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CASE STUDY

A multi-criteria methodology for wind energy resource assessment and development at an intercontinental level: Facing low-carbon energy transition

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Abstract

Quantitative assessment and effective utilization of wind energy resources in global range are substantively meaningful in contemporary low-carbon energy scenarios. In order to enrich the assessment with large-scale applicability, multi-factor consideration and quantitative economic analysis, a multi-criteria assessment method for global wind energy with consideration of both environmental and economic factors (existing power grids, transportation, etc.) is proposed. Based on 18 items of basic digital data, a model is established from three dimensions of theoretical, technical and economic criteria, respectively. Global wind resources assessment is then accomplished with a spatial resolution of 500 m. The results indicate that global technical potential is 206 TW, of which 73% is from onshore wind, and around 132 TW is suitable for centralized development. Specifically, the global average development cost is 4.28 ¢/kWh, including 4.13 ¢/kWh onshore and 4.57 ¢/kWh offshore. The global distribution maps are drawn. Furthermore, combining geospatial calculation and statistical analysis, the cumulative probability distribution curves are obtained with two key indexes of capacity factor and development cost. A case study supporting a low-carbon energy transition scenario indicates the overall cost of the future wind power demand of 6.76 TW can reduce to 2.48 ¢/kWh ideally in 2035. Finally, a rationality verification method is proposed. By the case study of global built wind farms, the geographical location coincidence of the assessment results is 83%.

1 | INTRODUCTION

1.1 | Motivation

The paradox of increasing energy demand and climate change mitigation has become a major concern globally, especially facing more complicated circumstances involving human-related factors like politics, economics, and even pandemics [1–3]. Low-carbon energy transition as the main solution to this problem is now a research focus from technical development to policy-making [4, 5]. It can be anticipated that higher renewable energy penetration would be an irresistible tendency in energy (esp. electric energy) generation, transmission, and storage systems [6]. Wind energy, as the 2nd installed capacity (only to hydroelectric) of all renewable energy technologies for generating electricity, is experiencing rapid development, and playing a more and more important role in low-carbon energy systems worldwide [7, 8]. As the foundation of wind energy development and utilization of global range, the importance of quantitative assessment and distribution analysis of the resources on a continental scale or larger cannot be overestimated [9, 10].

The assessment of energy experienced a transition from a geographical/meteorological problem in early times to a multi-discipline issue contemporarily. After all, the assessment of energy resources is never a pure technic problem dealing with physical parameters. Instead, human-related factors often occupy more weight when making the assessments and decisions, from geography to practical engineering. Therefore, in the last few years, multi-criteria or integrated assessment models have been proposed for conducting techno-economic assessments [10–12]. Nevertheless, previous assessment of such multi-criteria method is often aimed at micro-siting of wind farms in smaller areas such as specific provinces and regions, cities, and sites [13–15]. Generally speaking, the traditional assessment methods come into two categories. One is the geographical assessment at different spatial scales, but only providing physical parameters. The other is the multi-criteria method in a relatively small region. Nevertheless, facing the demand for contemporary globally low-carbon energy scenarios, it would become significant to promote multi-criteria assessment research at the level of national, continental, or even global. It will be a step further in supporting low-carbon politics and optimizing industrial projects.

Accordingly, this work will place higher demands on the coverage of basic data, the wide-area applicability of assessment models, the comprehensive consideration of influencing factors, the quantitative calculation of technical and economic analysis, and the calculability of model tools.

1.2 | Literature review

Research has been done on the large-scale wind energy resource assessment from a geographical approach. For the national-scale assessment, research has been conducted by the National Meteorological Centre of China (NMC), the Australian Commonwealth Scientific and Industrial Research Organisation (CSIRO), the National Centre for Renewable Energy of Spain (CENER), the Meteorological Service of Canada, the Risoe National Laboratory of Denmark, the National Renewable Energy Laboratory (NREL) of the United States, and other institutions, based on the observation data from meteorological stations or numerical simulation data [16–26]. However, the main topics of those studies/reports are either on the assessment of the natural characteristics of wind energy [16–24] or on the improvement of resource data processing and analysis [25, 26], in order to draw a distribution map of wind speed and power density considering the geographical (terrain) factors such as topographic relief, land cover etc. Some institutions have estimated the total theoretical reserves of the wind energy endowment in their country, but the restrictions of technological level, land status, and geological and topographical conditions on development are not considered.

To achieve the transition from the natural source to electrical energy in grids, more economic factors and restrictions should be considered during the assessment process. China Meteorological Administration and NREL have considered the influence of grassland, forest, scrub, and other land covers, and established a coefficient relationship between slope and installed capacity [17, 18, 27–29]. However, the quantitative analysis of different development methods as well as cost-effectiveness are not considered in both cases. The Ontario Energy Board in North America has conducted a study of environmentally sensitive areas in Ontario and estimated the technical available areas and the technical potential installed capacity, taking into account grid and transportation factors [30]. The International Renewable Energy Agency (IRENA) and other institutions have completed the assessment of wind energy resources in Africa and analyzed the land use capacity (excluding areas not suitable for development such as cities, urban areas, and farmland) [31, 32]. In general, for the existing report on assessing wind energy resources in large regions, the concerns are mainly on resource reserves and land use analysis, while the cost-effectiveness is relatively less concerned.

Fortunately, economic factors are receiving more attention recently, promoting a more considerate assessment of wind energy. Some scholars have calculated the cost-effectiveness using indicators such as Levelized Cost of Energy (LCOE) [33–36]. For example, the spatial suitability of renewable energy development in Mongolia is assessed in the literature [37] with due consideration of resources, slope, road network, and substation distribution, while the cost-effectiveness is calculated only for wind farms to be developed. However, more technical factors like traffic conditions (for development) and grid integration are not well considered before. Therefore, it is of great significance for large-scale wind power development and promoting the low-carbon transformation of power systems in the world to realize the theoretical, technical, and economic assessment of global wind energy resources based on a unified model and parameters, which is suitable for various development modes.

1.3 | Contributions

Here, from the perspective of low-carbon electric system with sustainable development of renewable energy, the potential of global wind power resources considering different development approaches like centralized, distributed and offshore have been assessed. A multi-criteria assessment method, including the quantitative models of theoretical reserves, technical potential installed capacity, and development cost, is proposed. Based on geographical information technology (GIS) technology, a global database and research platform are completed, which could accomplish the economic impact evaluation of global power grids and highway networks with 500 m spatial resolution.

Based on the proposed model, the global wind energy resources assessment is performed. The results indicate that: (1) The global technical potential installed capacity is 206 TW, of which 73% is from the onshore wind, moreover, the onshore wind power suitable for large-scale centralized development is 132 TW in total. (2) The average development cost of wind energy in the world is 4.28 ¢/kWh, including 4.13 ¢/kWh onshore and 4.57 ¢/kWh offshore. (3) About 15% of onshore wind has a capacity factor of more than 0.34 (full-load hours 3000) with total capacity of about 23 TW, while 38% of offshore resources have a capacity factor of more than 0.45 (full-load hours 4000).

The major contributions of this paper in wind energy resource assessment are as follows:

1. A comprehensive wind energy resource assessment is conducted from three dimensions of theoretical, technical and

economic criteria in an intercontinental level for the first time in the literature. To support the assessment, 18 items of basic database are integrated in establishing the multi-criteria assessment model. Therein, the theoretical reserves, technical potential installed capacity and development cost suitable for centralized, distributed and offshore wind power development modes are given, and the distribution maps are drawn.

2. Based on the assessment results, a refined development potential evaluation is conducted with quantitative statistics between resource conditions and the cost, which helps to visualise the optimal strategies under different circumstances. To achieve this, we combined geographical information calculation and statistical probability analysis, and the probability distribution characteristics of the technical potential installed capacity of wind energy to capacity factor and development cost is analyzed to realize the refined evaluation of development potential.
3. A rationality verification method based on the data of global built wind farms and the quantitative assessment results is proposed to verify the applicability of the assessment method and the rationality of the results.

2 | ASSESSMENT METHOD AND MODEL

Resource-related data such as wind speed, pressure, and temperature are essential for wind energy assessment. To comprehensively analyse the restrictions affecting wind power development and to balance practicality with practical reference values, data such as global land cover, elevation and other geographical information, as well as data related to human activities such as conservation areas, traffic and power grids, are adopted here to establish a basic database for global resource assessment [38], see Table A1 for details.

The quantitative assessment model for global wind energy resources is established by three main indicators, namely theoretical reserves, technical potential installed capacity, and development cost. The assessment is carried out from multiple dimensions, such as the upper limit of convertible energy, the scale of development realized by technology, and the economic calculation considering facility development and grid integration. The relevant models and results can provide reference and support for research, planning, decision making, and different objectives.

2.1 | Theoretical reserves

The theoretical reserves are the total kinetic energy of the wind available at a certain height in the assessment area, which is an indispensable criterion for the wind energy assessment, generally not considering the energy conversion efficiency from kinetic energy to mechanical energy or electricity. This model does not concern the detailed aerodynamic calculations at small space scale around the wind turbine generator (WTG). Instead, a widely accepted simplification on aerodynamic was made that the disturbance of wind field by WTG (characteristic radius of R_{WTG}) becomes negligible at $10R_{\mathrm{WTG}}$ away from the WTG. Thus, the arrangement of WTGs would not be close-packed, but at least one WTG at 100 units of area ($100{R_{\mathrm{WTG}}}^2$) [16, 17]. Then, the assessment of wind energy theoretical reserves Q_{TR}, which is calculated as follows:

$$Q_{\mathrm{TR}} = \frac{1}{100}\sum_{i=1}^{N}\sum_{j=1}^{8760} D_{\mathrm{WP}ij}A_i \tag{1}$$

$$D_{\mathrm{WP}} = \frac{1}{2}\rho v^3 \tag{2}$$

where A_{i} is the area of the selected grid i, N is the number of grids in assessment area, D_{WPij} is the wind power density of the grid i at the hour j, ρ is the air density, v is the wind speed.

In some previous research, the wind power density is obtained by the aerodynamics relations [39–42]. Although, this kind of method is precise, it is almost impossible to achieve large spatial scale estimation of the wind (too many nodes and calculations). Therefore, as the first attempt to assess the wind energy resources at an intercontinental level, this work has conducted rational simplification for the physical parameters of the wind, as stated above.

2.2 | Technical potential installed capacity

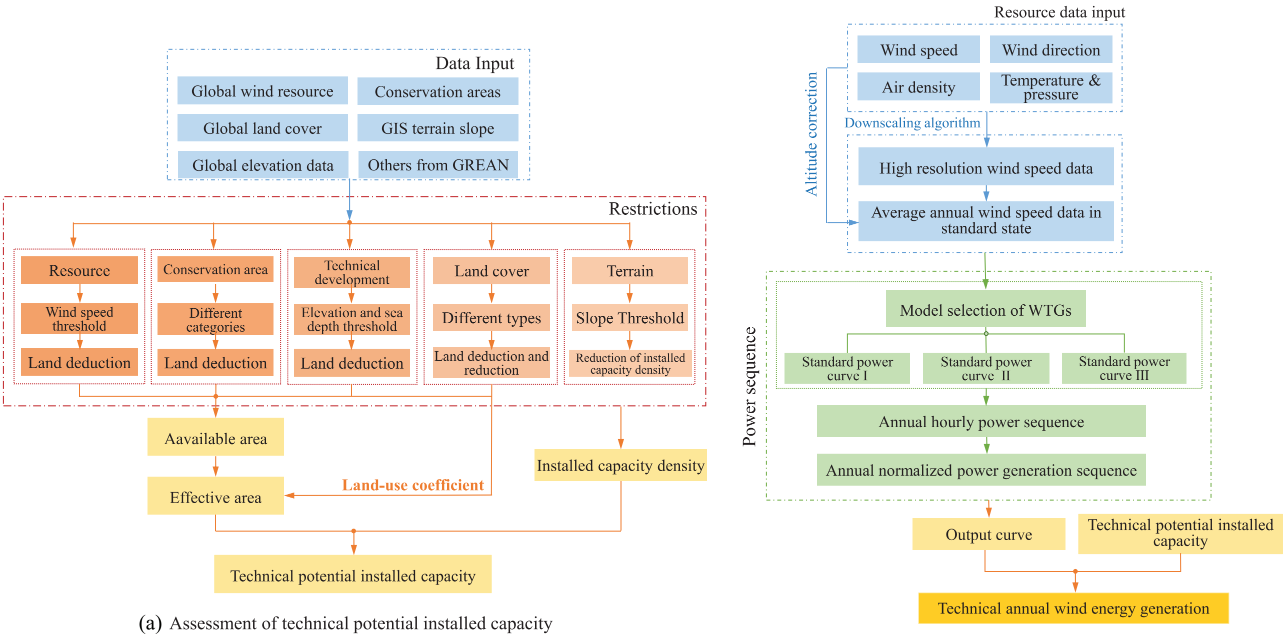
The technical potential installed capacity is the total installed capacity that can be developed at the level of technology in the assessment year. The flow chart of the technical potential installed capacity assessment model for wind resources is shown in Figure 1.

The key is to exclude the areas unsuitable for development due to resource endowment, conservation areas, altitude and sea depth, land cover and other restrictions, and then to calculate the available area A_{avl}. Then, considering the influence of different land covers, set a series of land-use coefficients and calculate the effective installed capacity area A_{eft}.

$$\begin{aligned} A_{\mathrm{eft}} &= \eta A_{\mathrm{avl}} \\ &= \eta\left(A_{\mathrm{sum}} - \sum_{i=1}^{n} A_{\mathrm{con}i} - \sum_{i=1}^{m} A_{\mathrm{res}i} - \sum_{i=1}^{r} A_{\mathrm{alt}i} - \sum_{i=1}^{w} A_{\mathrm{land}i}\right) \end{aligned} \tag{3}$$

where η is the land-use coefficient (seen in Table 1), A_{sum} is the total area of the assessment areas, A_{con}, A_{res}, A_{alt} and A_{land} are the areas restricted to development due to conservation areas restrictions, poor wind resources restrictions, high altitude restrictions and land cover restrictions, respectively.

Taking into account the characteristics and restrictions of onshore, offshore, centralized and distributed development modes, the main indicators and recommended parameters that should be used in the calculation of the effective installed capacity area are shown in Table 1. In general, the centralized and distributed development modes are often selected based on



(a) Assessment of technical potential installed capacity

(b) Assessment of technical annual generation

FIGURE 1 Flow chart of technical potential installed capacity assessment model for wind resources. a) Assessment of technical potential installed capacity. b) Assessment of technical annual generation

the difference in land-use status in the areas to be developed. For example, cultivated land and forest are generally unsuitable for centralized development, but the distributed development mode may be adopted in the fields, forest edges, and low wind speed areas to make full use of and further explore wind energy resources.

The influence of terrain factor on the installed capacity per unit area can be calculated quantitatively by setting the slope influencing factor α. According to the literature [38, 43–45], the installed capacity P_{unit} per unit area on flat land surface is about 5 MW/km^2. With reference to the technical standards for wind resource assessment in China and the achievements of other research institutions [17, 29, 43], the classification and recommended values of the slope influencing factor α adopted here are illustrated in Table 2. At this moment, the five main restrictions to assess technical potential installed capacity is ascertained, and more details could be found in Table A1.

Therefore, to evaluate the technical potential installed capacity P_{TPG}, it is necessary to calculate the effective installed capacity area and the actual installed capacity of each grid in the area, calculate the annual average wind speed in the standard state as a technical indicator, and calculate the annual hourly power generation sequence according to the typical wind turbine power curve by interpolation method [38], so as to obtain the annual wind energy generation Q_{TPG}. The calculation formula is as follows. In this paper, the power curves of GW103-2500, GW109-2500 and GW121-2500 wind turbines from Goldwind Science Technology Co., Ltd. (China) are selected as typical parameters for Type I, Type II and Type III units, respectively. The power curves of these three typical wind turbines can be seen in Figure A1.

$$P_{\mathrm{TPG}} = P_{\mathrm{unit}} \sum_{i=1}^{n} \left(A_{\mathrm{eft}i} \alpha_i\right) \tag{4}$$

$$Q_{\mathrm{TPG}} = P_{\mathrm{unit}} \sum_{i=1}^{n} \left(A_{\mathrm{eft}i} \alpha_i \sum_{j=1}^{8760} P_j\right) \tag{5}$$

where α_{i} is the slope influencing coefficient of the selected grid i, n is the total grids number in the assessment area, P_{j} is the normalized power generation of a typical wind turbine at the hour j. In some of the existing research, the control strategy of the WTG is considered at the equipment level [46–48]. In this model, those relations are gathered into the ratio α.

2.3 | Economic potential installed capacity

In the assessment process, each geographical grid is regarded as a calculation unit, the *LCOE* of each grid is calculated separately and compared with the given threshold price $LCOE_{\mathrm{THR}}$, and grids whose *LCOE* is lower than the threshold price are cost-effective. In this study, the $LCOE_{\mathrm{THR}}$ is set to be 8 ¢/kWh based on the consideration of the average global electricity cost. The technical potential installed capacity of all cost-effective grids is accumulated to obtain the economic potential installed capacity P_{EPG} in the area, and the calculation formula is as

TABLE 1 The main indicators and recommended parameters used in the assessment model of technical potential installed capacity of wind energy

			Land-use coefficients η	
Type	**Restriction**	**Threshold value**	**Suitable for centralised development**	**Suitable for distributed development**
Resource restrictions	Annual average wind speed	>5 m/s (Centralized)@@@@ > 4.5 m/s (Distributed) > 7 m/s (Offshore)		
Technical development restrictions	Land elevation	<4000 m	–	–
	Ocean Depth	>−150 m	–	–
Conservation area restrictions	Natural ecosystem	unsuitable	0%	0%
	Wildlife	unsuitable	0%	0%
	Natural relics	unsuitable	0%	0%
	Natural resources	unsuitable	0%	0%
	Others	unsuitable	0%	0%
Land cover restrictions	Forest	unsuitable	0%	10%
	Cultivated land	unsuitable	0%	25%
	Wetland and swamp	unsuitable	0%	0%
	Cities and urban areas	unsuitable	0%	0%
	Ice and snow	unsuitable	0%	0%
	Shrub	unsuitable	80%	0%
	Grassland	unsuitable	80%	0%
	Bare ground	unsuitable	100%	0%

TABLE 2 The influence of different slopes on installed capacity

GIS Slope (°)	**Slope influencing factor α**
0–1.7	1
1.8–3.4	0.5
3.5–16.7	0.3
16.8–30	0.15
>30	0

follows:

$$P_{\mathrm{EPG}} = \sum_{i=1}^{n} \left(P_{\mathrm{TPGi}} \lambda_i\right) \tag{6}$$

$$\lambda = \begin{cases} 0, & LCOE > LCOE_{\mathrm{THR}} \\ 1, & LCOE \le LCOE_{\mathrm{THR}} \end{cases} \tag{7}$$

where λ is the economic judgement factor, which is 0 when the *LCOE* exceeds the threshold price and it is not cost-effective for development, otherwise the value is 1.

The key to the assessment lies in the quantitative calculation of *LCOE*, which is closely related to the equipment and construction costs, financial parameters, policy environment, and infrastructure conditions that affect the cost-effectiveness, in addition to the resource endowment and the technical potential installed capacity. In previous studies, a prediction model of wind power development investment level has been established by integrating the multiple linear regression prediction methods and the deep self-learning artificial neural network (ANN) algorithm-based correlation analysis prediction method [34, 38, 49]. In this paper, with 2035 as a target year, predictive parameters of the relevant equipment and project costs are selected to emphatically predict the comprehensive initial investment in wind power development in various continents. The results are shown in Table A2.

Further, the model enables the first quantitative analysis of the influence of the distribution of grids and traffic facilities on development costs. Based on the global grid vector data of AC/DC backbone transmission networks in 147 countries on six continents as of the end of 2017, the grid integration cost can be calculated through the calculation of grid integration distance in different transmission modes and at different voltage levels and the calculation of grid integration cost factors under different conditions based on the practical engineering experience [34, 38], and the relevant parameters are shown in Table A3.

Transportation cost refers to the cost of newly constructing transportation facilities from the existing road network transportation infrastructure (including roads, railways etc.) to the resource location for the development of renewable energy power generation resources. Generally, there is a certain distance between large scale renewable energy power bases and existing roads, and necessary outside connecting roads need to be built to meet the requirements of project construction. This part of the increased construction cost should be included in the total cost of resource development. Based on the data of global road network, this study calculates the length from every grid point to be developed to the nearest external transportation road. Meanwhile, the transportation cost per unit installed capacity per kilometre of wind power development is estimated to be USD 800/km based on the engineering experience parameters such as mountainous areas, plains, and the construction cost of primary roads [49]. In addition, altitude, transportation and other factors in the actual development will further affect the operation and maintenance costs, and the relevant information will be supplemented below.

Based on the above-mentioned models and methods, GEIDCO has established the Global Renewable-energy Exploitation ANalysis platform (GREAN), which can allow basic data access, assessment and characteristic analysis of wind and solar resources in the world etc.

2.4 | Refined development potential evaluation method

Upon completion of the wind energy assessment of hundreds of millions of geographical grid points worldwide, the refined development potential evaluation will be further carried out. The so-called refined evaluation refers to the analysis of probability distribution characteristics by the technical potential installed capacity and other key indicators in the technical dimension represented by the capacity factor (the ratio of full-load hours to 8,760, which is an important indicator reflecting the technical development conditions of regional resources) and in the economic dimension represented by the *LCOE*, with the consideration of the difference in evaluation purposes and concerns, so as to obtain the distribution histogram and the cumulative probability distribution diagram of the regional potential installed capacity to capacity factor and *LCOE*. The refined evaluation results will enable a more comprehensive, rapid and accurate quantitative analysis of regional development potential.

For example, the following two typical problems can be quickly solved by the refined development potential evaluation results. Scenario 1: If it is known that wind energy resources will be developed on a certain scale in an area to be assessed, how can the optimal cost be calculated quickly and quantitatively? The comprehensive cost to meet this installed capacity scale in the most economical mode can be obtained by analyzing the distribution characteristics and cumulative curve of the technical potential installed capacity to *LCOE*, which is also the lowest cost for future development and can effectively provide decision support for planning. Scenario 2: Technical and economic comparison of multiple large areas to be developed often requires the technical and economic assessments to obtain the total potential and distribution maps, but it is difficult to make comparisons or to quickly and comprehensively reflect the characteristics of these areas. In such a case, the comparison of the refined evaluation results shows that the technical potential installed capacity is mostly distributed in areas with high-capacity factors and low development costs and showing a steeper cumulative probability curve tend to have higher development potential. Overall, the refined development potential evaluation allows the efficient, accurate and easy "reflection and description" of the wind power development characteristics in different areas.

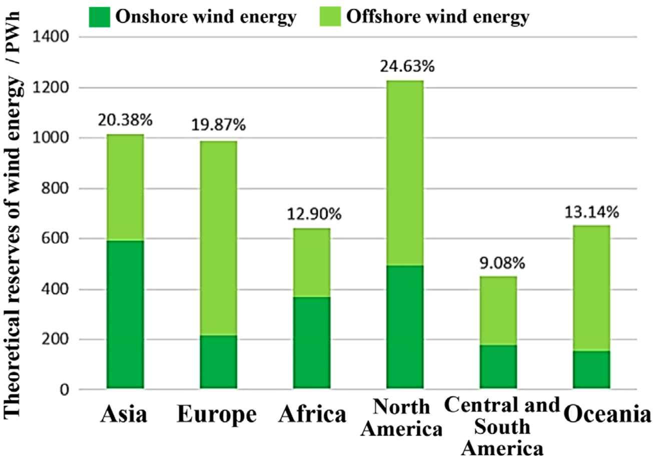


FIGURE 2 Assessment results of theoretical reserves of wind energy resources by continent

3 | GLOBAL WIND ENERGY RESOURCE ASSESSMENT RESULTS

3.1 | Theoretical reserves

The total theoretical reserves of global wind energy, measured at the height of 100 m above the ground, is 4,986 PWh/a, including 2,002 PWh/a from onshore wind energy. Figure 2 below shows the assessment results of the theoretical reserves of wind energy resources on six continents. North America, Asia, and Europe, with the theoretical reserves accounting for 24.6%, 20.4%, and 19.9% of the total, rank the top in the world. Onshore wind energy is mainly distributed in Asia and North America, accounting for 29.7% and 24.7% of the world total. Offshore wind energy is mainly distributed in Europe and North America, accounting for 26% and 24.6% of the world total, with excellent wind energy resources in the North Sea, Iceland, Greenland, Alaska, and other waters.

3.2 | Technical potential installed capacity

The technical potential installed capacity of global wind energy resources is 206 TW in total, of which 73% is from the onshore wind energy resources, and the technical potential installed capacity of onshore wind power suitable for large-scale centralized development is 132 TW in total. Figure 3 shows the assessment results of technical potential installed capacity of wind power by continent. Africa and Asia have a large area for wind energy development and higher annual average wind speed because of their vast territory and large-scale distribution of bare ground, desert grasslands and other land covers, so their technical potential installed capacity is 55.6 and 50.9 TW,

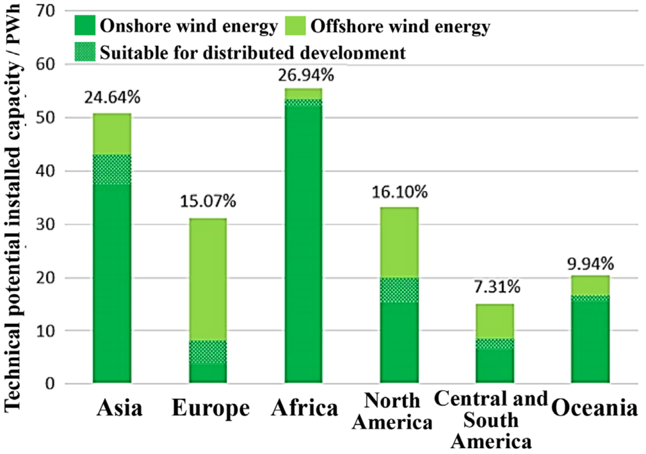


FIGURE 3 Assessment results of technical potential installed capacity of wind power by continent

respectively, accounting for 26.9% and 24.6% of the world total. Europe has 31.1 TW of the technical potential installed capacity of wind energy due to its land is mostly covered with cities, forests and other land covers not suitable for centralized development. However, since it is bordered by the Norwegian Sea, the Greenland Sea and the Barents Sea in the north, the wind resources in the offshore areas are excellent. It is estimated that about 75% of the technical potential installed capacity in Europe is from offshore regions, making Europe the largest region in the world for offshore wind power generation.

The distribution of global technical available areas for wind power generation and capacity factors thereof is shown in Figure 4. Overall, the global average capacity factor for wind power generation is 0.32, with the maximum value for onshore wind power generation near North Horr in northern Kenya, Africa, at over 0.62, and the maximum value for offshore wind power generation in the southern waters of Chile, South America, at 0.72. By continent, South America has the highest capacity factor of 0.32 for onshore wind power generation. The average capacity factor for offshore wind power generation in Europe and South America is high, which reaches 0.5 especially in waters in the North Sea, indicating great potential for future development.

Onshore wind energy in Asia is mainly distributed in China and Mongolia in East Asia, Kazakhstan in Central Asia, and Iran, Saudi Arabia and Oman in West Asia, accounting for 70% of the world total. The capacity factor of resource-rich areas such as southern Mongolia and the coastal regions of Oman exceeds 0.34. Southeast China, the Korean Peninsula and India are densely populated countries having extensive cultivated land, and Southeast Asia is covered with dense rainforests, which are not suitable for centralized development. Instead, the distributed development mode can be adopted around forests and villages. Onshore wind energy in Europe is mainly distributed in the UK, Iceland, Norway, and Russia, with a capacity factor of more than 0.34 in the northern areas. Since cities and urban areas and cultivated land are mostly distributed in the southwest, while forests are mostly distributed in the north, it is appropriate to adopt the distributed development mode, and the total technical potential installed capacity is about 4.3 TW. The offshore wind energy is distributed in the North Sea, the Baltic Sea, the Barents Sea, and coastal waters in Ireland, and the capacity factor in some areas exceeds 0.57. Wind energy in Africa is mainly distributed in the north of the Sahara to the coastal regions of the Mediterranean, that in North America is mainly distributed in the central United States and north-eastern Canada, and that in South America is mainly distributed in southern Argentina and the southeast coast of Uruguay, accounting for about 80% of the world total.

3.3 | Development cost analysis

According to assessment results, the average development cost of wind energy in the world is 4.28 cents, including 4.13 cents onshore and 4.57 cents offshore. The distribution of global wind power development costs is shown in Figure 5, and the continental analysis is shown in Figure 6.

Taking the current global average integrated generation price of 8 cents as an economic criterion, the global economic potential installed capacity of wind energy is 188 TW (including 140 TW from onshore wind energy and 48 TW from offshore wind energy), accounting for 91% of the technical potential installed capacity. Globally, the cost-optimal areas are distributed in Northern China, Mongolia, Kazakhstan, Pakistan, Saudi Arabia and other countries in Asia, Egypt, Sudan and South Africa in Africa, Denmark in Europe, Argentina in South America and central North America, where development costs are below 3 cents. These areas have excellent resource conditions, and better grid infrastructure conditions, and also are easily accessible, so the development costs are relatively low. However, due to the difference in off-site access and grid integration costs, the development costs are significantly different in different areas and show a regular distribution similar to that of highways and grids.

4 | REFINED DEVELOPMENT POTENTIAL EVALUATION

4.1 | Global refined evaluation results

Wind energy development generally follows the principle of prioritizing the development of high-quality resources with good resource conditions and low development costs. The probability distribution characteristics of the technical potential installed capacity of wind energy to capacity factor and development cost are shown in Figures 7 and 8, thereby facilitating more efficient and accurate characterization and refined evaluation of wind power development potential. The analysis shows that the capacity factor for global onshore wind power generation mainly ranges from 0.21 to 0.34, with a peak in the range of 0.30 to 0.34. About 15% of the onshore wind resources have a capacity factor of more than 0.34 (annual full-load hours of 3,000) and an installed capacity of about 23 TW, which are

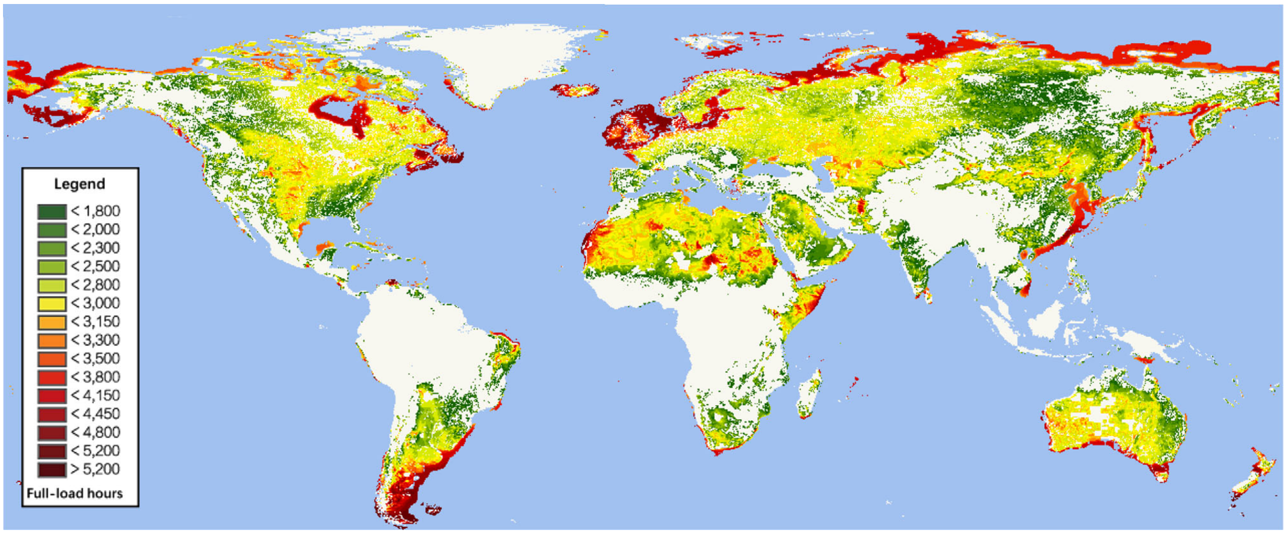


FIGURE 4 Distribution of global technical available areas for wind power generation and their full-load hours

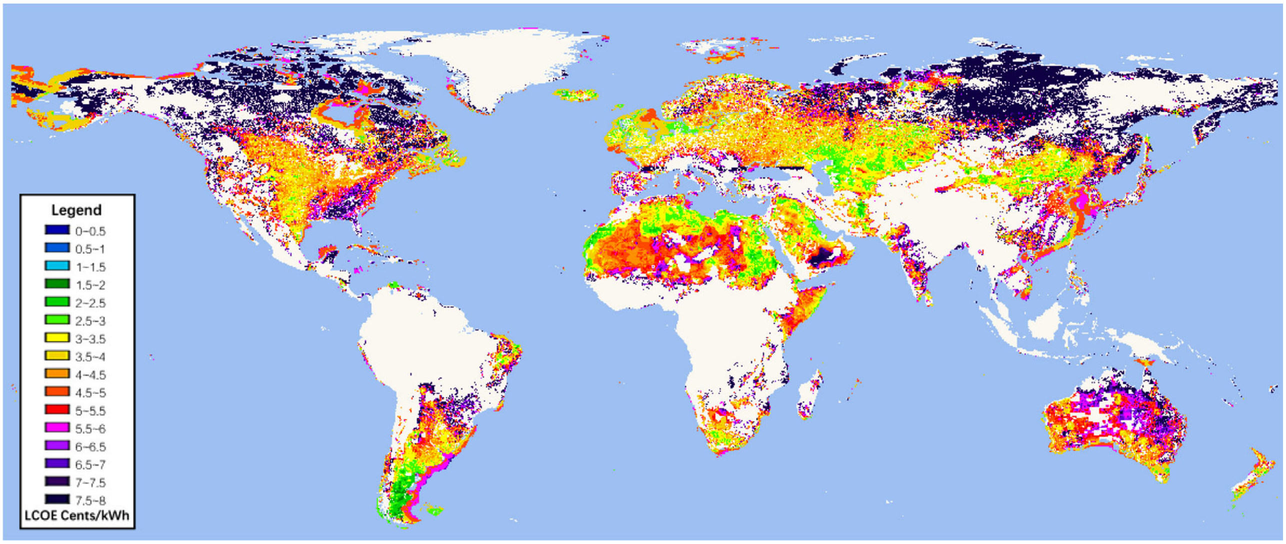


FIGURE 5 Distribution of global wind power development costs

high-quality resources. The capacity factor for offshore wind power generation mainly ranges from 0.35 to 0.55 with a higher average, and 38% of wind resources have a capacity factor of more than 0.45 (annual full-load hours of 4,000).

The analysis of the distribution characteristics of development costs of global technical available resources for wind power generation shows that the onshore wind power development cost mainly ranges from 2.5 to 4.5 cents, showing a "double-incline curve" with two peaks at 3 and 4 cents respectively. The global development cost of about 24 TW wind power is below 3 cents, accounting for about 16%, so these wind resources are high-quality resources. The development cost of offshore wind power mainly ranges from 3.5 to 5.5 cents, where the development cost of about 41 TW installed capacity is below 5.5 cents, accounting for nearly 83%. Offshore resources (the cost is below 4 cents), which have an economic advantage over onshore resources, have an installed capacity of about 10.5 TW, accounting for about 21%.

Further, Guangdong Province, Shandong Province, and Yunnan Province of China are selected as typical cases to draw the scatter diagrams of capacity factors and development costs at millions of geographical grid points, respectively, as shown in Figure 9. The analysis reveals a certain regularity: the lower edge of the distribution diagram of capacity factor and development approximates to a power function, and the fitting results are shown in the scatter diagrams, which are decreasing functions in the range of [0,1], that is, the development cost is often lower when the capacity factor is higher, and the number of grid points with higher capacity factors is generally less than that with medium and lower capacity factors. The development

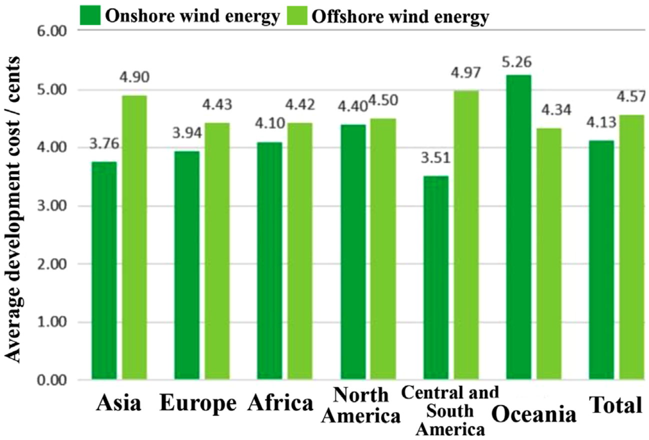


FIGURE 6 Assessment results of average development costs for wind power generation by continent

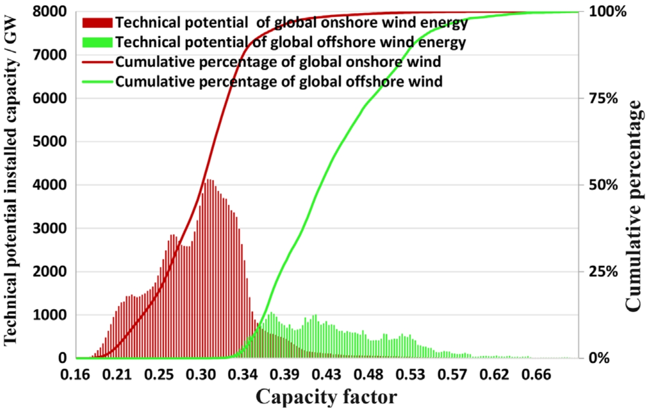


FIGURE 7 Statistical characteristics of technical development scales and capacity factors for global onshore and offshore wind energy

costs at the grid points with lower capacity factors are often distributed more diffusely and discretely, and distributed more intensely as the capacity factor increases.

4.2 | Analysis of low-carbon energy transition scenarios

Global climate change has become a global challenge that requires all countries in the world to face together. The fundamental way out for promoting clean energy transition is to control carbon emissions and address climate change, which has become a global consensus, and major countries in the world have successively put forward their clean development goals. Studies show that the proportion of clean energy in primary energy is required to reach 65% or above to deliver carbon neutrality, but the current development speed and scale of clean energy are far from meeting the needs of carbon neutrality [50, 51]. To achieve the low-carbon and zero-carbon transition of the power system, a top priority is to accelerate the clean energy (represented by wind power) substitution on the power supply side.

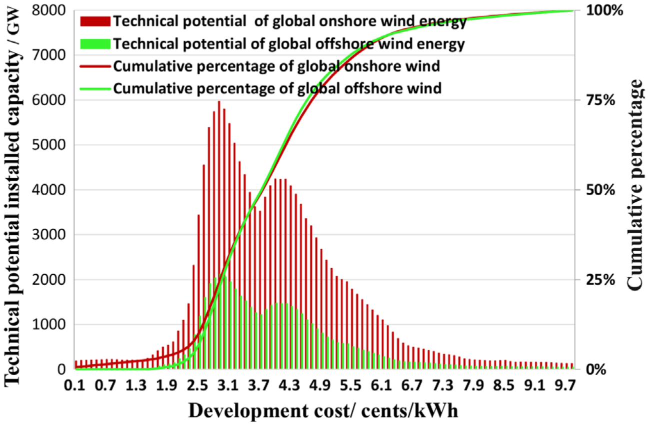


FIGURE 8 Statistical characteristics of technical development scales and cost levels for global onshore and offshore wind energy

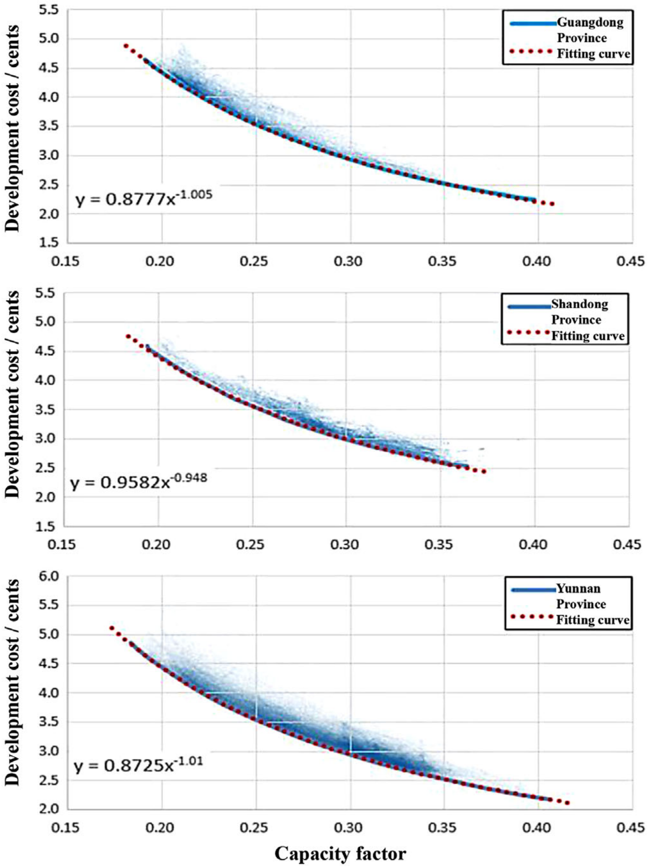


FIGURE 9 Scatter diagrams and fitting curves of capacity factor and development cost in typical areas

Therefore, the development potential analysis based on the global energy low-carbon transition scenarios can provide an important reference for relevant planning studies. Studies show that to meet the requirements of the global low-carbon transition and development, the global clean energy installed capacity is required to reach 21,800 to 28,400 GW, including 6760 to 8804 GW of wind power installed capacity [52], which is about 15 times the current global wind power installed capacity [53].

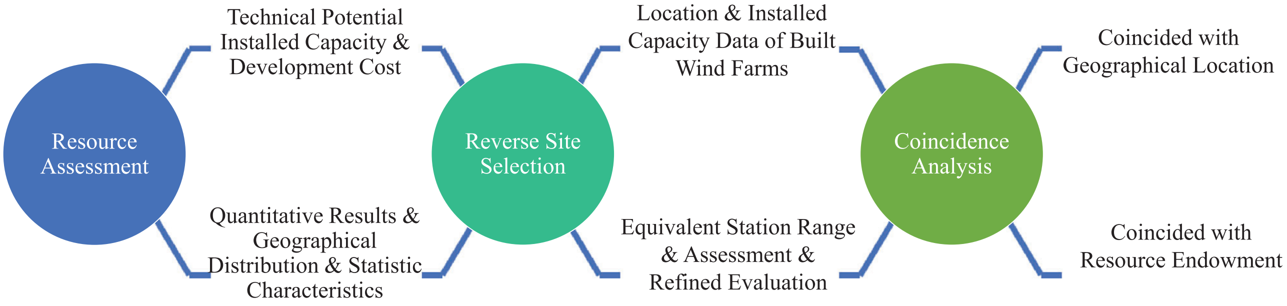


FIGURE 10 Flowchart of the rationality verification method

The refined evaluation results shown in Figure 8 reveal that the resources with the lowest cost will be developed first in the most economical mode. The global comprehensive development cost of 6.76 TW wind energy resources is only 2.48 cents, well below the global average of 4.28 cents. A temperature rise of 1.5°C requires the development of 8.80 TW wind energy resources globally, with the comprehensive cost increasing to 2.54 cents. In such a case, the area for development is about 1.5 million km^2(including 1.45 million km^2 of land area), equivalent to only 5% of the total global desert area (including scrub and bare ground), and the development is mainly distributed in southern South America, coastal areas of North Africa and Nile Region, Central Asia, Inner Mongolia of China and other places where the LCOE is less than 2.8 cents, as shown in Figure 5.

5 | RATIONALITY VERIFICATION

5.1 | Verification method

To verify the rationality of wind resource assessment results, a novel verification method is proposed, which mainly includes three steps: resource assessment, reverse site selection, and coincidence analysis, as shown in Figure 10. Firstly, after the wind assessment, the quantitative results, geographical distribution and statistic characteristics of both technical potential installed capacity and development cost worldwide are obtained. Secondly, based on the information contained in the basic database of global built wind farms, including the location, installed capacity and other parameters, a macro reverse site selection is carried out. Specifically, under the condition of unchanged installed capacity, by taking the geographic coordinates of the wind farm as the center of the circle, the reverse site selection radius R_{site} can be calculated by the regional average installed capacity density per unit area to generate an equivalent station range, as shown in Equation (8).

$$R_{site\_i} = \sqrt{\frac{P_{\mathrm{farm\_i}}}{\pi \cdot P_{unit}}} \tag{8}$$

where R_{site_i} is the reverse site selection radius of wind farm, P_{farm_i} is the installed capacity of wind farm i, and P_{unit} is the regional average installed capacity density.

Thirdly, the assessment and refined evaluation of wind resources in this equivalent station range for each built wind farms will be conducted for coincidence analysis. A geographical coincidence coefficient ζ is proposed, which can be calculated as Equation (9). Generally, the value of ζ over 80% means the assessment results proposed by this paper are coincided with the geographical locations of built wind farms. Besides, from the practical point of view, the built wind farms should be definitely located in the wind-rich areas and always with better economic efficiency for development. Hence, based on the refined evaluation results in this paper, if the capacity-costs statistical characteristics of the real case shows a sharper cumulative probability curve than the global general level, which means the assessment results proposed by this paper are coincided with the wind resource endowment.

$$\zeta = \frac{\sum_{k=1}^{M} \sigma_k}{M} \begin{cases} \sigma_k = 1, P_{\mathrm{TPG}\_k} \neq 0 \mathrm{and} LCOE_k \leq LCOE_{THR} \\ \sigma_k = 0 \end{cases} \tag{9}$$

where M is the number of wind farms in the assessment area, P_{TPG_k} and $LCOE_{\mathrm{k}}$ are the technical potential installed capacity and average development cost of farm k, respectively, σ is the judgment factor, which equals to 1 when the built farm located in the economic development area shown in Figure 5, otherwise, σ is 0.

5.2 | Case study of built wind farms worldwide

Here, the rationality of wind energy assessment method is verified using the wind farms data from the Global Power Plant Database released by the World Resources Institute (WRI) in 2018. This data set provides geographical distribution, installed capacity and other information of 5,084 wind farms in 57 countries around the world. The wind farms in this data set are more than half of the existing built wind farms worldwide, which are extensive and can be used as reference samples for comparative analysis.

For the case study, 4.5 MW/km^2 is selected as the average installed capacity density per unit area for reverse site selection. According to calculation, 4,210 of the 5,084 wind farms worldwide are located within the technical available areas as indicated

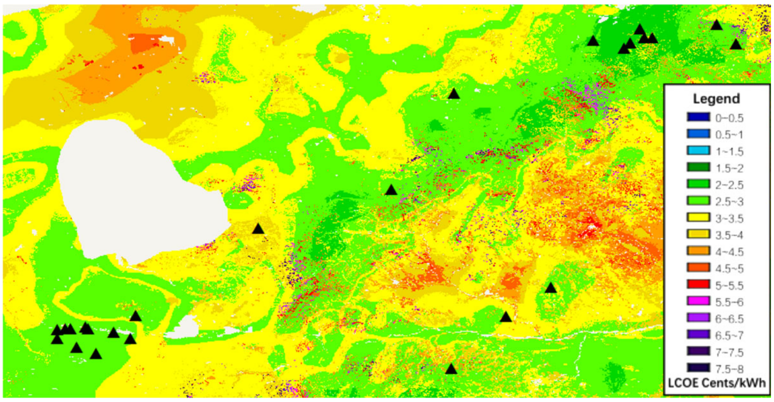


FIGURE 11 Geographical location and development cost distribution of built wind farms in central Inner Mongolia in north China

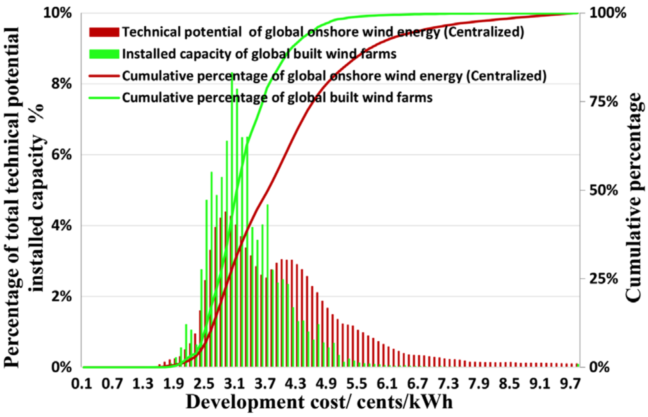


FIGURE 12 Comparison of the capacity-costs statistical characteristics of built wind farms and global assessment results

by the assessment results of this study, with the geographical coincidence coefficient ζ of 83%. In China, 792 of the 836 wind farms are located in the technical available areas, with the geographical coincidence coefficient ζ of 95%. Further analysis reveals that wind farms not located in the technical available areas are mainly located in the coastal intertidal zones, conservation areas on land and sea, and other areas that are not suitable for wind power development as assessed here. Figure 11 shows the comparison between the geographical locations (black triangle symbol) of wind farms in the east of Xilinhot in central Inner Mongolia in north China and the development cost distribution in this area assessed here. As shown from the Figure 11, all the built wind farms are located in high-quality resource development regions with better economic efficiency as indicated by the assessment results.

The refined development potential evaluation is carried out on reverse site selection areas of 5,084 built wind farms, and the comparison is made between the evaluation results of this real case and the global overall wind energy distribution characteristics, as shown in Figure 12. According to the analysis, the average development cost of the resources developed for the built wind farms is 3.51 cents, which is 22% lower than the global average cost and thus is more cost-effective. The steeper cumulative probability distribution curve indicates that more wind energy resources with lower costs are also developed for built wind farms as indicated by the result of this paper. This result is consistent with the principle of site selection for wind farm development, which in turn validates the rationality of the global wind energy assessment results here.

6 | CONCLUSION

Here, a basic database for global resource assessment is established, and a quantitative assessment model is proposed to expand the wind energy assessment by calculating the theoretical reserves a comprehensive assessment from multiple dimensions such as technical potential installed capacity and cost-effectiveness by considering more data related to geographical information and human activities information.

Through this study, a quantitative assessment of the theoretical reserves, technical potential installed capacity and development cost of global wind energy resources suitable for centralized, distributed, and offshore development modes is completed, and the global distribution map is drawn. The results show that the technical potential installed capacity of the wind energy resources worldwide is 206 TW in total with an average development cost of 4.28 cents, of which 73% is from the onshore wind energy resources with the development cost of 4.13 cents.

Combined with geospatial calculation and statistical probability analysis, the refined evaluation of the development potential of global wind energy resources can be realized based on capacity factor and development cost. The distribution diagram of development costs of the technical potential installed capacity shows a “double-incline curve”, with its lower edge where the capacity factor and the development cost are distributed approximates to a power function. The global development cost of about 24 TW wind power is below 3 cents, accounting for about 16%, so these wind resources are high-quality resources. In the case of supporting low-carbon energy transition, 8.8 TW wind power can be developed in the most economical mode at a comprehensive cost of 2.54 cents using only 5% of the total global desert area and about 50,000 km^2 of offshore waters.

A rationality verification method is proposed. By the case study of global built wind farms, the geographical location coincidence of the assessment results is 83%, and the development cost with reverse site selection study is 22% lower than the global average level, which is more cost-effective. Therefore, the rationality of the results and the feasibility of the method are verified.

In general, the results of global wind energy resource assessment and development potential analysis can provide decision support for all regions and countries in formulating carbon neutral and clean development strategies and plans. Next, it is necessary to refine information on the conservation areas, military areas, and sea routes based on the energy development policies and actual conditions of various countries, so as to improve the accuracy of resource assessment results.

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AUTHOR CONTRIBUTIONS

Jiawei Wu: Conceptualization; Formal analysis; Methodology; Validation; Writing—Original draft. Jinyu Xiao: Conceptualization; Methodology; Project administration; Supervision; Writing—Review and editing. Jinming Hou: Methodology; Project administration; Resources. Wei Sun: Data curation. Peng Li: Data curation; Visualization; Writing—review and editing. Xunyan Lyu: Data curation; Visualization

CONFLICT OF INTEREST

The authors declare that they have no conflicts of interest.

FUNDING INFORMATION

This work was supported by the Science and Technology Project of State Grid Corporation of China: Model Research and Key Technology Evaluation on Low Carbon Development of Energy and Power in China under the Background of Carbon Peak and Carbon Neutralization (1300-202155460A-0-0-00).

DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available from the corresponding author upon reasonable request. (Dr. Jinyu Xiao, e-mail: jinyu-xiao@geidco.org). Some raw/processed data may not be shared at this time as the data also forms part of an ongoing study.

NOMENCLATURE

A_{alt}	area restricted by high altitude, km^2
A_{avl}	available area for development excluding restrictions, km^2
A_{con}	area restricted by conservation areas, km^2
A_{eft}	effective installed capacity area considering the influence of different land covers, km^2
A_{i}	area of the selected area *i*, km^2
A_{land}	area restricted by land cover, km^2
A_{res}	area restricted by poor wind resources, km^2
A_{sum}	total area of assessment areas, km^2
D_{WPij}	wind power density of the grid *i* at the hour *j*, W/m^2
i	index for each grid of the assessment area ($i = 1,\ldots,N$)
j	index for each hour of the year ($j = 1,\ldots,8760$)
k	index for each wind farm for coincidence analysis ($k = 1,\ldots,M$)
$LCOE_{\mathrm{THR}}$	threshold price, USD cents
P_{EPG}	economic potential installed capacity, kW
$P_{\mathrm{farm\_}i}$	installed capacity of wind farm *i*, kW
P_{j}	normalized power generation of a typical wind turbine at the hour *j*, kW
P_{TPG}	technical potential installed capacity, kW
P_{unit}	installed capacity density of flat land surface, MW/km^2
Q_{TPG}	the annual wind energy generation, kWh
Q_{TR}	theoretical reserves of wind energy, kWh
$R_{\mathrm{site\_}i}$	radius for reverse site selection of wind farm *i*, km
v	wind speed, m/s
α	slope influencing coefficient
ζ	coincidence coefficient of wind farm location
η	land-use coefficient
λ	economic judgement factor for each grid
ρ	air density, W/m^2
σ_k	Site selection judgment factor of wind farm *k*

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APPENDIX A

TABLE A1 The data source and detailed information of GREAN platform

Category	Data description	Data Source, spatial resolution and data type
Resources	Global hydrological data	Daily hydrological data is from the Global Runoff Data Center (GRDC), which is from 9484 hydrological stations covering major rivers in the world for more than 30 years.
	Global mesoscale wind resources data	Wind resource data is calculated and produced by Vortex, with a spatial resolution of 9 km × 9 km, a temporal resolution of hourly data of typical years. Raster data.
	Global solar energy resource data	Solar resource data is calculated and produced by SolarGIS, with a spatial resolution of 9 km × 9 km, a temporal resolution of hourly data of typical years. Raster data.
Geographic information	Classification information of global land covers	Land cover data covers the land range from 80° degrees north latitude to 80° south latitude released by National Geomatics Center of China, with a resolution of 30 m × 30 m. Raster data.
	Global distribution of major reservoirs	Reservoirs data is from the global water system projects in Bonn, Germany, including more than 6,500 artificial reservoirs with a cumulative storage capacity of about 6.2 trillion m^3 Raster data.
	Global distribution of lakes and wetlands	Lakes and wetlands data is jointly developed by the World-Wide Fund for Nature, the Environmental Systems Research Center and Kassel University in Germany, including lakes and permanent open water bodies other than artificial reservoirs with a resolution of 1 km × 1 km. Raster data.
	Global distribution of major geological faults	Geological faults data is from the American Environment Systems Research Institute. Vector data.
	Global distribution of plate boundaries	Plate boundary data is from the American Environmental Systems Research Institute. Vector data
	Global distribution of historical seismic activity frequency	Historical earthquake frequency data is from the World Resources Institute (WRI), including the geographical distribution of earthquakes with magnitude 4.5 or higher since 1976 with a resolution of 5 km × 5 km. Raster data
	Global distribution of main stratum	Major stratum data is from the joint research results of European Commission, German Federal Ministry of Education and Research, German Science Foundation and other institutions. Vector data
	Global terrain elevation data	Global terrain elevation data is from the digital products of National Aeronautics and Space Administration (NASA) and Ministry of Economy Trade and Industry (METI) with a resolution of 30 m × 30 m. Raster data
	Global ocean boundaries data	Ocean boundary is from the Flanders Marine Institute (VLIZ) in Belgium, including the 200-nautical-mile exclusive economic zone, 24-nautical-mile contiguous zone, 12-nautical-mile territorial sea area and other information stipulated in the United Nations Convention on the Law of the Sea. Vector data
Human activities	Global distribution of major conservation areas	Conservation areas is from the data set jointly released by the International Union for Conservation of Nature (IUCN) and the World Conservation Monitoring Center of the United Nations Environment Programme (UNEP-WCMC). Vector data
	Global population distribution	Population distribution data is from Columbia University's International Geoscience Information Network Center, including the population distribution data in 2000, 2005, 2010 and 2015, with a resolution of 900 m × 900 m. Raster data
	Global distribution of transportation infrastructure	Transportation infrastructure is from the global railway, airport and port data set released by the North American Cartographic Information Society (NACIS) and the global road network data set released by the Socioeconomic Data and Applications Center of NASA. Vector data
	Geographic distribution of global power grid	Global grid geographic wiring diagram is from the Global Energy Interconnection Development and Cooperation Organization, covering the backbone transmission network data of 147 countries in Europe, Asia, America, Africa and Oceania as of 2017, including 110–1000 kV AC power grids and major DC transmission projects. Vector data
	Global power plant information and geographic distribution	Power plant information and geographical distribution data is from the joint research results of Google, Royal Institute of Technology in Stockholm and World Resources Institute (WRI), including the location distribution and installed capacity of global power plants of 2017. Vector data

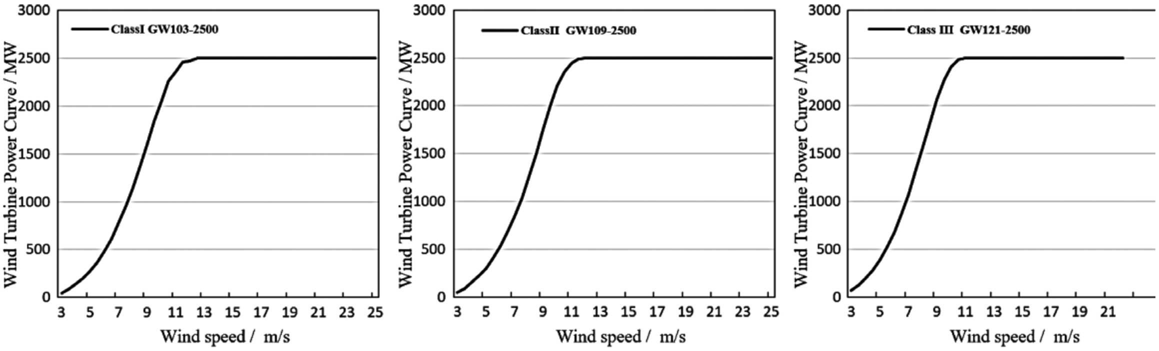

FIGURE A1 Power curves of typical wind turbines

TABLE A2 Initial investment forecast results of wind power stations

	Unit: USD/kW	
	2035	
	Offshore Wind Power	**Onshore Wind Power**
Asia	1197–1386	646–748
Europe	1490–1642	872–961
Africa	1454–1683	808–935
North America	1548–1706	872–961
South America	1435–1631	798–907
Oceania	1509–1617	892–956
Global average	1397–1617	732–847

TABLE A3 Recommended values for cost-effectiveness parameters of renewable energy development and grid integration

Onshore AC transmission

Voltage level (kV)	**Transmission distance (km)**	**Unit transmission cost (USD/km/kW)**
1000	500	0.28
745–765(750)	400	0.34
500	300	0.39
380–400(400)	220	0.59
300–330	200	0.65
220	150	1.06
110–161(110)	100	1.37
Onshore DC transmission		
Voltage level (kV)	Transmission distance (km)	Unit transmission cost (USD/km/kW)
±1100	3000–5000	0.14
±800	1500–3000	0.15
±500	800–1200	0.30
Offshore AC transmission		
Voltage level (kV)	Transmission distance (km)	Unit transmission cost (USD/km/kW)
220	150	3.33
Offshore DC transmission		
Voltage level (kV)	Transmission distance (km)	Unit transmission cost (USD/km/kW)
±320	150-400	1.26