Environmental Science and Ecotechnology 19 (2024) 100323

Contents lists available at ScienceDirect

Environmental Science and Ecotechnology

journal homepage: www.journals.elsevier.com/environmental-science-and-ecotechnology/

Original Research

Cost dynamics of onshore wind energy in the context of China's carbon neutrality target

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ARTICLE INFO

Article history:
Received 12 January 2023
Received in revised form
24 September 2023
Accepted 24 September 2023

Keywords:
Wind power
Carbon neutrality
Electricity potential
Economic competitiveness
Grid parity

ABSTRACT

Wind energy has become one of the most important measures for China to achieve its carbon neutrality goal. The spatial and temporal evolvement of economic competitiveness for wind energy becomes an important concern in shaping the decarbonization pathway in China. There has been an urgent need in power system planning to model the future dynamics of cost decline and supply potential for wind power in the context of carbon neutrality until 2060. Existing studies often fail to capture the rapid decline in the cost of wind power generation in recent years, and the prediction of wind power cost decline is more conservative than the reality. This study constructs an integrated model to evaluate the cost-competitiveness and grid parity potential of China's onshore wind electricity at fine spatial resolution with updated parameters. Results indicate that the total onshore wind potential amounts to 54.0 PWh. The average levelized cost of wind power is expected to decline from CNY 0.39 kWh^{-1} in 2020 to CNY 0.30 and CNY 0.21 kWh^{-1} in 2030 and 2060. 28.3%, 67.6%, and 97.6% of the technical potentials hold power costs lower than coal power in 2020, 2030, and 2060.

1. Introduction

To limit the increase in average global temperature to 1.5 °C by this century, it is imperative to attain net-zero greenhouse gas (GHG) emissions by 2050 [1,2]. China, the largest developing country and the largest GHG emitter in the world, plays a key role in global GHG mitigation. In 2020, China emitted 9.9 Gt CO_2, contributing to approximately 30.7% of global emissions [3]. Power generation accounted for 43.1% of total energy-related emissions in China, with thermal power accounting for 68.5% of the total electricity generation in 2020 [4]. In September 2020, in a noteworthy declaration made during the 75th session of the United Nations General Assembly, China will aim to peak carbon emissions before 2030 and achieve carbon neutrality by 2060. Decarbonizing the coal-dominated power system will be a pivotal measure to reduce GHG emissions in China [5].

The trajectory of wind power development in China has experienced significant acceleration following the implementation of the Renewable Energy Law in 2006 [6,7]. As one of the most influential policies for wind industry development [8,9], the national feed-in tariff (FIT) mechanism has further provided strong financial support and improved the cost-competitiveness of wind power generation since 2009 [6,10], facilitating a leap in China's wind power capacity [11–16]. China has led the global wind power installed capacity since 2010 [17,18]. In 2020, the cumulative wind installed capacity reached 281.5 GW, accounting for 37.9% of the global total [4,19]. Wind power supplied 466.5 TWh of electricity for the country, equivalent to 6.1% of national electricity production [20]. Such rapid growth in wind power is estimated to further expand in the context of the carbon neutrality goal. To align such a goal, China will need to aim for a cumulative installed wind power capacity of at least 2500 GW by 2060 [21].

Such expansion was accompanied by the significantly declining wind power cost and advanced wind power generation technology. The capital costs of China's onshore wind have reduced by 16% between 2010 and 2020 [22]. Subsidy policies supporting wind power were adapted in response to these cost reductions.

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https://doi.org/10.1016/j.ese.2023.100323

Specifically, the FIT policy offers a spatially differentiated guaranteed above-market purchase price for wind power according to wind power resource availability. Regions with better wind resource conditions received lower purchase prices, with the highest nationwide price reaching CNY 0.61 kWh^{-1} in 2009 [23]. The FIT prices have decreased over the years, reflecting the technological advancements and cost reductions in onshore wind power [24]. In particular, the lowest FIT prices were adjusted to CNY 0.29 kWh^{-1} in 2020, falling into the coal power benchmark prices range from CNY 0.25 to CNY 0.45 kWh^{-1}. Recognizing wind power's competitiveness with coal, the FIT policy for onshore wind power was announced to be completely phased out in 2021 [25].

In view of the future cost decline of wind power, the cost-competitiveness of wind power impacts China's approach to achieving carbon neutrality goals through wind capacity deployment. The cost and economic competitiveness of wind power generation were generally calculated with the levelized cost of electricity (LCOE) model, which represents the average cost of power generation during the lifetime [10,26–29]. As wind capacity expands and technological advancements occur, wind power costs decrease. The learning curve model has been adopted to examine such learning-by-doing and learning-by-researching effects on the LCOE decline [30–34], thereby projecting future wind power generation costs [35–37]. Furthermore, the cost-competitiveness of wind power could be assessed by comparing the power generation costs of wind and other power sources [38–40]. For China, coal power prices often serve as the benchmark, and the grid parity refers to the status that wind power is cheaper than coal power [36,41].

However, leading assessments of wind economic availability [42–45] and grid parity feasibility [37,40,46] in China had mainly presented results on the country- and provincial-level or based on individual wind power projects [26,47,48]. The spatial difference in wind resource availability, which could change drastically within relatively small geographical areas, was not fully factored in the current analysis. Thus, these estimations were insufficient to support the energy planning under the carbon neutrality goals due to a lack of high-resolution spatial information. In addition, the cost competitiveness of wind power versus coal power has been evaluated for certain years using static data [36,38,49]. As the cost experiences a huge decline along with the large-scale deployment of wind power capacity [50], it is necessary to model the cost-competitiveness trajectories of wind power in China in a dynamic framework with updated economic parameters. The cost-competitiveness trajectories across regions were not sufficiently studied, considering the varied wind resource conditions and coal power prices. The spatial difference in the tipping point of grid parity of wind power versus coal power with high spatial resolution remains unclear.

To better understand the dynamics of the wind power potentials and cost competitiveness in China, the study built an integrated technical-economic evaluation model to generate spatial-temporal data on the cost competitiveness of wind power. First, an integrated resource assessment model was constructed to evaluate the technical potential of onshore wind power at a spatial resolution of 0.0625° longitude by 0.0625° latitude. Next, the cost dynamics were evaluated by integrating the learning model with the potential evaluation model. Furthermore, we conducted an assessment to determine when, where, and to what extent onshore wind power in China will achieve grid parity versus coal power. The wind power cost-competitiveness was continuously evaluated from 2020 to 2060 under the fine spatial resolution. The long-term cost competitiveness dynamics of onshore wind power and detailed potential distribution of wind power in this study hold practical significance for the wind power deployment and the capacity planning of the electricity sector under the carbon neutrality target. The results also have implications for evaluating the economic feasibility to fast transform energy demand sectors like industry and transportation through electrification [51–53], where the energy cost is one of the determinants for whether the decarbonization effects of wind power could be extended far beyond the electricity sector.

2. Article review

Along with the consensus over the pivotal role of renewable energy in low-carbon transition [21,54], assessments of the power potential and cost competitiveness of wind power are rapidly increasing. Leading studies on China's onshore wind power potential have mainly focused on the technical and economic potentials at national and provincial levels. The estimation for wind technical potential in China, the theoretical feasible physical wind-generated electricity potential assuming full deployment in feasible regions, ranges from 1.2 to 39 PWh [42,45,55,56]. Several studies further assessed the economic potential of wind power, which represented the maximum economically feasible technical potential under a given purchase price. McElroy et al. [45] found that the annual economic potential of China's onshore wind power could reach 6.96 PWh at CNY 0.516 kWh^{-1}. Another study [44] estimated an annual economic potential of 8.13 PWh given a price of CNY 0.60 kWh^{-1}. Davidson et al. [43] showed that with a price of CNY 0.5 to CNY 0.7 kWh^{-1}, the economic potential of China's onshore wind power could reach 12.6–21.6 PWh.

However, the earlier studies did not address the variation of economic potential and the cost declines of wind power. Such dynamics could be modeled with the learning curve model to inform the wind power industry policy-makers and wind project investors. The learning curve model tracks the decline of the capital investment in wind turbines and system balance along with the industry scales-up and researching [32]. The learning curve method was further combined with the LCOE models to calculate and forecast the wind power generation costs in China [29,31,33,57,58]. A report from the International Energy Agency (IEA) [59] projected that the LCOE of China's onshore wind would be USD 0.030 to USD 0.058 kWh^{-1} (about CNY 0.21 to CNY 0.40 kWh^{-1}) in 2020. The estimation by Zhang and Huang falls between CNY 0.31 and CNY 0.50 kWh^{-1} for the same year [36]. Tu et al. [37] used data from 2006 to 2015 to evaluate the learning rate of Chinese onshore wind power and projected that the LCOE of wind power would decrease to CNY 0.34 kWh^{-1} in 2025. In context, the real LCOE of onshore wind in China has declined by 48% over the last decade [22].

Several recent studies assessed the time when wind power could reach grid parity [36,37,48,57] by comparing the generation costs of wind and coal power with projections for economic parameters. Some research examined the impact of parameters of learning rate, average annual utilization hours, extra financial support for wind power, and coal power price on the status of grid parity [31,40,41,47,49]. Fan et al. [49] found that the grid parity of northern and western provinces of China with great wind resources is not easily accessible due to the relatively low coal power prices prevailing in these areas.

Existing literature on the potential and cost of wind power in China offers valuable information for policymakers. However, two notable limitations hinder its ability to guide precise decision-making for the upcoming large-scale transformation of the power sector in the context of carbon neutrality: the spatial-temporal resolution of the current analysis requires improvement, and the parameters, especially the learning curve, needs updating to reflect the current industry trend. Scientific deployment of wind energy capacity requires an in-depth and precise understanding of spatial difference and temporal evolution of resource availability and economic competitiveness with fine resolution and updated parameters. This paper makes several contributions: (1) Precise estimation of learning rate. The learning rate of China's onshore wind power reflecting the most recent cost trend and the technology progress of the wind industry was estimated with an extensive dataset covering the large-scale deployment period from 2013 to 2020; (2) Detailed assessment of spatial and temporal variations. The spatial difference and temporal changes of the technical and economic potential of China's onshore wind were assessed with high-resolution data, laying a solid foundation for planning the wind power capacity and the power system design; (3) Grid parity analysis. When, where, and to what extent that onshore wind in China could achieve grid parity relative to coal power was examined annually from 2020 to 2060 with fine spatial resolution; (4) Insights for policy and deployment. Our research comprehensively analyzes wind power's technical potential, cost competitiveness, and grid parity status. These insights will contribute to the energy policy design and wind project deployment under the carbon neutrality goal.

3. Material and methodology

3.1. Data

The database in this study was derived from the Goddard Earth Observing System Model, Version 5 (GEOS-5) FP Atmospheric Data Assimilation System (ADAS) by NASA as well as the Global Wind Atlas (GWA) version 3.0 [60,61]. In a couple of studies [56,62,63], the GWA dataset was applied to correct wind speeds with its high spatial accuracy. The study thus adopted long-term mean wind speed data from the Global Wind Atlas version 3.0 with a spatial resolution of 0.25 km. The data was rescaled to 0.0625° longitude by 0.0625° latitude to facilitate the calculation. As the GWA is static in time, the temporal evolutions of wind data were obtained by calibrating the hourly GEOS-FP wind speed data with a fixed scale factor to ensure that the mean value of the hourly data is consistent with the GWA data for each data cell. To do this, hourly GEOS-5 wind speed was obtained by averaging the temporal variation for a five-year interval from 2015 to 2019. The temporal characteristics of GEOS-FP data available at a spatial resolution of 0.3125° longitude by 0.25° latitude were applied to the calibration through spatial interpolation of the GEOS-FP data to match the resolution of GWA data. The calibrated hourly wind data with a spatial resolution of 0.0625° longitude by 0.0625° latitude thus has both high temporal and spatial resolution and further input to estimate wind energy in this study.

3.2. Power generation

To calculate the wind power generation, we estimated hourly wind speeds at 100 m, which is the appropriate hub height for GE 2.5 MW turbines, using a vertical power law profile [64]:

$$V(z) = V_{50}\left(\frac{z}{z_{50}}\right)^{\alpha} \tag{1}$$

where z and z_{50} are the turbine hub height and reference height of 50 m; $V(z)$ and V_{50} indicate hourly values of the wind speed at the turbine hub height and 50 m; and α defines the friction coefficient, a parameter varying as a function of the terrain where wind farms are located. Instead of taking a value of 1/7 as a rough approximation for α, we apply equation (1) based on the wind speeds at 10 and 50 m to estimate the value of α for each hour at each grid cell of the GEOS-5 FP domain [65].

Wind speeds in the power curves were adjusted according to the formula [55]:

$$V_{\text{corrected}} = \left(\frac{P}{1.225RT}\right)^{\frac{1}{3}} \times V_{\text{original}} \tag{2}$$

where P and T identify the air pressures and temperatures at the hub height, which were collected from the GEOS-5 FP data; R is the atmospheric gas constant as 287.05 N m kg^{-1} K^{-1} for dry air.

The wind power outputs were calculated by the power curve appropriate for GE 2.5 MW turbines. The power curve for the GE 2.5 MW wind turbine was used to convert wind speeds to turbine outputs. The hub height and rotor diameter of this land-based wind turbine are 100 m; cutting-in, rated, and cutting-out wind speeds of 3.5, 12.5, and 25 m s^{-1}, respectively. Following Lu et al. [66], we assumed an area for individual turbines of 5 × 10 rotor diameters (0.5 km^2), with an estimated power loss of 10%. Such configuration considered the wake effect on wind speed by interactions among individual turbines [64]. In the analysis, forested areas, areas covered by water and permanent snow or ice, and urban or developed regions [66,67] were excluded. We also excluded regions with slopes exceeding 20% or capacity factors falling below 18%. Topographic data were derived from the Global Digital Elevation Model (GTOPO30) of the Earth Resources Observation and Science Data Center of the U.S. Geological Survey [68]. Land use data were derived from the Moderate-Resolution Imaging Spectroradiometer (MODIS) with a spatial resolution of 1 km × 1 km [69].

3.3. Economic cost

3.3.1. Learning curve approach

The learning curve is widely used to illustrate the effects of technology learning on the initial costs of wind power [70–72]. The basic one-factor learning curve assumes that the cost declines with the enlarged accumulated capacity [31,33]. Such learning-by-doing (LBD) effect helps analyze the quantitative relationship between the initial capital costs and cumulative capacity over time. The one-factor learning curve for wind power can be expressed as:

$$C_t = C_0\left(\frac{CC_t}{CC_0}\right)^{-\beta} \tag{3}$$

where C_t and C_0 are the unit capital installed cost in the year t and the initial year; CC_t is the cumulative installed capacity in the year t; CC_0 is the initial installed capacity; β is the learning-by-doing coefficient. We use continuous data from 2013 to 2020 to estimate the learning rate (Table S1, Supplementary Material, Note 2) [73]. As the learning rate (LR) indicates the cost reduction with each doubling of cumulative installed capacity [31], the relationship between β and LR is as follows:

$$\text{LR} = 1 - 2^{-\beta} \tag{4}$$

The learning coefficient β is evaluated to be 0.8274, corresponding to a learning rate of 43.6%, and the R-Square is 0.94. To project future capital cost, the study adopts future capacity projections from averages of several forecasts [74].

While learning-by-doing effects, which have been examined in the analysis, are recognized as the predominant method for modeling the cost dynamics of wind power, it is crucial to acknowledge the existence of other influential factors. These factors may include, but are not limited to, research and development investment, exchange rates, and key materials prices [74]. To further investigate the impacts of these factors, two or multi-factor learning curve methods could be utilized. By incorporating these additional variables, a more comprehensive understanding of the cost dynamics of wind power can be achieved.

3.3.2. Levelized cost of electricity

Levelized cost of electricity refers to the lowest feasible prices at which developers could deliver wind-generated electricity to the grid and make a certain level of profits. The Net Present Value (NPV) model was adopted to account for all discounted cash flows associated with the wind power project in China. The threshold LCOE for any grid cell can be found where the NPV of wind power projects, including all revenues and costs over their lifetimes and a predetermined return on investment, equals zero [66]. The NPV model was applied for each grid cell from 2020 to 2060, enabling the generation of a dynamic spatial distribution of LCOE (Supplementary Material, Note 3). The equation to calculate NPV can be written as:

$$NPV = \sum_{t=1}^{T} \frac{Cash_t}{(1 + r_d)^t} \quad (5)$$

where NPV is the net present value; $Cash_t$ is the cash flow in each year t; r_d is the discount rate, which is equal to the internal rate of return when the NPV is 0; T is the total lifetime of the project, which is set as 26 years (one year of construction and 25 years of operation); and t is the number of the year. The $Cash_t$ flow includes six aspects: the annual revenue (R_t), the inflow of loan fund ($Debt_t$), initial capital costs (C_t), repayment of the loan and interest ($Loan_t$), the costs of operation and maintenance (OM_t), and payment of taxes (Tax_t). Each year, the future cumulative installed capacity of onshore and offshore wind power was estimated according to the growth rates projected by the Global Energy Interconnection Development and Cooperation Organization (GEIDCO) [75]. By 2030, 2050, and 2060, the cumulative wind capacity is projected to reach 800, 2200, and 2500 GW, respectively. Specifically, the onshore wind power capacity is expected to increase to 745, 2068, and 2341 GW in 2030, 2050, and 2060, respectively (Table S2, Supplementary Material, Note 4). The installed capacity in years between was estimated, assuming the same annual growth rate between the intervals.

3.4. Grid parity status

Coal power has been the major form of power source in China, and its price often served as a benchmark for evaluating the economic viability of wind power [76]. Grid parity time (GPT) suggests when the wind electricity generation cost can compete with on-grid coal power price [40]. In addition to assessing the GPT for each grid cell, we also used the grid parity index (GPI) to measure the cost competitiveness of wind power relative to coal power. The GPI can be calculated with the following equation:

$$\mathrm{GPI} = \frac{\mathrm{WP}}{\mathrm{CP}} \quad (6)$$

where WP is the LCOE of wind power; CP is the local on-grid desulfurized coal power price. When the wind power price is less than or equal to the coal power price, i.e., GPI ≤ 1, wind power reaches grid parity and thus is economic-competitive. A lower GPI value signifies a higher level of competitiveness for wind power when compared to coal power. The total technical potential with cost-competitive wind power prices is defined as the parity potential.

4. Results

4.1. Technical potential

Fig. S1 (Supplementary Material, Note 1) shows the onshore wind power technical potential. The total wind technical potential in China amounts to 53.9 PWh, equivalent to approximately 7.2 times the electricity consumption in 2020 [21]. The Three North (Northeast, Northwest, and North China) region accounts for 74% of the national power generation potential, and the respective power generation potentials of North China, Northeast China, and Northwest China are all over 11.5 PWh. Nei Mongol, which spans Northeast China and North China, has an onshore wind power generation potential of 14.7 PWh, equivalent to 27.2% of the national total. The power generation potentials of the Northeast, North China, and Northwest regions are about 25, 6, and 20 times the total regional electricity consumption in 2020. Xizang holds an onshore wind power generation potential of 8.3 PWh, accounting for 15.5% of the national total and far exceeding its electricity demand in 2020 (8.2 TWh). In contrast, the power generation potential of onshore wind power in the eastern and central regions is relatively limited. The power generation potential of Central China, East China, and South China is about 5.7 PWh, accounting for only 10.5% of the national total. Due to the high population density and high electricity demand in Eastern and Southern China, the power generation potential in 2020 is only equivalent to the regional electricity demand.

Regarding the installed capacity potential, the national potential is estimated at 22 TW. The installation target under carbon neutrality of at least 2340 GW in 2060 represents only 10.7% of the available technical potential [75]. The top five provinces with the highest installed capacity potential include Nei Mongol, Xizang, Xinjiang Uygur, Qinghai, and Heilongjiang. Each province has a potential of over 1.28 TW, accounting for 70% of the national total. The installed capacity potential of the Northwest region is as high as 7.05 TW, equivalent to 32.1% of the national total. Northeast China, North China, and Xizang account for 20.0%, 18.9%, and 16.0% of the national total, respectively. With limited land suitable for installation, the capacity potential of Central China, East China, and South China together only accounts for 12.9% of the national total.

The capacity factor is the ratio of the hourly output to the nameplate power. The annual average capacity factor distribution reflects the wind resource availability (Fig. S2, Supplementary Material, Note 1). The average capacity factor of wind power generation at a height of 100 m above the ground is about 27.2% after excluding regions considering geographical constraints and wind energy resource limitations. In 2060, the electricity consumption is projected to grow to 17 PWh [21]. Using onshore wind power to meet 50% of the year's power demand would require deploying about 3567 GW of turbine capacity, assumed with the national average capacity factor, representing 16.3% of the total technical installed capacity potential in 2020. Generally, wind potentials with high CF are mainly concentrated in three areas: the North Three regions, the southeastern coastal area, and the hinterland of the Qingzang Plateau. The capacity factors for the North China, Northeast China, and Northwest regions averaged 30.8%, 30.2%, and 25.7%, respectively. Influenced by terrain and monsoon, Nei Mongol is endorsed with potentials with an average CF of 33.5%. The CF of most wind energy resources in Heilongjiang, western Jilin, and the coastal areas of Liaodong Peninsula are above 35%. The CF of wind energy resources in the coastal areas of East China is also higher than 30%. Most of Xizang has abundant wind energy resources, especially the northern Qingzang Plateau and the Himalayas region. However, the average capacity factor of Central China, East China, and South China is only about 22.5%.

4.2. Economic feasibility

The spatial distribution of LCOE of wind power in 2020, 2030, and 2060 is shown in Fig. S3 (Supplementary Material, Note 1). The LCOE ranges from CNY 0.21 to CNY 0.53 kWh^{-1} (2020 constant value, the same as below) nationally in 2020. The national average LCOE is about CNY 0.39 kWh^{-1} (Fig. S3a, Supplementary Material, Note 1). The spatial distribution of LCOE is contrary to that of the capacity factor. Regions with higher capacity factors tend to have lower prices. The low-price areas are mostly located in the Three North regions, especially in northern North China and western Northeast China, as well as Xizang and the coastal regions of East China. The LCOE of wind power is expected to decline in the future. Figs. S3b and c (Supplementary Material, Note 1) shows the declining trends for wind power, with the map representing the spatial difference within the nation. In 2030 and 2060, the average LCOE for onshore wind power in China is expected to drop to CNY 0.30 and CNY 0.21 kWh^{-1}, respectively, 23.1% and 46.2% lower than in 2021. The spatial difference in LCOE across the nation declines from CNY 0.24 kWh^{-1} in 2021 to CNY 0.15 kWh^{-1} in 2060. Compared to other regions, China has a higher average LCOE than Russia and Canada, indicating the relatively favorable wind resource conditions in those countries [56]. However, China's LCOE is lower than that of the European Union, the United States, India, and South East Asia (Table S8, Supplementary Material, Note 7). It is worth noting that while there is currently a gap in absolute numbers, this gap is expected to diminish in the future.

In the base case, we assume that the operation cost remains unchanged at CNY 0.05 kWh^{-1}. However, we also investigated the potential impact on the LCOE for wind power if the operation cost decreases in the future, aligned with the increase in wind power capacity. In scenarios where the operation cost decreases annually by 1% and 2% relative to the 2020 level [77], the projected LCOE range in 2030 decreases from CNY 0.167–0.402 kWh^{-1} to CNY 0.162–0.397 and CNY 0.157–0.392 kWh^{-1}, respectively. This represents an average decrease of 1.67% and 3.35%. By 2060, the average decrease in LCOE resulting from the reduction in operation cost is projected to be 9.35% and 18.71% in respective scenarios (Table S7, Supplementary Material, Note 6).

The technical potential with a price lower than or equal to a given price is defined as the economic potential. The wind LCOE and the corresponding wind economic potential up until 2060 were demonstrated in the supply curve of Fig. 1. Taking the average on-grid price of CNY 0.37 kWh^{-1} of onshore wind power in 2020 as a reference, the economic potential of onshore wind power in 2020 reaches 31.4 PWh (Fig. 1a). The Northeast region has the highest economic potential of 9.6 PWh, accounting for 30.7% of national total. The Northwest and North China regions each hold economic potentials higher than 7 PWh, accounting for 25.0% and 27.3% of the national total, followed by the 4.5 PWh potential of Xizang. The economic potential of the other three regions is about 0.8 PWh, accounting for only 2.6% of the national potential. The supply curve of wind power moves downward gradually, suggesting that wind power potential could be accessed at a lower cost in the future (Fig. 1b). In 2030, it is estimated that the LCOE of about 2.0 PWh potential is below CNY 0.20 kWh^{-1}, 34.8 PWh below CNY 0.30 kWh^{-1}, and 53.9 PWh below CNY 0.40 kWh^{-1}. By 2060, under the price level of CNY 0.20 and CNY 0.25 kWh^{-1}, the economic potential will reach 29.3 and 50.0 PWh, accounting for 54.3% and 92.7% of the total technical potential, respectively. As indicated in the figure, the rate of decline of the LCOE of wind power will gradually slow down over time.

Driven by the carbon neutrality target, the installed capacity of China's onshore wind power is expected to increase to 745 GW in 2030 and further reach 2340 GW in 2060, up from 271 GW in 2020 (Supplementary Material, Note 4) [75]. Fig. 2 demonstrates the required wind power prices to achieve the installation target for each region from 2030 to 2060. The bars and lines in equivalent colors symbolize the regional installation and the lowest regional wind power LCOE required for the installations, respectively. As the figure suggests, the required price for each region to achieve the installation ranges from CNY 0.19 to CNY 0.28 kWh^{-1} in 2030. North China, Northeast, and Northwest regions hold abundant onshore wind power resources and together are estimated to account for more than 65% of installed capacity after 2030. Required wind power prices will be as low as CNY 0.20, CNY 0.19, and CNY 0.22 kWh^{-1} to achieve installed capacity of 200, 79, and 227 GW in North China, Northeast, and Northwest regions in 2030. To achieve a higher installation target of 608, 294, and 588 GW in those three regions in 2060, the required prices will be CNY 0.16, CNY 0.15, and CNY 0.17 kWh^{-1} for the respective regions. To account for the uncertainty in the regional installed capacity of wind power in the future, which can influence the LCOE required, we examined the variation in LCOE when the installed capacity deviates from the base scenarios with a −10% and +10% variation (Table S3, Supplementary Material, Note 4). The results indicate that the cost of wind power in East China is particularly sensitive to changes in capacity. If the wind capacity increases by 10% or decreases by 10% in 2030, the LCOE in East China is projected to increase by 2.97% or decrease by 0.26%, respectively. The specific cost range under the varied capacity scenarios was included in Table S4 (Supplementary Material, Note 4).

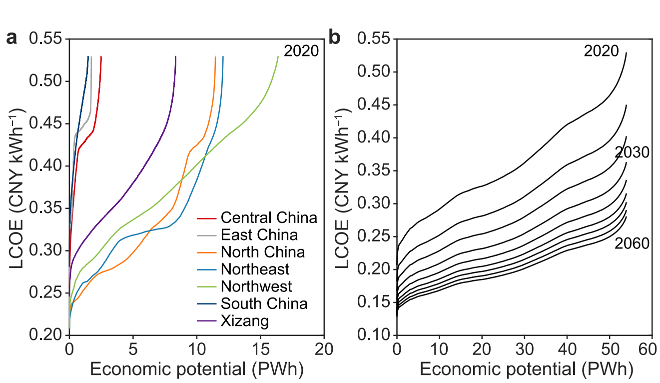

Fig. 1. Supply curves of wind power in China. **a**, The supply curves by regions in 2020. **b**, The supply curves of China's onshore wind power every five years from 2020 to 2060.

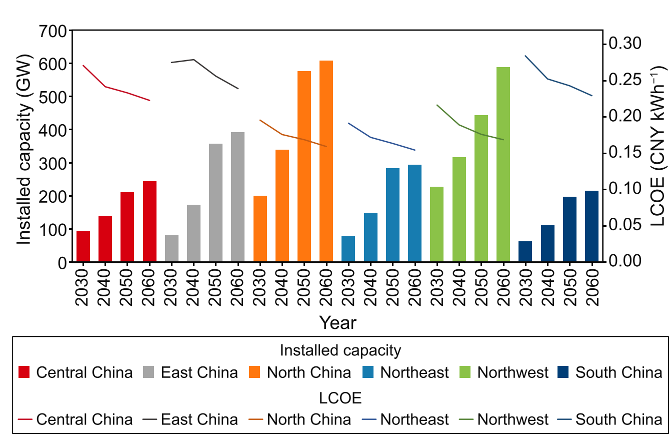

Fig. 2. The predicted levelized cost of electricity (LCOE) to meet the installation target.

4.3. Grid parity competitiveness

The grid parity refers to the status in which wind power could obtain reasonable profits even if purchased at the equivalent price of coal power. Taking the latest coal power on-grid tariff as the comparison benchmark (Supplementary Material, Note 5), the grid parity status of the wind power potential of China was evaluated. The GPT is defined as the time when the wind power price is equal to or lower than the coal-fired benchmark price. The potential to achieve grid parity relative to coal power is parity potential. The ratio of the parity potential to the total technical potential of onshore wind power is defined as the parity ratio. Additionally, the ratio of the onshore wind power price to the coal power price is defined as the GPI to illustrate competitiveness.

There are large differences in the distribution of GPT across the country, mainly due to the difference in wind power resources and coal power prices (Fig. S4, Supplementary Material, Note 1). Coal power prices are higher in the eastern and southern regions and lower in the western and northern regions [78]. Due to the abundant wind power resources, wind power in the Northeast will be able to achieve grid parity by 2024 on an average level. With higher coal-fired power prices, Central China can also achieve grid parity by 2024. The average parity time for East China and North China is expected to fall in 2025 and 2026, respectively. In South China, Guangdong, Guangxi, and Hainan could achieve grid parity earlier than Yunnan and Guizhou despite similar wind power resources attributed to different coal power prices. Due to the lower coal-fired prices, grid parity in the Northwest will not be fully realized until 2038.

The national parity ratio is estimated to be 28.3% in 2020, and parity capacity potential is equivalent to 18 times the installed capacity of the same year. The Northeast region has the highest parity ratio of 63.0%, with about 7.6 PWh technical potential that could achieve grid parity (Fig. 3a). The grid parity potential of North China and Northwest China reached 4.4 and 1.9 PWh, respectively, in the same year, but the parity ratio is only 38.7% and 11.9% due to the huge amounts of technical total. The parity ratios in Central China, East China, and South China are estimated to be 28.3%, 17.1%, and 19.6%, respectively, in 2020. As the LCOE decreases year by year, the economic competitiveness of onshore wind power expands, and the parity potential increases. In 2030, the national parity ratio of onshore wind power will increase to 67.6%. In 2030, the parity ratios in North China, East China, and Central China will be more than 90%. Northwest, Northeast, and South China will increase its parity ratio to 46.8%, 79.0%, and 19.6% during this period. In 2060, the national onshore wind power parity ratio is 97.6%. The parity ratio of onshore wind power for each region will be above 94%.

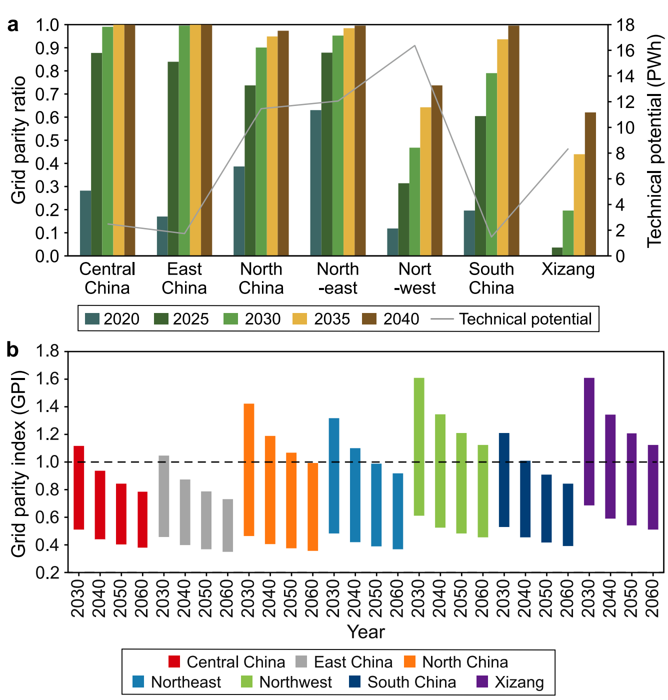

Fig. 3. Evolution of cost competitiveness of wind power over coal power. **a**, Parity ratios of wind power by electric grid regions from 2020 to 2040. **b**, Temporal evolution of Grid Parity Index (GPI). The color bars indicate the range of GPI within each region.

The future price of coal power may be subject to uncertainties arising from factors such as coal price fluctuations and power system marketization. To assess the near-term grid parity potential of wind power, this study examined how it would be influenced by low and high coal power cost scenarios. These cost variations are derived from recent policies that propose dynamic adjustments to coal power prices [79] (Table S5, Supplementary Material, Note 5). Under the low coal power cost scenario (15% lower than the base case), the national total parity potential for wind power is projected to decrease by 51.4% and 37.8% in 2025 and 2030, respectively. Conversely, under the high coal power cost scenario (10% higher than the base case), the national total parity potential is expected to increase by 23.7% and 16.6% in 2025 and 2030, respectively.

Over time, the cost competitiveness of wind energy over coal has shown a steady increase, reflected in the nationwide GPI decrease. As indicated in Fig. 3b, the national mean GPI across the nation decreases from 1.3 in 2021 to 0.98 in 2030 and 0.70 in 2060. The average GPI in 2030 is lowest for Northeast regions at 0.80, followed by Central China at 0.83, and the GPI for the regions is expected to further decrease to 0.58 and 0.59 in 2060. This suggests that the cost competitiveness of wind power over coal power will be further amplified. The ratio of parity potential to projected power demand in each region from 2021 to 2060 was used to demonstrate the supply potential of parity wind power (Supplementary Material, Note 4). For North China, Northeast China, Northwest, and Xizang, the parity potential always far exceeds power demand, although the ratio fluctuates slightly as power demand grows. The ratios for East China, Central China, and South China are always below 1 due to the relative scarcity of the parity potentials in these regions compared to the power demand of the load center.

5. Conclusions and policy implications

In the study, we construct a dynamic integrated model to explore the economic potential and grid parity feasibility of China's onshore wind power. The analysis provides high temporal-spatial resolution assessments of China's onshore wind potential and the grid parity trajectory over the next 40 years. The results offer insights into the economic competitiveness of wind projects and site-selection strategies for large-scale wind power deployment and low-carbon transformation of the power sector. If China installs 745 and 2340 GW of wind power capacity by 2030 and 2060, the installations represent only 3.4% and 10.7% of the capacity potential, respectively. However, deploying the corresponding capacities could supply 2.5 and 6.9 PWh of clean power at a competitive price of less than CNY 0.22 and CNY 0.24 kWh^{-1} in 2030 and 2060, potentially meeting 23.2% and 40.7% of the total electricity demand in those respective years. Furthermore, the future cost competitiveness of wind power may accelerate the penetration of wind power:

First, the decline in wind power cost allows the inter-regional transmission of wind power in northern China to meet power demand in load centers at a competitive price even after accounting for the transmission cost. As the results suggest, the wind parity potentials of South China, East China, and Central China are relatively small compared to the projected local demand. The average wind power price could be averaged at CNY 0.34 kWh^{-1} due to the inferior wind resource in 2030. In contrast, the average LCOE of wind power is CNY 0.29 kWh^{-1} in the same year for the Three North regions. After accounting for the inter-regional transmission costs through ultra high voltage (UHV) lines from Three North regions to load centers (CNY 0.02–0.05 kWh^{-1}) [25,80], the transmitted electricity prices are still lower than or equal to the local wind LCOE and coal-power benchmark prices in South, East, and Central China. Thus, the cost-competitiveness of transmitted wind power over traditional local coal power offers strong momentum for redistributing renewable energy across provinces. Enabling wind power transmission across regions holds the potential to fully exploit the wind power cost advantage and solve the resource endowment and electricity consumption mismatch. Such redistribution of power could help alleviate the power curtailment issues in Northwest regions due to the oversupply. In the meantime, such transmission may help mitigate the variability of wind power when integrating multiple wind power bases with varied variability characteristics [81].

Secondly, the cost advantage of wind power lays the foundation for properly managing its variability to better match the power demand. The effective use of energy storage technology has been promoted in reducing the variability of wind power and improving power grid flexibility [46,82,83]. Currently, the incorporation of storage facilities will increase the power cost by CNY 0.15 to CNY 0.40 kWh^{-1} [84]. However, along with the cost decline of wind power generation, the cost of various types of storage technology is also expected to fall by 50% and 60% over the next decade [85]. Thus, the combined system of wind and storage may be not only cost-competitive but flexible in the future. Such cost reduction will drive the rapid growth in installed capacity to increase the economies of scale further to benefit the cost decline of wind power.

Accelerating the deployment of wind power requires concerted efforts from both technology and the market. In terms of technology, micro-site selection with favorable wind resources, accurate spacing planning, and selecting suitable turbines are particularly critical to reducing power generation costs. Sensitivity analysis shows that the LCOE is most sensitive to the changes in the capacity factor and the capital investment cost (Supplementary Material, Note 6 and Table S6). Under the change rate of $\pm$20% for the capacity factor and the initial investment cost, the LCOE varies by more than 17%. Besides, it is necessary to increase investments in the research and development of the wind power industry to reduce the initial investment in wind power. Furthermore, non-technical costs, including land use fees and taxes, could be further reduced through policy to accelerate the grid parity of wind power in China [86].

From the market mechanism perspective, wind power's cost competitiveness can be further enhanced by integrating its low-carbon and pollution-free attributes into the pricing mechanism. This integration can be facilitated through policy initiatives, such as the implementation of a green certificate trading system or Chinese Certified Emission Reduction (CCER) [16]. On the other hand, an additional avenue for progress lies in the integration of carbon emissions of traditional coal power into the power pricing structure, potentially through the carbon tax or carbon trading mechanism. Taking the carbon tax mechanism as an example, if a carbon tax is imposed on the power sector, and the price of CO_2 emitted will be charged at CNY 100 ton^{-1} in 2030, the parity ratio of the onshore wind power in 2030 will rise by 67%.

Data and code availability

All data and code are available from the corresponding authors upon reasonable request. Data that support the findings of this study are available within the paper and its Supplementary Material.

CRediT authorship contribution statement

Shi Chen: Conceptualization, Methodology, Software, Formal Analysis, Investigation, Writing - Original Draft, Writing - Review & Editing, Visualization. **Youxuan Xiao:** Conceptualization, Methodology, Software, Formal Analysis, Investigation, Writing - Original Draft, Writing - Review & Editing, Visualization. **Chongyu Zhang:** Writing - Review & Editing. **Xi Lu:** Conceptualization, Methodology, Formal Analysis, Writing - Review & Editing, Visualization, Supervision, Project Administration, Funding Acquisition. **Kebin He:** Conceptualization, Supervision, Project Administration, Funding Acquisition. **Jiming Hao:** Conceptualization, Supervision, Project Administration.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

This work was supported by National Natural Science Foundation of China (72025401, 71974108, 72140003, and 72204132), the China Postdoctoral Science Foundation BX2021148, the Shuimu Tsinghua Scholar Program 2021SM014, the Tsinghua University-Inditex Sustainable Development Fund, the Erdos - Tsinghua University Collaborative Innovation Project, the Tsinghua-Toyota Joint Research Institute Cross-discipline Program.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.ese.2023.100323.

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