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An assessment of wind energy potential in the Beibu Gulf considering the energy demands of the Beibu Gulf Economic Rim

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Abstract: The Beibu Gulf Economic Rim of China is a key economic region in western China as demonstrated by the "Beibu Gulf Cities Development Project" (2017) that plans to build a "Blue Livable Gulf" to balance environmental protection while providing sustainable economic development. This region has significant energy needs and is predicted to exhibit rapid growth in the future.

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The authors have taken this suggestion and comment on the influence of the data gap in the conclusion. Furthermore, a new subsection has been added to the paper to state the limitation of the present analysis due to this data loss, and also to recommend follow-up work and further analysis. Please see Subsection 3.5 (P. 11-12) and the last paragraph of Conclusions (P. 20 Lines 28-30, P. 21 Lines 1-6).

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An assessment of wind energy potential in the Beibu Gulf considering the energy demands of the Beibu Gulf Economic Rim

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Abstract

The Beibu Gulf Economic Rim of China is a key economic region in China as demonstrated by the “Beibu Gulf Cities Development Project” (2017) that plans to build a “Blue Livable Gulf” to balance environmental protection while providing sustainable economic development. This region has significant energy needs and is predicted to exhibit rapid growth in the future.

By means of meteorological observations located at seven islands, a comprehensive statistical analysis on wind energy potential in the northern coastal part of the Beibu Gulf is conducted in this study. Specifically, wind speed, Weibull parameters, wind power density, as well as wind directions on various timescales are analyzed. The analysis shows that annual mean wind power density during 2010-2017 at 100m above mean sea level was, respectively, 605.6, 542.0, 368.0, 282.0, 265.6, 87.6 and 321.5 Wm⁻² at the seven sites, with average value of 353.2 Wm⁻². Evidently, wind power potential demonstrates intra-annual variability, with greatest values occurring in December, while another peak value is observed in July. Wind speeds are lowest in May with another trough occurring in August. The data also display weak inter annual variability. The prevailing wind directions in the rim are mainly from opposing directions of N (winter and autumn) and S (summer).

Keywords: Beibu Gulf, Wind energy, Renewable energy, Wind power, Wind climate

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1. Introduction

The use of wind power as an alternative energy source, both on- and off-shore, has increased rapidly over the last 10 years [1–4]. The offshore market is expected to grow at a higher pace than the onshore market, representing about one quarter of the total new wind power installations by 2020 [3]. One significant development in recent years is the spectacular drop in offshore wind power prices, thus making offshore wind power as competitive as fossil fuels and nuclear power [5]. Besides the cost of wind power, renewables like wind can also provide solutions to relieve some key environmental and social challenges, including improving energy security, creating more jobs, reducing public health and air pollution problems, and mitigating against greenhouse gas emissions (GHG) [3, 6].

When comparing development of wind energy sources, offshore sources have been shown to be superior to onshore sources in a number of ways [7, 8]. For example, offshore wind speeds are usually greater and more steady, leading to less turbulence effects than those on land at nearby sites [9, 10]. A number of studies have assessed offshore wind characteristics and wind power potential, either globally or at specific sites [e.g., 11–35], providing fundamental information for offshore wind power exploitation, for example, spatial and potential variability of wind energy potential display for different offshore regions.

1.1 The development of wind energy in China

China possesses and can potentially harness abundant quantities of onshore and offshore wind energy. It has been reported by the Global Wind Energy Council (GWEC) [5] that as the driver of global market growth for most of the last decade, China installed 21.2 GW of onshore wind and 1.8 GW of offshore wind in 2018, representing 45% and 40% of global market share respectively. In 2018, the second largest market was the US with 7.6 GW of new onshore installations, followed by Germany (2.4 GW), India (2.2 GW) and Brazil (1.9 GW). For the offshore market in 2018, China took the lead for the first time, followed by the United Kingdom with 1.3 GW. Germany took the third place (0.9 GW) [5].

1 Although China is the world's largest wind power market in both new and
2 cumulative installations, China also has a very large population of about 1.4 billion. In
3 particular, more than half the people in China live in the eastern coastal region, where
4 the economy is relatively developed, thereby leading to a huge energy demand.
5 Therefore, compared with other countries such as the USA, United Kingdom and
6 Germany, new installations in both onshore and offshore wind market is actually
7 much lower on a per capita basis, indicating that China still needs to strive to develop
8 wind energy exploitation, particularly for nearshore and offshore wind energy.

9 Additionally, China has a very long coastline, approximately 18,000 km running
10 from the Bohai Sea in the north to the Beibu Gulf in the south, adjacent to a
11 12-nautical-mile territorial sea with depths mostly less than 100m. This means that,
12 firstly, offshore wind is a very viable solution located close to the major coastal urban
13 areas of Tianjin, Shanghai, Guangzhou, Shenzhen and so on, with their many millions
14 of citizens. Secondly, wind power resources vary spatially and temporally: wind
15 power densities along the coast of the Chinese Seas regions range from 200 Wm^{-2} to
16 1000 Wm^{-2} [36–39], which can also be realized from the Global Wind Atlas
17 (<https://globalwindatlas.info/>). The potential for offshore wind power has been
18 examined for some coastal regions of China. For example, wind power potential was
19 assessed for the Pearl River Delta region [41] and for Hongkong [29, 42–44]; the
20 nearshore wind energy resources off the Shenzhen coast was carefully evaluated [45];
21 while a model-based climatology analysis was made for wind power resources over
22 the Bohai Sea and the Yellow Sea [46]. Furthermore, previous studies have shown that
23 even in relatively small offshore areas, wind energy potential can display spatial and
24 temporal differences [35, 45]. Therefore, before selecting a site to build wind power
25 plants, it is an essential and important first step to conduct a precise survey and
26 assessment of wind energy resources around the region, especially for the offshore
27 region where observational data are still rare and good quality information is limited.

28 The area of interest in this study is off the coast of Guangxi Zhuang Autonomous
29 Region, located in the Beibu Gulf Economic Rim (BGER) of China, located in the
30 South China Sea (see Figure 1). This is one of the least developed regions of China,

and especially for a coastal region. As an important part of the "China Western Development Strategy", in 2017, the central government of China has sanctioned the "Beibu Gulf Cities Development Project" (BGCD project). The project aims to build 3 "City Centre Circles", 2 "City Development Roles" and 1 "Blue Liveable Gulf" (the Beibu Gulf). Various infrastructures will be built, and a large amount of manpower, resources and capital investments and other invisible privileges needed are planned to promote the development of the whole BGER and to thoroughly shake off the relative poverty and backwardness of this region.

Figure 1 : Area of the study relative to the northern South China Sea (left) and geographic locations of the seven meteorological sites in red crosses (+ right).

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1.2 Energy demands and policy changes in the Beibu Gulf Economic Rim

Figure 2: (Top) Electricity consumption of the Guangxi Zhuang Autonomous Region (Guangxi province) for the period 2008-2017; (Bottom) monthly electricity consumption of Guangxi in 2015, 2016 and 2017. (Data resource: China Energy Statistical Yearbook (2008-2017) [47]).

Electricity consumption of Guangxi province in the past 11 years was analyzed to reflect the energy demand for this rim. As shown in Figure 2, the electricity consumption in Guangxi and Hainan provinces has been rising continuously for the past 11 years [47]. Furthermore, since the BGCD project was sanctioned in 2017, the growth rate of the electricity consumption in Guangxi province has risen rapidly, exceeding expectations. In 2018, electricity consumption in Guangxi had reached 170.28TWh, with growth rate up 17.84% compared with the value of 2017 (144.23 TWh), which is much higher than the growth rate of China (8.5%). From the official report, energy consumption in Zhanjiang municipal city in this rim was, 10.80 TWh and 18.15 TWh in 2016 and 2017, respectively, and its year-on-year growth rate was 7.8% and 18.4%, respectively, with the latter leaping to the top in Guangdong province (Zhanjiang is a municipal city of Guangdong province). Overall, electricity consumption in this rim has rapidly grown, especially from 2017, reflecting the rapid growth of energy demand in the rim.

1 However, air pollution and smog have already occurred in many regions of
2 China, especially in eastern coastal regions, including Beijing, Tianjin, and Hangzhou.
3 Development in Eastern China has followed the well-worn global routine of priority
4 for economic growth and expansion, inevitably resulting in air pollution, thus
5 sacrificing the environment without consideration of necessary steps to address the
6 resultant environmental and pollution problems. This approach has resulted in many
7 painful lessons for China, generating serious dialogue and deep thought, thereby
8 compelling China to express its resolute determination to avoid further pollution in
9 less developed regions such as the western region of China. China is now
10 implementing a sustained developmental strategy to accelerate the change of energy
11 structure, particularly with a view to increasing the share of clean sources in its
12 energy mix [48].

13 The BGER is one such new region to be developed in China, and has been
14 endowed to construct and provide non-polluting industry and tourism. For example,
15 Hainan Island (province), an important part of the BGER, recently officially
16 published the “Implementation plan of National pilot ecological zone (Hainan
17 Province) of China” in May 2019. This initiative clearly points out that Hainan plans
18 to build a “Clean Energy Island”, including measures leading to the step by step
19 prohibition of the selling of all petrol vehicles.

20 At the outset of action formulation and plan development for the BGER, clean
21 green energy, including wind energy, will be the primary consideration. However,
22 wind energy development in this zone has fallen far behind. In 2017, more than 1.16
23 GW of additional offshore wind power capacity was installed in Chinese coastal areas,
24 while there has been no installed capacity in the Beibu Gulf up to the end of 2017 [47].
25 Thus, especially because of inadequate knowledge and understanding of coastal wind
26 characteristics, the exploitation of coastal wind energy resources in the region is still
27 lacking.

28 To assist in the venture of optimal harvesting and utilization of wind power, this
29 paper presents a careful and comprehensive statistical assessment on wind field and
30 energy potential with detailed resource characterization for the period 2010 to 2017,

by means of measurement data collected from seven meteorological stations on coastal islands in the Beibu Gulf. The present study aims to provide insight toward understanding of wind energy potential required in exploring wind energy resources in the study area, in terms of wind speed variation, Weibull parameters and wind power density, as well as wind direction on various timescales. Additionally, to discuss the specific ability of energy development within the region, this study also provides the insight to meet the energy demand for the rim.

2. Wind data measurement and adjustment

In this study, data measured at seven meteorological stations on offshore islands and acquired by the CMA, are available for the region. The geographic locations of these seven meteorological stations are given in Figure 1. Before the stations were built, the site selections were fully demonstrated, following related standards and specifications, and data records were carefully checked by the data center of CMA, to ensure that the data are no problem for further analyses. Data collected at the stations are representative of wind climate for different areas of the study region. Data are gathered mainly to monitor atmospheric changes in the region, including forecasting and scrutiny of meteorological and environmental issues, etc. The stations are located at different heights above mean sea level (MSL), while the anemometer for each station is installed at 10m height above the surface of each station ground.

In China, each station for surface meteorological measurement must be followed the standard of the “Specifications for surface meteorological observation” (QX/T 45-2007) that published in 2007 (the modified new version is published in 2017 (GB/T 35221-2017)), which specified that surface meteorological stations must be located in the relatively flat and open terrain so as to be representative of relatively large local meteorological characteristics. The stations used in this study meet the standard. The wind monitors at the stations are high performance wind monitor sensors (RM Yong 5106) with blade helicoid propellers, purchased from R.M. Young.

The wind data adapted in the present study include wind speed and direction parameters over the period January 2010 to December 2017. Wind speed parameters

were sampled every 1s and averaged over 1 min. Wind direction data was recorded 6 times per minute, and also averaged over 1 min. The stations at QC, DM, SD, DY and BH are located very close to shore, of which QC and DM are located in the mouth of Qingzhou Bay; SD is located in Zhenzhu Bay; DY is located near Fangcheng Port. BX is further offshore, and ZZ and XY are located furthest from shore.

The sensor height at which wind data is measured at the different stations is shown in Table 1. We note the large variability in recorded wind speed, and also that wind speed will vary as a function of recorded height. To extrapolate recorded wind data to likely turbine hub height, hub height is set at 100m above MSL for this study, unless otherwise stated. A number of earlier studies have employed mathematical models representing height variability of wind speed, of which the log-law model has been most commonly employed [49]. The simple power-law model is frequently applied to offshore energy applications [14, 49–51], which is also employed in this study. The value 0.13 for the power law exponent has been chosen for this assessment, taken from the previous study of a Korean offshore wind farm, where the farm area is more semi-closed than ocean areas without nearby obstacles and thereby substantially affected by geomorphologic influences [35]. In comparison with the area in this previous study, the geomorphologic condition of the present study area is closer to that of the Korea wind farm.

Table 1 : List of measurement sites in the Guangxi coastal region with some fundamental mean wind and energy characteristics. Hourly collected observational data covered for the period August 2009 to the end of 2017. Table No. of observations represents the valid number of observations used in the study for each station. Total number of the hours over the study period is 70128. Height (m) in the table represents the wind sensor height above the mean sea level at each station. Main wind characteristics were statistically calculated, including wind speed, V (ms^{-1}); Weibull parameters, κ and c (ms^{-1}); V_{mp} (ms^{-1}); $V_{max,E}$ (ms^{-1}); wind power, P (W m^{-2}).

Site	BX	DY	SD	QC	DM	ZZ	XY
No. of observations	53216	57908	61610	59657	50221	70001	54017
Height	17.1	13.5	20.6	21.0	28.0	65.7	42.8
V_{mean}	7.6	7.2	6.1	6.0	5.8	4.0	5.7
κ	1.8	1.7	1.6	1.9	1.8	1.9	1.5
c	8.6	8.0	6.8	6.8	6.6	4.6	6.4

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V_{mp}	7.8	7.1	5.8	6.1	5.8	3.9	5.3
V_{maxE}	9.4	8.8	7.7	7.6	7.3	5.3	7.3
P_{mean}	605.6	542.0	368.0	282.0	265.6	87.6	321.5

3. Analytical methods

To provide the statistical analysis of wind characteristics and the assessment of wind energy potential sources associated with wind energy exploitation, several analytical methods are applied and briefly described below.

3.1 Weibull distribution function

Probability distribution models are commonly used to fit wind speed distributions over a time period and to obtain a clear view of the available wind potential for a region. A large number of different distribution models have been proposed for statistically analysing both wind characteristics and potential wind as energy assessment. Amongst all the available probability distribution functions, the Weibull probability distribution functions, particularly the two-parameter Weibull function, are commonly used and widely adopted for wind energy applications, not only due to their great flexibility and simplicity but also because they can provide a good representation of recorded wind data [29, 35, 50, 54–57]. Therefore, the two-parameter Weibull distribution model was utilized for the assessment of wind energy potential sources in this study.

The general form of the two-parameter Weibull function can be characterized by the Probability Density Function (PDF), $f(v)$ ($f(v) = \left(\frac{\kappa}{c}\right)\left(\frac{v}{c}\right)^{\kappa-1} \exp\left[-\left(\frac{v}{c}\right)^\kappa\right]$), and cumulative distribution function, $F(v)$. Here, v is wind speed in ms^{-1} , κ is the dimensionless Weibull shape parameter, and c is the Weibull scale parameter having the same units as v .

Several different numerical methods have been proposed and compared to estimate the Weibull parameters in previous studies [56,57]. The performance of these methods improves with increasing dataset size [56]. Following these studies, different common numerical methods, including the moment, graphical, empirical, energy pattern factor method, maximum likelihood and modified maximum likelihood, are

tested in determining the parameters of the Weibull distribution, so as to select the most effective method by comparing performance for this study. The methods for estimating Weibull parameters used in this study can be found in previous studies, e.g., [56,57].

Figure 3 : Weibull distributions based on the six methods for estimating Weibull parameters (i.e., the moment, graphical, empirical, energy pattern factor method, maximum likelihood and modified maximum likelihood) for the seven sites shown in Figure 1. The values in parentheses represent RMSEs (root mean square errors).

The performance of the methods for estimating Weibull parameters listed above (i.e., the moment, graphical, empirical, energy pattern factor method, maximum likelihood and modified maximum likelihood) are compared to test which are effective for this study. Figure 3 shows the PDFs (probability density functions) for each of the seven sites located in the Beibu Gulf, and calculated from wind data for the period 2010 to 2017. The difference between the curve calculated using the graphical method and the other methods is most obvious. To further test the accuracy of these methods, the judgment of accuracy of the RMSE (root mean square error) used in [56,57] is adapted for the present study. The RMSE is defined as $RMSE = \left[\frac{1}{N} \sum_{i=1}^N (y_i - x_i)^2 \right]^{\frac{1}{2}}$, where y_i is the frequency of observations, x_i represents the frequency of Weibull, and N is the number of observations. The RMSEs of the six methods for the seven sites are listed in the parentheses of Figure 3. It can be seen from these values that the performance of the maximum likelihood method is on

average best. Therefore, the study uses this method for determining the Weibull parameters for further analyses in the following sections.

3.2 Most probable wind speed

The estimated Weibull parameters are directly used so as to obtain most probable wind speeds, thereby indicating most frequent wind speed for a given PDF. The most probable wind speed, V_{mp} , is computed in terms of Weibull distribution parameters [29,51]:

$$V_{mp} = c(1 - \frac{1}{\kappa})^{\frac{1}{\kappa}} \quad (1)$$

3.3 Wind speed carrying maximum energy

The Weibull parameters are also used to compute wind speed containing maximum energy, $V_{max.E}$, for a wind turbine, which is also the speed that produces the most energy. $V_{max.E}$ can also be adapted for estimating wind turbine rated wind speeds, which can be defined as follows [29, 43, 50]:

$$V_{max.E} = c(1 + \frac{2}{\kappa})^{\frac{1}{\kappa}} \quad (2)$$

3.4 Wind power density

Wind power density is an important parameter for evaluating available resources at potential sites. Wind power, measured in Wm^{-2} , per unit swept area of a turbine is proportional to the cube of the wind speed. In terms of Weibull distribution parameters, the wind power per unit area can be defined as follows [29, 50, 60–63]:

$$P = \frac{1}{2}\rho \int_0^{\infty} v^3 f(v) dv = \frac{1}{2}\rho c^3 \Gamma(1 + \frac{3}{\kappa}) \quad (3)$$

where c and κ are still the Weibull parameters.

3.5 Limitations of the analysis of this study

We wish to state for the record that the analysis of the present study is meant as a first pass only at estimating the viable offshore wind resource in order to highlight the availability of this resource within the study region.

For the study period from August 2009 to December 2017, the valid number of observations from all data records used in the study at each of the stations (i.e., BX, DY, SD, QC, DM, ZZ, XY) was, respectively, about 76%, 83%, 88%, 85%, 72%, 99%, 77% (see Table 1). This means that there were data losses of approximately 24%, 17%, 12%, 15%, 28%, 1% and 23% for each station, respectively, indicating that better and more reliable datasets are needed for the region, especially for stations BX,

DM and XY. This is a recommendation of the present study for follow-up work. Moreover, the analysis is also limited by wind turbine hub height and measurement locations. However, once better datasets become available for the region, further analysis will be undertaken using the latest offshore wind turbine parameters.

4. Wind energy assessment in the Beibu Gulf

To interpret wind climate and potential wind energy characteristics at the stations shown in Figure 1, wind features were analyzed based on detailed observational data, including mean wind speed, prevailing direction, diurnal and monthly variations, together with Weibull distributions, and the wind power density. The observed wind speed data have been converted from anemometer height to wind turbine hub height by use of the power-law approximation introduced in Section 2. Converted data have been used in this study, whereas we assumed wind directions do not vary with height. Moreover, for the present study, the four boreal seasons are winter (December-February), spring (March-May), summer (June-August), and Autumn (September-November).

1
2 Figure 4 : Intra- and inter-annual variability of wind speeds (ms^{-1}) over the period 2010 to 2017 for the
3 seven sites shown in Figure 1. (A) Monthly wind speed; (B) Monthly climatology of wind speed;
4 (C1-C4) Year-to-year variability for different month (December, May, July and August) of the
5 wind speed.

6 4.1 Inter- and intra-annual wind speed variations

7 Monthly mean and seasonal wind speed characteristics were investigated for the
8 study sites, based on observations collected over the period 2010 to 2017, to show
9 inter- and intra-annual wind speed variability.

Figure 4(A) illustrates monthly wind speed for the seven sites. Intra- and inter-annual variability is obvious. Monthly wind speed values at the sites ranged from about 3.0 ms^{-1} to 12.0 ms^{-1} , with annual mean wind speed values varying between 4.0 ms^{-1} and 7.6 ms^{-1} (see Table 1), although January 2011 values were relatively higher at all sites, with a highest monthly wind speed value of about 15.6 ms^{-1} found at DY.

Figure 4(B) shows monthly wind speed climatologies for the seven sites. Intra-annual wind speed variability is evident, with annual climatologies exhibiting two cycles per year: largest wind speeds occurring in December with another peak value in July, and lowest wind speeds apparent in May with another trough in August.

Figure 4(C1-C4) shows year-to-year wind speed variability for months containing peak and trough wind speed values. Inter-annual variability seems weaker than intra-annual variability. In addition, most of the seven sites display quite similar inter-annual variations, especially for December and July.

The long-term trend of the wind speed at the seven sites was also checked, however, no significant trend can be verified for the period of interest. This is because the observational period is relatively short to for determining a conclusion on the long-term trend in wind climate change for the study area, especially when considering response to global climate change.

4.2 Diurnal wind speed variations

Figure 5 : Diurnal mean wind speed (ms^{-1}) for the eight sites shown in Figure 1.

Besides monthly and seasonal probability wind speed distributions, diurnal mean wind speed variations are also analyzed in this study to explain hourly wind speed probabilities, and are presented in Figure 5 for each of the seven sites. A clear feature

at each site is that for sites BX, DY, ZZ and XY, which are the furthest from shore and closer to the open sea, hourly mean wind speed is largest in day time (8:00-18:00); while at SD, QC and DM, closer to the mainland, wind speeds are relatively small in the afternoon.

4.3 Weibull distribution

Figure 6 : Annual Weibull probability distributions at all sites for the period 2010 to 2017.

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Annual wind speed Weibull distributions at all sites are highlighted in Figure 6, and annual mean Weibull parameters for period 2010-2017 are listed in Table 1. As seen in Figure 6, the curve peak represents the most frequent wind speed.

The shape parameter, κ , was in the range 1.5-1.9 at all stations, while scale parameter, c , varied between 4.6 ms^{-1} and 8.6 ms^{-1} . The average values of the shape and scale parameters for all sites were, respectively, 1.7 ms^{-1} and 6.8 ms^{-1} .

4.4 Variations of V_{mp} and $V_{max.E}$

Figure 7 : Monthly variation of V_{mp} and $V_{max.E}$ at all sites for the period 2010 to 2017.

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Figure 7 plots the variability in monthly mean values of most probable wind speed, V_{mp} , and wind speed containing most energy, $V_{max.E}$, observed at the seven sites. Concerning V_{mp} , monthly values were mostly confined to the range 2-9 ms^{-1} at all sites. V_{mp} displayed seasonality similar to that of wind speed and Weibull parameters: relatively high values in December and January, low values in April, May and August, with increased values in June and July. Likewise, $V_{max.E}$ also exhibits obvious seasonal changes. Annual mean values of V_{mp} and $V_{max.E}$ for the seven sites over the period 2010 to 2017 are also given in Table 1. The largest annual mean values of V_{mp} and $V_{max.E}$ were found at BX and DY, with values of $\sim 7.8 \text{ ms}^{-1}$ and $\sim 7.1 \text{ ms}^{-1}$, respectively, while a smallest value of 3.9 ms^{-1} occurred at ZZ.

4.5 Seasonal wind speed and direction roses

Beside wind speed, wind direction is another important parameter for assessing of wind energy resources. Seasonal distributions of incoming wind direction and wind speed for the seven sites are presented in terms of a wind rose figure, Figure 8. It is apparent from this figure that seasonal wind direction variability is occurring at the seven locations, mainly reflecting the monsoon characteristics in this region.

In winter and autumn, northerly to northeasterly offshore winds, i.e. winds from land, prevailed at each of the sites, accounting for greater than 50% of directional winds, while onshore winds, i.e. winds from the open sea, from S, SW and SE, provided the largest contribution to wind energy resources. In spring, winds from N to E and to S accounted for most, mainly reflecting transition season characteristics in wind direction. It is noted, but not surprising, that westerly to northwesterly winds were rare in all seasons at all sites (on average less than 5%), reflecting South China Sea monsoon characteristics.

Overall, prevailing wind directions in the rim are mainly from opposite N-S directions, which might be good for energy exploitation since focus of wind direction and concentration of energy benefit several types of wind turbines designed to convert wind resources as fully as possible.

Figure 8 : Seasonal wind speed and direction roses based on the site measurements for the period 2010 to 2017.

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Figure 8 also displays wind speed range percentages at the sites over the period 2010 to 2017. The wind scale is in accordance with the Beaufort scale, as represented by the colors. At BX and DY, wind speeds were mostly from 4 to 9 on the Beaufort

scale, i.e., from 5.5 ms^{-1} to 24.5 ms^{-1} , reaching 10 on the Beaufort scale in autumn and winter about 5% of the time. Wind speeds were mostly in the range of 3-8 Beaufort scale at SD and QC, while mostly varied from 3 to 6 on the Beaufort scale at DM and XY, with seasonal changes as mentioned above. Smallest wind speed scales were found at BH and ZZ where over 90% of wind speeds were below 5 Beaufort scale (less than 10.8 ms^{-1}).

4.6 Wind power density

Wind power densities were calculated for the period 2010 to 2017 by use of eq. 33. Wind power density, calculated based on the measurements, are, respectively, 605.6, 542.0, 368.0, 282.0, 265.6, 87.6 and 321.5 Wm^{-2} at BX, DY, SD, QC, DM, ZZ and XY stations (see Table 1). It is noted that the Global Wind Atlas (<https://globalwindatlas.info/>) wind power range for the study region is $200\text{-}450 \text{ Wm}^{-2}$ at 100m above MSL. Wind power is higher than the Global Wind Atlas wind power range only at BX and DY, while mean wind power averaged over the seven stations is 353.2 Wm^{-2} , which is within the range of Global Wind Atlas.

Figure 9 describes the intra- and inter-annual variation in terms of monthly mean wind power density for each site. Since wind power density is a function of wind speed only, characteristics of its variability are in good agreement with the corresponding wind speed variations. Intra- and inter-annual variability in wind power patterns display quite similar characteristics at most of the seven sites. Intra-annual variability was evident at all sites: wind power density values were largest in December, while lowest in August; another peak/trough wind speed occurred in July/May. This variability might somehow favour wind energy exploitation and usage: monthly changes in electricity consumption for Guangxi province in the rim is relatively high in summer time, while lowest in February and April (see Figure 2).

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Figure 9 : Seasonal (left) and monthly (right) mean wind power density (Wm^{-2}) for the sites shown in Figure 1.

In accordance with mean wind-speed and Weibull parameters, for spatial variation, the annual mean wind power density, P_{mean} (shown in Table 1), was greatest at BX with a value of 605.6 Wm^{-2} , and least at ZZ with a value of 87.6 Wm^{-2} .

4.7 Estimation of the potential contribution of coastal wind in the study area

In 2017, more than 1.16 GW of additional offshore wind power capacity was installed in Chinese coastal areas, while there has been no installed capacity in the Beibu Gulf up to the end of 2017 [47]. If a turbine with 5 MW capacity is installed in the study area, it would provide about 11 GWh in one year, with annual utilization time of installed capacity in Guangxi being 2280 hours in 2017, based on official data [47]. Thus, a wind farm with 100 such turbines would generate about 1.1 TWh electricity, which can contribute about 0.8% and 3.6% of total electricity consumption in 2017 for Guangxi and Hainan provinces, respectively.

5. Conclusions

The Beibu Gulf Economic Rim is critical for China's development, and especially for the western China region. The “Beibu Gulf Cities Development Project” sanctioned in 2017 plans to build a “Blue Livable Gulf” to avoid the well-worn routine of priority for economic development, while sacrificing the environment. Electricity consumption data of the rim shows a rising demand in the past ten years and indicates rapid growth in the future, reflecting the huge amount of energy required for developing these cities, with primary consideration given to clean energy.

1 In this study, a comprehensive statistical analysis and assessment of wind field
2 and associated energy potential with detailed resource characterization in the study
3 area for the period 2010 to 2017 was conducted at seven offshore coastal sites
4 mention the sites again here. Annual mean wind speed values for the period 2010 to
5 2017 for the seven sites at 100m ranged from 4.0 ms^{-1} to 7.6 ms^{-1} , resulting in annual
6 mean wind power densities, respectively, of 605.6, 542.0, 368.0, 282.0, 265.6, 87.6
7 and 321.5 Wm^{-2} at the seven sites (BX, DY, SD, QC, DM, ZZ and XY), with average
8 value of 353.2 Wm^{-2} . Intra-annual variability of wind power potential is evident at the
9 seven sites, with the greatest wind power occurring in December and another peak
10 value in July, while lowest wind speed values occur in May with another trough in
11 August. The data also display also shows weak inter-annual variations. However, no
12 significant annual trends were found over the period.

13 The annual mean Weibull shape parameter, κ , for period 2010-2017 varied from
14 1.5 to 1.9 at the sites, while the Weibull scale parameter, c , was found to have values
15 between 4.6 ms^{-1} and 8.6 ms^{-1} . The annual mean V_{mp} and $V_{max.E}$ for the sites were,
16 respectively, in the range $3.9\text{-}7.8 \text{ ms}^{-1}$ and $5.3\text{-}9.4 \text{ ms}^{-1}$.

17 Seasonal variability is evident in wind direction, mainly reflecting monsoon
18 characteristics in the region: in winter and autumn, winds were predominantly from
19 the north, with a considerable northeasterly contribution, while southerly winds
20 prevailed in summer. The prevailing wind direction distribution in the rim is good for
21 energy exploiting and usage. Statistical estimates suggest that a wind farm with 100
22 turbines each of 5 MW capacity would contribute about 0.8% and 3.6% of the total
23 electricity consumption in 2017 for Guangxi and Hainan provinces, respectively.

24 Overall, this study suggests that China, including the Beibu Gulf, has relatively
25 large resources of offshore wind energy that can reduce its dependency on imported
26 fossil fuels, thus ensuring security of energy supply as well as reduced GHG
27 emissions in the Beibu Gulf Economic Rim, China and the world.

28 Finally, it should be stated that there was a data loss of more than 20% in the
29 measurement records at three of the seven stations (i.e., 24%, 28% and 23%,
30 respectively, for stations BX, DM and XY) used in this study. Estimates of wind

speed and wind power variability may be influenced by gaps in the data. We wish to state, for the record, that the analysis of the present study is meant as a first pass only at estimating the viable offshore wind resource in order to highlight the rich offshore wind resource available for the study region. Better and more reliable datasets are needed for follow-up work. Once these improved datasets become available for the region, further analysis will be undertaken using the latest offshore wind turbine parameters.

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An assessment of wind energy potential in the Beibu Gulf considering the energy demands of the Beibu Gulf Economic Rim

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Abstract

The Beibu Gulf Economic Rim of China is a key economic region in China as demonstrated by the “Beibu Gulf Cities Development Project” (2017) that plans to build a “Blue Livable Gulf” to balance environmental protection while providing sustainable economic development. This region has significant energy needs and is predicted to exhibit rapid growth in the future.

By means of meteorological observations located at seven islands, a comprehensive statistical analysis on wind energy potential in the northern coastal part of the Beibu Gulf is conducted in this study. Specifically, wind speed, Weibull parameters, wind power density, as well as wind directions on various timescales are analyzed. The analysis shows that annual mean wind power density during 2010-2017 at 100m above mean sea level was, respectively, 605.6, 542.0, 368.0, 282.0, 265.6, 87.6 and 321.5 Wm⁻² at the seven sites, with average value of 353.2 Wm⁻². Evidently, wind power potential demonstrates intra-annual variability, with greatest values occurring in December, while another peak value is observed in July. Wind speeds are lowest in May with another trough occurring in August. The data also display weak inter annual variability. The prevailing wind directions in the rim are mainly from opposing directions of N (winter and autumn) and S (summer).

Keywords: Beibu Gulf, Wind energy, Renewable energy, Wind power, Wind climate

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1. Introduction

The use of wind power as an alternative energy source, both on- and off-shore, has increased rapidly over the last 10 years [1–4]. The offshore market is expected to grow at a higher pace than the onshore market, representing about one quarter of the total new wind power installations by 2020 [3]. One significant development in recent years is the spectacular drop in offshore wind power prices, thus making offshore wind power as competitive as fossil fuels and nuclear power [5]. Besides the cost of wind power, renewables like wind can also provide solutions to relieve some key environmental and social challenges, including improving energy security, creating more jobs, reducing public health and air pollution problems, and mitigating against greenhouse gas emissions (GHG) [3, 6].

When comparing development of wind energy sources, offshore sources have been shown to be superior to onshore sources in a number of ways [7, 8]. For example, offshore wind speeds are usually greater and more steady, leading to less turbulence effects than those on land at nearby sites [9, 10]. A number of studies have assessed offshore wind characteristics and wind power potential, either globally or at specific sites [e.g., 11–35], providing fundamental information for offshore wind power exploitation, for example, spatial and potential variability of wind energy potential display for different offshore regions.

1.1 The development of wind energy in China

China possesses and can potentially harness abundant quantities of onshore and offshore wind energy. It has been reported by the Global Wind Energy Council (GWEC) [5] that as the driver of global market growth for most of the last decade, China installed 21.2 GW of onshore wind and 1.8 GW of offshore wind in 2018, representing 45% and 40% of global market share respectively. In 2018, the second largest market was the US with 7.6 GW of new onshore installations, followed by Germany (2.4 GW), India (2.2 GW) and Brazil (1.9 GW). For the offshore market in 2018, China took the lead for the first time, followed by the United Kingdom with 1.3 GW. Germany took the third place (0.9 GW) [5].

Although China is the world's largest wind power market in both new and cumulative installations, China also has a very large population of about 1.4 billion. In particular, more than half the people in China live in the eastern coastal region, where the economy is relatively developed, thereby leading to a huge energy demand. Therefore, compared with other countries such as the USA, United Kingdom and Germany, new installations in both onshore and offshore wind market is actually much lower on a per capita basis, indicating that China still needs to strive to develop wind energy exploitation, particularly for nearshore and offshore wind energy.

Additionally, China has a very long coastline, approximately 18,000 km running from the Bohai Sea in the north to the Beibu Gulf in the south, adjacent to a 12-nautical-mile territorial sea with depths mostly less than 100m. This means that, firstly, offshore wind is a very viable solution located close to the major coastal urban areas of Tianjin, Shanghai, Guangzhou, Shenzhen and so on, with their many millions of citizens. Secondly, wind power resources vary spatially and temporally: wind power densities along the coast of the Chinese Seas regions range from 200 Wm^{-2} to 1000 Wm^{-2} [36–39], which can also be realized from the Global Wind Atlas (<https://globalwindatlas.info/>). The potential for offshore wind power has been examined for some coastal regions of China. For example, wind power potential was assessed for the Pearl River Delta region [41] and for Hongkong [29, 42–44]; the nearshore wind energy resources off the Shenzhen coast was carefully evaluated [45]; while a model-based climatology analysis was made for wind power resources over the Bohai Sea and the Yellow Sea [46]. Furthermore, previous studies have shown that even in relatively small offshore areas, wind energy potential can display spatial and temporal differences [35, 45]. Therefore, before selecting a site to build wind power plants, it is an essential and important first step to conduct a precise survey and assessment of wind energy resources around the region, especially for the offshore region where observational data are still rare and good quality information is limited.

The area of interest in this study is off the coast of Guangxi Zhuang Autonomous Region, located in the Beibu Gulf Economic Rim (BGER) of China, located in the South China Sea (see Figure 1). This is one of the least developed regions of China,

and especially for a coastal region. As an important part of the "China Western Development Strategy", in 2017, the central government of China has sanctioned the "Beibu Gulf Cities Development Project" (BGCD project). The project aims to build 3 "City Centre Circles", 2 "City Development Roles" and 1 "Blue Liveable Gulf" (the Beibu Gulf). Various infrastructures will be built, and a large amount of manpower, resources and capital investments and other invisible privileges needed are planned to promote the development of the whole BGER and to thoroughly shake off the relative poverty and backwardness of this region.

Figure 1 : Area of the study relative to the northern South China Sea (left) and geographic locations of the seven meteorological sites in red crosses (+ right).

1.2 Energy demands and policy changes in the Beibu Gulf Economic Rim

Figure 2: (Top) Electricity consumption of the Guangxi Zhuang Autonomous Region (Guangxi province) for the period 2008-2017; (Bottom) monthly electricity consumption of Guangxi in 2015, 2016 and 2017. (Data resource: China Energy Statistical Yearbook (2008-2017) [47]).

Electricity consumption of Guangxi province in the past 11 years was analyzed to reflect the energy demand for this rim. As shown in Figure 2, the electricity consumption in Guangxi and Hainan provinces has been rising continuously for the past 11 years [47]. Furthermore, since the BGCD project was sanctioned in 2017, the growth rate of the electricity consumption in Guangxi province has risen rapidly, exceeding expectations. In 2018, electricity consumption in Guangxi had reached 170.28TWh, with growth rate up 17.84% compared with the value of 2017 (144.23 TWh), which is much higher than the growth rate of China (8.5%). From the official report, energy consumption in Zhanjiang municipal city in this rim was, 10.80 TWh and 18.15 TWh in 2016 and 2017, respectively, and its year-on-year growth rate was 7.8% and 18.4%, respectively, with the latter leaping to the top in Guangdong province (Zhanjiang is a municipal city of Guangdong province). Overall, electricity consumption in this rim has rapidly grown, especially from 2017, reflecting the rapid growth of energy demand in the rim.

1 However, air pollution and smog have already occurred in many regions of
2 China, especially in eastern coastal regions, including Beijing, Tianjin, and Hangzhou.
3 Development in Eastern China has followed the well-worn global routine of priority
4 for economic growth and expansion, inevitably resulting in air pollution, thus
5 sacrificing the environment without consideration of necessary steps to address the
6 resultant environmental and pollution problems. This approach has resulted in many
7 painful lessons for China, generating serious dialogue and deep thought, thereby
8 compelling China to express its resolute determination to avoid further pollution in
9 less developed regions such as the western region of China. China is now
10 implementing a sustained developmental strategy to accelerate the change of energy
11 structure, particularly with a view to increasing the share of clean sources in its
12 energy mix [48].

13 The BGER is one such new region to be developed in China, and has been
14 endowed to construct and provide non-polluting industry and tourism. For example,
15 Hainan Island (province), an important part of the BGER, recently officially
16 published the “Implementation plan of National pilot ecological zone (Hainan
17 Province) of China” in May 2019. This initiative clearly points out that Hainan plans
18 to build a “Clean Energy Island”, including measures leading to the step by step
19 prohibition of the selling of all petrol vehicles.

20 At the outset of action formulation and plan development for the BGER, clean
21 green energy, including wind energy, will be the primary consideration. However,
22 wind energy development in this zone has fallen far behind. In 2017, more than 1.16
23 GW of additional offshore wind power capacity was installed in Chinese coastal areas,
24 while there has been no installed capacity in the Beibu Gulf up to the end of 2017 [47].
25 Thus, especially because of inadequate knowledge and understanding of coastal wind
26 characteristics, the exploitation of coastal wind energy resources in the region is still
27 lacking.

28 To assist in the venture of optimal harvesting and utilization of wind power, this
29 paper presents a careful and comprehensive statistical assessment on wind field and
30 energy potential with detailed resource characterization for the period 2010 to 2017,

1 by means of measurement data collected from seven meteorological stations on
2 coastal islands in the Beibu Gulf. The present study aims to provide insight toward
3 understanding of wind energy potential required in exploring wind energy resources
4 in the study area, in terms of wind speed variation, Weibull parameters and wind
5 power density, as well as wind direction on various timescales. Additionally, to
6 discuss the specific ability of energy development within the region, this study also
7 provides the insight to meet the energy demand for the rim.

8 **2. Wind data measurement and adjustment**

9 In this study, data measured at seven meteorological stations on offshore islands
10 and acquired by the CMA, are available for the region. The geographic locations of
11 these seven meteorological stations are given in Figure 1. Before the stations were
12 built, the site selections were fully demonstrated, following related standards and
13 specifications, and data records were carefully checked by the data center of CMA, to
14 ensure that the data are no problem for further analyses. Data collected at the stations
15 are representative of wind climate for different areas of the study region. Data are
16 gathered mainly to monitor atmospheric changes in the region, including forecasting
17 and scrutiny of meteorological and environmental issues, etc. The stations are located
18 at different heights above mean sea level (MSL), while the anemometer for each
19 station is installed at 10m height above the surface of each station ground.

20 In China, each station for surface meteorological measurement must be followed
21 the standard of the “Specifications for surface meteorological observation” (QX/T
22 45-2007) that published in 2007 (the modified new version is published in 2017
23 (GB/T 35221-2017)), which specified that surface meteorological stations must be
24 located in the relatively flat and open terrain so as to be representative of relatively
25 large local meteorological characteristics. The stations used in this study meet the
26 standard. The wind monitors at the stations are high performance wind monitor
27 sensors (RM Yong 5106) with blade helicoid propellers, purchased from R.M. Young.

28 The wind data adapted in the present study include wind speed and direction
29 parameters over the period January 2010 to December 2017. Wind speed parameters

were sampled every 1s and averaged over 1 min. Wind direction data was recorded 6 times per minute, and also averaged over 1 min. The stations at QC, DM, SD, DY and BH are located very close to shore, of which QC and DM are located in the mouth of Qingzhou Bay; SD is located in Zhenzhu Bay; DY is located near Fangcheng Port. BX is further offshore, and ZZ and XY are located furthest from shore.

The sensor height at which wind data is measured at the different stations is shown in Table 1. We note the large variability in recorded wind speed, and also that wind speed will vary as a function of recorded height. To extrapolate recorded wind data to likely turbine hub height, hub height is set at 100m above MSL for this study, unless otherwise stated. A number of earlier studies have employed mathematical models representing height variability of wind speed, of which the log-law model has been most commonly employed [49]. The simple power-law model is frequently applied to offshore energy applications [14, 49–51], which is also employed in this study. The value 0.13 for the power law exponent has been chosen for this assessment, taken from the previous study of a Korean offshore wind farm, where the farm area is more semi-closed than ocean areas without nearby obstacles and thereby substantially affected by geomorphologic influences [35]. In comparison with the area in this previous study, the geomorphologic condition of the present study area is closer to that of the Korea wind farm.

Table 1 : List of measurement sites in the Guangxi coastal region with some fundamental mean wind and energy characteristics. Hourly collected observational data covered for the period August 2009 to the end of 2017. Table No. of observations represents the valid number of observations used in the study for each station. Total number of the hours over the study period is 70128. Height (m) in the table represents the wind sensor height above the mean sea level at each station. Main wind characteristics were statistically calculated, including wind speed, V (ms^{-1}); Weibull parameters, κ and c (ms^{-1}); V_{mp} (ms^{-1}); $V_{max.E}$ (ms^{-1}); wind power, P (W m^{-2}).

Site	BX	DY	SD	QC	DM	ZZ	XY
No. of observations	53216	57908	61610	59657	50221	70001	54017
Height	17.1	13.5	20.6	21.0	28.0	65.7	42.8
V_{mean}	7.6	7.2	6.1	6.0	5.8	4.0	5.7
κ	1.8	1.7	1.6	1.9	1.8	1.9	1.5
c	8.6	8.0	6.8	6.8	6.6	4.6	6.4

V_{mp}	7.8	7.1	5.8	6.1	5.8	3.9	5.3
$V_{max.E}$	9.4	8.8	7.7	7.6	7.3	5.3	7.3
P_{mean}	605.6	542.0	368.0	282.0	265.6	87.6	321.5

3. Analytical methods

To provide the statistical analysis of wind characteristics and the assessment of wind energy potential sources associated with wind energy exploitation, several analytical methods are applied and briefly described below.

3.1 Weibull distribution function

Probability distribution models are commonly used to fit wind speed distributions over a time period and to obtain a clear view of the available wind potential for a region. A large number of different distribution models have been proposed for statistically analysing both wind characteristics and potential wind as energy assessment. Amongst all the available probability distribution functions, the Weibull probability distribution functions, particularly the two-parameter Weibull function, are commonly used and widely adopted for wind energy applications, not only due to their great flexibility and simplicity but also because they can provide a good representation of recorded wind data [29, 35, 50, 54–57]. Therefore, the two-parameter Weibull distribution model was utilized for the assessment of wind energy potential sources in this study.

The general form of the two-parameter Weibull function can be characterized by the Probability Density Function (PDF), $f(v)$ ($f(v) = \left(\frac{\kappa}{c}\right)\left(\frac{v}{c}\right)^{\kappa-1} \exp\left[-\left(\frac{v}{c}\right)^\kappa\right]$), and cumulative distribution function, $F(v)$. Here, v is wind speed in ms^{-1} , κ is the dimensionless Weibull shape parameter, and c is the Weibull scale parameter having the same units as v .

Several different numerical methods have been proposed and compared to estimate the Weibull parameters in previous studies [56,57]. The performance of these methods improves with increasing dataset size [56]. Following these studies, different common numerical methods, including the moment, graphical, empirical, energy pattern factor method, maximum likelihood and modified maximum likelihood, are

tested in determining the parameters of the Weibull distribution, so as to select the most effective method by comparing performance for this study. The methods for estimating Weibull parameters used in this study can be found in previous studies, e.g., [56,57].

Figure 3 : Weibull distributions based on the six methods for estimating Weibull parameters (i.e., the moment, graphical, empirical, energy pattern factor method, maximum likelihood and modified maximum likelihood) for the seven sites shown in Figure 1. The values in parentheses represent RMSEs (root mean square errors).

The performance of the methods for estimating Weibull parameters listed above (i.e., the moment, graphical, empirical, energy pattern factor method, maximum likelihood and modified maximum likelihood) are compared to test which are effective for this study. Figure 3 shows the PDFs (probability density functions) for each of the seven sites located in the Beibu Gulf, and calculated from wind data for the period 2010 to 2017. The difference between the curve calculated using the graphical method and the other methods is most obvious. To further test the accuracy of these methods, the judgment of accuracy of the RMSE (root mean square error) used in [56,57] is adapted for the present study. The RMSE is defined as $RMSE = \left[\frac{1}{N} \sum_{i=1}^N (y_i - x_i)^2 \right]^{\frac{1}{2}}$, where y_i is the frequency of observations, x_i represents the frequency of Weibull, and N is the number of observations. The RMSEs of the six methods for the seven sites are listed in the parentheses of Figure 3. It can be seen from these values that the performance of the maximum likelihood method is on

average best. Therefore, the study uses this method for determining the Weibull parameters for further analyses in the following sections.

3.2 Most probable wind speed

The estimated Weibull parameters are directly used so as to obtain most probable wind speeds, thereby indicating most frequent wind speed for a given PDF. The most probable wind speed, V_{mp} , is computed in terms of Weibull distribution parameters [29,51]:

$$V_{mp} = c(1 - \frac{1}{\kappa})^{\frac{1}{\kappa}} \quad (1)$$

3.3 Wind speed carrying maximum energy

The Weibull parameters are also used to compute wind speed containing maximum energy, $V_{max.E}$, for a wind turbine, which is also the speed that produces the most energy. $V_{max.E}$ can also be adapted for estimating wind turbine rated wind speeds, which can be defined as follows [29, 43, 50]:

$$V_{max.E} = c(1 + \frac{2}{\kappa})^{\frac{1}{\kappa}} \quad (2)$$

3.4 Wind power density

Wind power density is an important parameter for evaluating available resources at potential sites. Wind power, measured in Wm^{-2} , per unit swept area of a turbine is proportional to the cube of the wind speed. In terms of Weibull distribution parameters, the wind power per unit area can be defined as follows [29, 50, 60–63]:

$$P = \frac{1}{2}\rho \int_0^{\infty} v^3 f(v) dv = \frac{1}{2}\rho c^3 \Gamma(1 + \frac{3}{\kappa}) \quad (3)$$

where c and κ are still the Weibull parameters.

3.5 Limitations of the analysis of this study

We wish to state for the record that the analysis of the present study is meant as a first pass only at estimating the viable offshore wind resource in order to highlight the availability of this resource within the study region.

For the study period from August 2009 to December 2017, the valid number of observations from all data records used in the study at each of the stations (i.e., BX, DY, SD, QC, DM, ZZ, XY) was, respectively, about 76%, 83%, 88%, 85%, 72%, 99%, 77% (see Table 1). This means that there were data losses of approximately 24%, 17%, 12%, 15%, 28%, 1% and 23% for each station, respectively, indicating that better and more reliable datasets are needed for the region, especially for stations BX,

DM and XY. This is a recommendation of the present study for follow-up work. Moreover, the analysis is also limited by wind turbine hub height and measurement locations. However, once better datasets become available for the region, further analysis will be undertaken using the latest offshore wind turbine parameters.

4. Wind energy assessment in the Beibu Gulf

To interpret wind climate and potential wind energy characteristics at the stations shown in Figure 1, wind features were analyzed based on detailed observational data, including mean wind speed, prevailing direction, diurnal and monthly variations, together with Weibull distributions, and the wind power density. The observed wind speed data have been converted from anemometer height to wind turbine hub height by use of the power-law approximation introduced in Section 2. Converted data have been used in this study, whereas we assumed wind directions do not vary with height. Moreover, for the present study, the four boreal seasons are winter (December-February), spring (March-May), summer (June-August), and Autumn (September-November).

Figure 4 : Intra- and inter-annual variability of wind speeds (ms^{-1}) over the period 2010 to 2017 for the seven sites shown in Figure 1. (A) Monthly wind speed; (B) Monthly climatology of wind speed; (C1-C4) Year-to-year variability for different month (December, May, July and August) of the wind speed.

4.1 Inter- and intra-annual wind speed variations

Monthly mean and seasonal wind speed characteristics were investigated for the study sites, based on observations collected over the period 2010 to 2017, to show inter- and intra-annual wind speed variability.

Figure 4(A) illustrates monthly wind speed for the seven sites. Intra- and inter-annual variability is obvious. Monthly wind speed values at the sites ranged from about 3.0 ms^{-1} to 12.0 ms^{-1} , with annual mean wind speed values varying between 4.0 ms^{-1} and 7.6 ms^{-1} (see Table 1), although January 2011 values were relatively higher at all sites, with a highest monthly wind speed value of about 15.6 ms^{-1} found at DY.

Figure 4(B) shows monthly wind speed climatologies for the seven sites. Intra-annual wind speed variability is evident, with annual climatologies exhibiting two cycles per year: largest wind speeds occurring in December with another peak value in July, and lowest wind speeds apparent in May with another trough in August.

Figure 4(C1-C4) shows year-to-year wind speed variability for months containing peak and trough wind speed values. Inter-annual variability seems weaker than intra-annual variability. In addition, most of the seven sites display quite similar inter-annual variations, especially for December and July.

The long-term trend of the wind speed at the seven sites was also checked, however, no significant trend can be verified for the period of interest. This is because the observational period is relatively short to for determining a conclusion on the long-term trend in wind climate change for the study area, especially when considering response to global climate change.

4.2 Diurnal wind speed variations

Figure 5 : Diurnal mean wind speed (ms^{-1}) for the eight sites shown in Figure 1.

Besides monthly and seasonal probability wind speed distributions, diurnal mean wind speed variations are also analyzed in this study to explain hourly wind speed probabilities, and are presented in Figure 5 for each of the seven sites. A clear feature

at each site is that for sites BX, DY, ZZ and XY, which are the furthest from shore and closer to the open sea, hourly mean wind speed is largest in day time (8:00-18:00); while at SD, QC and DM, closer to the mainland, wind speeds are relatively small in the afternoon.

4.3 Weibull distribution

Figure 6 : Annual Weibull probability distributions at all sites for the period 2010 to 2017.

Annual wind speed Weibull distributions at all sites are highlighted in Figure 6, and annual mean Weibull parameters for period 2010-2017 are listed in Table 1. As seen in Figure 6, the curve peak represents the most frequent wind speed.

The shape parameter, κ , was in the range 1.5-1.9 at all stations, while scale parameter, c , varied between 4.6 ms^{-1} and 8.6 ms^{-1} . The average values of the shape and scale parameters for all sites were, respectively, 1.7 ms^{-1} and 6.8 ms^{-1} .

4.4 Variations of V_{mp} and $V_{max.E}$

Figure 7 : Monthly variation of V_{mp} and $V_{max.E}$ at all sites for the period 2010 to 2017.

Figure 7 plots the variability in monthly mean values of most probable wind speed, V_{mp} , and wind speed containing most energy, $V_{max.E}$, observed at the seven sites. Concerning V_{mp} , monthly values were mostly confined to the range 2-9 ms^{-1} at all sites. V_{mp} displayed seasonality similar to that of wind speed and Weibull parameters: relatively high values in December and January, low values in April, May and August, with increased values in June and July. Likewise, $V_{max.E}$ also exhibits obvious seasonal changes. Annual mean values of V_{mp} and $V_{max.E}$ for the seven sites over the period 2010 to 2017 are also given in Table 1. The largest annual mean values of V_{mp} and $V_{max.E}$ were found at BX and DY, with values of $\sim 7.8 \text{ ms}^{-1}$ and $\sim 7.1 \text{ ms}^{-1}$, respectively, while a smallest value of 3.9 ms^{-1} occurred at ZZ.

4.5 Seasonal wind speed and direction roses

Beside wind speed, wind direction is another important parameter for assessing of wind energy resources. Seasonal distributions of incoming wind direction and wind speed for the seven sites are presented in terms of a wind rose figure, Figure 8. It is apparent from this figure that seasonal wind direction variability is occurring at the seven locations, mainly reflecting the monsoon characteristics in this region.

In winter and autumn, northerly to northeasterly offshore winds, i.e. winds from land, prevailed at each of the sites, accounting for greater than 50% of directional winds, while onshore winds, i.e. winds from the open sea, from S, SW and SE, provided the largest contribution to wind energy resources. In spring, winds from N to E and to S accounted for most, mainly reflecting transition season characteristics in wind direction. It is noted, but not surprising, that westerly to northwesterly winds were rare in all seasons at all sites (on average less than 5%), reflecting South China Sea monsoon characteristics.

Overall, prevailing wind directions in the rim are mainly from opposite N-S directions, which might be good for energy exploitation since focus of wind direction and concentration of energy benefit several types of wind turbines designed to convert wind resources as fully as possible.

Figure 8 : Seasonal wind speed and direction roses based on the site measurements for the period 2010 to 2017.

Figure 8 also displays wind speed range percentages at the sites over the period 2010 to 2017. The wind scale is in accordance with the Beaufort scale, as represented by the colors. At BX and DY, wind speeds were mostly from 4 to 9 on the Beaufort

scale, i.e., from 5.5 ms^{-1} to 24.5 ms^{-1} , reaching 10 on the Beaufort scale in autumn and winter about 5% of the time. Wind speeds were mostly in the range of 3-8 Beaufort scale at SD and QC, while mostly varied from 3 to 6 on the Beaufort scale at DM and XY, with seasonal changes as mentioned above. Smallest wind speed scales were found at BH and ZZ where over 90% of wind speeds were below 5 Beaufort scale (less than 10.8 ms^{-1}).

4.6 Wind power density

Wind power densities were calculated for the period 2010 to 2017 by use of eq. 3. Wind power density, calculated based on the measurements, are, respectively, 605.6, 542.0, 368.0, 282.0, 265.6, 87.6 and 321.5 Wm^{-2} at BX, DY, SD, QC, DM, ZZ and XY stations (see Table 1). It is noted that the Global Wind Atlas (<https://globalwindatlas.info/>) wind power range for the study region is $200\text{--}450 \text{ Wm}^{-2}$ at 100m above MSL. Wind power is higher than the Global Wind Atlas wind power range only at BX and DY, while mean wind power averaged over the seven stations is 353.2 Wm^{-2} , which is within the range of Global Wind Atlas.

Figure 9 describes the intra- and inter-annual variation in terms of monthly mean wind power density for each site. Since wind power density is a function of wind speed only, characteristics of its variability are in good agreement with the corresponding wind speed variations. Intra- and inter-annual variability in wind power patterns display quite similar characteristics at most of the seven sites. Intra-annual variability was evident at all sites: wind power density values were largest in December, while lowest in August; another peak/trough wind speed occurred in July/May. This variability might somehow favour wind energy exploitation and usage: monthly changes in electricity consumption for Guangxi province in the rim is relatively high in summer time, while lowest in February and April (see Figure 2).

Figure 9 : Seasonal (left) and monthly (right) mean wind power density (Wm^{-2}) for the sites shown in Figure 1.

In accordance with mean wind-speed and Weibull parameters, for spatial variation, the annual mean wind power density, P_{mean} (shown in Table 1), was greatest at BX with a value of 605.6 Wm^{-2} , and least at ZZ with a value of 87.6 Wm^{-2} .

4.7 Estimation of the potential contribution of coastal wind in the study area

In 2017, more than 1.16 GW of additional offshore wind power capacity was installed in Chinese coastal areas, while there has been no installed capacity in the Beibu Gulf up to the end of 2017 [47]. If a turbine with 5 MW capacity is installed in the study area, it would provide about 11 GWh in one year, with annual utilization time of installed capacity in Guangxi being 2280 hours in 2017, based on official data [47]. Thus, a wind farm with 100 such turbines would generate about 1.1 TWh electricity, which can contribute about 0.8% and 3.6% of total electricity consumption in 2017 for Guangxi and Hainan provinces, respectively.

5. Conclusions

The Beibu Gulf Economic Rim is critical for China's development, and especially for the western China region. The “Beibu Gulf Cities Development Project” sanctioned in 2017 plans to build a “Blue Livable Gulf” to avoid the well-worn routine of priority for economic development, while sacrificing the environment. Electricity consumption data of the rim shows a rising demand in the past ten years and indicates rapid growth in the future, reflecting the huge amount of energy required for developing these cities, with primary consideration given to clean energy.

1 In this study, a comprehensive statistical analysis and assessment of wind field
2 and associated energy potential with detailed resource characterization in the study
3 area for the period 2010 to 2017 was conducted at seven offshore coastal sites
4 mention the sites again here. Annual mean wind speed values for the period 2010 to
5 2017 for the seven sites at 100m ranged from 4.0 ms^{-1} to 7.6 ms^{-1} , resulting in annual
6 mean wind power densities, respectively, of 605.6, 542.0, 368.0, 282.0, 265.6, 87.6
7 and 321.5 Wm^{-2} at the seven sites (BX, DY, SD, QC, DM, ZZ and XY), with average
8 value of 353.2 Wm^{-2} . Intra-annual variability of wind power potential is evident at the
9 seven sites, with the greatest wind power occurring in December and another peak
10 value in July, while lowest wind speed values occur in May with another trough in
11 August. The data also display also shows weak inter-annual variations. However, no
12 significant annual trends were found over the period.

13 The annual mean Weibull shape parameter, κ , for period 2010-2017 varied from
14 1.5 to 1.9 at the sites, while the Weibull scale parameter, c , was found to have values
15 between 4.6 ms^{-1} and 8.6 ms^{-1} . The annual mean V_{mp} and $V_{max.E}$ for the sites were,
16 respectively, in the range $3.9\text{-}7.8 \text{ ms}^{-1}$ and $5.3\text{-}9.4 \text{ ms}^{-1}$.

17 Seasonal variability is evident in wind direction, mainly reflecting monsoon
18 characteristics in the region: in winter and autumn, winds were predominantly from
19 the north, with a considerable northeasterly contribution, while southerly winds
20 prevailed in summer. The prevailing wind direction distribution in the rim is good for
21 energy exploiting and usage. Statistical estimates suggest that a wind farm with 100
22 turbines each of 5 MW capacity would contribute about 0.8% and 3.6% of the total
23 electricity consumption in 2017 for Guangxi and Hainan provinces, respectively.

24 Overall, this study suggests that China, including the Beibu Gulf, has relatively
25 large resources of offshore wind energy that can reduce its dependency on imported
26 fossil fuels, thus ensuring security of energy supply as well as reduced GHG
27 emissions in the Beibu Gulf Economic Rim, China and the world.

28 Finally, it should be stated that there was a data loss of more than 20% in the
29 measurement records at three of the seven stations (i.e., 24%, 28% and 23%,
30 respectively, for stations BX, DM and XY) used in this study. Estimates of wind

speed and wind power variability may be influenced by gaps in the data. We wish to state, for the record, that the analysis of the present study is meant as a first pass only at estimating the viable offshore wind resource in order to highlight the rich offshore wind resource available for the study region. Better and more reliable datasets are needed for follow-up work. Once these improved datasets become available for the region, further analysis will be undertaken using the latest offshore wind turbine parameters.

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1. In this study, a comprehensive statistical assessment on wind energy potential in the Beibu Gulf region of the South China Sea was conducted for the period 2010 to 2017.
2. Wind power development in the study area has its own unique advantages, including policy and geographic advantages.
3. Results display evidence of seasonal variability in wind speed and direction, while no significant interannual variability or trends were identified for the period 2010-2017.
4. The Beibu Gulf evidently has vast resources of offshore wind energy that will reduce its dependency on imported fossil fuels such as natural gas.