020 can be achieved in a 20 RI and 30 RI scenario under current standard of FIT, whereas approximately 83% and 73% of the target can be accomplished in a 50 RI 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 economically viable 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.

From the point view of R&D on tropical cyclone-resistant wind turbines, it would be highly beneficial for capital investments. Considering the high proportion of the total available offshore wind energy locates in tropical cyclone risky regions, developing a tropical cyclone-resistant offshore wind turbine is expected to avoid at least €51 billion economic losses. The calculated value would even be much higher considering on-/offshore wind energy development in other tropical cyclone prone regions such as Japan, Australia and North America. Currently, Minyang Wind Power of China developed a tropical cyclone-resistant wind turbine with a single capacity of 1.5 MW. 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 50 m/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. [32] proposed a design of wind turbines in tropical cyclone prone areas and estimated a 20–30% increase of turbine cost in an area with an estimated reference wind speed of 60 m/s compared to a site with that of 50 m/s. But for offshore wind turbines, they face new

challenges from the harsh offshore environment, especially considering the influence of wave heights caused by topical cyclones. The design of tropical cyclone-resistant offshore wind turbines would be a demanding topic for further studies.

Finally, 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 [33]. 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 200 TWh of offshore wind potential can be developed without tropical cyclone risk 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.

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