Exploring China's offshore wind energy potential in a comprehensive perspectives of technical, environmental and economic constraints

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Abstract

Adequate recognition of offshore wind energy potential may have far-reaching influence on the development of future energy strategies. This study aims to investigate available offshore wind energy resource in China's exclusive economic zones (EEZs) with the aid of a Geographical Information System (GIS), which allows the influence of technical, spatial and economic constraints on raw offshore wind potential being reflected in a continuous space. Firstly, based on ocean wind speed data gained from satellite QuikSCAT, raw potential are identified. Those findings are then used along with projections of current wind turbine technology development to calculate the maximum amount of offshore wind energy that could be generated. Secondly, to calculate practical potential, the migratory path of an endangered bird and existing shipping lanes and submarine cables are excluded from the calculated technical potential. 4km, 8km and 12km buffer to coast are repsectively applied to avoid annoying visual impacts for coastal zones from offshore wind farms. Thirdly, a GIS based cost model for bottom-mounted offshore wind energy farms is established. Levelised production cost is calculated and showed across wide regions, and sensitivity analysis is conducted to reflect how various factors influence cost of energy. The results of the study can serve as a foundation for future policy-making. More detailed assessments at regional or local scale are needed for decisions on developing offshore wind farms.

Keywords: offshore wind potential; constraints; cost; GIS; China

Introduction

Along with fast economic growth of nearly 10% per year and improvement of people's living standards, China's energy use has increased sharply during the last three decades. Annual consumption has grown at an average annual rate of 12.6%, reaching 21,631TWh in 2006 (Energy Information Administration, 2007). Annual generation has increased at an average of 9.5% in this period, to 19,852TWh in 2006 (Energy Information Administration, 2007). While China is the second largest generator of electricity in the world, with installed capacity of 518GW in 2006, per capita consumption in 2006 was only 1930kWh, less than 25% of average level in developed countries (International Energy Agency, 2007). What makes China's situation particularly challenging, however, is the coal-intensive nature of its energy mix. While coal represents about 30% of primary energy consumption worldwide, it represents 70% for primary energy consumption and 77% of total power generation in China (BP Statistical Review of World Energy, 2007). Coal use is expected to keep pace with increased power needs in the next couple of decades, reaching 950GW of capacity and 16,794TWh of generation by the year 2030(International Energy Outlook, 2009).

China's large population of 1.32 billion combined with its dependence on coal results in a significant contribution to world CO2 emissions. Its CO2 emissions in 2006 were 6.1 billion metric tons, about 21.5% of the world total. If current energy use and economic trends continue, various studies have projected that carbon emissions in the year 2030 will reach 9.3 billion metric tons. By that year annual world emissions are estimated to be 18 billion Metric tons (International Energy Outlook, 2009).

An increasing energy demand, worries about energy security and environmental pressure has compelled the Chinese government to focus on developing renewable energy alternatives. Wind power is deemed to be one of the most cost-effective energy supply options, less expensive than incremental hydropower, nuclear power or photovoltaics (Lew, 2000). China's wind resources are world-class, with many sites of class 5(>6m/s), and the total potential of wind power is about 1000GW. A booming onshore wind energy market in China has came into being since the enactment of the nation's renewable energy law on Jan.1, 2006 and 11th Five-Year Plan which attaches great importance on wind energy. China's onshore wind energy has been growing at a breakneck pace, with installed capacity doubling each year during the past four years. In 2009, it was the world's largest market, raising its wind generation capacity from 12.1GW in 2008 to 25.1 GW at the end of 2009(Global Wind Energy Council, 2010). However, spatial mismatch between onshore wind resource and load center will caused great losses of electricity by long distance transmission.

Offshore wind power, though about 50% more expensive than onshore wind, is too energy advantageous to be ignored. Three-quarters of China's wind resources locate offshore, which is roughly estimated to be 750GW at 10 meter's height. Because wind speeds typically increase with height above the ground, the total electrical potential could be 1.7 times of this figure at a modern turbine hub height of 90m. Furthermore, coastal wind resources have very good economic prospects. With the nation's 40% population, the coastal area is the most developed area in China and also the largest consuming market for electricity. Because local coal resources are scarce, coal must be transported to the region via railway. This strains an already overburdened transport system, where coal already uses 40% of the rail capacity in the country (Fang *et al*., 1998). Hydropower is currently transmitted to this region from the west, and there is good complementarity between the wind and hydro resources. Monsoon winds, generally confined to the islands and a strip of land several tens of kilometers wide along the coastline, often complement hydropower production, because the winds are greatest during the dry season when hydro can only produce 20-25% of its capacity (Shen, 1995). The first Chinese offshore wind farm in Shanghai Donghai Bridge consists of 34 wind turbines with single installed capacity of 3 MW and is expected to be in operation by May 2010. Further ambitious plans to build more offshore wind farms are proposed in the coastal provinces of Jiangsu, Zhejiang, Fujian, Guangdong and Shandong. It is estimated that Jiangsu province will establish offshore wind farms with the total capacity of 7GW and Zhejiang province of 2.7GW by the year of 2020.

Resource and economic assessment is the prerequisite of exploitation and utilization. The study of geographical distribution of wind speeds, characteristic parameters of the wind, topography and local wind flow and measurement of the wind speed are very essential in wind resource assessment for successful application of wind turbines. By using the MesoMap software, which require a variety of geographical and meteorological inputs, Manwell et al. (2007) assess the wind energy resource off the coast of southern New England in the United States. Recently more researchers are not satisfied with resource assessment, but turn to available offshore wind potential in a practical way. Wind resource is combined with a specific technology and a number of local constraints, such as ecology and conflicts of interest with other users (Henderson et al., 2003; Pimenta et al., 2008; Yue & Yang, 2009). In one of EEA’s reports (EEA, 2009), the raw potential, constrained potential and economically competitive potential of local wind resources across Europe in 2020 and 2030 are calculated, which confirms that wind energy can play a major role in achieving the European renewable energy targets. What’s more, the Intelligent Energy Europe project Windspeed (Jacquemin et al., 2009) has developed a methodology to estimate the cost of wind energy over the North Sea. A handful of studies focus on the resource assessment in a specific region of China (Li, 2000; Elliott et al., 2002; Zhou, 2006), however, there is little knowledge of offshore wind potential over large extensional areas.

This paper aims to assess the amount of China’s offshore wind potential from the perspective of current technical, spatial and economic constraints, the suitable sites for future offshore wind farms and its possible contribution to the nation’s energy system, all of which provide macroscopic information for policy-makers and investors as a basis for decision-making. For investment of offshore wind farms on a specific site, detailed investigations of local wind data and topography conditions would be necessary in order to ensure investment effectiveness. Such an investigation goes beyond the scope of this study. With the aid of Geographic Information System, offshore wind energy resources are evaluated according to QuikSCAT ocean wind L2B12 data from September 1999 to September 2009. The ocean boundary of this study is the Exclusive Economic Zones (EEZs) of the People’s Republic of China. Article 3 of the United Nations Convention on the Law of the Sea (UNCLOS) states that the People's Republic of China exercises its sovereign rights over the Exclusive Economic Zone for the purpose of exploring, exploiting, conserving and managing the natural resources of the waters superjacent to the sea-bed and of the sea-bed and its subsoil, and in its other activities for economic exploitation and exploration of the zone, such as production of energy from water, currents and winds.

Methodology

Offshore wind energy

The technological potential of offshore wind power within China's EEZs is calculated by the following steps:

- Assume a 600MW offshore wind farm which consists of 120 turbines with single installed capacity of 5MW. The rotor diameter and hub height of a 5M turbine are 126m and 90m respectively, based on the prototype of Repower Systems 5MW. A power coefficient (C_p) of 44% is set.
- The layout of the offshore wind farm considers radial network solutions, with 8 turbines a row and 15 turbines a column. The distance between wind turbines are set to 8 times the rotor diameter, which is suggested as optimum array (Nielsen, 2003). Besides, 20km buffer between wind farms is assumed in order to reduce wake effects. Therefore, array density of turbines is 0.24MW/ km^2 in China's EEZs.
- Measured wind speed at 10m's height is converted to that of the hub height according to the classic log law, as given in formula (1).

  $$\frac{V_2}{V_1} = \frac{\log(Z_2/Z_0)}{\log(Z_1/Z_0)} \tag{1}$$

  where v_1 equals to wind velocity at the lower height; v_2 equals to wind velocity at desired hub height of 90m; Z_0 represents ocean surface roughness, here we assume a constant sea level roughness of 0.2mm (Frank, 2006). Z_1 equals to lower height in m, and Z_2 equals to upper height in m.
- With the help of WindPro software, we get corresponding wind energy density (P_d) in kWh/m^2.
- Here we estimate the availability coefficient (C_A) as 90%.
- Annual energy output from a single turbine (P, kWh) can be calculated with the following expression:

  $$P = C_A \cdot C_p \cdot P_d \cdot \frac{\pi}{4} D^2 \tag{2}$$
- The total area of China's EEZs is about 877,019km^2. Based on the number of turbines which can be installed and annual energy output from a single turbine, the total technical potential of offshore wind power can therefore be calculated.

Levelised energy cost

The levelised production cost (LPC) is the cost of one production unit (kWh) averaged over the wind power station's entire expected lifetime. The total utilized energy output and the total costs over the lifetime of the wind turbine are both discounted to the start of operation by means of the chosen discount rate, and the LPC is derived as the ratio of the total discounted cost and the total discounted utilized energy (Tande & Hunter, 1994). Assuming the annual utilized energy to be constant from year to year, the LPC can be calculated as (Tande & Hunter, 1994):

$$LPC = \frac{I}{aE} + \frac{OM}{E} \tag{3}$$

where I is the total initial capital cost in €/km^2, E represents annual energy output in kWh/km^2, and OM represents annual operation and maintenance cost in €/km^2.

$$a = \frac{1-(1+i)^{-n}}{i} \tag{4}$$

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 cost was broken down into turbine cost, foundation cost, grid cost and other.
- A 20 year technical and economic lifetime is assumed.
- According to international studies of electricity generation costs (NEA & IEA, 2005), 5% annual discount rate is adopted.

GIS-based cost model

A great number of factors might have influence on the total cost of offshore wind farms. Some are geographically-related such as sea depth and distance to shore, while others are irrelevant of spatial parameters such as equipment costs. Two principles are applied in the GIS-based cost model: spatial parameters play an important role in deciding the total cost of offshore wind energy; while other geographically-irrelevant costs are deemed as fixed costs.

- The unit cost of a 5MW turbine model has been estimated at 0.8M€/MW.
- Among many factors such as sea depth, soil and wave conditions that influence the choice of a foundation type, sea depth shows a close correlation with foundation cost. Acceptable depths for offshore wind farms are divided into four categories: ≤5m depth for concrete gravity structures, ≤20m depth for monopole structures, ≤50m depth for jacket structures, and ≤200m depth for floating support structures (Henderson *et al.*, 2003; Dvorak *et al.*, 2010; Dhanju *et al.*, 2008). According to empirical data from existing offshore wind farms, foundation cost in €/MW/km2 was described as a function of sea depth and array density.

$$I_f = (141d^2 + 722d + 338172) \cdot \rho \quad (5)$$

where I_f represents the foundation cost in €/MW/km^2, d represents the sea depth in m, and ρ represents the array density of turbines. The correlation coefficient reaches 0.976.

- A comprehensive electrical system between the offshore wind turbines and the onshore transmission system usually consist of internal cabling, export cabling and substation. The cost of internal cabling is basically determined by the layout of wind farm, while cost of export cabling relies largely on the distance to shore. Substation cost is deemed as fixed cost as well. Based on the empirical data of AC system (Jacquemin *et al.*, 2009) and above assumptions for layout of 600MW offshore wind farm, a cost-weighted distance function was developed, which help finding the least cost by optimal cabling routes.

$$I_g = (c_s d_s + c_l d_l + c_f) \cdot \rho / 600 \quad (6)$$

where I_g represents the grid cost in M€/MW/km^2, c_s represents the cost of subsea cables with a fixed value of 0.84M€/km, ds represents the least subsea cost distance, c_l represents the cost of land cables with a fixed value of 0.48M€/km, d_l represents the least land cost distance, c_f represents the fixed cost for substations and etc., and ρ represents the array density of turbines.

- Operation and maintenance (O&M) cost of offshore wind turbines increase with the decreasing accessibility to nearest harbor. An empirical function was developed and used in this study.

$$OM = \left(0.29d_h^2 + 159d_h + 50415\right) \cdot \rho \quad (7)$$

where OM represents the annual operation and maintenance cost in €/MW/km^2, d_h represents the nearest distance to harbor, and and ρ represents the array density of turbines. The correlation coefficient is approximately 0.96.

offshore wind energy potential

technological potential

The top two maps of Fig.1 display average wind speed maps at the heights of 10 and 90m above sea level. According to world classes of wind power at 10m, 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 part of EEZ between 22 °N and 28 °N have higher wind speeds(>10m/s at 90m height), compared with the north part of EEZ between 30 °N and 40 °N, at 7.5-9m/s. Moderately high winds are found at the southern China below 22 °N, around Guangdong and Hainan. The power density, shown in the lower left in Fig.1, averages between 4500-7000kWh/m^2 for the southeast domain and 2500-3500kWh/m^2 for northern and southern China. In the lower right of Fig.1, we plot the annual output of 5M turbine, which indicates the average power at any location within the EEZ if a turbine was placed there. The plot identifies the southeast shelf (between 22 °N and 28 °N) as the best areas for offshore wind power development. Around the southern part of Guangdong and Hainan, an average output of 13,000MWh is expected. Northern coast of China, including Jiangsu, Shandong and Bohai Bay, yields 10,000MWh per year. However, as the large-scale exploitation of offshore wind power, extra space between offshore wind farms is needed in order to avoid wake effects. Considering the array density of turbines as 0.24MW/km^2, only 25% of the annual outputs illustrated in Fig.1 are realistic.

When assessing wind energy potential in 2020 and 2030, it is necessary to make projections with respect to the technological development of wind turbines. These include factors such as rated power, rotor diameter, hub height, capacity factor and availability (Table 1). Parameters of present wind turbines are based on the prototype of Repower Systems 5MW. Because of economics of scale, turbine sizes may increase further. EWEA assumes an average wind turbine size of 10MW with a rotor diameter of around 150m (EEA, 2009). 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. Installing the assumed 5M wind turbines within the total 877,019km^2 of EEZs, the annual yield from wind energy amounts to 4022TWh, which is approximately 1.2 times of the total electricity consumption in 2008. Or if installing the 8M and 10M turbines within the EEZs, technological potential of offshore wind power will reach 4965TWh in 2020 and 5700TWh in 2030.

spatially constrained potential

As with land use, there are competing demands for the ocean use. Some competing demands, such as designated shipping lanes and submarine cables, are protected by state laws, definitely excluding offshore wind turbine placement. Others, such as distance needed to minimize visual impact from beaches, are flexible, and cannot be conclusively determined by the planners. In this paper, we divide various kinds of competing demands into hard and soft groups of constraints.

Hard constraints for offshore wind farms include designated shipping lanes, submarine cables, natural reserves and military zones. According to the UN Convention on the Law of the Sea (UNCLOS), the coastal state may establish reasonable safety zones around the artificial islands, installations and structures in order to ensure the safety navigation. 2 nautical miles is deemed as a safe boundary for shipping in single direction, and therefore 4 nautical miles buffered is chosen in this paper considering bidirectional navigation. Submarine Cables and Pipelines Protection Provisions of the People's Republic of China state that 500m buffer around submarine cables and pipelines should be set within wide sea areas, 100m buffer should be set within narrow sea areas such as bays, and 50m buffer should be set in harbor. Until now the State Council of the People's Republic of China has approved 32 national marine nature reserves covering 22831km^2, but most of them locate on coastal areas. Offshore oil & gas exploration areas and military zones are not considered in this study due to the unavailability of data.

This paper considers visual impacts and migratory path of an endangered bird as soft constraints for offshore wind development. 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. Current research suggests that visual impact of offshore wind turbines declined with distance in all atmosphere and lighting conditions (except the stormy sky). At 4 km distance the rate of negative responses was 70.4%, dropping to 46.4% at 8 km and 36.2% at 12km (Bishop & Miller, 2007). On the other hand, erecting offshore wind turbines might have detrimental impact on migrating birds. Here we consider the Black-faced Spoonbill (Platalea minor), a rare bird which can be seen only in East Asia. Currently, it exists only a few small rocky islands off the west coast of North Korea, with three major wintering sites at Hong Kong, Taiwan and Vietnam. Since the flight path from North Korea to Taiwan across the potential sites of offshore wind farms in China, a buffer zone of 5km may reduce the risk of collisions (Yue & Yang, 2009).

The individual exclusion areas shown in Fig.2 are quantitatively summarized in Table 2. It can be used to examine the areas that were excluded for any one use. For example, the designated shipping lanes we identified would exclude 202,828km^2 or 23.1% of the total EEZs. The submarine cable and bird path would exclude 8564km^2 and 7149km^2 respectively, but more than half of them locate in deep sea regions (above 50m sea depths), where are not suitable for building offshore wind farms under current technological conditions. The visual exclusion have an overwhelming influence in shallow waters (below 20m sea depths), where are considered as the best location for offshore wind farms. Considering differing distances of 4km, 8km and 12km, visual exclusion areas would reach a percentage as high as 17%, 34% and 50% of the total shallow waters. Table 3 gives the total areas before considering any exclusion and the available area after removing all other exclusion but no visual exclusion, and the available areas with three increasing distances of visual exclusion. Without visual exclusion, potential available areas are 668,062km^2, taking up 76.2% of the total 877,019km^2. As the distances of visual exclusion increase, the sharing of available areas drops to 65.2%. What's more, the effect is more pronounced in the 0-20m depths areas of greatest current attention.

economic analysis

On the basis of above GIS-based cost model, spatial distributions of levelised production cost for offshore wind energy within the EEZs is illustrated in Fig.3. The southeast shelf (between 22 °N and 28 °N), where enjoys the highest wind speed and power output, is also the cheapest areas for developing offshore wind farms. The technical potential of the cheapest offshore wind power, whose price range from 0.015€/kWh to 0.035€/kWh, counts to 34GW.

Available energy which costs between 0.035€/kWh and 0.055€/kWh, mainly located within the shallow water of Zhejiang province and the northern part of Guangdong province. The technical potential of this category is 78GW, about 17% of total available energy under current level of technology. Approximately 31% of the technical potential have a price of 0.055-0.075€/kWh, while 23% of the total potential costs from 0.075€/kWh to 0.095€/kWh. Most part of these potential locate in the deeper water of Zhejiang province and southern part of Guangdong province. The northern shelf and the deeper water of Guangdong province has the most expensive offshore wind energy, which costs above 0.095€/kWh. The technical potential of this category reaches 100GW, about 22% of the total technical potential.

Currently there is no policy on the price of on-grid offshore wind energy in China, but the fixed price of on-grid wind power can be used as a reference. In July of 2009, the National Development and Reform Commission (the nation's highest level of official planning organization), has set on-grid wind power price at about 0.051€/kWh, 0.054€/kWh, 0.058€/kWh and 0.061€/kWh in various regions. Coastal provinces, where are not rich in onshore wind resource as other regions, have the highest on-grid price of 0.061€/kWh. Comparing to the criteria, potential price under 0.055€/kWh can be considered as economically competitive potential. Furthermore, proper subsidy will make potential price from 0.055€/kWh to 0.095€/kWh become economically competitive. However, those have a price above 0.095€/kWh might not be economically feasible in a short run.

Taking constraints into consideration, four scenarios of spatial constraints are developed and corresponding practical potential and cost are shown in Fig.4. Without visual exclusion, the annual amount of practical available energy reduces to 3064TWh, about 76% of technological potential. Available energy costs under 0.055€/kWh reduces by 27%, while 50% of energy costs above 0.095€/kWh are unavailable. Economically competitive potential equals to 82GW, taking up 24% of the practical potential of offshore wind energy. On the other hand, visual exclusion will further reduce practical potential of offshore wind power. For example, only 72%, 69% and 65% of technological potential are available under the exclusive distances of 4km, 8km and 12km respectively. Furthermore, the effects of visual exclusion are most apparent in near shore areas, where are places capable of providing cheap energy. For example, the amounts of available energy pricing under 0.055€/kWh reduce from 974TWh to 617TWh, 524TWh and 433TWh in increasing distances of visual exclusion.

The model also allows further sensitivity studies to investigate the influence of geographical elements on the cost of energy, and provides guides for location choice of future offshore wind farms in China's EEZs. Distance to harbor contributes most in influencing energy cost. Fig.5 shows clearly that increasing the distance between offshore wind farms and harbors raises the cost of energy. This is due to the increasing costs of construction and operation and maintenance (O&M) of offshore wind farms. During the periods of construction and O&M, the ships have to make a number of trips between the site and harbor frequently. This travel period is costly and therefore the closer an offshore site is to an industrial port facility, the less expensive installation and O&M will be. Furthermore, the further distance to harbor also indicates longer transmission cables and greater transmission losses. An opposite trend is visible in Fig.6 where increasing wind speed reduces the costs of energy, owing to an increasing energy production. Experiences suggest that increasing sea depths increase the price of foundation by making cheaper gravity and monopile foundations impractical and requiring the use of more expensive jacketed and floating foundations. However, sea depth doesn't play an important role in determining costs within most part of China's EEZs. The reason is 54% areas of China's EEZs are shallow waters with the sea depths less than 50m. In addition to geographical and meteorological factors, interest rate influences the cost of energy. The general trend is that increasing interest rate raises the cost of energy.

Conclusions

- Leaving aside some of environmental, social and economic considerations, China's raw wind energy potential is huge. Current technological conditions suggest that it will equivalent to 459GW, 1.2 times of total electricity demands in 2008. In combinations with future turbine technology, energy potential of offshore wind power will reach 567GW in 2020 and 651GW in 2030. This confirms that offshore wind power would play an important role in China's renewable energy system.
- Spatial constraints have a great impact on technological potential. The designated shipping lanes, which exclude about 23% of the total EEZs, are identified as a major constraint for developing offshore wind farms. Without visual exclusions, the practical potential equals to 348GW in 2020. However, planners need to take careful tradeoff between visual exclusion and offshore wind farms. As the distances of visual exclusion increase, the sharing of available areas for offshore wind farms declines sharply. Furthermore, the effect is more pronounced in economically feasible sites.
- At least 24% of the practical potential, about 87GW, is cost-effective for meeting future domestic energy demands. If taking proper subsidy into account, economically feasible potential will increase to 303GW, about 87% of the total electricity demand in 2008. In other words, China's future sustainable energy system will be a combination of various technical alternatives.
- Southeast of China including Fujian, northern Guangdong and southern Zhejiang are good sites for developing offshore wind energy. However, for investment of offshore wind farms on a specific site, detailed investigations of local wind data and topography conditions would be necessary in order to ensure investment effectiveness.
- The sensitivity analysis illustrates that wind speed alone is not sufficient as a criterion for deciding sites for offshore wind farms.

Considering that most part of China's EEZs is shallow waters, sea depth doesn't play an important role in influencing cost as well. In contrast, distance to harbor is the most important factor to consider when making the location choice. In addition to geographical and meteorological factors, interest rate also influences the cost of energy. The general trend is that increasing interest rate raises the cost of energy.

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Table 1 *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 (%)	44	47	47
Availability (%)	90	90	90

Source: EEA, 2009

Table 2 *Areas of each individual exclusion (areas in km^2)*

Sea depths	0-20m	20-50m	50-100m	>100m	Total
Shipping lanes	22,006	126,919	34,461	9,858	202,828
Submarine cables	1,026	2,307	3,973	1,258	8,563
Bird migratory path	1,911	1,577	3,661	0	7,149
Visual exclusion from 4km	32,980	0	0	0	32,980
Visual exclusion from 8km	64,910	0	0	0	64,910
Visual exclusion from 12km	96,493	0	0	0	96,493

Table 3 *Available area in total and after removing each assumption of exclusion (areas in km^2)*

Sea depths	0-20m	20-50m	50-100m	>100m	Total
Total areas(no exclusion)	192,951	280,319	303,882	99,867	877,019
Available area, with no visual exclusion	168,008	149,516	261,787	88,751	668,062
Available area, with 4km visual exclusion	135,028	149,516	261,787	88,751	635,082
Available area, with 8km visual exclusion	103,098	149,516	261,787	88,751	603,152
Available area, with 12km visual exclusion	71,515	149,516	261,787	88,751	571,569

Figure 1 *Spatial distribution of wind characteristics in China's EEZ*
(Top left: wind speed at 10m; Top right: wind speed at 90m; Bottom left: wind power density; Bottom right: 5M mean turbine output power)

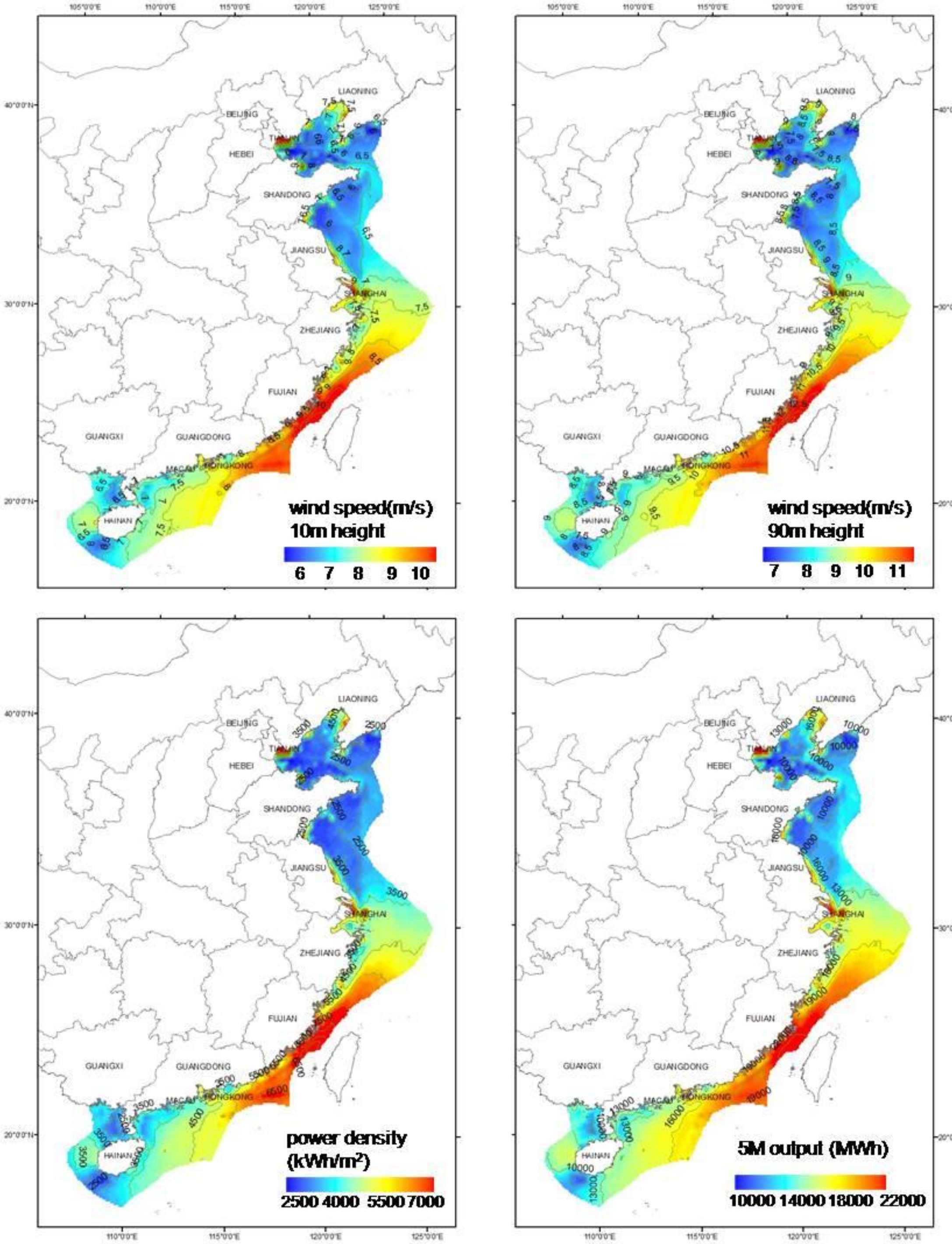

Figure 2 *Practical offshore wind potential under constraints*

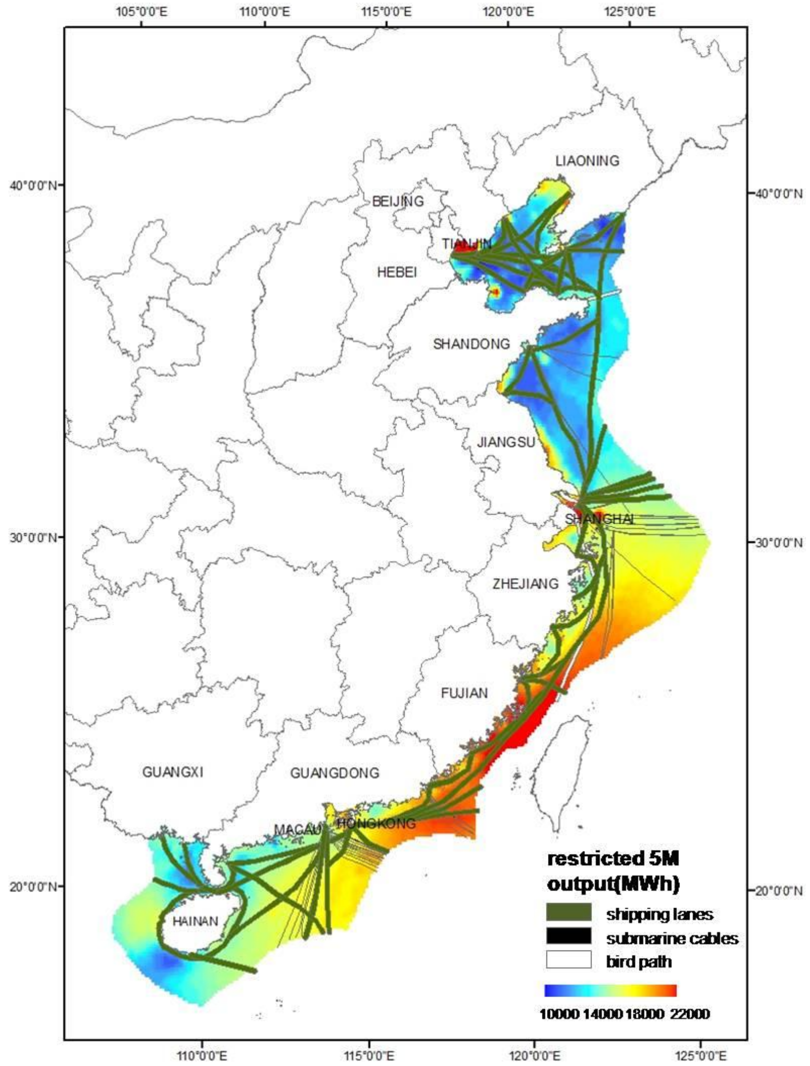

Figure 3 *Spatial distribution of levelised production cost*

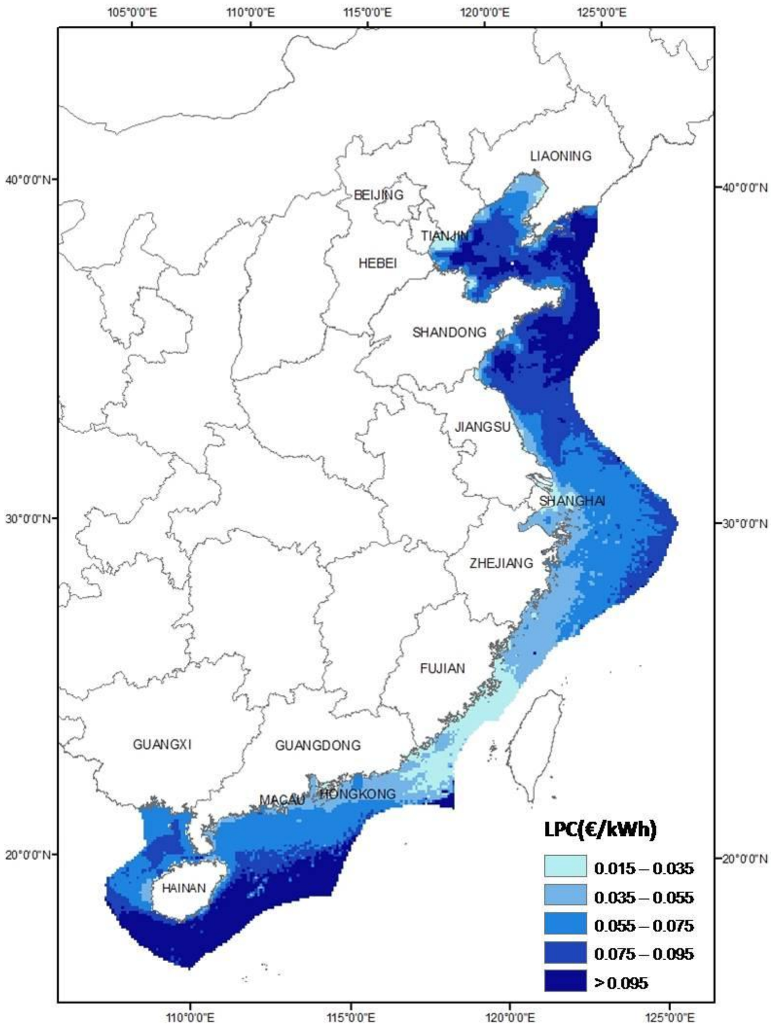

Figure 4 *Cost supply curves for available energy under different scenarios*

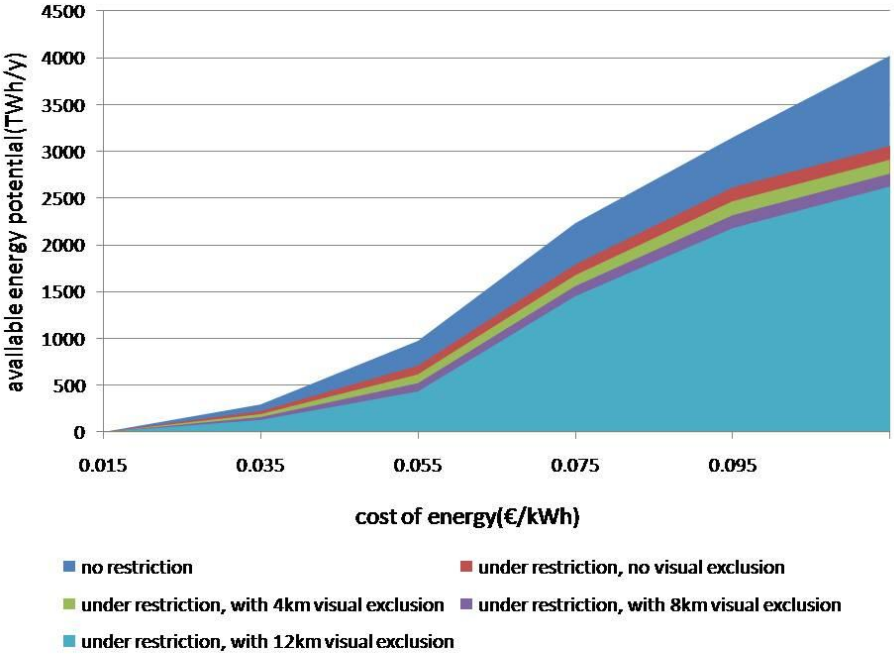

Figure 5 *Influence of distance to harbor on energy cost*

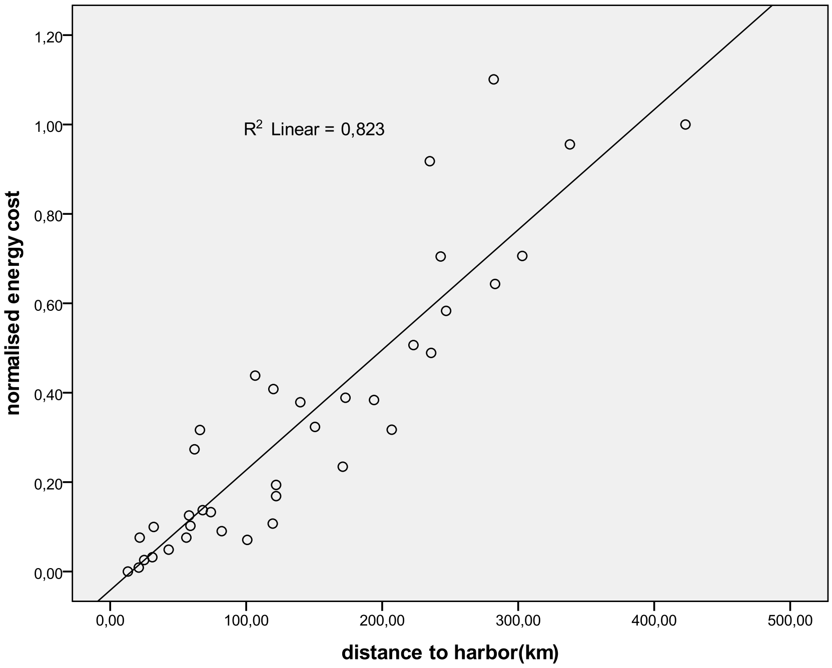

Figure 6 *Influence of average wind speed on energy cost*