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# Optimizing onshore wind power installation within China via geographical multi-objective decision-making

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ABSTRACT

Wind power, a promising renewable energy technology, not only offers an alternative to coal-fired power plants but also brings significant economic and environmental benefits. This study employs the hybrid analysis assessment and multi-objective optimization to propose various wind power schemes for Chinese provinces/municipalities under economic and decarbonization priority scenarios. The findings reveal that the plain wind power scheme in Northeast China presents the largest net economic benefit as well as the net emission reduction potential, ranging from 8.33 to 9.10 million CNY/MW and from 28.91 to 30.03 $ktCO_2$/MW, respectively. Inner Mongolia is projected to be the leading wind power installer between 2021 and 2030, potentially yielding the net economic benefit of 4.76 billion CNY and the net emission reduction potential of 12.50 million tons per year. For provinces with 0-10 $km^2$ of unexploitable land, such as Shanghai, Beijing, and Henan, the average economic benefit is almost less than 100 million CNY, and the average emission reduction is less than 500,000 tons. This study proposes the geographical multi-objective decision-making of different wind power schemes, which attempts to provide practical implications for the rational deployment of wind power installation within China toward low-carbon transition.

## 1. Introduction

Wind power is an alternative to coal-fired power plants in reducing greenhouse gas emissions [1] and one of the most promising renewable energy technologies [2,3]. Global Wind Energy Council (GWEC) predicted that global wind power will grow at a growth rate of 15 %, with a positive medium-term outlook [4]. By the end of 2022, the total installed capacity of wind power in China was 366 GW, accounting for 40 % of the total, and will continue to remain the largest wind power installer in the world [4,5]. Several studies showed that there were significant spatial differences in resource endowments of wind energy in China [6,7], and that there were spatial and temporal correlations in the installed capacity of wind power in various regions [8,9]. However, the inequalities in resource endowments, geographical conditions, and socioeconomic factors may cause difficulties in the rational deployment of wind power stations within different countries and regions [10,11]. In the context of the rapid growth of wind power capacities worldwide, China was a typical case in which to assess the spatial layout and rational deployment of wind power stations.

Although most studies focused on predicting installed wind capacities [12–14], several studies also projected the spatial layout of installed wind capacity mainly based on the historical growth rates of installed wind capacities [15], government targets [16], and wind energy potentials [17]. However, the rational deployment of wind power capacities needs more comprehensive factors, including cost-benefit, emission reduction, geographical conditions, and local government targets. In addition, while other studies assessed the cost-benefit [18,19] and emission reduction effects [20,21] of national wind farms, the economic and emission reduction characteristics of regionally differentiated and typologically differentiated wind farms must be further assessed to provide a database for rational deployment.

Based on the above literature review, some hypotheses are proposed

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to predict future wind power capacities: (a) huge differences existing in the net economic benefits and the net emission reduction potentials between different wind power schemes located in plain, hill, mountain, and complex mountain by province; (b) on the premise of meeting the constraints of wind power planning and available land areas, the government needs to balance economic development, carbon emission reduction, and land use occupation; (c) under the premise of fully considering resource endowments, geographical constraints, and government targets, there are optimized wind power schemes that prioritize the economic benefits as well as the emission reduction potentials under the restrictions of land use areas.

To verify the above assumptions, this study takes Chinese provinces/municipalities to propose different wind power schemes under economic and decarbonization priority scenarios based on the hybrid life cycle assessment and multi-objective optimization. The innovation and contribution mainly lie in the following aspects: (a) this study is to assess the life-cycle economic benefits and carbon emission reduction potentials of wind power stations in consideration of different land terrains including plain, rolling terrain, mountainous, and complex mountain; (b) to propose different onshore wind power schemes by 2030, which takes the maximization of economic benefits, emission reduction, and the minimum land occupation as the objective functions; (c) to incorporate multiple indicators including net economic benefits, net emission reduction potentials, land use areas, geographical terrains, and government planning targets that may affect wind power layout through the multi-objective optimization modeling. The rest of the work is structured as follows: Section 2 reviews the relevant literature. Section 3 presents the employed methodology, Section 4 demonstrates the results, Section 5 discusses the major findings and policy implications, and Section 6 draws conclusions.

## 2. Literature review

The prediction of wind power capacities has been a hot topic in recent years. Generally, the grey model [22], technology diffusion model [23], neural network [24], machine learning [25], MV optimum combined model [26], and mathematical programming [27] are commonly adopted. For example, based on the grey model, Yang et al. [28] used historical wind power capacity data to forecast China's wind power capacity from 2017 to 2025. To predict the installed capacity of China's wind power in 2030, Lu et al. [29] established a dynamic optimization model based on cost minimization with the constraints of wind energy potentials, government targets, and government investment.

Previous studies also predicted the installed capacity of wind power at the provincial level. With the technology diffusion model, Shang and Jie [15] predicted the growth trend of wind power in China's provinces through historical wind power installed capacities and government plannings. Based on scenario analysis, Yu et al. [17] predicted the installed capacity of wind power at the provincial level in China by 2030 and 2060 through government goals and wind energy potentials. With the system dynamics model, Wang et al. [30] predicted the growth trend of wind power in China's provinces through historical wind power installed capacities and wind energy resource potentials. However, the rational deployment of wind power capacities also needs more comprehensive factors, such as cost-benefit, emission reduction, geographical conditions, and local government targets.

Regarding geographical conditions, previous studies predicted wind energy potentials considering suitable land areas for wind power installation. Generally, the Geographic Information System (GIS) and Multi-Criteria Decision Making (MCDM) can be applied to process grid data such as wind speed, terrain, and altitude [31,32]. Among them, Zhou et al. [33] estimated the global onshore wind energy potentials based on the wind speed data, wind turbine technical performance, land suitability factors, and economic costs, emphasizing geographical exclusion based on protected areas, altitude, and suitability. Obane et al. [34] analyzed different land use types in Japan and proposed an axiom of 3428 $m^2$ of total land that could be used for photovoltaic and wind turbine development.

Note that the constraints commonly adopted in previous studies mainly included wind speed constraints [35], capacity factor constraints [36], and geographical constraints such as slope [37], altitude [38], land use type [39], etc. Among them, Genç et al. [40] identified potential sites of wind power with 3 main criteria, i.e., technical (wind speed and water depth), environmental (ship density, cables, bird migrations, etc), and social (visual impacts, legislations, and fishery zones). Feng et al. [41] excluded areas with an altitude of more than 3500 m and a capacity factor of less than 0.2 and set different capacity conversion coefficients for different landforms such as grassland, forest, water, and bare land, considering the capacity conversion coefficient affected by slope. Referring to existing studies, this study selects land use type, topography, wind speed, and population density as constraints on the available land for wind power installation.

There were also studies evaluating the economic features of wind farms. To measure the cost-effectiveness during the construction and operation stages, the levelized cost of energy (LCOE) was adopted to measure the total costs of wind power during the capital recovery period [42]. Wu et al. [43] identified the main factors affecting the implementation of cost control and the hierarchical relationship based on the structural interpretation model (ISM). Noonan et al. [44] and Wiser et al. [45] mentioned that lower costs in the wind power operation and maintenance phases would drive the cost of wind power further down. Shafiee et al. [46] optimized maintenance decision-making and inspection procedures during the wind farm operation and maintenance inspection phase to reduce operational cost-effectiveness. Veers et al. [47] explored potentials for reducing wind power costs and identified the influencing factors such as project location and scale, turbine scale, and operational synergy. Rinne et al. [48] estimated the costs of different wind power technologies and calculated investment costs for comparing turbine models-hub height configurations. Beiter et al. [49] identified expected costs and value drivers to achieve optimal solutions based on a combination of multiple methods. Gao et al. [50] applied the Multi-Population Genetic Algorithm (MPGA) to obtain a minimum energy cost with maximum power generation and optimal offshore wind turbine layout configurations in Hong Kong, China.

Previous studies were also carried out based on the life cycle analysis regarding emission reduction potentials [51]. Among them, Zhao et al. [52] quantified the carbon footprints of coal-fired power plants and wind farms in China based on the life cycle assessment method. Xue et al. [53] analyzed the life cycle of the wind power industry, proposing that wind farms only release 1/40 of the total $CO_2$ emissions generated by coal power generation systems. Feng et al. [54] found that wind energy could save more than 79 % of total life cycle carbon dioxide emissions per kilowatt-hour of power generation by integrating process-based life cycle analysis and input-output analysis. In addition to the life cycle assessment, some other methods were also applied to assess the wind power emission reduction potentials and the synergistic benefits [55,56]. Some studies also evaluated emission reduction efficiency based on the Data Envelopment Analysis model [57], used the method of separating marginal emission displacement of wind power generation [58], or used I–O analysis to evaluate the impacts of wind power generation systems on the environment and economy [59].

## 3. Method and data sources

Fig. 1 presents the multi-objective optimization framework of China's onshore wind power installation. Firstly, the life-cycle economic benefits and net emission reduction potentials of different wind power types by province are assessed based on the hybrid LCA assessments; secondly, available land use areas for different wind power types by province are extracted; thirdly, through net economic benefits, net emission reduction, land use areas, and government planning targets,

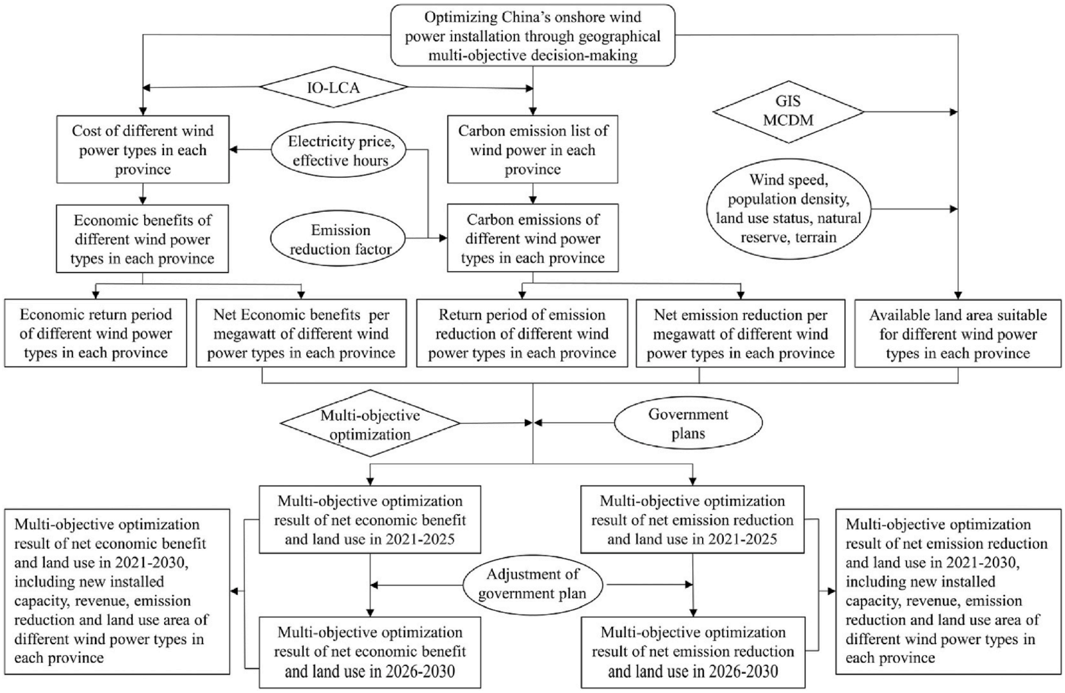



**Fig. 1.** The optimization framework of China's onshore wind power installation.

the spatial-temporal layout of newly installed wind power stations in China was optimized by 2030 with multiple objectives.

### 3.1. Hybrid life cycle assessment

In this study, the life-cycle carbon intensity inventory by province and sector could be derived based on the hybrid life cycle assessment (hybrid LCA). The embodied carbon intensities of the whole life cycle inventory can be calculated as:

$$EE_i = DE_i[I - A_i]^{-1}F_i \tag{1}$$

where, $i$ represents the province, and $i = 1, 2, \ldots, 31$. $n$ represents the sector and $n = 1, 2, \ldots, 42$. $EE = [ee_n]_{42\times1}$, and $ee_n$ represents the carbon emission of sector $n$. Diagonal matrix $DE = [de_n]_{42\times42}$, and $de_n$ represents the carbon emission intensity of sector $n$. $[I - A_i]^{-1}$ denotes the Leontief inverse matrix of province $i$. $F = [f_n]_{42\times1}$, $f_n$ represents the final demand of the sector $n$.

According to Equation (2), the life-cycle carbon emission intensities by province and by sector can be calculated as:

$$EDE_i = EE_iF_i^{-1} \tag{2}$$

where, $EDE_i$ represents the column vector of embodied carbon intensity of the province $i$, and the $n^{th}$ element in the vector represents the embodied carbon intensity of sector $n$.

In this study, the net economic benefits of wind power installation by province can be calculated by deducting the costs from the profits. The economic payback period could be obtained as:

$$B_i = T_i \times P_i \times L \tag{3}$$

$$NB_{ij} = B_i - C_j \tag{4}$$

$$TB_{ij} = \frac{C_j}{T_i \times P} \tag{5}$$

where, i represents the province, i = 1, 2, 3 …, 30, j represents the installed wind power type, j = 1, 2, 3, 4 respectively represent plain, hill, mountain, and complex mountain. B denotes the economic benefits of wind power installation per megawatt, T denotes the annual effective utilization hours of wind power, P denotes the price of wind power generation, L denotes the whole life cycle of wind power stations, generally 20 years. NB denotes the net economic benefits per megawatt, and C denotes the economic cost of wind power installation per megawatt. TB refers to the economic payback period of wind power installation.

This study calculates the carbon emissions of different wind power schemes based on the wind power emission reduction factors by province. The payback period of carbon emissions could thus be calculated as:

$$E_{ij} = \sum_{k=1}^{k} PC_{jk} \times EDE_{ik} \tag{6}$$

$$R_{ij} = T_i \times F_i \times L \tag{7}$$

$$NR_{ij} = R_{ij} - E_{ij} \tag{8}$$

$$TR_{ij} = \frac{E_{ij}}{T_i \times F_i} \tag{9}$$

where, k represents the sector, $PC_{jk}$ represents the economic cost of the $k^{th}$ industry in the $j^{th}$ wind power scheme, $EDE_{ik}$ represents the carbon intensity of the $k^{th}$ industry in the $i^{th}$ province, E denotes carbon emission, R denotes emission reduction potential, $F_i$ denotes the emission reduction factor of wind power stations in province i, NR denotes net emission reduction, and TR refers to the payback period of carbon emission reduction.

### 3.2. Multi-objective optimization

Based on the multi-objective optimization, this study conducts the multi-objective optimization of wind power installation considering the net economic benefits, the net emission reduction, land use areas, and government planning targets. In this study, objective functions considering net economic benefits, emission reduction potentials, and land use areas are respectively as:

$$min\sum_{i=1}^{30}\sum_{j=1}^{4}-\alpha NB_{ij}^{'}X_{ij}+(1-\alpha)S_{j}^{'}X_{ij} \tag{10}$$

$$min\sum_{i=1}^{30}\sum_{j=1}^{4}-\beta NR_{ij}^{'}X_{ij}+(1-\beta)S_{j}^{'}X_{ij} \tag{11}$$

where, S′ is the normalized land use area per megawatt, NB' is the normalized net economic benefit, NR' is the normalized net emission reduction, and X is the newly installed wind power capacity. α reflects the relative weight of the net economic benefits, and β reflects the relative weight of the net emission reduction, α, β∈[0, 1].

Wind power installation is mainly subject to the constraints of land areas and government planning targets. The specific constraints are as follows:

$$\begin{cases} PLmin_i \leq \sum_{j=1}^{4} X_{ij} \leq PLmax_i, i=1,2,...,30 \\ 0 \leq X_{ij} \leq TS_{ij}/S_j, i=1,2,...,30, j=1,2,3,4 \\ \sum_{i=1}^{30}\sum_{j=1}^{4} X_{ij} \geq TPL, i=1,2,...,30, j=1,2,3,4 \end{cases} \tag{12}$$

where PL is the local government's wind power planning target. Regarding the average achievement of provincial planning targets for wind power during the 13th Five-Year Plan, this study assumes that the installed capacities of wind power float in the range of 30 % [60]. S denotes the number of megawatts per area, and TS denotes the unused land area that is suitable for wind power installation. If the maximum exploitable wind power capacity of a province is less than 0.7 times the government planning target, this study assumes that the province tends to exploit all the available land areas suitable for wind power installation. TPL is the national wind power planning target. According to the Beijing Declaration on Wind Energy, 250 GW of new wind power capacity will be installed from 2021 to 2025 and 300 GW from 2026 to 2030.

Assume that the unused land areas suitable for wind power development by 2025 and 2030 are $TS^1$ and $TS^2$ respectively, and the newly installed capacities are $X^1$ and $X^2$, respectively. The relationship between $TS^1$ and $TS^2$ can be presented as:

$$TS_{ij}^{2}=TS_{ij}^{1}-S_{j}X_{ij}^{1} \tag{13}$$

Assume that the upper limit of multi-objective optimization by 2025 and 2030 are $PLmax^1$ and $PLmax^2$ respectively, and the lower limit is $PLmin^1$ and $PLmin^2$ respectively, $PLmax^2$ and $PLmin^2$ can be calculated as:

$$PLmin_i^2 = min\left\{1.2\times PLmin_i^1, \frac{\sum_{j=1}^{4}TS_{ij}^2}{\sum_{i=1}^{30}\sum_{j=1}^{4}TS_{ij}^2}\times 0.7\times TPL\right\} \tag{14}$$

$$PLmax_i^2 = max\left\{1.2\times PLmax_i^1, \frac{\sum_{j=1}^{4}TS_{ij}^2}{\sum_{i=1}^{30}\sum_{j=1}^{4}TS_{ij}^2}\times 1.3\times TPL\right\} \tag{15}$$

### 3.3. Data sources

To calculate the economic benefits of different wind power schemes, the equipment inputs for the wind power stations with an installed capacity of 2.50 MW in different terrains are derived from the Cost Controlling Indexes of Wind Power Engineering in the State Power Investment Corporation Limited (2019). The effective utilization hours of wind power by province are the average value of the effective utilization hours of wind power by province from 2013 to 2019 issued by the National Energy Administration. The electricity price data by province in 2020 are derived from the Guidance Prices for Newly Installed Photovoltaic Power Generation and Wind Power Projects issued by the National Development and Reform Commission in 2021. All the economic data are converted to the 2020 price based on the GDP deflator.

To calculate embodied carbon intensities, China's input-output tables of 31 provinces/municipalities are derived from the official websites of Provincial Statistics Bureaus. The sectoral $CO_2$ emission data by province are from the China Carbon Emission Accounting Database (CEADs). Regarding wind power emission reduction potentials by province, the carbon emission reduction factors by province come from China's regional power grid emission factors published by the Ministry of Ecology and Environment of China.

For unused land use areas that are suitable for wind power development, China's 1 × 1 km land use data in 2020 are from the Resource and Environment Science Data Center of the Chinese Academy of Sciences. The topographic layer is derived from the China Digital Elevation Map (1 km) released by the National Qinghai Tibet Plateau Science Data Center. 1 × 1 km population density data in 2020 comes from the WorldPop website, and 1 × 1 km grid data of annual mean wind speeds at a height of 100 m in 2020 comes from the annual report on China's wind and solar energy resources in 2021. China's provincial wind power planning targets are summered based on the 14th Five Year Planning and Renewable Energy Development Planning by province.

The layout of wind power installation is restricted by a variety of factors: (1) land use type: unused land except for marsh (sand, gobi, bare land, bare rock, saline, etc.), excluding nature reserves; (2) topography: the height difference within 1 $km^2$ is less than or equal to 450 m; (3) population density: less than or equal to 700 people/$km^2$ [61]; (4) wind speed: wind speed at 100 m height is greater than or equal to 6 m/s [62]. Compared with the wind speed at 70 m height generally used and the requirements of wind speed and wind power density in the Wind Farm Wind Resource Evaluation Method published in 2002, the limit of high-altitude low wind speed adopted in this study could better match the reality. Referring to the Wind Power Engineering Design Cost Control Index (2019), the unused land types suitable for wind power installation are divided into plain, hill, mountain, and complex mountain, i.e., land areas with relative elevations of 0-50 m, 50–150 m, 150–300 m, and 300–450 m in 1 $km^2$ respectively.

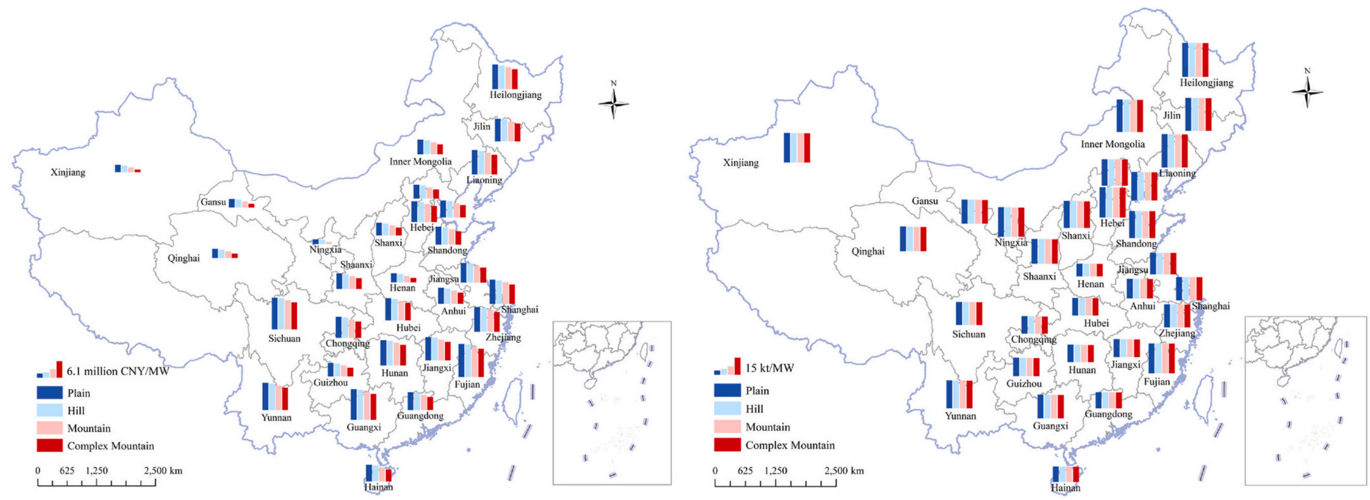
For the multi-objective optimization, the megawatts per area of wind power installation in plain terrain in this study is calculated by referring to the megawatts per area of the wind power station in plain terrain in the Land Use Indexes of Electric Power Engineering (wind farm), which is 415.89 MW/$km^2$. Considering that the more complex the terrain is, the larger the land use area of wind farms with the same installed capacity, this study assumes that the MW per unit area of wind power installation in hilly terrain is 0.9 times that in plain terrain, the MW per unit area of wind power installation in mountainous is 0.9 times that in hilly terrain, and the MW per unit area of wind power installation in complex mountainous is 0.9 times that in mountainous terrain.

## 4. Results

From the results, the life-cycle economic benefits and net emission reduction potentials of different wind power schemes within China are analyzed, and the spatial layout of China's wind power is proposed and compared by 2030 under different priority scenarios.

### 4.1. Life-cycle assessments of wind power installation

Based on the hybrid life cycle analysis and the input inventories of different wind power types, the net economic benefits and net emission reduction potentials of wind power installation by province are assessed and compared in Fig. 2 and Tables S1–S2. From Fig. 2 (a), the net




(a) Net economic benefits (b) Net emission reduction

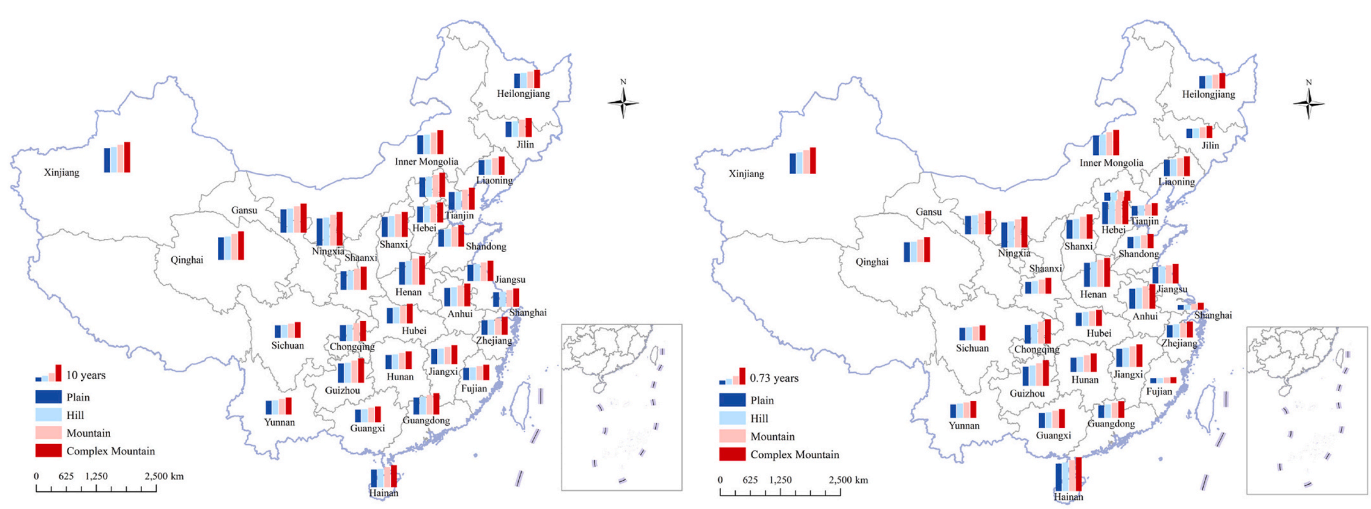
**Fig. 2.** The economic benefits and emission reduction potentials of wind power installation by province. Note: GS(2020)4619.

economic benefit of wind power installation in Fujian's plain terrain is the highest, at 12.14 million CNY/MW. The net economic benefit of wind power stations in Ningxia's complex mountain is the lowest, at nearly 0 million CNY/MW. The top three provinces regarding the average net economic benefit per megawatt are Fujian, Sichuan, and Guangxi, which are 11.40, 10.88, and 10.54 million CNY/MW, respectively. The last three provinces with the average net economic benefits are Ningxia, Xinjiang, and Gansu, which are 1.01, 1.97, and 2.42 million CNY/MW. The highest net economic benefit is 8.06 million CNY/MW in Northeast China, closely followed by 7.86 million CNY/MW in Southwest China and 7.61 million CNY/MW in East China. The lowest net economic benefit per megawatt in Northwest China is at 2.60 million CNY/MW. Regarding different wind power schemes by province, the net economic benefit of wind power stations in the plain terrain is higher than that in rolling terrain, mountainous, and complex mountains, which are 6.99, 6.74, 6.04, and 5.25 million CNY/MW, respectively.

From Fig. 2 (b), the net emission reduction potential of wind power station in Heilongjiang's plain terrain is the highest, which is 30.03 kt/MW, while the net emission reduction of wind power station in Henan's complex mountain terrain is the lowest, which is 11.03 kt/MW. The top three provinces in terms of average net emission reduction are Heilongjiang, Liaoning, and Jilin at 29.92, 29.30, and 28.80 kt/MW, respectively, while the last three are Guangdong, Hainan, and Henan at 14.11, 13.46, and 11.14 kt/MW, respectively. The average net emission reduction in Northeast China is the highest, at 29.34 kt/MW, followed by Northern China at 25.36 kt/MW and Northwest China at 23.21 kt/MW. The net emission reduction of wind power stations in Central China is the lowest, at 13.96 kt/MW. Regarding different wind power schemes, the average net emission reduction in plain terrain is higher than that in rolling terrain, mountain terrain, and complex mountain terrain, which are 21.41, 21.36, 21.27, and 21.16 kt/MW, respectively.

### 4.2. *Economic and environmental payback periods of wind power installation*

By balancing initial inputs in the construction stage and continuous outputs in the operation stage, the payback periods for wind power installations' economic benefits and carbon emissions are further presented in Fig. 3 and Tables S3–S4. From Fig. 3 (a), the economic payback period of different wind power schemes by province ranges between




(a) Economic payback period (b) Emission reduction period

**Fig. 3.** The economic payback periods and emission reduction periods of wind power installation by province. Note: GS(2020)4619.

7.26 and 20.00 years. Among them, the economic payback period for wind power installation in Fujian's plain terrain is the smallest, and the economic payback period for Ningxia's complex mountain is the largest. The last three provinces in terms of average economic payback period are Fujian, Sichuan, and Guangxi, which are 8.03, 8.26, and 8.41 years, respectively. The top three provinces in terms of average economic payback period are Ningxia, Xinjiang, and Gansu, respectively 17.68, 15.90, and 15.20 years. The economic payback period in Northwest China is the longest, at 15.16 years. Central China and North China are closely followed, at 11.50 and 12.10 years. The economic payback period in Northeast China is the shortest, at 9.74 years. Regarding different wind power schemes, the economic payback period of the plain terrain is less than that of the rolling terrain, mountain terrain, and complex mountain, which are 10.34, 10.72, 11.76, and 12.95 years, respectively.

From Fig. 3 (b), the emission reduction periods of different wind power schemes by province range from 0.20 to 1.47 years, among which Shanghai's plain terrain is the shortest, while Hainan's complex mountain terrain is the longest. The last three provinces in terms of average emission reduction period are Fujian, Shanghai, and Beijing, which are 0.23, 0.24, and 0.39 years, respectively. The top three provinces in terms of average emission reduction period are Hainan, Ningxia, and Henan, which are 1.31, 1.19, and 1.14 years respectively. The average payback period for wind power stations in Northwest China is the longest, 0.92 years, followed by 0.89 and 0.82 years in Southern and Central China, respectively. The average payback period for wind power stations in Eastern China is the shortest, 0.61 years. Regarding different wind power schemes, the emission reduction period of wind power stations in plain terrain is smaller than that in rolling terrain, mountain terrain, and complex mountain terrain, which are 0.68, 0.71, 0.78, and 0.86 years, respectively.

### *4.3. Multi-objective optimization in economic priority scenarios*

The multi-objective optimization of net economic benefits and land use areas by province are depicted in Fig. 4 and Tables S5–S7. When the net economic benefit weight is less than 0.63, the newly installed capacity is at the lowest level, while the land use area will increase slightly, which indicates that the wind power installation in hilly, mountainous, or complex mountainous in provinces with a higher level of net economic benefit may replace the plain wind power installation in provinces with a lower level of net economic benefits. When the net economic benefit gradually increases, the net emission reduction potentials tend to decrease first and then increase. Although the net economic benefit of wind power installation in some provinces is relatively high, the net emission reduction of wind power construction is relatively low.

From Fig. 4, Heilongjiang's newly installed wind power capacities maintain 13.00 GW by 2025 and 15.60 GW by 2030. The newly installed wind power capacities in Shanghai and Chongqing remain at 0 GW until 2030. Even though the newly installed capacity of 0.40 GW appears in Henan and Hubei's hill terrain by 2025, it still could not meet the government's planning targets. The newly installed wind power capacities in Gansu's plain terrain suddenly change from 17.36 GW to 32.24 GW by 2025 when the net economic benefit weight is 0.75, and the newly installed wind power capacity in Gansu's plain terrain changes from 20.83 GW to 50.24 GW by 2030, when the net economic benefit weight is 0.76. The newly installed wind power capacity in Sichuan's hills will increase from 4.50 GW to 10.50 GW when the net economic benefit weight is 0.12 by 2025 and from 0.93 GW to 15.60 GW when the net economic benefit weight is 0.12 by 2030. Meanwhile, Shanxi and Jiangsu's newly installed wind power capacity will be less than 0.01 GW by 2030, with a continuous downward trend. As the weight of net economic benefits increases, the newly installed wind power capacities in Qinghai's plain terrain decrease from 21.53 GW to 13.26 GW and then increase to 24.63 GW by 2025, while the newly installed wind power capacities in Qinghai's plain terrain increase from 15.91 GW to 53.23 GW by 2030.

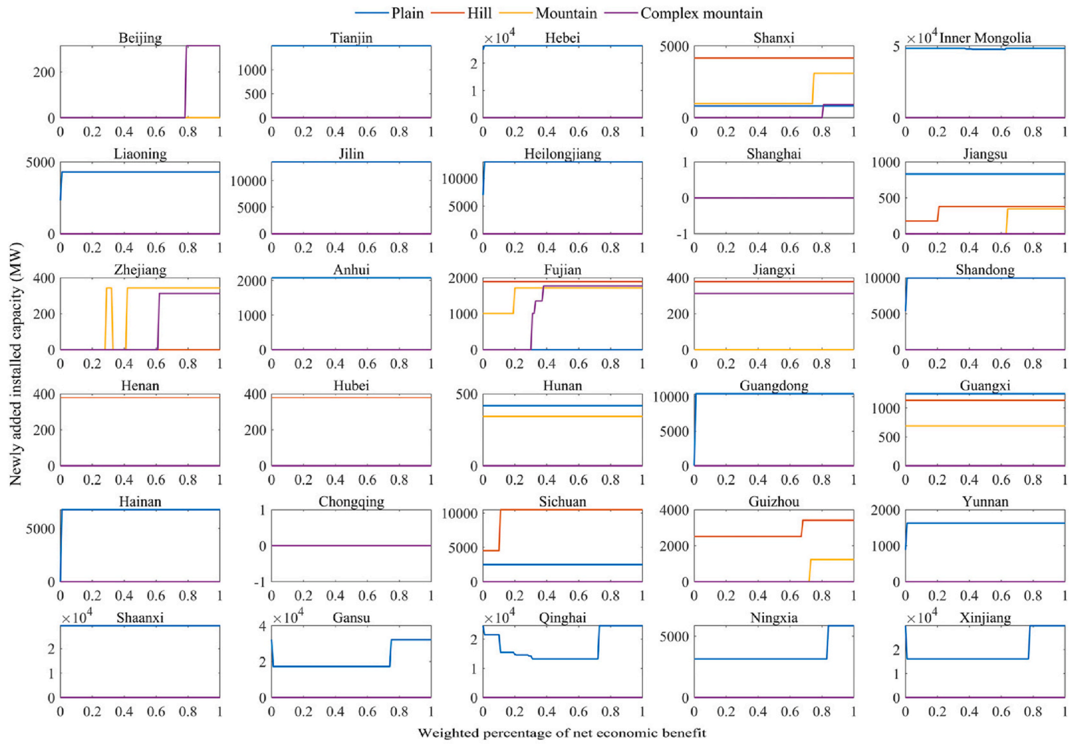
### *4.4. Multi-objective optimization in decarbonization priority scenarios*

Considering the decarbonization priority scenarios with different weight coefficients, the multi-objective optimization of the net emission reduction and land use areas by province are depicted in Fig. 5 and Tables S8–S10. Although there are disparities between different scenarios, the wind power installation schemes maintain the same weight when the net emission reduction and net economic benefit are 1 due to the hypothesis that all provinces will develop wind power to the greatest extent. Specifically, the newly installed wind power capacity in Gansu's plain suddenly changes from 17.36 GW to 32.24 GW by 2025 when the net emission reduction weight is 0.59, and the newly installed wind power capacity in Gansu's plain changes from 20.83 GW to 50.24 GW by 2030 when the net emission reduction weight is 0.60. As the weight of net emission reduction increases, the newly installed wind power capacities in Shanxi and Jiangsu will gradually decrease by 2030. The newly installed wind power capacity in Sichuan's hills will increase from 4.50 GW to 10.50 GW by 2025 when the net emission reduction weight is 0.65 and from 0.93 GW to 15.60 GW by 2030 when the net emission reduction weight is 0.65. As the weight of net emission reduction increases, the newly installed capacities of wind power in Qinghai's plain terrain will decrease from 22.19 GW to 19.97 GW and then increase to 24.63 GW, while the newly installed capacity of wind power will increase from 15.91 GW to 53.23 GW by 2030.

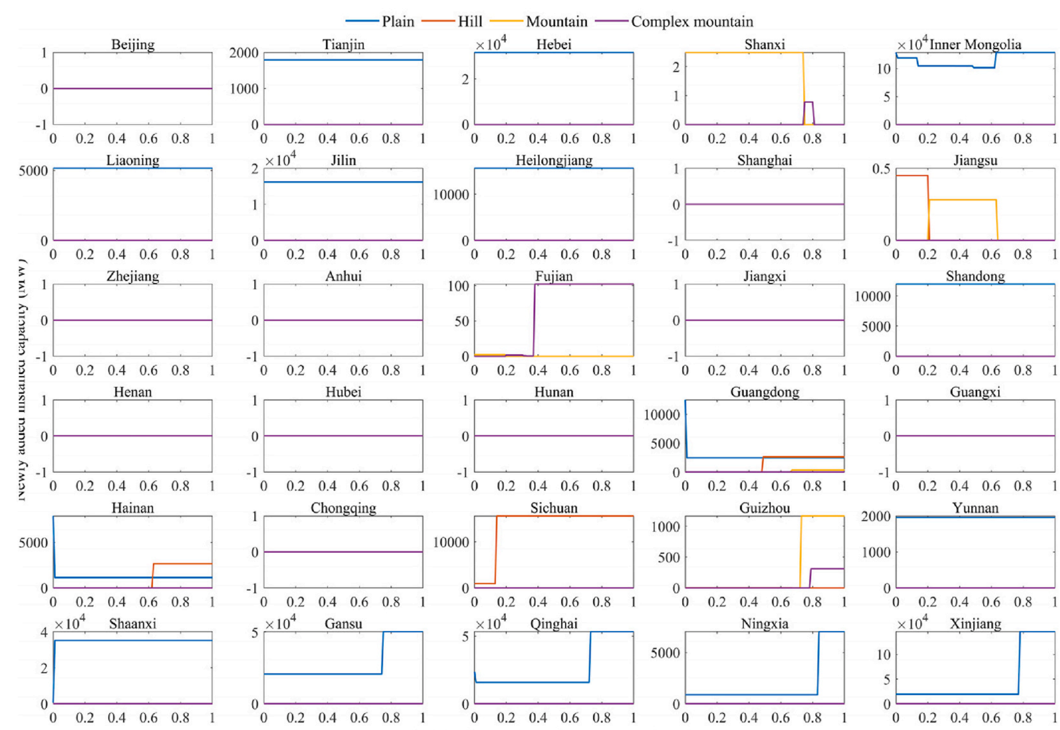
## 5. Discussion and policy implications

Considering different priority scenarios with a weight coefficient of 0.75, Table 1 presents net economic benefits and emission reduction potentials of different wind power schemes from the life cycle perspective. The total available area within China is 650,000 km$^2$, of which provinces/regions in northern China, such as Inner Mongolia and Xinjiang, occupy more than 70 % of the national total. The available areas of 11 provinces/municipalities are within 10 km$^2$, including Shanghai, Jiangsu, and Hubei, which are mainly located in East and Central China. Available land areas of wind power in different topographies of China's provinces/municipalities can be found in Table S11. In the economic priority scenario, Inner Mongolia has the largest annual economic benefit, with an average of 1.79 billion CNY in 2025 and 7.74 billion CNY in 2030. Qinghai, Gansu, Hebei, Shaanxi, and Heilongjiang are closely followed, ranking among the top in the annual economic benefits of wind power installations, mainly located in Northwest China, North China, and Northeast China. In the decarbonization priority scenarios, Inner Mongolia and Xinjiang occupy the top two emission reduction potentials, with 5.08 and 2.78 million tons in 2025 and 19.92 and 16.74 million tons in 2030. Gansu, Qinghai, Shaanxi, Hebei, and Heilongjiang are closely followed, mainly in the Northwest, North, and Northeast China. Especially for provinces with 0~10 km$^2$ of exploitable land, such as Shanghai, Beijing, and Henan, the average economic benefits of wind power are almost less than 100 million CNY, and wind power's average emission reduction potentials are less than 500,000 tons. For most provinces with exploitable land areas less than 100 km$^2$, such as Hubei, Fujian, and Shanxi, the newly installed wind power capacities will be maintained at 0 after 2025.

This study further summarizes the 14th Five-Year Plan for wind power installation with the optimization of the two scenarios in Table 2, presenting the proportion of wind power generation to power demand in 2025 and 2030. Under the economic priority scenario, 18 of the 30 provinces/municipalities reached the development targets for wind power planning, which are mainly concentrated in North China, Northeast China, and Southwest China. For example, the cumulative installed capacity of wind power in Inner Mongolia, Heilongjiang, Guizhou, and Sichuan reached 85.77 GW, 19.86 GW, 17.26 GW, and

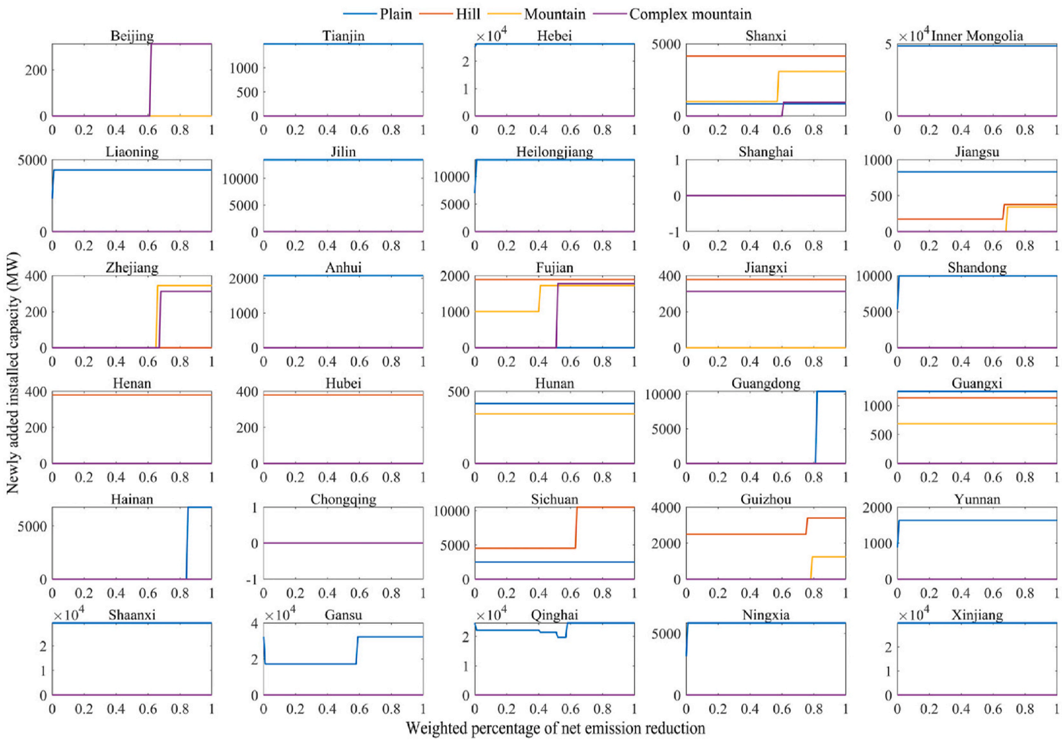



(a) 2025

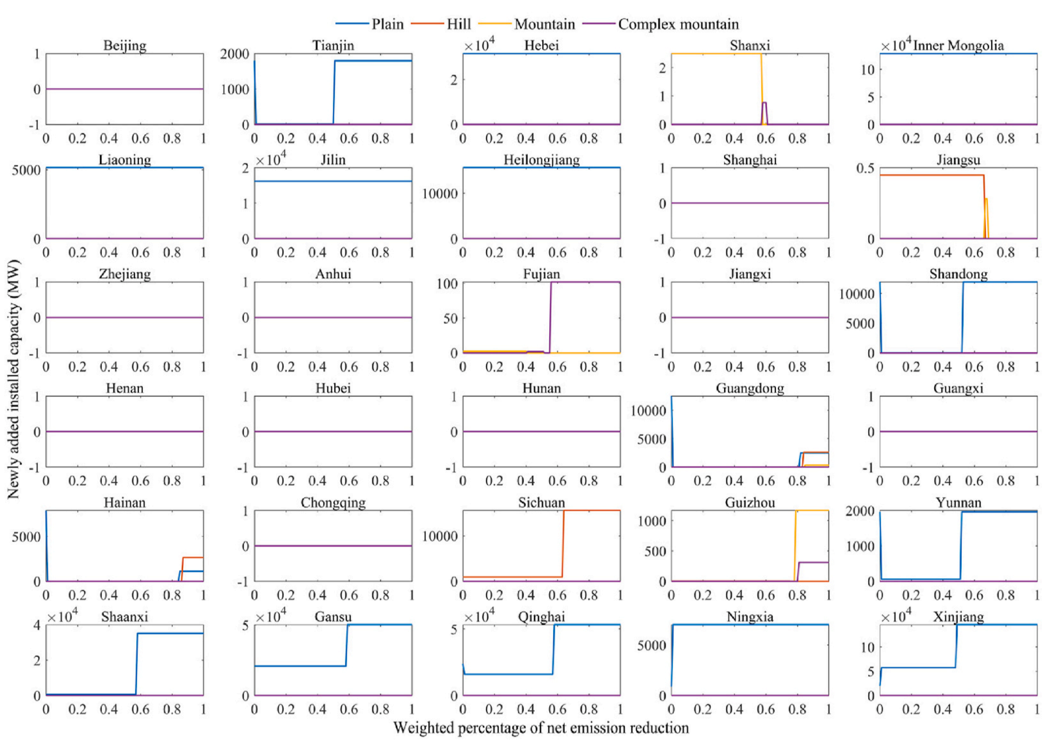



(b) 2030

**Fig. 4.** Multi-objective optimization of the net economic benefits and land use areas by province in China. Notes: The optimal installed capacities of newly added wind power in different provinces of China by 2025 and 2030 are depicted when the weight of net economic benefit is 0–1. The abscissa is the weight of net economic benefit $\alpha$, which reflects the importance of the net economic benefit of wind power relative to the area of wind farm in government decision-making. The increase of $\alpha$ means that the government pays more attention to the net economic benefit of wind power and less to the area of wind farms.




(a) 2025




(b) 2030

**Fig. 5.** Multi-objective optimization of the net emission reduction and land use areas by province. Notes: The optimal installed capacities of newly added wind power in different provinces of China by 2025 and 2030 are depicted when the weight of net emission reduction is 0–1. The abscissa is the weight of net emission reduction $\beta$, which reflects the importance of the net emission reduction of wind power relative to the area of wind farms in government decision-making. The increase of $\beta$ means that the government pays more attention to the net emission reduction of wind power and less to the area of wind farms.

**Table 1**
Newly installed capacities, average economic benefits, and emission reduction potentials of wind power installation by province.

| Unexploited land use area ($km^2$) | Province | Economic return priority | | | | Emission reduction priority | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | By 2025 | | By 2030 | | By 2025 | | By 2030 | |
| | | Newly installed capacity (10 MW) | Annual average economic benefit (100 million CNY) | Newly installed capacity (10 MW) | Annual average economic benefit (100 million CNY) | Newly installed capacity (10 MW) | Annual average emission reduction (million tons) | Newly installed capacity (10 MW) | Annual average emission reduction (million tons) |
| 0~10 | Shanghai | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | Chongqing | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | Beijing | 0 | 0 | 0 | 0 | 31 | 0.03 | 0 | 0.04 |
| | Henan | 38 | 0.12 | 0 | 0.19 | 38 | 0.02 | 0 | 0.03 |
| | Hubei | 38 | 0.17 | 0 | 0.28 | 38 | 0.03 | 0 | 0.04 |
| | Zhejiang | 66 | 0.31 | 0 | 0.52 | 66 | 0.05 | 0 | 0.07 |
| | Jiangxi | 69 | 0.32 | 0 | 0.54 | 69 | 0.05 | 0 | 0.07 |
| | Hunan | 76 | 0.37 | 0 | 0.62 | 76 | 0.05 | 0 | 0.07 |
| | Jiangsu | 155 | 0.66 | 0 | 1.10 | 155 | 0.11 | 0 | 0.17 |
| | Anhui | 208 | 0.79 | 0 | 1.32 | 208 | 0.14 | 0 | 0.20 |
| | Guangxi | 307 | 1.67 | 0 | 2.79 | 307 | 0.25 | 0 | 0.37 |
| $10\sim10^2$ | Fujian | 538 | 3.08 | 10 | 5.19 | 538 | 0.52 | 10 | 0.78 |
| | Guizhou | 464 | 1.67 | 117 | 3.19 | 250 | 0.16 | 0 | 0.23 |
| | Shanxi | 808 | 2.82 | 0 | 4.70 | 902 | 0.79 | 0 | 1.20 |
| | Hainan | 676 | 2.65 | 379 | 5.91 | 0 | 0 | 0 | 0 |
| | Tianjin | 150 | 0.59 | 179 | 1.69 | 150 | 0.13 | 179 | 0.35 |
| | Guangdong | 1040 | 4.21 | 548 | 9.25 | 0 | 0 | 0 | 0 |
| $10^2\sim10^3$ | Shandong | 996 | 4.06 | 1195 | 11.63 | 996 | 0.84 | 1195 | 2.2 |
| | Liaoning | 429 | 2.04 | 515 | 5.86 | 429 | 0.47 | 515 | 1.20 |
| | Yunnan | 163 | 0.83 | 196 | 2.38 | 163 | 0.16 | 196 | 0.39 |
| | Hebei | 2634 | 11.47 | 3161 | 32.88 | 2634 | 2.57 | 3161 | 6.69 |
| $10^3\sim10^4$ | Shaanxi | 2925 | 11.04 | 3510 | 31.65 | 2925 | 2.45 | 3510 | 6.48 |
| | Ningxia | 315 | 0.82 | 88 | 1.59 | 585 | 0.46 | 702 | 1.22 |
| | Sichuan | 1300 | 7.23 | 1560 | 20.72 | 1300 | 1.21 | 1560 | 2.72 |
| | Heilongjiang | 1300 | 6.25 | 1560 | 17.91 | 1300 | 1.43 | 1560 | 3.68 |
| | Jilin | 1352 | 6.18 | 1622 | 17.73 | 1352 | 1.42 | 1622 | 3.65 |
| $10^4\sim10^5$ | Gansu | 3224 | 9.74 | 5024 | 31.4 | 3224 | 2.50 | 5024 | 7.43 |
| | Qinghai | 2463 | 7.61 | 5322 | 29.15 | 2463 | 1.86 | 5322 | 6.56 |
| $>10^5$ | Inner Mongolia | 4848 | 17.89 | 12893 | 77.41 | 4848 | 5.08 | 12892 | 19.92 |
| | Xinjiang | 1610 | 4.65 | 1932 | 13.33 | 2990 | 2.78 | 14580 | 16.74 |
| | Total | 28192 | 109.25 | 39811 | 330.92 | 28037 | 25.56 | 52028 | 82.50 |

10.44 GW, respectively. Unlike economic priority scenarios, provinces/regions such as Guangdong, Hainan, and Guizhou may fail to achieve the wind power targets under decarbonization priority scenarios. In contrast, provinces/regions like Xinjiang and Ningxia could exceed the target. Although the wind power schemes in different provinces differ, the national cumulative installed capacities of wind power in the two scenarios are higher than the government planning targets.

The *Notice on Matters Related to the Development and Construction of Wind Power and Photovoltaic Power Generation in 2021* issued by the National Energy Administration pointed out that in 2025, the proportion of wind power and photovoltaic power generation in the total social electricity consumption will reach 16.5 %. According to the State Grid Energy Research Institute's prediction of the total electricity demand [64], wind power generation will account for 13 % and 20 % of the total in 2025 and 2030. Wind power generation of economic return priority and emission reduction priority by province can be found in Table S12. In 2030, the proportion of wind power generation to the total electricity demand will exceed 50 % in Inner Mongolia, Jilin, Heilongjiang, Gansu, Qinghai, and Xinjiang, which are mainly located in Northern China. There are 16 provinces/municipalities with wind power generation accounting for less than 10 % of the total electricity demand, such as Beijing, Shanghai, Guangdong, and Zhejiang.

Table 3 shows that when compared, the available area of wind power in China calculated by relevant studies is 530,000–4,250,000 $km^2$, and the exploitable area in this study is 650,000 $km^2$, within the range of other studies. Considering that the *14th Five Year Plan of Renewable Energy* advocated wind power installation in desert areas, this study only includes part of unused land into the assessment framework, excluding arable land, forest, grassland, etc., leading to a small scale of available areas. Besides, taking wind speed as the assessment standard, the wind speed threshold was generally $v_{80m} \geq 6.9$ m/s [65] and $v_{70m} \geq 6$ m/s [66], however, the latest research increased the height and reduced the threshold of wind speeds. In this study, the wind speed criteria is determined as $v_{100m} \geq 6$ m/s according to the *Guidelines for Type Selection of Low Wind Speed Wind Turbine* issued by the National Energy Administration of China in 2017. As for the altitude and slope, this study refers to McElroy et al. [67] and Liu et al. [68], setting no limit on the altitude, and refers to the terrain classification standard in the *Wind Power Engineering Design Cost Control Index (2019)*, limiting the undulation to within 450 m. This study also calculates and compares the economic indices and emission indices of onshore wind power in China's provinces/municipalities with other studies in Table S13. The LCOE of wind power installation calculated in this study is 0.11–0.27 CNY/kWh, and the life cycle $CO_2$ emission intensity is 6.48–50.18 g/kWh. Both LCOE and life cycle $CO_2$ emission intensity of wind power installation in this study are in the same order of magnitude as results obtained in previous studies.

Since China put forward the dual carbon targets, almost all the provinces and regions actively carried out low-carbon development planning and promoted the utilization of renewable energy. Among them, 28 out of 30 provinces/municipalities in China put forward wind power planning targets in the 14th Five-Year Planning and Renewable Energy Development Planning. Besides, the National Development and Reform Commission issued the 14th Five-Year Planning for Renewable

**Table 2**
Cumulative installed capacity of wind power in 2025 and 2030 and the proportion of wind power generation to total electricity demand.

| | | 2025 | | | | 2030 | | | |
|---|---|---|---|---|---|---|---|---|---|
| | Scenarios | Economic return priority | | Emission reduction priority | | Economic return priority | | Emission reduction priority | |
| Province | 2025 target (GW) | Cumulative capacity (GW) | Share (%) | Cumulative capacity (GW) | Share (%) | Cumulative capacity (GW) | Share (%) | Cumulative capacity (GW) | Share (%) |
| Beijing | 0.19 | 0.19 | 0.27 | 0.5 | 0.71 | 0.19 | 0.26 | 0.5 | 0.68 |
| Tianjin | 2 | 2.35 | 4 | 2.35 | 4 | 4.14 | 5.95 | 4.14 | 5.95 |
| Hebei | 43 | 49.08 | 19.51 | 49.08 | 19.51 | 80.68 | 25.55 | 80.68 | 25.55 |
| Shanxi | 28.11 | 27.64 | 17.13 | 28.58 | 17.71 | 27.64 | 14.32 | 28.58 | 14.8 |
| Inner Mongolia | 74.58 | 85.77 | 47.8 | 85.77 | 47.8 | 214.69 | 113.53 | 214.69 | 113.53 |
| Liaoning | 13.11 | 14.1 | 9.98 | 14.1 | 9.98 | 19.25 | 10.82 | 19.25 | 10.82 |
| Jilin | 16.17 | 19.29 | 39.25 | 19.29 | 39.25 | 35.51 | 56.33 | 35.51 | 56.33 |
| Heilongjiang | 16.86 | 19.86 | 35.85 | 19.86 | 35.85 | 35.46 | 53.66 | 35.46 | 53.66 |
| Shanghai | 3.82 | 0.82 | 0.84 | 0.82 | 0.84 | 0.82 | 0.73 | 0.82 | 0.73 |
| Jiangsu | 16.91 | 17.02 | 4.5 | 17.02 | 4.5 | 17.02 | 4.24 | 17.02 | 4.24 |
| Zhejiang | 6.3 | 2.45 | 0.9 | 2.45 | 0.9 | 2.45 | 0.86 | 2.45 | 0.86 |
| Anhui | 7.09 | 6.17 | 4.33 | 6.17 | 4.33 | 6.17 | 4.65 | 6.17 | 4.65 |
| Fujian | 9 | 10.24 | 9.17 | 10.24 | 9.17 | 10.34 | 8.85 | 10.34 | 8.85 |
| Jiangxi | 7 | 5.79 | 6.63 | 5.79 | 6.63 | 5.79 | 7.1 | 5.79 | 7.1 |
| Shandong | 25 | 27.3 | 6.8 | 27.3 | 6.8 | 39.25 | 9.62 | 39.25 | 9.62 |
| Henan | 25.18 | 15.56 | 4.84 | 15.56 | 4.84 | 15.56 | 3.75 | 15.56 | 3.75 |
| Hubei | 10.02 | 5.4 | 3.66 | 5.4 | 3.66 | 5.4 | 3.1 | 5.4 | 3.1 |
| Hunan | 13.22 | 7.23 | 5.61 | 7.23 | 5.61 | 7.23 | 4.74 | 7.23 | 4.74 |
| Guangdong | 13.65 | 16.05 | 3.24 | 5.65 | 1.14 | 21.53 | 4.26 | 11.13 | 2.2 |
| Guangxi | 21.43 | 9.5 | 9.54 | 9.5 | 9.54 | 9.5 | 8.91 | 9.5 | 8.91 |
| Hainan | 5.49 | 7.05 | 26.6 | 0.29 | 1.09 | 10.84 | 37.62 | 4.08 | 14.16 |
| Chongqing | 2.48 | 0.98 | 1.3 | 0.98 | 1.3 | 0.98 | 1.14 | 0.98 | 1.14 |
| Sichuan | 14.26 | 17.26 | 12.78 | 17.26 | 12.78 | 32.86 | 22.89 | 32.86 | 22.89 |
| Guizhou | 9.37 | 10.44 | 10.03 | 8.3 | 7.97 | 11.61 | 9.91 | 9.47 | 8.08 |
| Yunnan | 10.07 | 10.44 | 13.03 | 10.44 | 13.03 | 12.4 | 14.57 | 12.4 | 14.57 |
| Shaanxi | 31.31 | 38.06 | 32.39 | 38.06 | 32.39 | 73.16 | 60.5 | 73.16 | 60.5 |
| Gansu | 38.53 | 45.97 | 47.16 | 45.97 | 47.16 | 96.21 | 83.83 | 96.21 | 83.83 |
| Qinghai | 27.37 | 33.06 | 63.53 | 33.06 | 63.53 | 86.28 | 155.2 | 86.28 | 155.2 |
| Ningxia | 18.27 | 16.92 | 24.11 | 19.62 | 27.96 | 17.8 | 22.81 | 20.5 | 26.27 |
| Xinjiang | 46.37 | 39.47 | 28.18 | 53.27 | 38.03 | 58.79 | 51.71 | 72.59 | 63.85 |
| **Total** | 556.16 | 561.46 | 12.84 | 559.91 | 12.89 | 959.55 | 20.18 | 958 | 20.24 |

Notes: a. The wind power goals of all provinces/municipalities in 2025 come from the 14th Five-Year Plan and renewable energy plan of all provinces/municipalities. b. The 2030 power demand in China comes from He and Kammen [63].

**Table 3**
Comparisons between wind power available areas in this study and previous studies.

| Source | Year | Turbine size (MW) | Height (m) | Wind regime constraints | Suitable areas (million km$^2$) | Geographical constraints |
|---|---|---|---|---|---|---|
| Lu et al. [69] | 2009 | 2.5–3.6 | 100 | $C_f$>20 % | 2.08 | Exclude forested, snow or ice areas, water areas, and urban areas. |
| McElroy et al. [67] | 2009 | 1.5 | 80 | $C_f$>20 % | 2.37 | Exclude forested, snow or ice areas, water areas, and urban areas. |
| Davidson et al. [37] | 2016 | 1.5 | 80 | – | 4.14 | Slope<10°; exclude forests, water bodies and urban areas. |
| Bosch et al. [38] | 2017 | 1.5 | 100 | $C_f$>15 % | 2 | Elevation<2000; slope<20°; include part of farmland, forest, shrublands, grassland, barren; Exclude nature reserves, water areas, urban areas. |
| Dupont et al. [39] | 2018 | 3 | 100 | $C_f$>15 % | 2.33 | Include part of the farmland, forest, shrublands, barren; exclude nature reserves, remote areas, urban areas. |
| Feng et al. [41] | 2020 | 3 | 100 | $C_f$>20 % | 0.53–0.73 | Elevation<3500; slope<20°; include part of the farmland, forest, shrublands, grassland, barren; exclude nature reserves, water areas, development areas. |
| Yu et al. [17] | 2022 | 3–4.5 | 80–150 | >2.5 m/s | 1.44–4.25 | Plains, platforms, hilly terrains with an altitude of less than 3500 m, and mountainous terrains with undulating heights of less than 1000 m. |
| Li et al. [36] | 2022 | 1.5 | 80–151 | $C_f$>20 % | 0.79 | The terrain with 0–5000 m of altitude and 0–1000 m of undulation. Include part of the arable areas, forest, pastures, undeveloped lands. |
| Liu et al. [35] | 2022 | 2–3.4 | 100 | >4.8 m/s | 1.37 | Slope<30°; include part of the farmland, forest, shrublands, grasslands, barren; exclude water areas, urban areas. |
| This study | | 2.5 | 100 | >6 m/s | 0.65 | Undulation<450 m; include part of the barren; exclude nature reserves, urban areas. |

Notes: The suitable areas of [35,37,41,67,69] are obtained by dividing the wind power generation potential by the effective utilization hours of wind power. The effective utilization hours of wind power are assumed to be 2100 h, equivalent to $C_f$ of 0.24.

Energy Development based on the Outline of the 14th Five-Year Plan for National Economic and Social Development and Vision 2035 of China and the 14th Five-Year Planning for the Modern Energy System. Considering different development priorities and planning targets by province, this study aims to compare different wind power schemes based on the multi-objective optimization of wind power installation by province until 2030. Some suggestions and implications are provided as follows:

(1) The western and northern regions are rich in desert, gobi, desert, and other unused land types with great potential for wind power development and the construction of large-scale wind power bases in North China, Northwest, and Northeast China, such as Inner Mongolia, Hebei, Xinjiang, Gansu, and Heilongjiang would be essential. For Hunan, Hubei, and Chongqing, which are less suitable land areas for wind power installation, distributed wind power would be more suitable to be established.
(2) Without renewable energy subsidies, the economic payback periods for wind power in most provinces become much longer, and the electricity prices in Inner Mongolia and the northwest provinces are lower than the national average. In consideration of the economic payback period of wind power installation, appropriate subsidies are suggested in less developed provinces/regions such as Inner Mongolia, Ningxia, Xinjiang, Gansu, and Qinghai, which occupy large wind power potentials but relatively small profitability.
(3) The installed capacity of wind power in Inner Mongolia, Xinjiang, Gansu, and Qinghai may increase significantly, which poses a severe risk to the local electricity storage and local consumption capacities. In this context, speeding up the construction of wind power storage facilities, strengthening the construction of power grid infrastructure and intelligent upgrading, and improving the adaptability of the power system to a high proportion of renewable energy while actively promoting the grid connection of green electricity would be practical.
(4) The installed capacity of newly added onshore wind power stations in Northern China may far exceed that in Southern China, leading to the irrational allocation between supply and demand. It is thus necessary to actively promote the establishment of wind power transmission and consumption mechanisms and inter-provincial transaction mechanisms, plan new channels to improve the transmission scale of existing UHV transmission channels, and conduct inter-provincial transactions of wind power resources with Central and Southern China.

## 6. Conclusions

Considering net economic benefits, net emission reduction potentials, available land areas, and government planning targets from the life cycle perspective, this study proposed different wind power schemes under economic and decarbonization priority scenarios based on the hybrid life cycle assessment and multi-objective optimization. From the results, the plain wind power scheme in the northeast region has the largest net economic benefits and emission reduction potentials, ranging from 8.33 to 9.10 million CNY/MW and from 28.91 to 30.03 ktCO$_2$/MW, respectively. Regarding different provinces/regions, Inner Mongolia is expected to be the largest wind power installer until 2030, which may bring a economic benefit of 4.76 billion CNY and an emission reduction potential of 12.50 million tons per year. For provinces with 0-10 km$^2$ of unexploitable land such as Shanghai, Beijing, and Henan, the average wind power economic benefit is almost less than 100 million CNY, and the average wind power emission reduction is less than 500,000 tons. On the one hand, this study assesses net economic benefits and net emission reduction potentials of different wind power schemes from the life cycle perspective; on the other hand, this study incorporates multiple indicators including net economic benefits, net emission reduction potentials, land use areas, geographical terrains, and government planning targets that may affect wind power layout through the multi-objective optimization modeling. Note that some limitations still exist in this study, including the predicted effective hours of wind power installation, the disparity existing in wind power schemes by province, and the accuracy of multi-objective optimization. However, the multi-objective optimization of different wind power schemes proposed in this study is expected to propose practical suggestions for rational deployment of wind power installation within China and provide potential implications for developing countries and regions toward low-carbon transition.

## CRediT authorship contribution statement

**Ershi Hua:** Data curation, Formal analysis, Validation, Writing – original draft. **Ruyi Sun:** Data curation, Formal analysis, Validation, Writing – original draft. **Ping Feng:** Data curation, Formal analysis, Validation, Writing – original draft. **Lili Song:** Conceptualization, Writing – review & editing. **Mengyao Han:** Conceptualization, Formal analysis, Writing – original draft, Writing – review & editing.

## 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.

## Data availability

Data will be made available on request.

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## Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.energy.2024.132431.

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