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Offshore wind energy potential in China: under technical, spatial and economic constraints

Key words: offshore wind; potential; GIS; China

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Abstract

This paper investigates available offshore wind energy resources in China's exclusive economic zone (EEZ) with the aid of a Geographical Information System (GIS), which allows the influence of technical, spatial and economic constraints on offshore wind resources being reflected in a continuous space. Geospatial supply curves and spatial distribution of levelised production cost (LPC) are developed, which provide information on the available potential of offshore wind energy at or below a given cost, and its corresponding geographical locations. The GIS-based models also reflect the impacts of each spatial constraint as well as various scenarios of spatial constraints on marginal production costs of offshore wind energy. Furthermore, the impacts of differing Feed-in-tariff (FIT) standards on the economic potential are calculated. It confirms that economic potential of offshore wind energy can contribute

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to 42%, 30% and 29% of the coastal regions' total electricity demands in 2010, 2020 and 2030. The shallow waters along the coasts of Fujian, Zhejiang, Shanghai, Jiangsu and northern Guangdong are identified as suitable areas for developing offshore wind energy in terms of wind resources and economic costs. However, the influence of tropical cyclone risks on these regions and detailed assessments at regional or local scale are worth of further discussions. Nevertheless, the models and results provide a foundation for a more comprehensive regional framework that would address additional infrastructure, planning and policy issues.

1. Introduction

The apparent advantages of offshore wind farms, compared to onshore wind farms, include better and more stable wind resources, generally less environmental impact, fewer constraints on turbine size, and increased transmission options etc [1]. European countries, especially the Britain and Denmark, are the world's pioneers of developing offshore wind farms, and a total of 2,056MW wind turbines are now installed and grid connected in European waters [2]. The European Wind Energy Association (EWEA) erected a 40GW target for offshore wind in the EU by 2020, while over 100GW of offshore wind energy projects have already been proposed or are currently being developed by Europe's pioneering offshore wind developers [3]. Other countries such as the U.S. and China also express strong interests in this arena. Though the development of the first offshore wind farm in the U.S. has been delayed, a large number of studies and discussions regarding resource assessment, economic cost and environmental impact have already been conducted [4-9]. Conversely, the

first Chinese offshore wind farm at Shanghai Donghai Bridge consists of 34 wind turbines with single installed capacity of 3 MW and has been in operation since June 2010. Besides, the first round of public tender for concession offshore wind farms comprising four projects has finished in September 2010, and all of them are under construction in east China's Jiangsu province. Two are offshore wind farms, located in Binhai and Sheyang, with an installed capacity of 300MW each. Another two inter-tidal projects[1] locates in Dongtai and Dafeng, sizing 200MW each. Further ambitious plans to build more offshore wind farms are proposed in the coastal provinces of China. It is estimated that the total installed capacity of offshore wind power will reach 10GW by 2015 and 30GW by 2020. Contrast to the booming development of offshore wind, only a handful of studies focus on offshore wind resource assessment in specific regions of China [10-12]. Recently China Meteorological Administration's Wind Energy and Solar Energy Resources Evaluation Centre forecast the country's offshore wind potential at 550GW, and 200GW of them locate at water depths of 5-25metres [13]. However, the results might exceed actual potential since this evaluation didn't take constraints for offshore wind energy developments into consideration.

This paper aims to shed light on macroscopic information for policy-makers and investors by investigating the large-scale potential of China's offshore wind energy from the perspective of current technical, spatial and economic constraints and its

[1] Intertidal offshore, which is in the area between high- and low-water marks, as is defined by China Meteorological Administration's Wind Energy and Solar Energy Resources Evaluation Centre.

possible contributions to the nation's energy system. With the aid of a Geographic Information System (GIS), offshore wind potential is evaluated as a combination of wind resources, technical projections of wind turbines, economic costs and spatial constraints of offshore wind farms. Location-specific levelised production cost (LPC) and cost supply curves of offshore wind energy are then developed on this basis, which can answer three key questions: (1) How much offshore wind energy is available at or below a given cost? (2) Given a desired level of installed capacity, how much will the delivered energy cost? (3) And how to prioritize locations suitable for developing offshore wind farms? The answers to these questions may provide a foundation for a more comprehensive planning framework to facilitate the making of policy suggestions.

2. Methodology

2.1 Data source

The ocean boundary of this study is the Exclusive Economic Zone (EEZ) of China, and wind data originates from QuikSCAT ocean wind L2B12, which has already been well applied for producing global ocean wind power density maps by National Renewable Energy Laboratory (NREL) as part of the Solar and Wind Energy Resource Assessment (SWERA) project for the United Nations Environment Program and offshore wind resource evaluation in Southeastern Brazil [14]. The spatial resolution is 1km^2 in a geographical reference framework of the Universal Transverse Mercator (UTM) system.

2.2 GIS-based energy output model

The purpose of a GIS-based energy output model is to reflect the spatial distribution of offshore wind generation within the EEZ. Based on the recommended guidelines for offshore wind farm installation, together with a GIS allowing calculations to be performed for the entire region, the technical potential of offshore wind energy is calculated by the following steps:

(1) Assume that the EEZ is filled with X (MW) offshore wind farms, which consists of N turbines with single installed capacity of Y (MW). In order to provide practical estimations of the potential power production, we use technical parameters of turbines such as rotor diameter D (m) and hub height H (m).

(2) The layout of each offshore wind farm considers radial grid connection, with 8 turbines a row and 15 turbines a column. The distance among wind turbines are set to 8 times the rotor diameter, which is suggested as optimum array [15]. Besides, a 20km buffer between neighboring offshore wind farms is assumed in order to reduce wake effects, and the loss rate L_w of which is estimated to be 8%. Given the fact that the total area of China's EEZ is 877,019km^2, the resulting array density of turbines D_A (MW/km^2) can be calculated.

(3) Measured wind speed at 10m height is converted to that of the hub height according to the classic log law [14], as given in formula 2.1.1.

$$\frac{V_2}{V_1} = \frac{\log(Z_2/Z_0)}{\log(Z_1/Z_0)} \tag{2.1.1}$$

where v_1 equals to wind velocity at the lower height; v_2 equals to wind velocity at desired hub height of H (m); Z_0 represents ocean surface roughness, and a constant

sea level roughness of 0.2mm is assumed [16]. Z_1 equals to lower height in m, and Z_2 equals to upper height in m.

(4) The software WindPRO 2.7 developed by EMD International A/S provides a power curve of the designed wind turbine and helps calculate its annual wind energy output E_d (MWh/y) corresponding to wind speed at the hub height of H (m). The k-parameter of Weibull distribution is set as 2, which indicates a Rayleigh distribution of wind speeds.

(5) Furthermore, the electricity generation of offshore wind is usually estimated at 10%-15% lower than the energy calculation based on wind turbine power curves, due to electrical loss in the transformers and cabling, and wind turbine downtime for schedule maintenance or technical failure [17]. The availability coefficient C_A can be set accordingly.

(6) Annual energy output per ocean area unit E (MWh/km^2/y) within the EEZ can be calculated with the following expression:

$$E = D_A \cdot (1 - L_w) \cdot C_A \cdot 1/Y \cdot E_d \tag{2.1.2}$$

where D_A is the arraying density of turbines within the EEZ (MW/km^2); L_W is loss rate of energy generation due to wake effects; C_A is the availability coefficient of turbines; Y is the single installed capacity of the wind turbine (MW); E_d is annual wind energy output of a designed turbine in a specific location (MWh/y).

2.3 GIS-based cost model

The goal of the GIS-based cost model is to show the spatial distribution of offshore wind energy costs and the locations suitable for developing offshore wind farms; as

well as to produce geospatial cost supply curves. The model gives the supply available within the EEZ region at any given cost and shows all the locations that can deliver energy at or below the corresponding cost. The main idea of the cost model is to calculate the cost of each component of an offshore wind farm with location-specific parameters (wind speed, water depth, distance to coast, etc.), while other geographically-irrelevant costs are deemed as fixed costs in the model. A predecessor of this idea can be found in the technical and economic evaluation of the Northern European offshore wind resource by Cockerill et al. [18]. NREL applied a GIS method for developing wind supply curves and provided a geographic and economic assessment of wind resources in the Zhangbei region of China [19]. The Danish Energy Agency (DEA) used a GIS-based decision support system to identify future offshore wind turbine locations in 2025 [20], but it is not continuously mapping suitable areas as in Möller [21]. The Energy research Centre of the Netherlands (ECN) published the project Windspeed for the purpose of analyzing the deployment of wind energy plant in the North Sea, which suggests a lot of valuable technical parameters [22].

The LPC is the least cost (i.e. without expected profits) of one production unit (MWh) produced by an offshore wind farm averaged over its entire expected lifetime. In order to show the spatial distribution of offshore wind cost, the total cost of an offshore wind farm is evenly distributed to the areas it takes up. All assumptions concerning the layout of offshore wind farms within the EEZ are identical with those in the GIS-based energy output model. LPC can be calculated through a standard discounting

calculation [23]:

$$LPC = \frac{I}{aE} + \frac{OM}{E} \tag{2.2.1}$$

where I is the total initial capital cost per ocean area unit (€/km^2), E represents annual energy output per ocean area unit (MWh/km^2/y), and OM represents annual operation and maintenance cost per ocean area unit (€/km^2).

$$a = \frac{1-(1+i)^{-n}}{i} \tag{2.2.2}$$

where i is the interest rate and n represents the expected lifetime of the project. It is important to point out that our calculations of the LPC are based under the following assumptions:

- Investment costs are broken down into turbines, foundations, electrical connections and other costs.
- A 20 year technical and economic lifetime is assumed.
- 7.5% annual discount rate is adopted [24].

The total cost of an offshore wind farm comprises investment and operation and maintenance costs. Investment cost includes turbine, foundation, electrical connection and other costs (construction and installation costs are broken down into the part of turbine, foundation and electrical connection costs). Foundation costs are calculated as a function of sea depths based on empirical data gleaned from existing offshore wind farms. In the model, gravity and monopile foundations are considered in the sea depth of 0-25m and jacket foundation is utilized in deeper waters above 25m.

Considering the seabed under water is mainly thick silt (around 30m) and silt quality soil layer in China, compares with that of fine sand soil layer (around 10m) in Europe [25], foundation costs for the same scale offshore wind farm in China might be 40% higher than that in Europe. Electrical connection costs are calculated using the nearest distance to high voltage access point on shore as a spatial variable. Operation and maintenance costs are assumed to be highly dependent on the distance to nearest service harbor. Turbines, transformer stations and etc. are deemed as fixed costs and are added to an investment cost map layer. Table 1 shows cost factors included in the model and their sources.

Table 1 Cost factors included in the model.

Cost factor	**Variables**	**Model**	**Source**
Turbine (M€/MW)	Turbine size	1.1	[24,49,50]
Foundation (€/MW)	Water depth x(m)	$(499x^2+6219x+311810)\cdot 1.4$ ($0 \prec x \prec 25$) $(440x^2-19695x+901691)\cdot 1.4$ ($x \geq 25$)	[6,17,22,34]
Grid (€/MW)	The least subsea cost distance d_s(km), the least land cost distance d_l(km)	$(0.38d_s+0.4d_l+76.6)\cdot 10^6/600$	[5,15,22,34, 51]
O&M (€/MW)	The least cost distance to service harbor d(km)	$(-0.29d^2+159d+50415)\cdot 0.4$	[22]
Other (%)	the percentage of investment costs	10%	[7,16]

Note: empirical data from European reference are modified according to actual prices of equipments and labor force in China.

2.4 GIS-based marine spatial planning

As with land use, there are competing demands for the ocean use, which reduce the total offshore areas within the EEZ of China. Marine spatial planning (MSP) is currently being promoted as the best means of providing a strategic planning framework to optimize the use of marine areas, allocate space in a rational way and enable a mix of uses that are compatible with each other and the environment [26-28]. A number of sector-specific efforts have focused on the use of GIS to identify at an early stage the areas that are most suitable for offshore wind energy [20,21,29-32]. The main sectors dealt with in the plan include oil and gas platform, submarine cables and pipelines, shipping, military training, nature conservation, fishing, visibility, tourism and leisure. Different studies suggest various buffers of main sectors need to be considered, and Table 2 shows a summary of them.

Table 2 Buffers of main spatial constraints.

Spatial constraints	Buffers	Source
Shipping	3.7km; 1km;3km	[21,27]
Cables and pipelines	0.5km	[30]
Oil and gas platform	0.5km	[27]
Bird	3km; 5km	[52,53]
Visibility	19km; 8-15km	[27,32]
Defense	outside	[21,30,31]
Nature conservation	1-5km	[21,30]
Marine Archaeology	outside	[32]

3. Results

3.1 Technical potential

According to world classes of wind power at 10m height, approximately 96% of areas in China's EEZ have appreciable wind power potential greater than class 5(>6m/s), and nearly 60% of them belong to the highest class of wind power (>7m/s). The southeast of EEZ between 22°N and 28°N have much higher wind speeds(>10m/s at 90m height), compared with the northern part of EEZ between 30°N and 40°N, at 7.5-9m/s. Moderately high winds at 9-10m/s are found at the southern coast of China below 22°N. The power density map shown in Fig.1, averages between 10,000-15,000kWh/m^2 for the southeastern domain including Fujian, Northern Guangdong and Southern Zhejiang, which are endowed with significant wind resources comparable to those in the Baltic and even the North Sea of Europe. Around the southern coast of Guangdong and Hainan, an average power density of 5,000-9,000kWh/m^2 is expected, which is similar to that in the southeastern Britain. Most areas of Northern China, including Jiangsu, Shandong and Bohai Rim, have an average power density of 3,500-5,000kWh/m^2. These provinces are less windy regions where offshore wind power density is parallel to that in the Mediterranean.

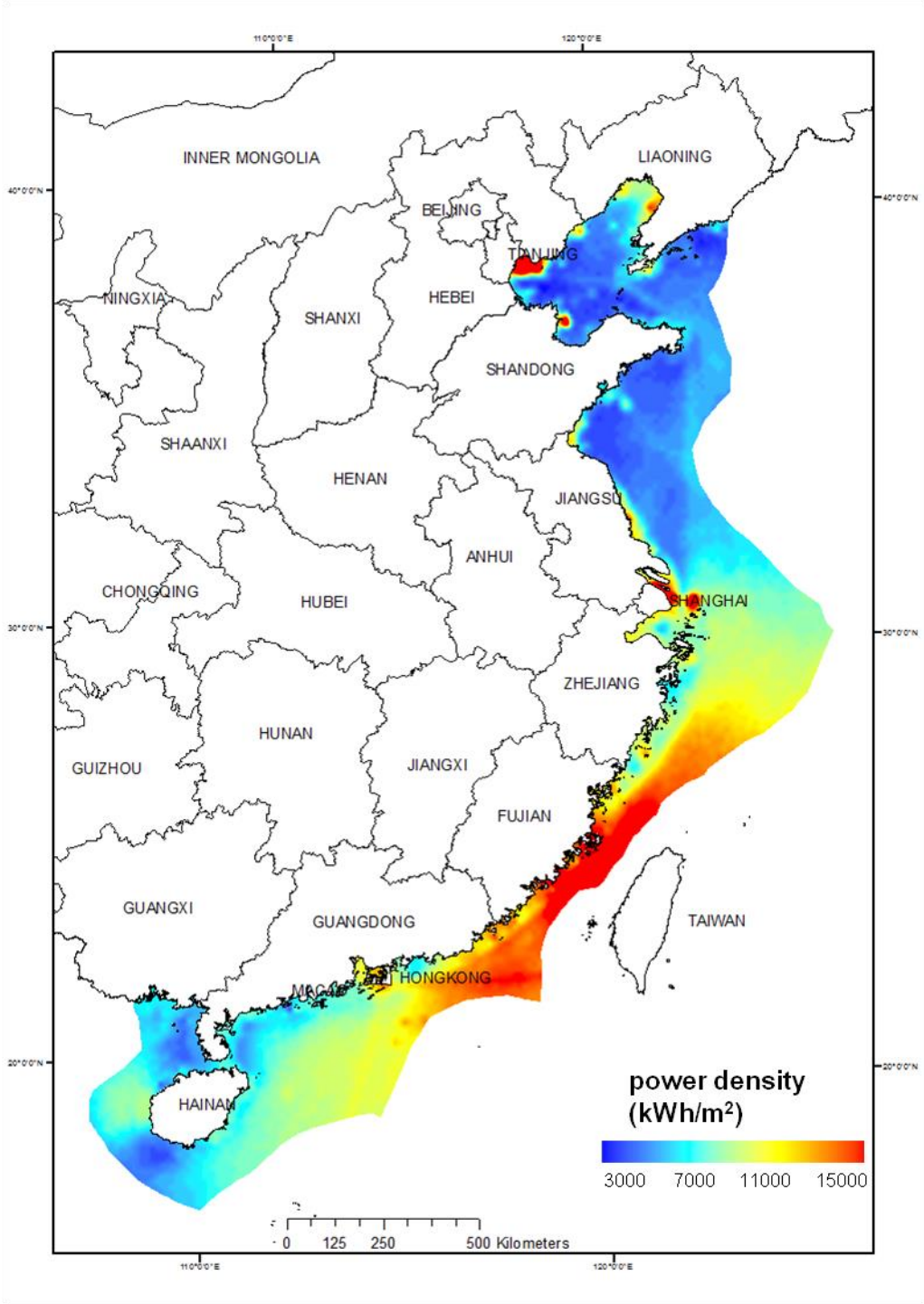

Fig. 1 Wind power density within the EEZ of China.

In this study, technical potential refers to the highest potential level of offshore wind energy generation [2], based on overall resource availability and the maximum

[2] In this study, the calculation of offshore wind potential doesn't incorporate intertidal offshore.

deployment density of turbines, using existing technology or practice. When assessing wind energy potential in 2010, 2020 and 2030, it is necessary to combine power density with a specific type of offshore wind turbine and make projections with respect to the technological development of future wind turbines. In the 2010 scenario, a 600MW offshore wind farm composed of 120 wind turbines with single capacity of 5MW is assumed to be an installation unit in the EEZ. And for 2020 and 2030 scenarios, installation units are a 960MW offshore wind farm consists of 8MW turbines and a 1200MW offshore wind farm consists of 10MW turbines respectively. Detailed parameters of a wind turbine comprise rated power, rotor diameter, hub height, capacity factor and availability (Table 3). Parameters of present offshore wind turbines are based on the Repower Systems 5MW turbine. Due to economies of scale, both turbine and farm sizes may increase further. EWEA assumes an average wind turbine size of 10MW with a rotor diameter of around 150m [33]. It is expected that large offshore wind turbines will have a possible tower height less than equal to the rotor diameter because of reduced wind speed disturbance. The capacity factor for offshore installations will on average be 37.5% for the whole period until 2030 [24], covering that new wind turbines will have a higher production being moderated by a lower availability of sites with high wind speeds. Hence, if installing the existing 5MW wind turbines within the total 877,019km^2 of EEZ, the annual yield from wind energy amounts to 1,715TWh in 2010. Or if installing the future 8MW and 10MW turbines within the EEZ, the technical potential of offshore wind power will reach 2,405TWh in 2020 and 2,758TWh in 2030. Table 4 shows the available technical

potential of offshore wind energy in different sea depths, which suggests approximately half of them locates in 0-50m of shallow waters.

Table 3 Major parameters of present and future wind turbines.

Parameters	2010	2020	2030
Rated power (MW)	5	8	10
Rotor diameter (m)	126	140	150
Hub height (m)	90	105	120
Capacity factor (%)	37.5	37.5	37.5
Availability (%)	85	90	90

Source: [17,24,33].

Table 4 Available technical potential in different sea depths (TWh).

Turbine	0-20m	20-50m	50-100m	>100m	Total
5MW	211	627	521	356	1,715
8MW	299	884	726	496	2,405
10MW	344	1,017	831	567	2,758

3.2 Spatial potential

The spatial potential refers to the amount of the total technical potential that can be produced once spatial constraints such as biodiversity protection have been taken into consideration. Due to the availability of data, shipping lanes, submarine cables, the path of the Black-faced Spoonbill (Platalea minor) and visibility are considered as spatial constraints for suitable areas of offshore wind development in this study (Fig.

2). A reference scenario consists of four spatial constraints is defined as follows: 1km buffer for shipping lanes, 500m buffer for cables and pipelines, 3km buffer for the bird path and 8km buffer from all coasts for visibility. Generally speaking, the considered spatial constraints would exclude around 8.7% of the available technical potential of offshore wind energy. Spatial potential of offshore wind within the EEZ of China is 1,566TWh, 2,196TWh and 2,518TWh in 2010, 2020 and 2030 respectively (Table 5). However, the impacts of spatial constraints vary greatly on the regions within different sea depths as illustrated in Table 6. Only 64% of the technical potential in the sea depth of 0-20m is free of spatial constraints, while the percentages are 93% in 20-50m, 97% in 50-100m and 98% in the sea depth above 100m.

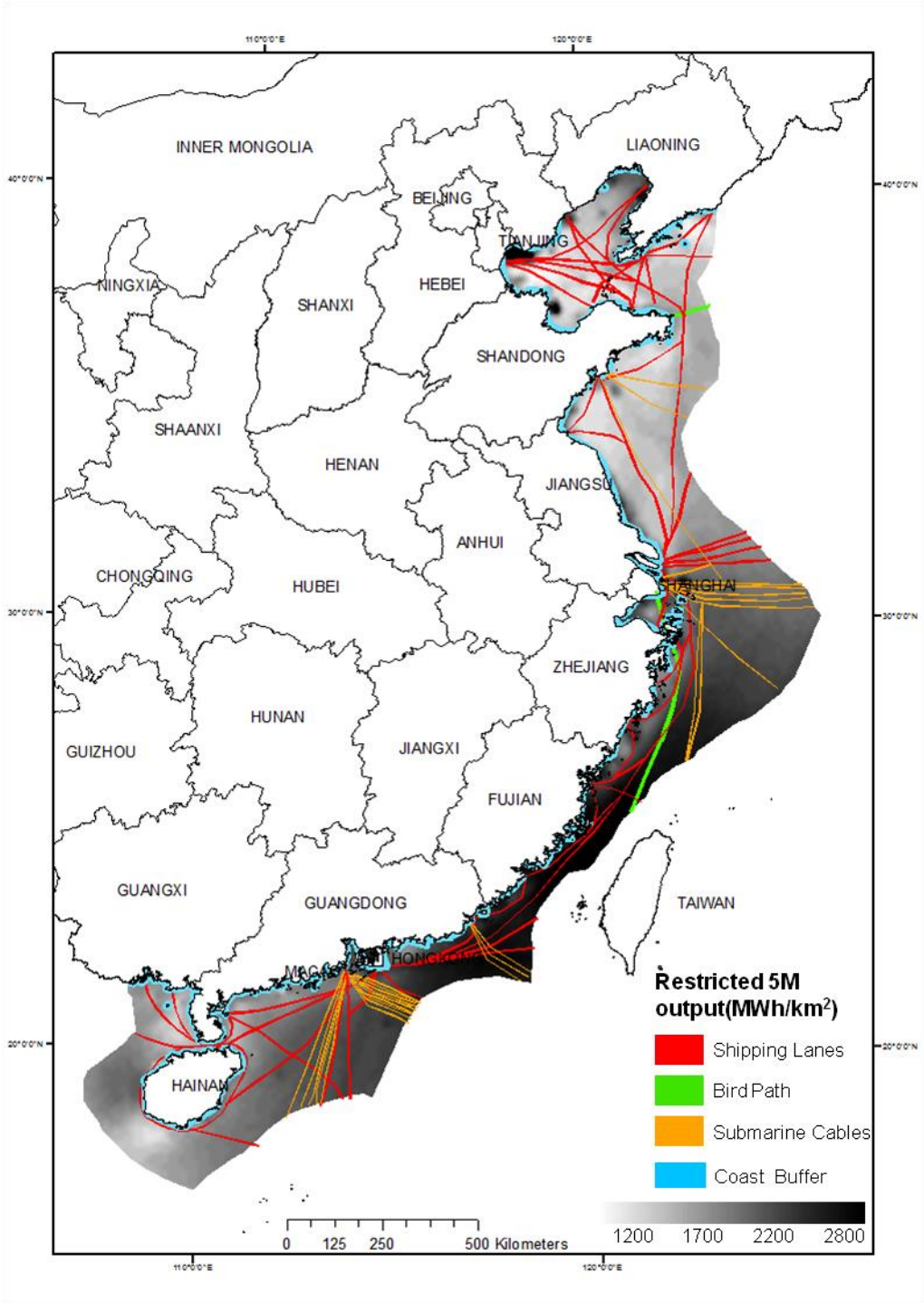

Fig. 2 Practical offshore wind potential under constraints.

Table 5 Available spatial potential in different sea depths (TWh).

Turbine	0-20m	20-50m	50-100m	>100m	Total
5MW	134	580	503	348	1,566
8MW	191	819	701	484	2,196
10MW	219	942	803	554	2,518

Table 6 Areas of each individual exclusion (km^2).

Sea depths	0-20m	20-50m	50-100m	>100m	Total
Shipping lanes	5,023	28,976	7,867	2,250	44,116
Submarine cables	998	2,245	3,866	1,224	8,333
Bird migratory path	1,765	1,455	3,380	0	6,619
Visual exclusion	63,769	0	0	0	63,769

The individual exclusion areas are quantitatively summarized in Table 6, which can be used to examine the areas that were excluded for any one use. For example, the designated shipping lanes we identified would exclude 44,116km^2 or 5% of the total EEZ. The submarine cable and bird path would exclude 8,333km^2 and 6,619km^2 each, but more than half of them locate in deep sea regions (above 50m water depths), where are not suitable for building offshore wind farms under current technological conditions. The visual exclusion has an overwhelming impact in shallow waters (below 20m sea depths), where are considered as technological and economical viable locations for offshore wind farms. Considering the distances of 8km, visual exclusion areas would reach a percentage as high as 34% of the total shallow waters.

3.3 Economic potential

According to the above-mentioned GIS-based cost model, the spatial distribution of LPC for offshore wind power within the EEZ is illustrated in Fig.3. The cost of offshore wind energy is highly correlated to water depth and wind resources. Simply speaking, the lower water depth and higher wind power density, the less production cost for offshore wind energy. For example, regions locate in the 0-50m waters of Fujian, 0-20m waters of Zhejiang, Shanghai and partly Jiangsu, are the least cost areas for developing offshore wind farms, with an average LPC ranges from 47 to 80€/MWh. The available energy in this category counts to 258TWh, approximately 15% of the total technical potential of China. Available energy which costs between 80 and 100€/MWh are mainly located within the 0-20m waters of Guangdong and partly Jiangsu, 20-50m waters of Zhejiang. The potential of this category is 303TWh, about 18% of the total available energy under current technological level. Approximately 22% of the total available energy, that is 373TWh, costs between 100 and 120€/MWh. It locates in the 20-50m waters of Jiangsu and southern Guangdong. The northern China including provinces around Bohai Rim and deeper waters (>50m) of Zhejiang, Guangdong and Hainan have the most expensive offshore wind energy, which costs above 120€/MWh. The annual amount of this category reaches 780TWh, about 45% of the total available energy.

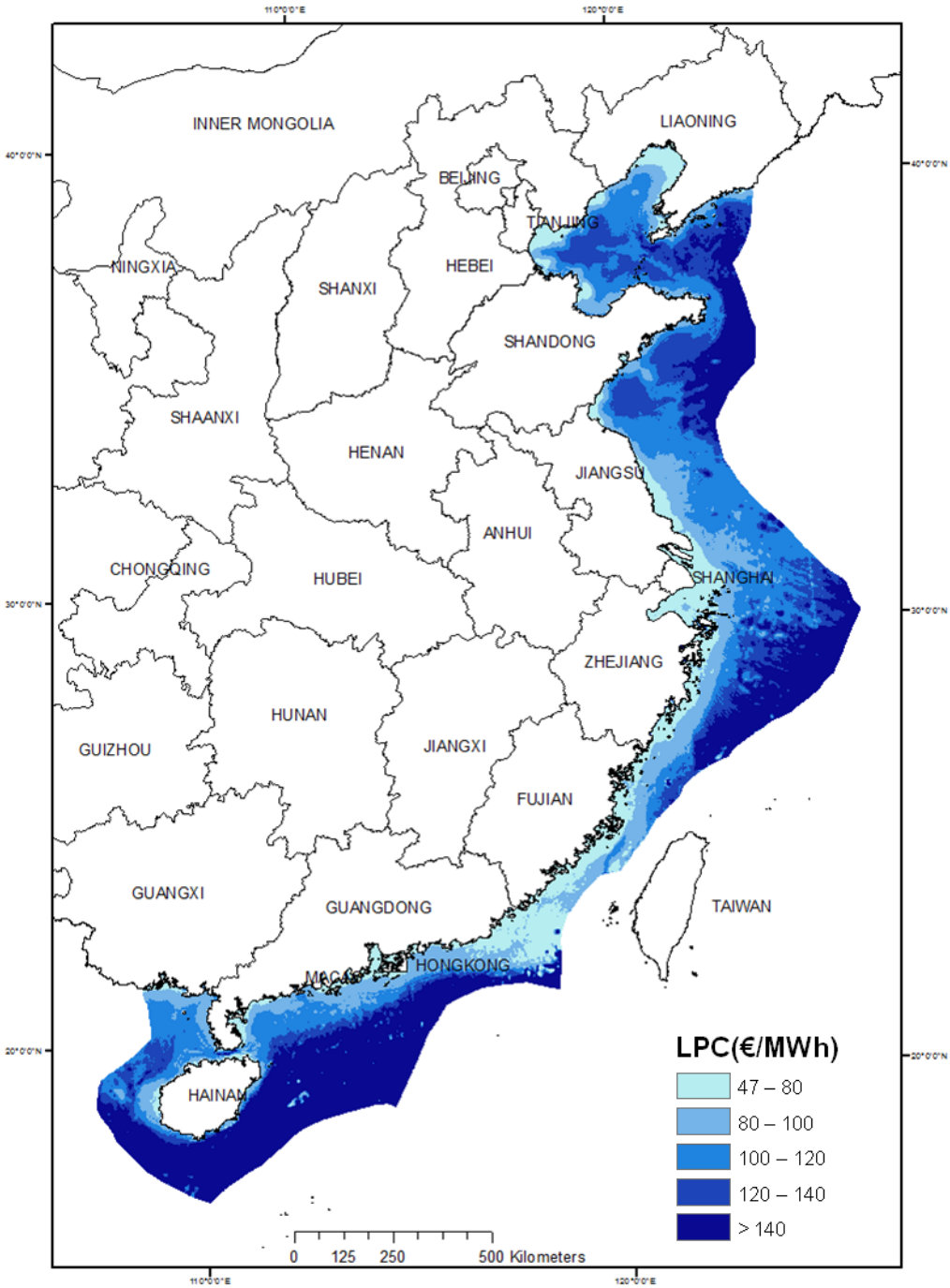

Fig. 3 Spatial distribution of LPC.

Combining the GIS-based cost model with the GIS-based marine spatial planning, we get the marginal production costs of offshore wind energy under the reference scenario of spatial constraints (Fig.4). In Europe, offshore wind is still 50% more

expensive than equivalent onshore wind [34], while this gap might be larger in China due to its nascent stage of development. However, long-term stable offshore prospects would support cost reductions as demonstrated by wind energy during the past 30 years [35]. In promoting wind power, the feed-in system has been used with some variations in Denmark, Germany and Spain and has proved superior to other methods that have been tried in the EU for promoting green electricity when evaluated in terms of installed RES-E capacity [36]. For example, Denmark has set a FIT of 66-70€/MWh for offshore wind farms [37], while it is around 150€/MWh in Germany [38]. Though there is no fixed FIT for offshore wind energy in China, the experience from Shanghai Donghai Bridge offshore wind farm suggests a price of around 106€/MWh. In this study, economical potential describes the proportion of spatial potential that can be realized under FIT in the light of projected average energy costs plus a reasonable internal rate of return (IRR) in the future. Assume an IRR of 15%, Table 7 shows available economic potential of offshore wind energy under different standards of FIT in 2010, 2020 and 2030. The growth rate of economic potential doubles as FIT increases from 80 to 100€/MWh and from 100 to 120€/MWh, but slows down to 50% and 75% from 120 to 140€/MWh for a 5MW scenario in 2010 and an 8MW scenario in 2020. As for the 10MW scenario in 2030, the growth rate of economic potential begin to decrease rapidly as FIT further increases from 140 to 160€/MWh. When FIT reaches 160€/MWh, it would be prohibitive to further develop offshore wind energy.

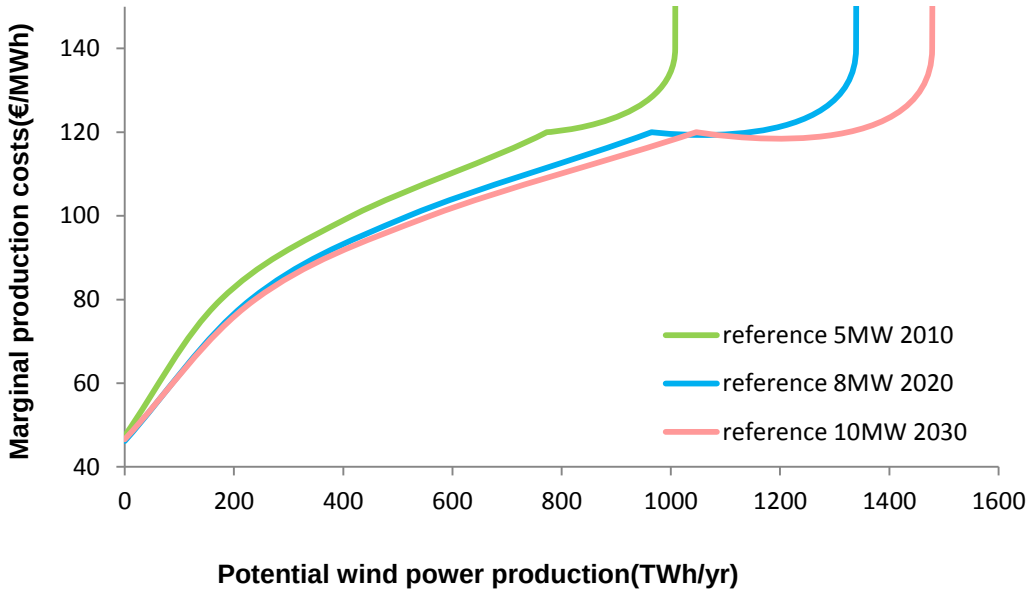

Fig. 4 Marginal production costs of offshore wind under spatial constraints.

Note: here we just show the influence of turbine size on marginal production costs, without taking economies of scale and learning curves etc. into consideration.

Table 7 Economic potential of offshore wind under different FIT standards (TWh).

Turbine	80€/MWh	100€/MWh	120€/MWh	140€/MWh	160€/MWh
5MW	100	250	500	790	1,000
8MW	150	300	600	1,050	1,300
10MW	160	320	680	1,350	1,500

3.4 Energy demands of the coastal region

With 40% of the nation's population, the coastal region is the most economically advanced part of China, and includes clusters of mega-cities in the Pearl River Delta, Yangtze River Delta and Bohai Rim (Fig. 5). Eleven provinces located in the coastal region produce 60% of China's GDP and 90% of exports. The coastal region has been the main driver of China's increasing energy use because of a high concentration of export industries, investment and urbanization. The region accounts for 70% of growth in energy demands and 55% of electricity consumption in China. However, the coastal region lacks coal resources and become increasingly dependent upon imported fuels, either from inland Chinese provinces or from the international market. By 2030, 68% of coastal coal demand is met by supply from the inland provinces and 15% from abroad, with the remaining 17% being produced in the coastal region itself [39]. Because coal is transported from inland provinces via railway, it strains an already overburdened transport system, where coal already uses 40% of the rail capacity [40]. Furthermore, hydro power from western China (such as the Three Gorges Hydro Plant) is transmitted by a High Voltage Direct Current (HVDC) system to the coastal region. Long distance transmission of bulk power not only cause losses, but pose challenges on the capabilities of transmission lines and the stabilities of grids [41].

Fig. 5 Coastal and inland regions in China.

Note: Bohai Rim Economic Zone includes liaoning, beijing, tianjing, hebei and shandong; Yangtze River Delta Economic Zone includes jiangsu, shanghai and Zhejiang; Pearl River Delta Economic Zone only refer to guangdong here.

With key significant problems indicated above, offshore wind might provide an answer to energy and climate dilemmas. On the national level, offshore wind complements hydropower production, because the winds are greatest during the dry season when hydro can only produce 20-25% of its capacity [42]. Moreover, it locates near the consumption market and therefore relieves the stresses on the nation's railway and grid systems. On the regional level, abundant energy resources which do not emit greenhouse gases, reduce the coastal regions' dependence on increasingly costly fuel imports. Furthermore, it facilitates to improve the industrial structure and may create thousands of jobs. In Fig. 6, the potential of offshore wind energy under

technical, spatial and economic constraints is compared to the electricity demands of coastal regions in 2010, 2020 and 2030 [39]. Setting a FIT of 140€/MWh, the economic potential of offshore wind energy can contribute to 42%, 30% and 29% of the regions' electricity demands in 2010, 2020 and 2030.

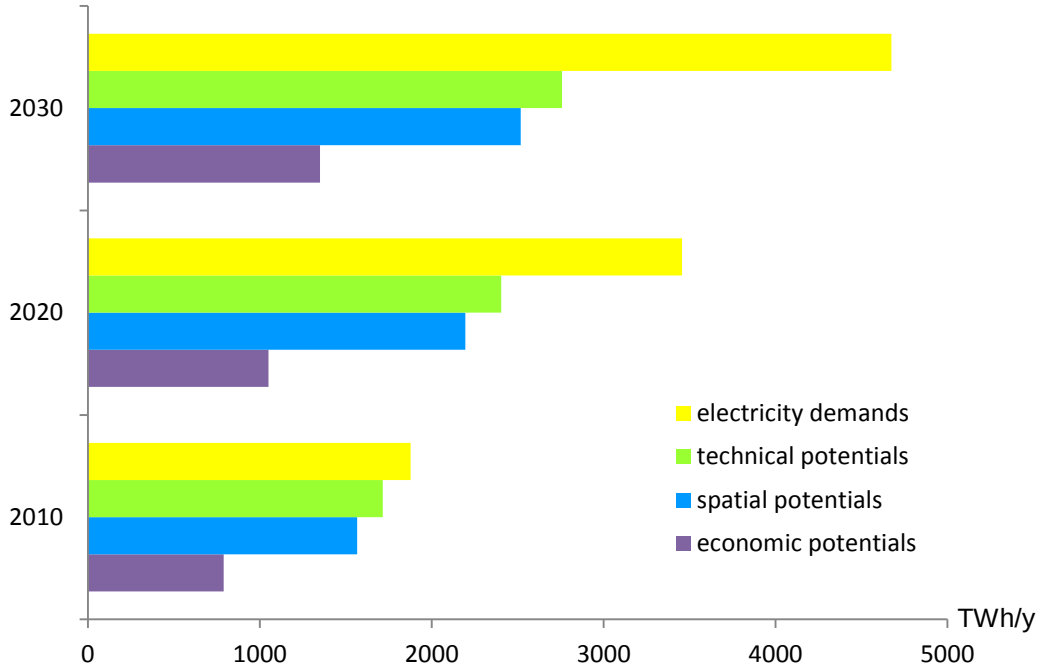

Fig. 6 Offshore potential compared to electricity demands in the coastal region.

3.5 Opportunity costs of spatial constraints

The model can facilitate to reflect the opportunity costs of each spatial constraint as well as scenarios of spatial constraints for offshore wind energy. Table 8 contains two scenarios with a series of measures for each scenario. The reference spatial scenario is used in the previous calculation of spatial potential, while the full concern spatial scenario has higher standards for environmental and social concerns. It is illustrated in Fig.7 that the full concern spatial constraints lead to a reduction of the available potential by 22%, and marginal production costs increase by 20€/MWh compared to

reference spatial constraints based on a 5MW turbine scenario in 2010 .

Table 8 Scenarios of spatial constraints.

Scenarios and measures	Reference	Full concern
Shipping Lanes	1km	3km
Submarine Cables	500m	1km
Birds	3km	5km
Visibility	8km	16km

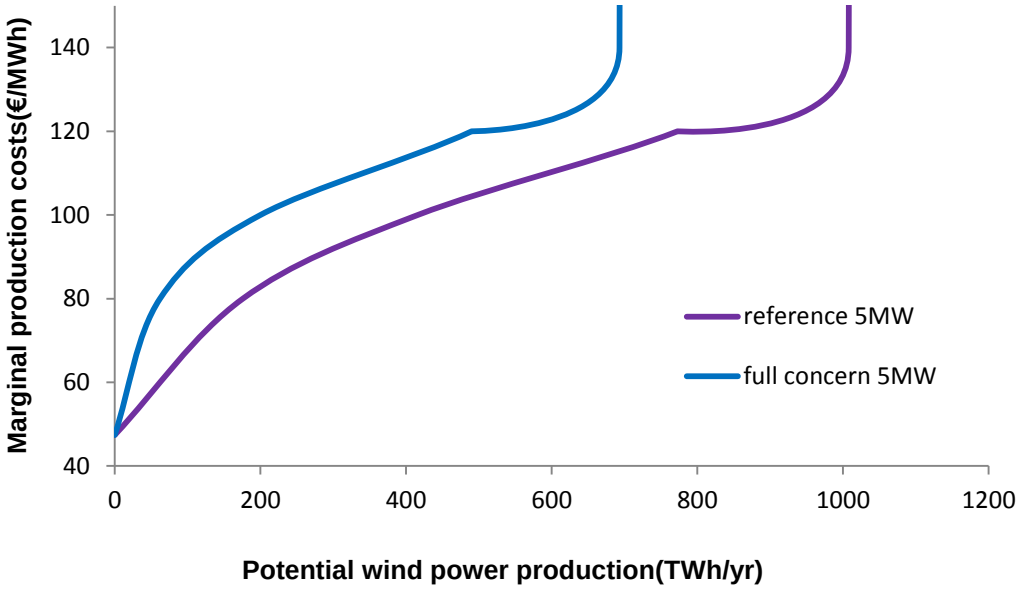

Fig. 7 Marginal production costs in two spatial scenarios.

Visibility from coastal areas has significant influence on the costs associated to the cumulative potential. China's coastline is approximately 18,400km, which covers a great diversity of ecosystems such as coast, estuary, coastal wetland, island, mangrove, coral reef and etc. A majority of coastal cities are places of interests, and

they are famous for either the golden beach, or the special natural landscape, or the local cultural heritage. Whether erecting offshore wind turbines will affect the local tourism industry and incur the opposition of the residents becomes a realistic problem. Ongoing research suggests that visual impact of offshore wind turbines declines with distance in all atmosphere and lighting conditions (except the stormy sky). By computer simulation of offshore wind farms at different distances from the viewer and an on-line survey, it was identified that at 4 km distance the rate of negative responses towards wind turbines was 70.4%, dropping to 46.4% at 8 km and 36.2% at 12km [43]. Marginal production costs of 4km, 8km, 12km and 16km criteria for visibility in scenario 2010 are reflected in Fig. 8, which can help planners make a tradeoff between erecting offshore wind turbines and reserving the space for aesthetic values. Similarly, marginal production costs of various buffers for shipping lanes in scenario 2010 are developed in Fig. 9. By comparing the relative costs of diverting shipping along new routes with opportunity costs of placing wind arrays further out as sea, it is possible to get the most cost-effective mix use of marine space and hence refigure the spatial planning. For example, serious consideration has been given to the possibility of moving shipping lanes in the vicinity of Rotterdam in order to create more space for wind energy in areas that are more economically attractive for them [27].

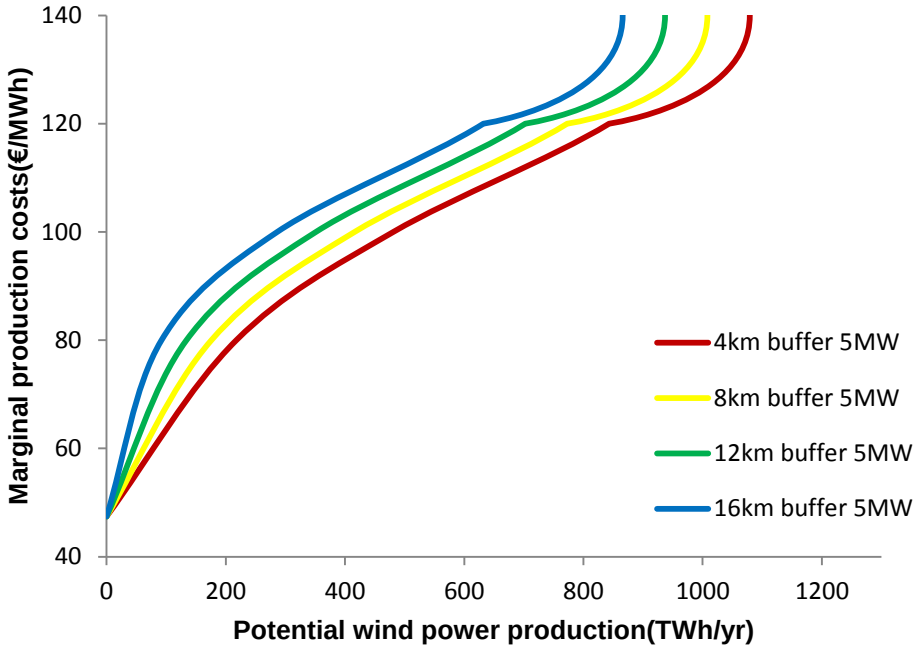

Fig. 8 Marginal production costs under different buffers for visibility.

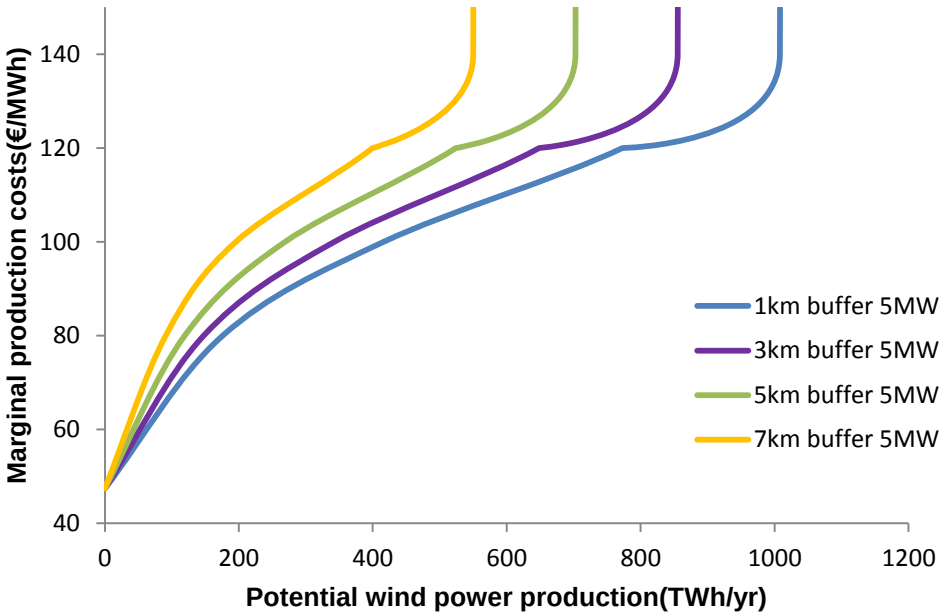

Fig. 9 Marginal production costs under different buffers for shipping lanes.

4. Conclusions

Offshore wind energy is seen as a promising option in China's future to replace depleting indigenous energy resources and decrease greenhouse gas emissions. A target of 30GW ambitious plans for large-scale offshore wind energy developments has been proposed by 2030. Besides the first operating pilot project in Shanghai, another four concession offshore wind farms with a total capacity of 1000MW have accomplished public tender processes and are under construction. But high costs and potential risks of developing offshore wind farms as well as rational planning remain a challenge. Therefore, basic studies regarding resource assessment, site selection, marine spatial planning etc. are essential for decision-makers to avoid the high risk of exploiting offshore wind energy and promote its future development in a strategic way. In this study, a series of GIS-based models are developed and employed to evaluate the potential of offshore wind energy within the EEZ of China under technical, spatial and economic constraints. The geospatial supply curves and spatial distribution of LPC give information on the amount of available offshore wind energy at or below a given price and the geographic locations that correspond to any given point on the supply curve. They provide a foundation for a more comprehensive regional planning framework that would address additional infrastructure, planning and policy issues.

The calculated technical potential of offshore wind energy is 1,715TWh, 2,405TWh and 2,758TWh in 2010, 2020 and 2030. Spatial constraints such as shipping lanes and submarine cables would exclude 8.7% of the total technical potential in general, yet

the impacts of them vary greatly on the regions within different sea depths. In shallow waters with sea depths of 0-20m, technically mature and economically viable for offshore wind energy, are more spatially restricted than deeper water regions. Economic potential of offshore wind energy in 2010, 2020 and 2030 is further entailed, and approximately 45% of the technical potential would be economically competitive under the FIT of 140€/MWh. Nevertheless, it confirms that economic potential of offshore wind energy can contribute to 42%, 30% and 29% of the coastal regions' total electricity demands in 2010, 2020 and 2030. Given the fact that the coastal regions are highly dependent on long-distance transportation of coal and transmission of electricity from inland provinces, it is of strategic importance to integrate offshore wind energy into the future energy system in order to ensure energy security and economic growths, reduce greenhouse gas emissions, and relieve the stresses on the nation's railway and grid systems.

On the other hand, large-scale integration of wind energy into power system grids present challenges to power system planners and operators, including transmission congestion, optimum power flow, system stability, power quality, system economics and load dispatch [44]. Ongoing wind integration studies have evolved from "is it possible to integrate wind reliably?" to focusing on the projected costs and actions necessary to integrate higher levels of wind generation with successive wind integration studies. The U.S. Department of Energy concluded that the U.S. can accommodate 20% electricity from wind generation by 2030 without the need for

storage, assuming continued advances in transmission planning and grid operators [45]. Grid-connected wind turbines have already cover 24% of consumed electricity in West Denmark, and the maximum share of wind power is calculated to be 57% [46]. The ability of different energy systems and regulation strategies to integrate wind power has been presented in [47]. On the cost side, at wind penetration of up to 20% of system peak demand, wind integration costs will amount to about 10% or less of the wholesale value of the wind generation in the U.S. [48]. However, related issues need to be further discussed on a Chinese context.

The study also identifies the shallow waters along the coasts of Fujian, Zhejiang, Shanghai, Jiangsu and northern Guangdong as suitable areas within the EEZ for developing offshore wind energy from the perspective of wind resources and economic costs. Yet the possible impacts and risks of frequent occurring tropical cyclones on these regions are beyond the scope of the study, and need further verification in order to better tap the wind resources and avoid economic losses.

The GIS-based tool provides the resource, economic and policy basis for planning the development of offshore wind energy within the EEZ of China. An enhanced version of the tool could be used as a comprehensive framework for addressing the regional planning issues required to implement China's plans for 30GW of new offshore wind installations by 2030. Moreover, as the target of 30GW is merely 5% of the calculated technical potential of offshore wind potential, the model could shed light on information for decision-makers in a long term. It also affords the opportunity to

refine the tool so that provincial governmental officials and investors can apply it to development plans for offshore wind prospect areas. In addition, the tool developed in the study incorporates transmission costs of offshore wind farms, and provides an economic and geographic foundation for extensions that would address the planning and analysis requirements of the grid operators. However, the geographic data contains significant gaps and approximations that should be addressed in future refinements and extensions. The wind data used here is appropriate to support this level of analysis, because it was developed in accordance with generally accepted international standards for large-scale wind resource assessment like SWERA. But for investment of offshore wind farms on a specific site, detailed investigations of local wind data and topography conditions would be necessary. The transmission system data available for this study was adequate only for a limited representation in the coastal region and the information on excluded areas could be improved, particularly in the areas of maritime nature reserves and fisheries. Nevertheless, it is not difficult to incorporate the latest information into the tool and hence improve final results.

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