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Fine-grained prediction of solar-wind deployment unlocks China's 2060 pathways to carbon neutrality and lower energy costs†

Jing Guo,‡[a] Ruomei Wang,‡[b] Li Zhang, *[c] Siqin Wang,[d] Linyan Li,[ef] Mengbing Du,*[g] Fangyuan Zhong,[g] Chuan Zhang, [h] Yafei Li,[b] Yixuan Zheng,[i] Xiaoya Liu,[b] Xi Lu[j] and Jinnan Wang[a]

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The global transition from fossil fuels to renewable energy is vital for mitigating climate change, yet plans to transition China are generally coarsely resolved. This study introduces the China New Energy Database, offering the first 10-km resolution feasibility ranking for wind and solar installations across China. By incorporating land-use regulations and construction constraints, we present an optimized development pathway from 2022 to 2060. Our results highlight substantial climate and economic benefits of renewable energy deployment, with wind and solar energy reducing up to 16.9 billion tons of carbon dioxide emissions and generating 12.8 trillion CNY economic benefits by 2060. Regions with abundant renewable resources show significant potential for economic gains, demonstrating that reasonable strategic deployment could effectively "turn resources into gold". These insights serve as a valuable reference for countries like India, Saudi Arabia, and South Africa in their transition to renewable energy, contributing to global progress in sustainable energy systems.

Broader context

The urgent global transition to renewable energy is essential for effectively combating climate change. It is crucial to establish high-resolution datasets and actionable pathways for renewable energy deployment. In this study, we develop a nationwide, grid-level database to present the first-ever 10 km resolution feasibility ranking for wind and solar installations in China, providing an optimized development pathway that incorporates land-use regulations and construction constraints from 2022 to 2060. Our analysis provides valuable insights into how grid-level renewable energy deployment fosters long-term climate and economic benefits. Our findings play a crucial role in shaping effective renewable energy policies, driving investment, and accelerating China's transition to a sustainable energy future, serving as a valuable reference for countries such as India, Saudi Arabia, and South Africa in their transition to renewable energy and contributing to global advancements in sustainable energy systems.

Introduction

The world is close to the 1.5 °C threshold of global warming, while air pollution contributes to over 7 million deaths each year.[1,2] For developing countries, *e.g.*, China, fossil fuel combustion and bioenergy use contribute substantially to air pollution-related premature deaths and respiratory diseases, intensifying public health and environmental challenges.[3] Stabilizing global temperatures necessitates a fundamental shift to energy systems with nearly zero carbon dioxide equivalent emissions worldwide.[4–8] Solar and wind resources frequently provide a significant portion of electricity,[9,10] contributing nearly two-thirds of the global growth in renewable energy capacity.[11] In particular, for developing nations, anticipated reductions in installation costs suggest a potential leapfrogging directly to solar and wind energy.[12] China's development of

[a] *Center for Carbon Neutrality, Chinese Academy of Environmental Planning, Beijing 100043, China*
[b] *Goldwind Science & Technology Co., Ltd, Beijing 100176, China*
[c] *School of the Environment and Safety Engineering, Jiangsu University, Zhenjiang 212013, China. E-mail: zhangli_1122@outlook.com*
[d] *Spatial Sciences Institute, University of Southern California, Los Angeles, 90089, California, USA*
[e] *Department of Data Science, City University of Hong Kong, Hong Kong SAR 999077, China*
[f] *Department of Infectious Diseases and Public Health, City University of Hong Kong, Hong Kong SAR 999077, China*
[g] *School of Political Science & Public Administration, Wuhan University, Wuhan 430072, China. E-mail: mengbingdu@whu.edu.cn*
[h] *Institute of Energy, Peking University, Beijing 100084, China*
[i] *Key Laboratory of Environmental Pollution and Greenhouse Gases Co-control, Ministry of Ecology and Environment, Chinese Academy of Environmental Planning, Beijing 100043, China*
[j] *Institute for Carbon Neutrality, Tsinghua University, Beijing 100084, China*

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‡ These authors contributed equally: Jing Guo, Ruomei Wang.

wind and solar clean energy is rapidly advancing, and its future goals are highly ambitious.[13,14] It sees the clean energy transition as a means to address both environmental and health concerns. By 2022, China's total installed capacity of wind and solar power stood at approximately 760 million kilowatts (kW). This figure grew significantly to 1.35 billion kilowatts by 2024, representing a remarkable 78% increase compared to 2022. This achievement surpassed the 2030 target of 1.2 billion kilowatts—more than six years ahead of schedule. To further meet the requirement of achieving carbon neutrality before 2060, China's installed wind and solar power capacity is projected to reach over 5 billion kilowatts—more than six times the total installed capacity of 2022.[15]

To advance China's clean energy transition, the central government has made substantial efforts in grid infrastructure development and related supporting systems. These investments have significantly reduced the geographical constraints on renewable energy spatial planning and lowered the grid-connection costs for clean energy projects.[16] As of 2024, China has completed the construction of 37 long-distance transmission lines, including five ±800 kV ultra-high-voltage interprovincial corridors. These lines facilitate interconnection across eastern, western, northern, and southern regions, with a single-corridor transmission capacity reaching up to 16 GW.[17]

To ensure grid stability in the context of large-scale renewable energy integration, China has also planned for 30 GW of storage capacity, including a combined 6 GW of planned storage in Gansu, Qinghai, and Inner Mongolia. China has already achieved 73.76 GW of new-type power storage capacity and 58.69 GW of pumped hydro storage, meeting and even exceeding its planning targets. In order to reach its dual carbon goals, recent research by Zhang *et al.*[18] suggests that China will need to install 538 GW of pumped hydro storage (8-hour duration) and 740 GW of battery storage (4-hour duration). Additionally, further development of interprovincial transmission lines—such as Inner Mongolia East to Shandong, and Ningxia to Shandong—is essential to balance supply and demand across regions.[18]

Although several studies have proposed and quantified 100% renewable energy pathways across multiple sectors in China and globally, demonstrating significant reductions in emissions, costs, and positive employment effects,[1,2,19,20] achieving China's renewable energy targets necessitates not only ambitious goals but also well-defined pathways that integrate resource deployment with national policy coordination and regional socio-economic considerations. For example, von Krauland *et al.*[21] developed high-resolution maps of wind and solar resource availability in India, underscoring the importance of spatial granularity in guiding large-scale renewable energy planning. Jacobson *et al.*[22] explored the variability, economics, and policy aspects of wind and solar energy, and deeply analyzed the feasibility of using wind and solar energy to support global energy demands across all sectors (electric power, transportation, heating/cooling, *etc.*). Without such detailed and integrative strategies, future renewable energy expansion in China may face substantial constraints, including grid supply-demand imbalances, infrastructure mismatches, and inefficient site selection. Therefore, a scientifically reasonable and clearly targeted wind and solar installation planning route is crucial to effectively align national and regional strategies, minimize energy lock-ins, and ensure strategic progress toward both climate and economic objectives.

China's abundant solar and wind resources have the theoretical potential to meet its long-term energy needs.[23–26] However, most studies to date have focused on energy potential assessment or technology, often neglecting the broader planning context that includes practical policy and economic considerations. Unlike traditional dispatchable energy sources such as coal or nuclear power, wind and solar energy are inherently variable, and heavily influenced by geophysical location, local terrain, and weather conditions.[27] High-resolution, grid-level analyses are crucial to address these challenges, enabling accurate assessment of the spatial distribution and variability of resources to identify optimal installation sites. Furthermore, policy constraints—such as regional land-use regulations, zoning restrictions, and the need to align local development with national renewable energy targets—must be integrated into planning. A comprehensive approach that combines spatial-temporal analyses with policy frameworks is essential for scaling up renewable infrastructure feasibly and sustainably across regions.

In wind-solar capacity planning, alternative land-use opportunity benefits reflect potential value losses from agriculture, forestry, or other economic activities while providing a scientific basis for regional resource allocation *via* quantified economic return differences among land use types. These differences directly shape development priority logic—regions where long-term wind-solar project benefits exceed current land-use opportunity costs receive higher development weights, especially in areas with scarce land or intense multi-use competition. For example, Lazo *et al.*[28] used a real options model to quantify agricultural land conversion costs for photovoltaic (PV) plants, finding that uncertainties delay land-use decisions and inform dynamic development timelines. Similarly, Lamy *et al.*[29] showed that U.S. Midwest wind farm siting balances land opportunity costs against transmission costs, requiring grid expansion for remote high-wind areas to offset land value losses.

In addition, advancements in technology and proactive climate policies have made renewable energy increasingly competitive with fossil fuels.[6,30,31] Studies from America,[32,33] German,[34,35] and United Kingdom[36] have highlighted the local economic and environmental benefits of renewable energy development, emphasizing its dual benefits in shaping the spatial layout and evolutionary pathway of future renewable energy. However, China's transition to renewable energy remains underexplored, particularly regarding the specific costs and economic benefits at a refined grid level. These assessments must account for installation constraints under carbon neutrality goals. Policymakers in China face the urgent challenge of assessing not only the feasibility of renewable energy deployment but also ensuring that the economic benefits are realized. Achieving this balance is critical to driving investment, accelerating the energy transition, and aligning renewable energy development with national and regional priorities.

This study presents a fine-grained, grid-level assessment of wind and solar development feasibility across China, offering a detailed roadmap for renewable energy deployment from 2022 to 2060. We introduce the first national-scale feasibility ranking for wind and solar installations at a 10 km resolution, incorporating land-use regulations, construction constraints, and alignment with both national and provincial "dual-carbon" targets. Additionally, using big data techniques, we collect provincial-level renewable energy installation cost data, enabling an assessment of the economic costs and environmental benefits from renewable energy development. This work provides fine-grained transition pathways for China and serves as a pioneer model for global renewable energy strategies.

Methodology

Fig. 1 presents the framework of this study, including calculation of grid-level wind and solar installation in 2022, evaluation of technical installation potential of wind and solar power, construction of wind-solar indicators, pathways for grided new energy installation under different scenarios, and estimation of potential climate and economic benefits.

Data source

We have collected geographical and statistical data (Table 1) from the National Bureau of Statistics of China,[37] NASA Earth data, OpenStreetMap (OSM),[38] Global Wind Atlas (GWA),[39] and Global Solar Atlas (GSA).[40] The National Bureau of Statistics collected installed wind and solar capacity by provinces, which is used to analyze the current status of national installed capacity. To understand the spatial distribution of installed equipment across the country, we combine this data with wind and solar spatial distribution data from the OSM platform, thereby preparing for future wind and solar spatial planning based on the current situation. In addition to providing spatial distribution data of wind and solar equipment, OSM data also includes land use data such as roads, residential areas, and water bodies, which pose restrictions on wind and solar energy construction. GWA and GSA both provide global wind and solar resource data, where average wind speed and global horizontal irradiation (GHI) are indicators used to assess the national installed capacity potential and future temporal and spatial layout.

Wind and solar installation grid calculation in 2022

Based on the provincial installed capacity in 2022, this study allocates the data to grid cells (10 km × 10 km) to reflect the spatial distribution of installed capacity across the country. Using wind turbine points data and PV panel polygon data from OpenStreetMap (OSM),[38] combined with wind and PV power development statistic data by province in 2022 from the National Bureau of Statistics,[37] these resources are assigned to grid cells across the country.

For wind power resource allocation, the proportion of wind power site numbers within each grid cell relative to the total number of turbines in the corresponding province is used to distribute the provincial wind power development capacity to each grid cell. For photovoltaic resource allocation, the

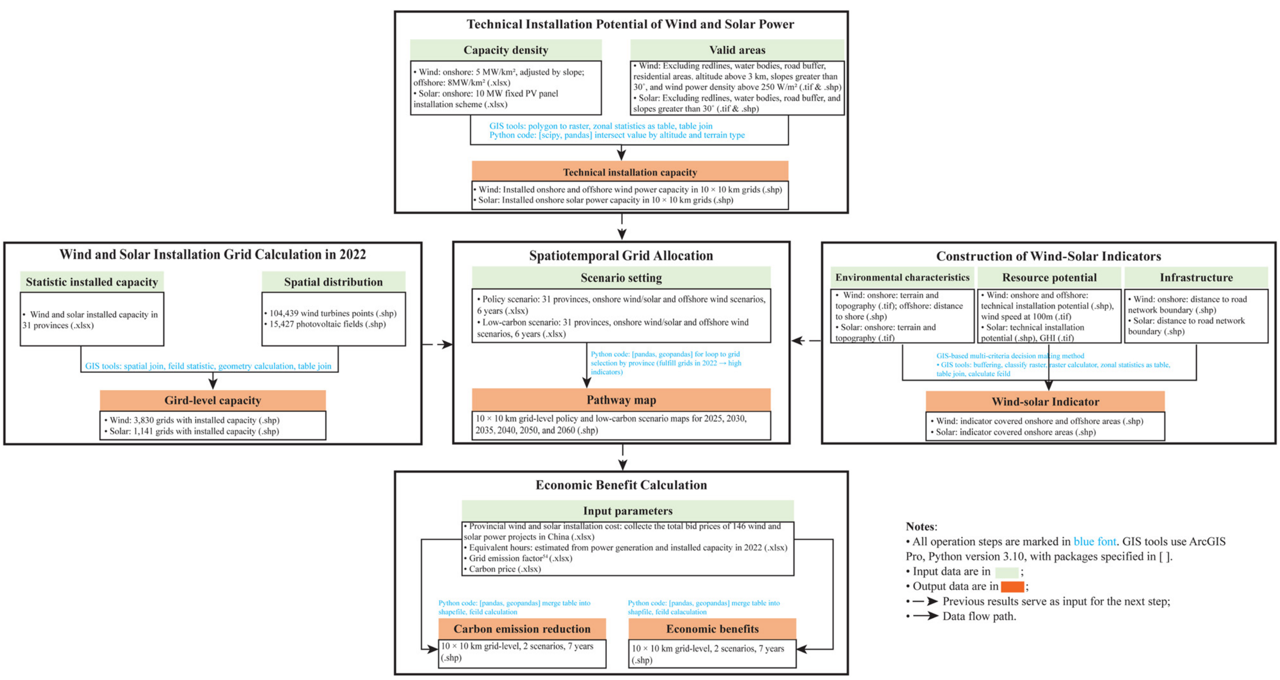

Fig. 1 Research framework of this study.

Table 1 Data source

Source	Name	Format	Note
National Bureau of Statistics	Current installation	Excel	Wind and solar capacity statistics by provinces
NASA	DEM	GeoTiff	Digital Elevation Model with 250 m spatial resolution
USGS	Global Mountains K3	GeoTiff	Global mountain map at 250 m resolution, based on terrain features
Open Street Map	Wind turbines	Points (shapefile)	Includes ∼10 000 turbine locations
	PV panels	Polygon (shapefile)	Covers ∼15 427 PV panel areas
	Roads	Polylines (shapefile)	Includes trunk, motorway, primary, and secondary roads
	Residential areas	Polygon (shapefile)	—
	Water body	Polygon (shapefile)	—
Global Wind Atlas	Wind speed	GeoTiff	250 m resolution wind data
	Wind power density	GeoTiff	
Global Solar Atlas	GHI	GeoTiff	250 m resolution solar radiation data

Notes: National Bureau of Statistics (available at **https://data.stats.gov.cn/easyquery.htm?cn=C01**), Open Street Map (**https://www.openstreetmap.org**), Global Wind Atlas (**https://globalwindatlas.info/**), Global Solar Atlas (**https://globalsolaratlas.info/download/world**), DEM (**https://www.un-spider.org/links-and-resources/data-sources/digital-elevation-model-srtm-41-cgiar-csi**, downloaded from Global Solar Atlas).

proportion of the coverage area of PV panels within each grid cell relative to the total provincial PV area is used to allocate the provincial PV development capacity to the respective grid cells.

Evaluation of the technical installation potential of wind and solar power by considering terrain and land-use policy constraints

The wind capacity measurement. The objective of wind capacity measurement is to analyze valid areas and calculate the potential installed capacity of these areas based on capacity density. The valid area takes into account factors such as redline area, slope, altitude, and residential area[41,42] (Fig. 2). For the onshore area, the assessment of technical installed capacity is 5 MW km^{-2} for the flat area.[43,44] As the terrain slope changes, the installed capacity decreases.[11] The variation in installed capacity density under the influence of slope is shown in Table S1 (ESI†). The offshore wind capacity density is 8 MW km^{-2} for all areas.[45] The installed capacity in each region of the country is reflected in the 10 km × 10 km grid. The detailed evaluation method can be found in Supplementary Note 1 (ESI†). The selection of reasonable installed capacity is essential to minimize the impact of the competition for available kinetic energy among the planned wind power installations, identified as the saturation wind power potential (SWPP) threshold by Jacobson & Archer.[46] Detailed information on the explanation of competition among turbines for available kinetic energy can be referred to Supplementary Note 2 (ESI†). Fengjiang 3.0 software (first Chinese software certified by international Det Norske Veritas, **https://fengjiang.goldwind.com.cn/login/common**) is used to simulate kinetic energy under varying capacity densities at three typical wind sites (*i.e.*, Gansu, Inner Mongolia, and Guangxi). In general, simulated generation hours decrease as capacity density increases, suggesting a loss in available kinetic energy (Table S2 and Fig. S1, ESI†). In addition, sensitivity analyses are also performed with onshore wind capacity density at 5, 8, 10, and 20 MW km^{-2}, and offshore wind capacity density at 5 and 8 MW km^{-2} (Tables S3 and S4, ESI†).

The solar capacity measurement. The solar capacity measurement also considers the valid areas and power capacity density. The identification of effective PV installation areas is primarily achieved by excluding restrictive zones, which include areas designated by redlines, roads, water bodies, and slope[47] (Fig. 2). The capacity density for PV installations referred to the method in "Land Use Control Indicators for Photovoltaic Power Station Projects" political instructions, which provides installation recommendations based on different altitude[14] (Table S5, ESI†). The PV installation density in residential areas is calculated by multiplying the above assessment density by 25%.[11] The detailed evaluation method can be referred to Supplementary Note 3 (ESI†).

Construction of wind-solar indicators

The wind and solar planning at the grid level is determined by using the construction priority score (from high to low) evaluated by the GIS-based multi-criteria decision-making method (MCDM).[47–49] The installation evaluation of technical weights is assessed based on environmental characteristics, resource potential, and infrastructure. Due to differences in installation methods and evaluation approaches, onshore wind power, offshore wind power, and onshore photovoltaics are analyzed separately.

Wind onshore power construction priority. The wind power onshore installation weight (Fig. 2a) is calculated as follows (Table 2).

(1) Environmental characteristics: terrain and topography are the main factors considered. China's terrain is relatively complex, with flatter areas being more suitable for the installation of most wind turbine units.[50,51] Therefore, for flat terrain with an elevation below 3 km, the installation index is 1; for small hilly terrain, the index is 0.8; for hilly areas with a large number of hills, the index is 0.6. For mountainous areas with an elevation higher than 3 km, the index is 0. Terrain and topography data sources are from Global Mountains K3[52] and 250m resolution DEM files published by USGS.[52]

(2) Resource potential: includes technical installation capacity and average wind speed.

(a) Technical installation capacity: the larger the installed capacity, the higher the priority for selection as a wind power development area. Since areas with a large installed capacity

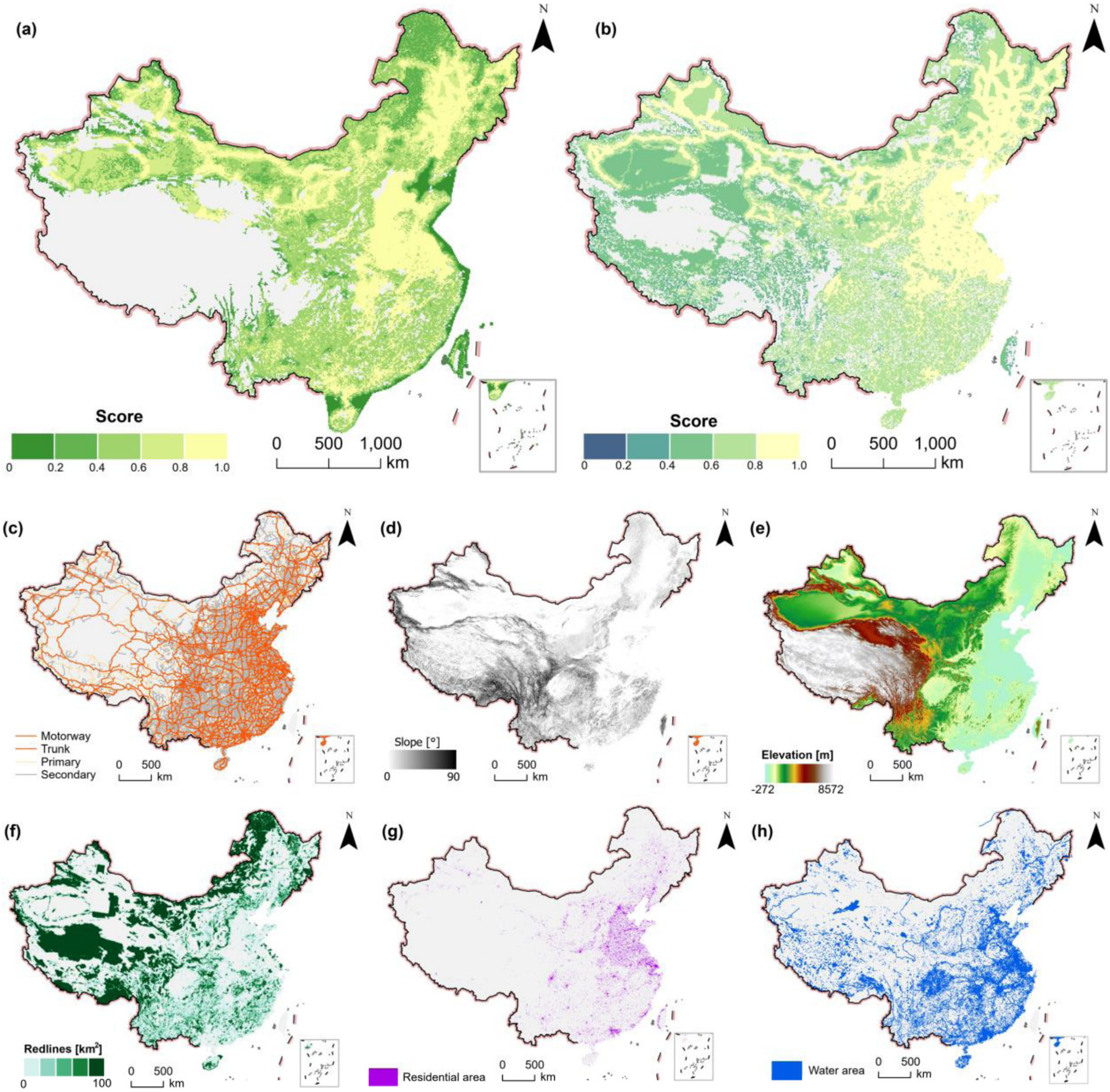

Fig. 2 Feasibility priority map and set of restrictive factors for wind power and solar photovoltaic installation. (a) and (b) Feasibility priority map of wind power (1 km × 1 km grid; (a)) and solar photovoltaic (b). The colour gradation of the block shows the feasibility priority score of installation. (c)–(h) Set of restrictive factors for wind power and solar photovoltaic installation. Restrictive factors include road (c), slope (d), elevation (e), redlines (f), residential area (g) and water area (h).

are more suitable for centralized installations, the associated infrastructure construction costs are relatively lower.[53] The data is normalized to a 0–1 range based on the 10 km × 10 km grid installation capacity for onshore areas.

(b) Average wind speed: wind speed is an important reference for wind power generation efficiency. The higher the wind speed, the higher the efficiency and power generation.[54] Based on current mainstream turbine models, the starting wind speed for turbines is above 4 m s^{-1}, so areas with wind speed below 4 m s^{-1} are considered inefficient and are excluded from the power generation evaluation.[24] Areas with average wind speeds above 7 m s^{-1} are considered to have favorable wind resource distribution, with higher power generation efficiency and better returns.[48] Wind speeds between 4 m s^{-1} and 7 m s^{-1} are distributed across the indices with a step size of 1 m s^{-1}. The average wind speed at a height of 100 meters used in this study is sourced from the Global Wind Atlas.[39]

(3) Infrastructure: due to the large size of wind power equipment, there are significant requirements for road width and height clearance.[55] Transporting the equipment on existing roads is more cost-effective than constructing new transport routes. Roads of Grade 2 and above are typically designed with at least two lanes wider than 3 meters, suitable for the transportation of wind turbine equipment.[25] Additionally, constructing shorter transport roads based on the existing road infrastructure can help save overall construction costs. We

Table 2 Onshore wind site selection weight scoring table

Primary factor	Weight (%)	Second factor	Weight (%)	Evaluation index					
				0[a]	0.2	0.4	0.6	0.8	1
Environmental characteristics	40	Terrain and topography	40	Ocean, high mountains, and mountain ranges with elevations > 3 km	—	—	Low mountain ranges with elevations ≤3 km	Low mountains with elevations ≤3 km	Flat terrain with elevations ≤3 km
Resource potential	20	Wind power installation density	10	Normalized to 0–1 scale					
		Average wind speed at 100 m	10	—	$\leq$4 m s^{-1}	4–5 m s^{-1}	5–6 m s^{-1}	6–7 m s^{-1}	> 7 m s^{-1}
Infrastructure	40	Distance to road network boundary	40	—	> 50 km	40–50 km	30–40 km	20–30 km	≤20 km
Total	100	—	100	—	—	—	—	—	—

[a] Note: if a grid score is zero, it is not permitted to build a power generation.

Table 3 Offshore wind site selection weight scoring table

Primary factor	Weight (%)	Secondary factor	Weight (%)	Evaluation criteria					
				0[a]	0.2	0.4	0.6	0.8	1
Environmental characteristics	40	Distance from shore	40	Distance from shore < 10 km	—	—	Distance from shore > 30 km	Distance from shore 20–30 km	Distance from shore 10–20 km
Resource potential	30	Wind power installation capacity	30	Normalized and adjusted to a 0–1 scale					
	30	Annual average wind speed	30	< 6 m s^{-1}	Wind speed ≥6 m s^{-1}, normalized and adjusted to a 0.2–1 scale				
Total	100	—	100	—	—				

[a] Note: if a grid score is zero, it is not permitted to build a power generation.

mainly discuss areas within a 50 km radius of main roads, standardized with a spatial index ranging from 1 to 0.2 in 10 km increments. Buffer zones greater than 50 km are all set to an index of 0.2. The road network is from OSM,[38] and only considers motorway, trunk, primary and secondary roads (Fig. 2c).

Wind offshore power construction priority. The analysis of the installation priority of offshore wind power is primarily based on the distance from the coastline and resource potential (Table 3).

(1) Environmental characteristics: unlike onshore wind power installation priorities, the further an offshore wind power project is from the coast, the higher the construction cost. In China's 12th Five-Year Plan, the optimal offshore wind power development zone is within 10–20 km from the coastline.[56] Later policies permitted the development of deep-sea areas, allowing wind power installations within a 30 km range from the coastline.[45] For this, the weight evaluation gives priority to the 10–30 km area, with compensation distribution based on the distance from the 10 km zone.

(2) Resource potential: includes installation capacity and average wind speed.

(a) The installation capacity is normalized based on the offshore 10 km × 10 km grid calculation.

(b) Average wind speed is an important factor for wind turbine efficiency. However, for power generation benefits, the average wind speed must exceed 6 m s^{-1}.[57] Areas with wind speeds greater than this threshold are selected, then standardized and adjusted to a range between 0.2 and 1.

Construction of photovoltaic indicators. The factors for determining the installation sequence of onshore PV installations include environmental characteristics, resource potential, and infrastructure. The PV onshore value of indicators is shown in Table 4.

(1) Environmental characteristics: even at the same latitude, the solar radiation received by photovoltaic (PV) modules installed in rugged terrain may differ significantly from that in flat terrain, primarily influenced by factors such as topographic shading and microclimate changes.[58–60] To reflect the potential constraints of terrain on PV resource utilization, we set a scoring index ranging from 0.6 to 0.8 based on terrain types. The relevant terrain data were derived from the Global Mountains K3 and the 250-meter resolution Digital Elevation Model (DEM) data published by the U.S. Geological Survey (USGS).

(2) Resource Potential: includes capacity potential and global horizontal irradiance (GHI) values.

(a) The technical potential is based on the solar capacity measurement results. The calculation method is to normalize the photovoltaic potential of the onshore areas to a range between 0 and 1.

(b) Global horizontal irradiance[61] is a main condition referring to the richness of solar resources.[62] We use GHI data provided by SolarGIS and normalize this data to a range between 0 and 1.

(3) Infrastructure: similar to the infrastructure assessment for onshore wind power.

Table 4 Photovoltaic site selection weight scoring table

Primary factor	Weight (%)	Secondary factor	Weight (%)	Evaluation index 0[a]	0.2	0.4	0.6	0.8	1
Environmental characteristics	30	Terrain slope	30	Ocean, high mountains, and mountain ranges with elevations > 3 km	—	—	Low mountain ranges with elevations ≤3 km	Low mountains with elevations ≤3 km	Flat terrain with elevations ≤3 km
Resource Potential	40	Technical installation potential	20	Normalized to a 0–1 scale					
		Global horizontal irradiance	20	Normalized to a 0–1 scale					
Infrastructure	30	Distance to road network boundary	30	—	> 50 km	40–50 km	30–40 km	20–30 km	≤20 km
Total	100	—	100	—	—	—	—	—	—

[a] Note: if a grid score is zero, it is not permitted to build a power generation.

Scenario setting

Two scenarios are considered based on the extent of the development of wind and solar energy generation. The Policy Scenario represents moderate wind and solar PV installation by considering comprehensive development indicators in existing national and provincial planning policies, as detailed in our previous studies.[63] Low-carbon Scenario represents a higher expectation of wind and solar energy development compared to the level in the Policy Scenario, by referring to scenario settings in the IPCC AR6 database. Specifically, the installed capacity in 2025 and 2030 refers to policy requirements and the installed capacity in 2060 is calculated by allocating the national target to provinces using the weight of provincial technical potential values. Then the provincial pathway among the above years is estimated, assuming a consistent growth rate.

Spatiotemporal grid allocation for installed capacity planning at the provincial level

(1) Ranking the installation potential data in descending order based on the score values.

$$S_{\text{desc}} = \{s_{1,j}, s_{2,j}, \ldots, s_{i,j}\} \quad (1)$$

$$P_{\text{sorted by } S_{\text{desc}}} = \{p_{1,j}, p_{2,j}, \ldots, p_{i,j}\} \quad (2)$$

In the formula, $s_{i,j}$ refers to the 10 × 10 km grid evaluation score; i is the national grid ID ($i \in \{1,2, \ldots, n\}$); j is the provincial ID ($j \in \{1,2, \ldots, 31\}$), with a total of 31 provincial administrative regions in this study. S_{desc} represents the national grid evaluation score dataset, which is arranged in descending order based on the score values($s_{1,j} \geq s_{2,j} \geq \ldots \geq s_{i,j}$). $P_{i,j}$ refers to the 10 × 10 km grid installation potential, measured in kW. $P_{\text{sorted by } S_{\text{desc}}}$ represents the technical installation capacity dataset, where the values are aligned in descending order according to the IDs in S_{desc}, reflecting the technical installation potential in each grid based on descending scores.

(2) Distributing the grid values by province. The distribution logic prioritizes the allocation of grids with existing installations in 2022 ($k_{i,j,2022}$) that have not yet reached their technical installation potential. If the total grid capacity does not meet the planned installation capacity, grids with higher scores are selected until the total installation capacity of the selected grids reaches the planned capacity, at which point the process stops.

$$k_{i,j,\text{year}}^{\text{remain}} = \min(p_{i,j} - \min(k_{i,j,2022}, p_{i,j}), p_{i,j}) \quad (3)$$

$$k_{i,j,\text{year}} = k_{i,j,2022} + k_{i,j,\text{year}}^{\text{remain}} \quad (4)$$

$$k_j^{\text{year}} = \sum_{i=1}^{n} k_{i,j,\text{year}} \quad (5)$$

$$K^{\text{year}} = \{k_1^{\text{year}}, k_2^{\text{year}}, \ldots, k_j^{\text{year}}\} \quad (6)$$

where k_j^{year} represents the total installation capacity of province j in the year in a scenario. $p_{i,j}$ is installed capacity, and $p_{i,j} \in P_{\text{sorted by } S_{\text{desc}}}$, measured in kW.

Economic benefit calculation

After completing the potential installation data and spatial planning models, it is now necessary to calculate the environmental and economic benefit characteristics in the temporal and spatial planning of wind and solar energy. The calculation methods include lifecycle cost (installation, operations, and maintenance), carbon reduction from clean energy construction and operation, and profit estimation.

(1) Installation cost calculation

$$c_{i,j,\text{cost}}^{\text{year}} = k_{i,j}^{\text{year}} \times c_{j,\text{cost}}^{\text{year}} \quad (7)$$

where, $c_{i,j}^{\text{year}}$is the installation cost for grid i in province j in year (year), unit: yuan; $c_{j,\text{cost}}^{\text{year}}$ is the unit installation cost in the province j in year (year), unit: yuan/W; $k_{i,j}^{\text{year}}$ is the installation capacity for a grid in a year (year), unit: kW. The unit installation cost is obtained from Table S6 (ESI†).

In addition, the share of installation cost in total lifecycle cost (including installation, operations and maintenance) is assumed to be 69.9%, 81.5%, and 76.4% for onshore wind, offshore wind, and solar PV, respectively (Table S7, ESI†).[64–68]

(2) Carbon emission reduction

$$e_{i,j}^{\text{year}} = k_{i,j}^{\text{year}} \times h_j \times \varepsilon_j^{\text{year}} \quad (8)$$

where, $e_{i,j}^{\text{year}}$ is carbon emissions reduction for grid i in province j in year (year), with unit kg; $\varepsilon_j^{\text{year}}$ is grid emission factor[69] for province j in year (year); h_j is provincial equivalent hours in 2022.

(3) Profit calculation

$$P_{i,j}^{\text{year}} = e_{i,j}^{\text{year}} \times c_{j,\text{emiss}}^{\text{year}} - c_{i,j,\text{cost}}^{\text{year}} \quad (9)$$

where, $P_{i,j}^{\text{year}}$ is profit for grid i in province j in year (year), unit: yuan; $c_{j,\text{emiss}}^{\text{year}}$ is the carbon price in province j in year (year), unit: yuan. The carbon price is estimated from Table S8 (ESI†).

Results

Spatial-temporal distribution and vast installation potential of gridded new energy resources

From 2012 to 2022, the total wind and solar power installed capacity experienced significant growth, with notable variation across different provinces. China's total wind and solar power capacity grew at a compound annual growth rate (CAGR) of 25.3% in the 10 years (79.6–758.0 GW), with wind power installations increasing from 75.3 to 365.4 GW and solar power capacity expanding from 4.2 to 392.6 GW (Fig. 3). The increase in total wind and solar capacity across provinces over these 10 years varies significantly, ranging from the smallest change of 1 GW in Beijing to the largest change of 60 GW in Shandong. Inner Mongolia remains the leader in total wind and solar installed capacity nationwide (18.9–61.1 GW), despite its share of the total capacity declining from 23.8% in 2012 to 8.1% in 2022 (Fig. 3a and b).

We assessed the grid-level spatial patterns of wind and PV installed capacity in 2022 based on the location of wind turbines and PV panels. We identified substantial regional disparities in wind and PV installed capacity (Fig. 3a and b). Northern regions dominate wind and solar grids compared to the southern regions, but the solar grids are more sparsely

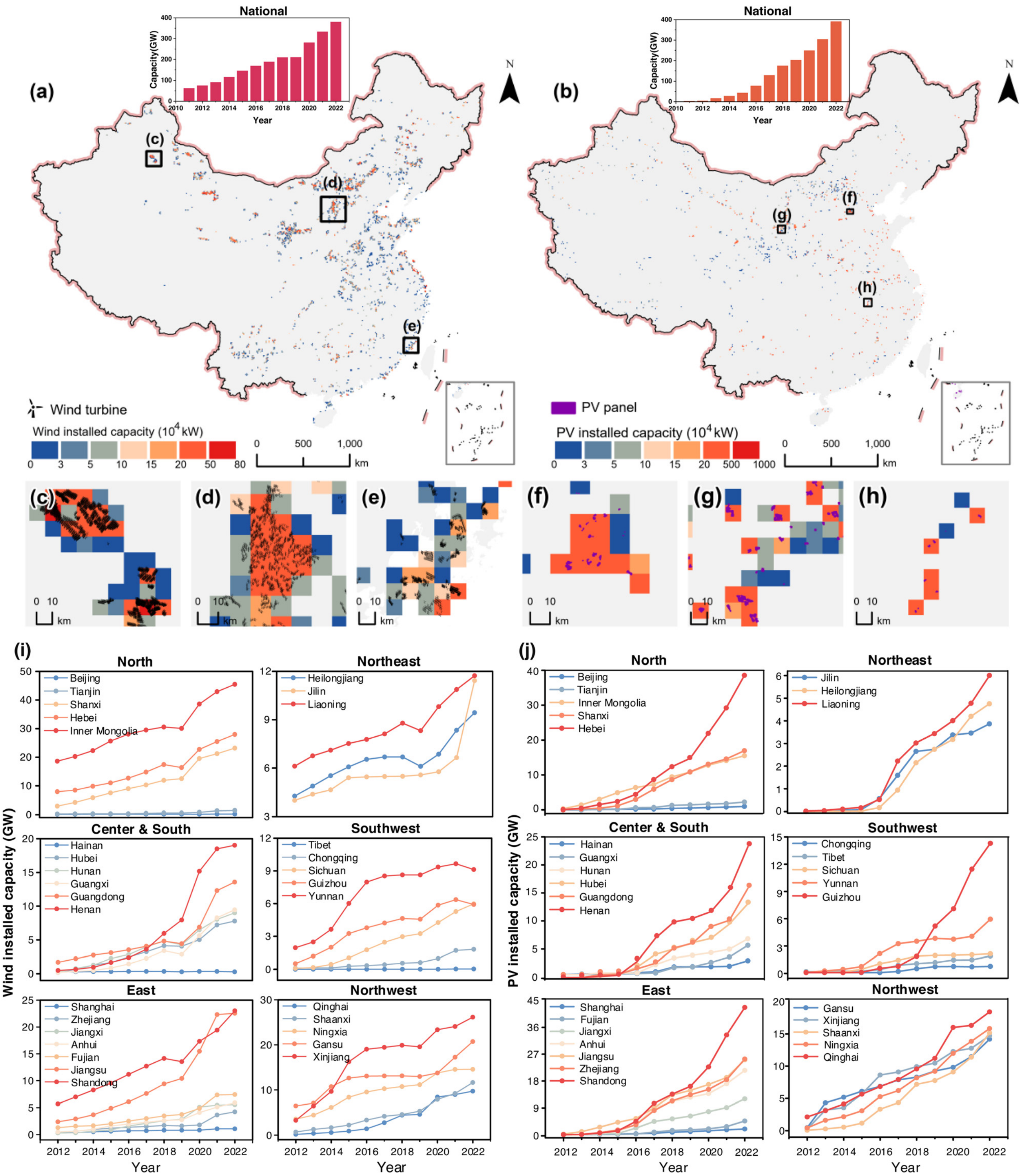

Fig. 3 The 10 km grid spatial distribution of Chinese wind turbine and solar photovoltaic installed capacity in 2022 and historical installed capacity of each region. (a) and (b) Distribution of wind power installed capacity in China (totaling 104 439 wind turbines; (a)) and solar photovoltaic (15 427 photovoltaic fields; (b)). The colour gradation of the block shows the installed capacity. The maximum installed capacity of wind power grids does not exceed 80 × 10^4 kilowatt (kW). The maximum installed capacity of solar power grids does not exceed 1000 × 10^4 kW. Inserts show the historical changes in the total installed capacity in China. (c)–(h) Typical high-density wind power installation area (c)–(e) and solar photovoltaic (f)–(h). (i) and (j) The historical wind power installed capacity of each region (i) and solar photovoltaic (j). The colour lines show the provinces within the region. The statistic wind and solar historical data do not include the regions of Hong Kong, Macau, and Taiwan.

distributed (Fig. 3a), while the wind grids are more concentrated (Fig. 3b). In southwestern regions such as Tibet, there are large areas without wind turbine installation grids, but there are solar power installation grids.

North, including Inner Mongolia, Shanxi and Hebei, East, including Shandong, and Northwest, including Xinjiang and Gansu, collectively account for over 166.5 GW of wind installed capacity, representing 45.6% of the wind power national total in 2022 (Fig. 3i). These regions also generate over 263.2 billion kWh of wind power in 2022, comprising 34.5% of the nation's total.[30] This dominance is attributed to favorable geographic conditions, abundant wind resources, and supportive policies. Specifically, Inner Mongolia boasts wind densities exceeding 200 W m^{-2}, with annual hours at wind speeds of $\geq$3 m s^{-1} surpassing 5000 hours and $\geq$6 m s^{-1} exceeding 3000 hours, resulting in high efficiency.[70] Conversely, southern regions exhibit relatively lower onshore wind energy potential, but the southern coastal areas offer promising offshore wind resources, which are inherently a key focus for future development. These findings highlight regional differences in wind energy potential and strategic opportunities for optimized deployment.

Similar to wind power, PV installed capacity also exhibits significant regional variation, with capacities ranging from 0.7 GW to over 42.6 GW in 10 years (Fig. 3j). China's solar energy potential is immense, with the land surface receiving approximately 50×10^{18} kJ of annual solar radiation. Total solar radiation varies across the country, ranging from 335 to 837 kJ cm^{-2}·a, with a median value of 586 kJ cm^{-2}·a.[71] Regions such as Qinghai and Gansu host the highest concentration of PV installations, underscoring their strategic importance in China's renewable energy landscape. Unlike wind energy, which is more concentrated in the north, PV installations appear to be more diversified, spanning western and southern China. This wider distribution is due to PV systems' adaptability across diverse geographic locations, from high-sunlight regions to areas with lower solar intensity.

China's regions have enormous wind and solar resource potential, and the geographical constraints for PV installations are lower than those for wind power installations. We estimated China's national wind technical potential at 16 276.1 GW, and the PV installed capacity potential is 276 206.9 GW (Fig. 4a and b). The North and Northwest regions exhibit a high proportion of wind power installation potential, each exceeding 30% (Fig. 4c). Regions such as Inner Mongolia, Xinjiang, Heilongjiang, and Gansu show the highest technical potential, collectively comprising approximately 50% of the national capacity, which aligns with the current state of wind power development (Fig. 4c). China's extensive coastline, spanning 18 000 kilometers and offering over 3 million square kilometers of exploitable marine area, estimated at approximately 2584 GW—15.9% of the total technical potential. Consistent with wind power installation potential, the Northwest region of China has immense PV installation potential, exceeding 30% (Fig. 4d). However, the Southwest region ranks second in terms of PV installed capacity, accounting for 24%, which contrasts sharply with the wind power distribution, where it only accounts for 2% (Fig. 4c and d). Notably, Xinjiang, Tibet, Inner Mongolia, and Qinghai stand out for their high technical accessibility, making significant contributions to China's PV-installed capacity—accounting for 40.9% of the national PV capacity, with Xinjiang alone contributing 17.9% of the total capacity, boasting a PV installed capacity of 49 342.4 GW.

Pathways for grided new energy resources in China by 2060

The technological potential for both wind and solar energy in China is vast, yet current development remains minimal. Wind power installations account for just 2.2% of their potential, while solar power installations represent only 0.1% in 2022. This gap highlights the urgent need for strategic planning to fully exploit these resources.

These findings are in line with prior research, which suggests that wind and solar energy have sufficient potential to support China's carbon neutrality vision.[72] Nevertheless, the key challenge lies in enhancing the precision of site-specific planning to ensure a successful energy transition. To address this, we propose a priority sequencing for installations that integrates natural endowments and technical potential, building on existing wind and solar development frameworks. This approach provides a tiered, grid-level (10 km × 10 km) planning roadmap for wind and solar deployment in each province, advancing the precision of site-specific planning and optimizing the allocation of resources for efficient wind and solar deployment.

Considering the adaptability of wind and solar power installations to their operating environments, we comprehensively incorporated factors including ground slope, elevation, ecological redlines, residential areas, restriction of land use, and water bodies (Fig. 2). Based on these factors, we developed an evaluation framework for prioritizing land-based wind power, offshore wind power, and land-based solar power installations in China at a 10 km grid scale. The resulting feasibility priority maps (Fig. 2a and b) reveal significant geographic disparities in renewable energy potential. Areas with high wind power priority are primarily located in the northeastern and western regions (characterized by elevated terrain and abundant natural resources resources) and the North China Plain (noted for infrastructure advancement). Optimal solar energy potential is concentrated in the northwestern and southwestern regions, where high sunlight exposure enhances feasibility.

Here, we employed two scenarios to assess the potential development pathways for new energy resources guided by weighted scores/feasibility by 2060: the Policy Scenario and the Low-carbon Scenario. The Policy Scenario represents moderate wind and PV installation by considering comprehensive development indicators in existing national and provincial planning policies. In contrast, the Low-carbon Scenario represents a higher expectation of wind and PV development, by referring to the scenario settings in the IPCC AR6 database.[73]

Under the Policy Scenario, from 2022 to 2060, all provinces in China experience an increase in installed wind capacity, but the pace of growth varies (Fig. 5a and e). Hainan, with the fastest growth rate (CAGR of 9%) in wind installation, is projected to have an installed capacity of only 7.7 GW by 2060 (Table S9, ESI†). In contrast, provinces such as Hebei (CAGR, 4.6%) and Shanxi (CAGR, 4.2%) exhibit growth rates close to the national average of 4.7% over the same period.

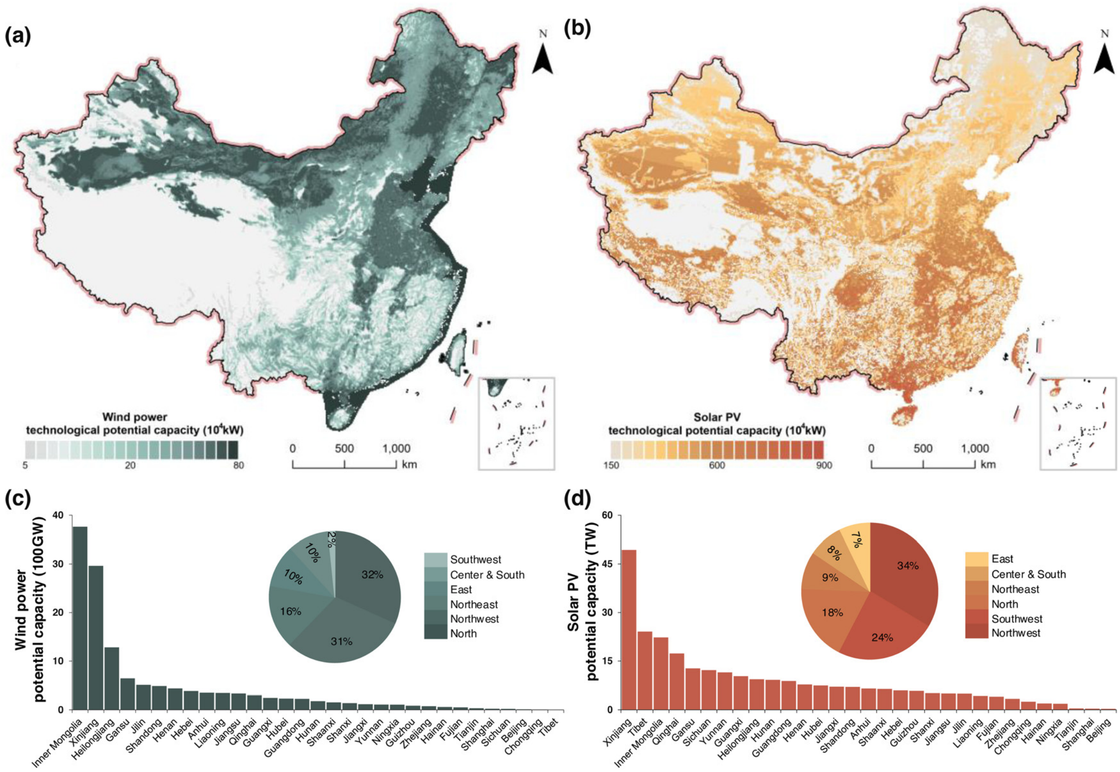

Fig. 4 The technological potential capacity of wind power and solar photovoltaic. (a) and (b) Technological potential capacity of wind power (1 km × 1 km grid; (a)) and solar photovoltaic (b). The colour gradation of the block shows the technological potential capacity. (c) and (d) The technological potential capacity of wind power (c) and solar photovoltaic (d) in each province.

Their total installed capacities rank among the top five in the country, 152.4 GW and 110.9 GW in 2060. Offshore wind power is expected to reach a total planned installed capacity of 615.3 GW by 2060, with a CAGR of about 8.2%.

In terms of regional installation growth, most provinces are expected to see grid expansion similar to 2022 levels by 2060, with notable exceptions such as Sichuan, Inner Mongolia, Xinjiang, Chongqing, and Shanxi, where grid expansion exceeds 400 grids. This significant increase in grid numbers is primarily attributed to two factors: the low installation capacity density per grid and the excessively large provincial installation targets. Sichuan's grids, for example, will expand from 59 in 2022 to 1259 by 2060. This is primarily driven by the terrain, as the lower installed capacity per grid in mountainous areas necessitates more grids to meet the planned capacity of 23.7 GW by 2060–well below the provincial average of 69.7 GW for onshore installations. On the other hand, Inner Mongolia, Xinjiang, and Heilongjiang plan for much larger installed capacities by 2060, reaching 486.2 GW, 382.9 GW, and 165.7 GW, respectively. These ambitious targets require extensive grid layouts to accommodate the higher installation demands.

From a spatial-temporal perspective, northern China (Xinjiang, Inner Mongolia, Liaoning, Jilin, Heilongjiang) and south-western China (Sichuan, Yunnan, Chongqing, Guizhou) will see significant additions of dense red grids, indicating that these regions will need more land area to meet planned capacity targets (Fig. 5a). Coastal areas will generally experience an increase in new grids, with the most significant concentration near Fujian, where superior wind resources (average wind speed at 100 meters exceeds 10 m s^{-1}) make it an optimal location for offshore wind development.

Similar to the wind power installation scenario, the provincial-level PV installation scenario also shows a mismatch between the growth amount and the growth rate (Fig. 5c and g). However, the changes in PV installation are generally larger than those in wind power. From 2022 to 2060, the total CAGR of PV installed capacity nationwide is expected to reach 7.8% (392.6–6917.6 GW), with the highest growth rate for Tibet (16.6%, 1.8–606.5 GW) (Table S9, ESI†). Shandong and Hebei were consistently among the top five provinces in planned installed capacity in the early stages of development. However, by 2060, they will be overtaken by Xinjiang and Tibet. The northern regions are the main drivers of PV development. In most provinces (25 out of 31), the CAGR of solar power exceeds that of wind power, with the largest differences observed in Sichuan and Tibet (exceeding 10%). In a few provinces (6 out of 31), wind power has a higher CAGR, but the differences are all within 2%. This variation is mainly due to the flexibility of land use for solar power construction, such as the ability to install rooftop solar panels in residential areas, as well as the fact that solar power generation is not restricted by high altitude.

The land area required to safely accommodate wind turbines is greater than that required for solar PV systems. By 2060, only

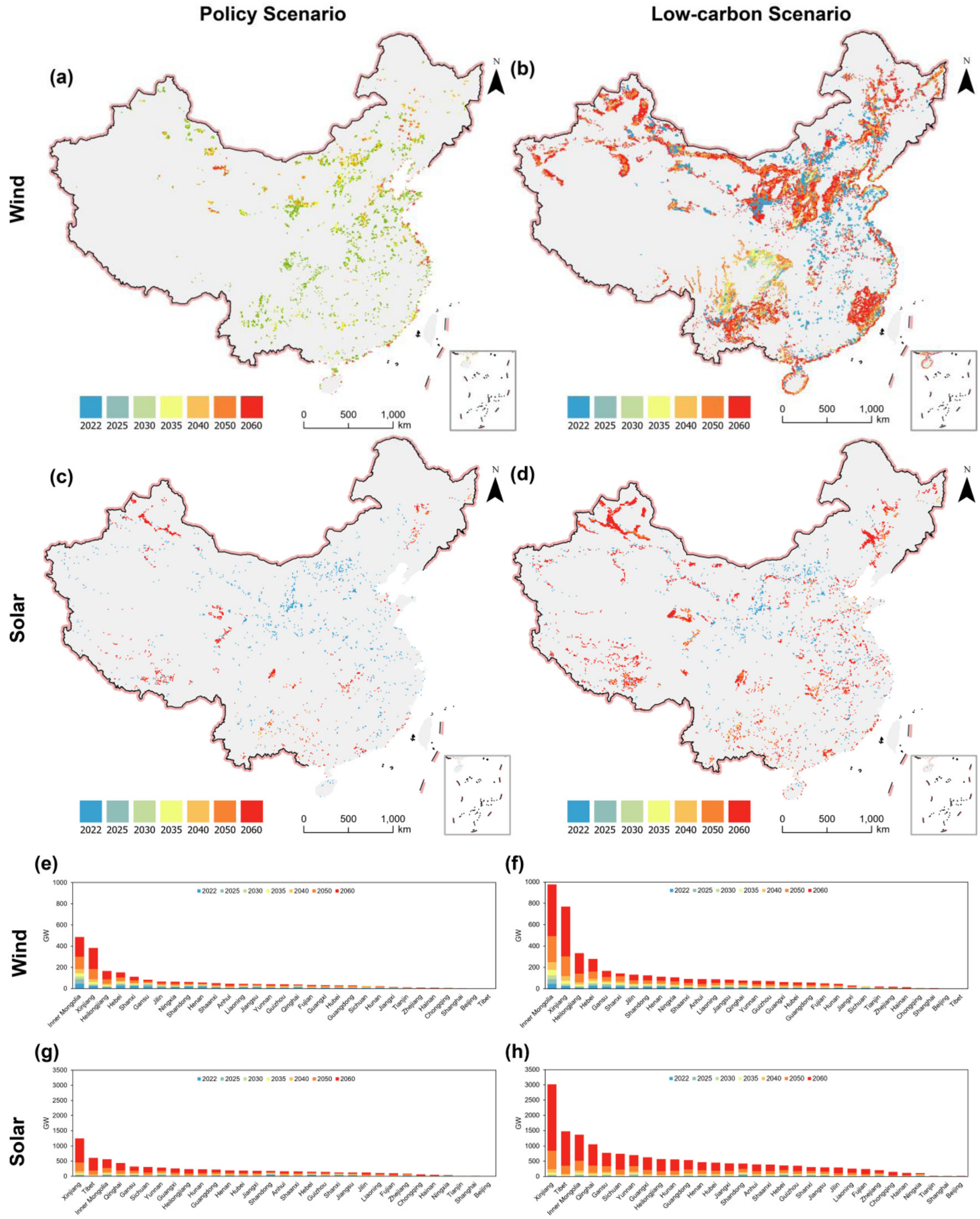

Fig. 5 The roadmap for gridded-level wind and solar installation from 2022 to 2060 under the Policy and Low-carbon Scenarios. (a)–(d) The roadmap for gridded level wind power (a) and (b) and solar photovoltaic (c) and (d) installation under the Policy (a) and (c) and Low-carbon (b) and (d) Scenarios. (e) and (f) The annual installed capacity of wind power (e) and (f) and solar photovoltaic (g) and (h) under the Policy (e) and (g) and Low-carbon (f) and (h) Scenarios from 2022 to 2060.

five provinces will have more than 100 grid units, including Xinjiang, Tibet, Qinghai, Inner Mongolia, and Gansu (Fig. 5c). Meanwhile, 12 provinces, including Inner Mongolia, Gansu, Ningxia, Hebei, Shanxi, Henan, Anhui, Jiangsu, Zhejiang, Hainan, Beijing, and Tianjin, will experience no growth in the number of grid units (Fig. 5c). These areas have higher land use efficiency for PV development. In certain regions of Tibet, Xinjiang, Qinghai, Northeast China, and Southwest China, a limited number of red grids emerge, signaling the need for enhanced land-use planning by 2060 to accommodate PV development requirements.

We further established an ambitious new wind energy expansion strategy, named the Low-carbon Scenario, which surpasses the targets outlined in the Policy Scenario. From

2022 to 2060, the CAGR of wind power in the Low-carbon Scenario in each province is expected to reach 6.4%, 1.4 times higher than the growth rate in the Policy Scenario. In particular, Inner Mongolia (977.3 GW in 2060), Xinjiang (769.6 GW), Heilongjiang (333.1 GW), Hebei (278.3 GW), and Gansu (167.4 GW) will be the main contributors to wind power installations by 2035 and 2060 (Table S10, ESI†). The enormous development demand in the Low-carbon Scenario of wind power requires more extensive land use. The number of land grids in Inner Mongolia, Xinjiang, Sichuan, Shanxi, and Fujian is expected to increase by over 1000 grids from 2022 to 2060, with Inner Mongolia and Xinjiang seeing an increase of more than 2000 grids (Fig. 5b). Offshore wind installations are projected to increase by 1455 grids from 2022 to 2060, doubling the number in the Policy Scenario. Post-2050, the planned wind installation space in central China, including regions near Ningxia, southern Fujian, and the southwest, will show a significant expansion (Fig. 5b).

Under the Low-carbon Scenario, the national average CAGR of PV installation is expected to reach 10.4% from 2022 to 2060, approximately 1.3 times higher than that under the Policy Scenario. Xinjiang and Inner Mongolia emerge as the main drivers of PV development, with installed capacities reaching 126.7 GW and 119.3 GW by 2035, and 3021.1 GW and 1364.6 GW by 2060, respectively. The combined installed capacity of these two provinces will account for 14.7% of the national total in 2035 and 26.1% in 2060. Xinjiang's planned grid units will reach 895 by 2060, becoming the province with the largest installed capacity (Fig. 5d).

In addition, by conducting sensitivity analyses for onshore and offshore wind power separately, we found that as capacity density increases (from 5 MW km^{-2} to 20 MW km^{-2} for onshore wind power and from 5 MW km^{-2} to 8 MW km^{-2} for offshore wind power), the technical installation potential of wind power in individual grid increases substantially, and the total number of grid cells required to reach the 2060 installation target gradually decreases, as shown in Fig. S2 and Table S3 (ESI†).

Both development scenarios show significant potential to meet China's future electricity needs, projected to reach 16 PWh by 2050 and 17 PWh by 2060.[72] Our analysis reveals that wind and solar energy can effectively meet China's low-carbon power demands. By 2060, under the Policy Scenario, the combined electricity generation of solar and wind energy is projected to reach 13.2 PWh, with 5.8 PWh from wind and 7.4 PWh from solar energy. In contrast, the Low-carbon Scenario projects a total electricity generation increase significantly to 29.2 PWh, driven by 18.0 PWh from solar energy and 11.2 PWh from wind energy. Over 60 years, the total electricity generated by wind power could be 2.2 to 5.0 times greater than that from thermal power in 2022.[74]

Potential climate and economic benefits of new energy resources in China by 2060

Our estimates of the potential climate and economic benefits from wind and solar energy reveal significant temporal and spatial variations across China. Both the Policy and the Low-carbon Scenario show a shift in economic benefits from negative to positive over time. Notably, the Low-carbon Scenario achieves this reversal earlier than the Policy Scenario, further accelerating positive outcomes due to stricter carbon reduction targets. Both scenarios enable the realization of the goal of "turning resources into gold" (Fig. 6 and Fig. S3, ESI†).

Under the Policy Scenario, we observed a gradual reduction in carbon emissions initially, followed by a marked acceleration from the mid-2030s, ultimately achieving a projected reduction of around 3.8 billion tons of CO_2 by 2060 for wind installation. Inner Mongolia, Xinjiang, and Heilongjiang are the major contributors to carbon emission reductions by developing wind power, with the reductions of 808.8 million tons, 566.5 million tons, and 254.1 million tons, respectively. Economically, the national benefits of wind power start negative in 2022 (−239.9 billion CNY), turn positive around 2050 (645 billion CNY), and are projected to reach their peak by 2060 (1923.9 billion CNY) (Fig. S3j, ESI†). Provinces like Inner Mongolia (521.45 billion CNY), Xinjiang (314.1 billion CNY), Hebei (165.96 billion CNY), and Heilongjiang (161.77 billion CNY) are expected to achieve the highest economic benefits by 2060. In the initial stage, before 2035, all provinces will experience negative profitability. After 2035, some provinces will gradually become profitable, starting with Hebei and Henan. However, Tibet, Hainan, Qinghai, Yunnan and Sichuan are projected to consistently experience negative returns by 2060, with estimated losses ranging from 0.02 billion CNY to −6.73 billion CNY. Additionally, offshore wind energy is expected to remain in a state of negative returns before 2040. However, we anticipate a shift to positive returns beginning in the late 2050s, with projections reaching 100 billion CNY by 2050 and 327.47 billion CNY by 2060.

The PV installation scenario also brings a huge amount of installed capacity. Xinjiang (reducing 1036.4 million tons of CO_2 in 2060), Inner Mongolia (619.2 million tons in 2060), Gansu (201.5 million tons in 2060), and Heilongjiang (198.2 million tons in 2060) are the top contributors to these reductions and generates substantial revenues (625.3 billion CNY, 416.6 billion CNY, 80.0 billion CNY and 63.7 billion CNY) (Fig. S3k, ESI†). The deployment of PV installations remains below zero until 2050, ultimately showing positive profitability by 2060 (Fig. S3l, ESI†). Power generation efficiency is a critical factor determining whether provinces can shift from negative to positive profitability. The substantial planned installation capacity in Qinghai results in costs (161.2 billion CNY in 2060) that cannot be offset by the revenues generated from power generation and carbon reduction, ultimately leading to a negative balance that persists until 2060 (−96.9 billion CNY), making it the province with the lowest return on investment.

In the Low-carbon Scenario, wind power deployment achieves substantial carbon emission reductions (Fig. 6). By 2060, the total reductions reach approximately 7.4 billion tons, with Inner Mongolia leading at 1.6 billion tons, followed by Xinjiang and Heilongjiang with 1.1 and 0.5 billion tons, respectively. Shanghai, Chongqing, Beijing, Sichuan and Tibet

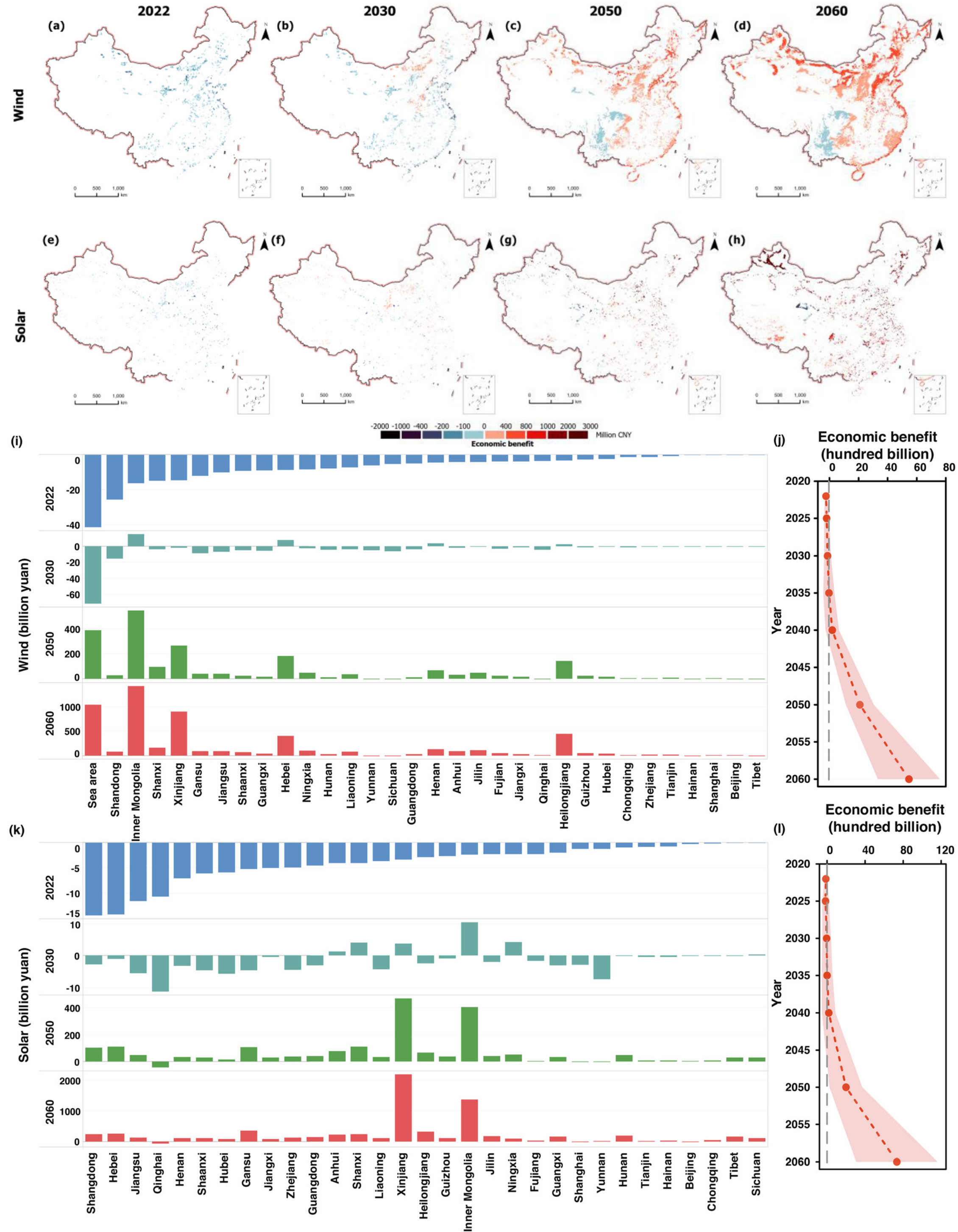

Fig. 6 Cost-benefit analysis from 2022 to 2060 under the Low-carbon Scenario. (a)–(h) Cost-benefit for gridded level wind power (a-d) and solar photovoltaic (e)–(h). (i)–(l) Cost-benefit analysis for provincial wind power (i) and solar photovoltaic (k). Insets show the corresponding national cost-benefit (j) and (l) from 2022–2060. The pink shaded area indicates the 95% confidence interval, reflecting the uncertainty of the data. The gray dash line at the zero scale serves as the division between positive and negative economic benefits, clearly differentiating between gains and losses.

experience lower reductions, less than 10 million tons, due to less favorable wind conditions and lower installed capacities. The national economic benefits of wind power under the Low-carbon Scenario initially show a negative return (−239.87 billion CNY in 2022) but shift to positive around 2040 (187.91 billion CNY), 5 years earlier than under the Policy Scenario (Fig. 6j). By 2060, the overall economic benefit is projected at about 5.47 trillion CNY. Inner Mongolia, Hebei, Henan and Heilongjiang are the 4 provinces that achieve profitability as early as 2030, with profits reaching between 2.48 billion yuan and 14.88 billion yuan. Yunnan and Sichuan are the only two provinces that will remain unprofitable by 2060, with a loss of −3.00 billion CNY and −3.71 billion CNY.

The deployment of PV installations under the Low-carbon Scenario is projected to result in substantial carbon emission reductions. The national carbon emissions, totaling 9.5 billion tons, are 2.4 times the total PV emissions under the Policy Scenario in 2060. Xinjiang (2.5 billion tons), Inner Mongolia (1.5 billion tons), and Gansu (0.5 billion tons) achieve the largest reductions in 2060. Economically, national profits are expected to turn positive by 2040, nearly 5 years earlier than in the Policy Scenario. By 2060, total economic benefits are estimated to reach 7.3 trillion CNY, 4.2 times greater than those under the Policy Scenario. Nearly all provinces are expected to achieve positive economic returns, with Xinjiang (2.2 trillion CNY in 2060), Inner Mongolia (1.4 trillion CNY in 2060), and Gansu (0.4 trillion CNY in 2060) realizing significant gains due to their substantial carbon mitigation efforts (Fig. 6k). The only exception is Qinghai, which is anticipated to continue reporting negative economic returns, projected at −0.1 trillion CNY by 2060. In 2060, Qinghai's installation cost is 256.2 billion CNY, making it the second highest among provinces. However, Qinghai's carbon emissions in 2060 are only 195.3 million tons. This significantly lower carbon emission level results in the benefits from carbon reduction and electricity generation, rendering them insufficient to cover the lifecycle costs.

Our analysis reveals that the transition to renewable energy resources in China by 2060 is projected to yield substantial climate and economic benefits. Under both scenarios, wind power will reduce carbon emissions by 3.8 to 7.4 billion tons, while PV systems are expected to cut emissions by 3.9 to 9.5 billion tons in 2060. Economically, the wind and solar power could generate 3.7 to 12.8 trillion CNY in 2060 under different scenarios, equivalent to 3.1% to 10.6% of the 2022 GDP.[75] Among total benefits, PV systems are expected to contribute between 42.7% and 57.3%. These economic benefits are particularly significant in regions like Inner Mongolia, Hebei, Xinjiang, Guangdong, and Jiangsu. Our findings highlight the critical role of these regions in driving both China's carbon reduction and economic growth through the transition to renewable energy.

In addition, as to the sensitivity analysis, based on the simulation results for different installed capacity densities using Fengjiang software, as the installed capacity density increases, the equivalent power generation hours decrease (Tables S2, ESI†). Therefore, we made corresponding reductions in the estimated power generation for different installed capacity densities (Tables S3 and S4, ESI†). The reduction rates for installed capacity densities of 8–20 MW km^{-2} are approximately 7–37%. Based on this, we calculated the changes in the profit estimation and found that under the 2060 Policy Scenario and Low-carbon Scenario, the economic benefits of onshore wind power generation at an installed capacity density of 20 MW km^{-2} decreased by 54.3% and 50%, respectively, compared to the situation at 5 MW km^{-2} (Fig. S4 and Table S3, ESI†).

Discussion and conclusions

Our study provides a pivotal assessment of wind and solar energy's transformative potential to reshape China's energy landscape, revealing their capacity to drive the nation's transition to a low-carbon economy. This transformation is expected to rely heavily on northern regions such as Inner Mongolia, Xinjiang, and Heilongjiang, which exhibit the greatest renewable energy potential. By evaluating grid-level data, we highlight that the Policy Scenario and Low-carbon Scenario offer robust pathways for achieving China's renewable energy targets. The anticipated climate and economic benefits of this transition are profound and multifaceted. Under the Policy Scenario, the planned installed capacity of wind and solar power is sufficient to support China's 100% renewable energy transition.[1] Under the Low-carbon Scenarios, the projected reductions in carbon emissions—up to 7.4 billion tons from wind power and 9.5 billion tons from solar PV—demonstrate the critical role of renewables in mitigating climate change. Economically, the potential gains of approximately 5.5 trillion CNY from wind and 7.3 trillion CNY from solar underscore the financial incentives for accelerated investment in these technologies. This dual impact of substantial emissions reductions coupled with significant economic returns positions renewables as central to China's sustainable development strategy. However, Sichuan, with lower resource conditions and challenging mountainous terrain that limits technical installation capacity, ultimately results in negative returns under the Policy Scenario.

Our findings present several far-reaching policy implications that align with China's policy framework. First, there is a pressing need for stronger policy support for wind and solar power. Especially, regions such as Inner Mongolia and Xinjiang, endowed with abundant renewable resources, hold the potential to generate significant economic benefits. By "turning resources into gold", these regions can meet China's future electricity needs while significantly boosting economic development in underdeveloped areas. This strategy leverages their natural resources to drive growth and support the nation's low-carbon transition efficiently. Furthermore, our grid-level comparison reveals that PV systems are more economically viable than wind energy, with PV offering economic advantages that are approximately 1 to 1.3 times greater than wind, primarily due to cost disparities. This finding highlights the importance of tailoring development strategies based on local resource endowments and economic feasibility. Our finding reinforces the need to move beyond general resource-based siting principles by incorporating localized cost-performance assessments, land-use constraints, and long-term policy alignment to guide technology-specific deployment strategies that are both economically efficient and regionally adaptive.

In addition to robust policies, adequate infrastructure support is critical for the successful transition to renewable energy. Current grid constraints, particularly the inability to fully absorb new energy electricity in high-generation regions, must be addressed. Expanding grid capacity and improving power transmission infrastructure are essential for guaranteeing renewable electricity consumption. Additionally, policies that encourage the spatial relocation of energy-intensive industries to regions with abundant renewable resources can help solve grid congestion issues. Establishing initiatives such as "zero-carbon electricity industrial and trade zones", where export-oriented enterprises receive certification for using zero-carbon electricity, can provide a concrete market-driven solution to scaling up renewable energy consumption. Coal-producing provinces, fossil fuel-dependent areas, and energy-importing regions can leverage this strategy to diversify energy sources, driving a more equitable and sustainable energy transition across China.

Furthermore, our findings suggest that China's total installed capacity of wind and solar power is projected to reach 22 184.7 GW under the 2060 Low-carbon Scenario. However, the current energy storage infrastructure is far from sufficient to accommodate the volatility introduced by such a large-scale integration of renewables, posing significant challenges to grid operation. To ensure stable grid performance, continuous power supply, and cost-effective operation, coordinated efforts across technological, policy, and financial dimensions are urgently needed. First, accelerating the construction of inter-provincial transmission corridors—such as Eastern Inner Mongolia–Shandong and Ningxia–Shandong—can help balance regional electricity supply and demand.[18] Second, given that China's current energy storage capacity is less than 1% of the projected requirement, substantial investments are recommended to expand and deploy new storage technologies to meet future grid flexibility needs. Finally, the development of ancillary services and capacity markets is critical for improving system flexibility. Since 2025, China has allowed renewables to participate in electricity markets, using price signals to promote peak shaving and lay the groundwork for a high-renewable power system.[76–78]

Our study makes several significant contributions to the field of renewable energy and climate change mitigation. First, we provide a long-term, high-resolution dataset of wind and solar capacity inputs for integrated assessment models, offering a robust foundation for future energy and climate policy research. Second, we offer a detailed and operationally implementable roadmap for wind and solar capacity planning, which can guide policymakers in achieving a balanced and sustainable energy mix. Third, by addressing the unequal distribution of renewable energy resources across provinces, we propose strategies to mitigate regional disparities in green energy supply and economic inequality through optimized renewable energy installations.

Moreover, our research provides valuable insights for other countries undergoing energy transitions from traditional fossil fuels to renewables. For nations, like India, Saudi Arabia, and South Africa, facing similar challenges in transitioning to clean energy, our findings offer strategic guidance on leveraging regional renewable energy potential to maximize both climate and economic benefits. Specifically, at the data level, countries should acquire medium- to long-term wind and solar deployment plans and integrate key spatial constraints—such as slope, elevation, land-use restrictions, and protected areas—while incorporating country-specific factors. For instance, in India, additional considerations include grid connection right-of-way, grid capacity requirements for new energy, public acceptance willingness, wildlife risks, vegetation distribution and shading conditions, as well as buffer zone.[21,79,80] In Saudi Arabia, critical factors include regional dust conditions, high-temperature extreme weather, employment impacts and transmission network maturity.[81] Methodologically, this study outlines a five-step framework—resource assessment, technical potential estimation, scenario-based deployment, generation simulation, and benefit evaluation—that can be directly adopted in other national or regional studies.

In our study, the economic benefits are assessed from an environmental economics perspective. However, we acknowledge that a more comprehensive evaluation should also consider the opportunity costs associated with alternative land uses. In renewable energy planning, land-use opportunity costs are not only a core dimension of economic evaluation but must also be dynamically balanced against the alternative economic functions of land—such as high-value agricultural production and ecosystem service provision. For example, the IEA[82] notes that in regions with exceptionally high agricultural productivity, solar PV development should adopt an agricultural-photovoltaic hybrid model to reconcile food security goals with energy transition priorities. Similarly, empirical studies on U.S. federal lands suggest that, despite the vast technical potential, actual deployment must prioritize the avoidance of ecologically sensitive areas and high-value farmland. Furthermore, research by Dinesh *et al.*[83] shows that the multifunctional value of land—such as biodiversity conservation—can substantially increase its opportunity cost, thereby altering the logic of siting priorities. In ecologically fragile regions, such trade-offs may raise the economic viability threshold for wind and solar projects significantly.

Author contributions

J. G., R. W., L. Z., X. Lu., and J. W. designed the research. J. G. and R. W. processed and analysed the data. L. Z., F. Z, Y. L., X. Liu., and Y. Z. conducted the experimental work. J. G., R. W., L. Z., S. W., L. L., M. D., and J. W. wrote the paper. All authors contributed to developing and writing the manuscript.

Conflicts of 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. Ruomei Wang, Yafei Li, and Xiaoya Liu are employees of Goldwind Science & Technology Co., Ltd.

Data availability

The data supporting this article have been included as part of the ESI.† Data for this article are available at the China New Energy Power Generation Potential Assessment Platform at https://newenergy.cityghg.com/. We have made all related data processing scripts publicly available on GitHub at https://github.com/Lilian12138/Renewable_energies.git. Further information and requests for resources should be directed to and will be fulfilled by the lead contact, Li Zhang (zhangli_1122@outlook.com).

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References

1 M. Z. Jacobson, D. Fu, D. J. Sambor and A. Mühlbauer, *Environ. Sci. Technol.*, 2025, **59**, 3034–3045.
2 M. Z. Jacobson, M. A. Delucchi, M. A. Cameron, S. J. Coughlin, C. A. Hay, I. P. Manogaran, Y. Shu and A.-K. von Krauland, *One Earth*, 2019, **1**, 449–463.
3 J. Lelieveld, J. S. Evans, M. Fnais, D. Giannadaki and A. Pozzer, *Nature*, 2015, **525**, 367–371.
4 D. Tong, D. J. Farnham, L. Duan, Q. Zhang, N. S. Lewis, K. Caldeira and S. J. Davis, *Nat. Commun.*, 2021, **12**, 6146.
5 D. Tong, Q. Zhang, Y. Zheng, K. Caldeira, C. Shearer, C. Hong, Y. Qin and S. J. Davis, *Nature*, 2019, **572**, 373–377.
6 F. J. M. M. Nijsse, J.-F. Mercure, N. Ameli, F. Larosa, S. Kothari, J. Rickman, P. Vercoulen and H. Pollitt, *Nat. Commun.*, 2023, **14**, 6542.
7 S. J. Davis, N. S. Lewis, M. Shaner, S. Aggarwal, D. Arent, I. L. Azevedo, S. M. Benson, T. Bradley, J. Brouwer and Y.-M. Chiang, *Science*, 2018, **360**, eaas9793.
8 J. Rogelj, G. Luderer, R. C. Pietzcker, E. Kriegler, M. Schaeffer, V. Krey and K. Riahi, *Nat. Clim. Change*, 2015, **5**, 519–527.
9 J. Rogelj, A. Popp, K. V. Calvin, G. Luderer, J. Emmerling, D. Gernaat, S. Fujimori, J. Strefler, T. Hasegawa and G. Marangoni, *Nat. Clim. Change*, 2018, **8**, 325–332.
10 D. Millstein, R. Wiser, M. Bolinger and G. Barbose, *Nat. Energy*, 2017, **2**, 17134.
11 S. Dey, A. Sreenivasulu, G. T. N. Veerendra, K. V. Rao and P. S. S. A. Babu, *Innov. Green Dev.*, 2022, **1**, 100006.
12 D. Neupane, S. Kafle, K. R. Karki, D. H. Kim and P. Pradhan, *Renewable Energy*, 2022, **181**, 278–291.
13 Y. Wang, R. Wang, K. Tanaka, P. Ciais, J. Penuelas, Y. Balkanski, J. Sardans, D. Hauglustaine, W. Liu and X. Xing, *Nature*, 2023, **619**, 761–767.
14 B. K. Sahu, *Renewable Sustainable Energy Rev.*, 2018, **81**, 1393–1405.
15 Tsinghua University, Technology outlook on wind and solar power toward China's carbon neutrality goal (in Chinese), https://www.efchina.org/Reports-zh/report-snp-20240131-zh, (accessed June, 2025).
16 A. Pascale, J. D. Jenkins and E. Leslie, 2021.
17 State Grid Corporation of China (SGCC), *Report on Supporting New Energy Development*, 2024.
18 D. Zhang, Z. Zhu, S. Chen, C. Zhang, X. Lu, X. Zhang, X. Zhang and M. R. Davidson, *Proc. Natl. Acad. Sci.*, 2024, **121**, e2306517121.
19 M. Chen, L. Gao, Z. Guo, Y. Dong, E. A. Moallemi, Y. Xu, K. Li, W. Lin, J. Yang, W. Xu, M. Pedercini and B. A. Bryan, *Nat. Commun.*, 2024, **15**, 9489.
20 S. Zhang and W. Chen, *Nat. Commun.*, 2022, **13**, 87.
21 A.-K. von Krauland and M. Z. Jacobson, *Cell Rep. Sustainability*, 2024, **1**, 5.
22 M. Z. Jacobson and M. A. Delucchi, *Energy Policy*, 2011, **39**, 1154–1169.
23 L. Liu, Y. Wang, Z. Wang, S. Li, J. Li, G. He, Y. Li, Y. Liu, S. Piao, Z. Gao, R. Chang, W. Tang, K. Jiang, S. Wang, J. Wang, L. Zhao and Q. Chao, *Resour., Conserv. Recycl.*, 2022, **180**, 106155.
24 Y. Gao, S. Ma, T. Wang, T. Wang, Y. Gong, F. Peng and A. Tsunekawa, *Energy Convers. Manage.*, 2020, **226**, 113580.
25 M. Li, E. Virguez, R. Shan, J. Tian, S. Gao and D. Patiño-Echeverri, *Appl. Energy*, 2022, **306**, 117996.
26 X. Guo, X. Chen, X. Chen, P. Sherman, J. Wen and M. McElroy, *Nat. Commun.*, 2023, **14**, 2447.
27 L. Liu, Z. Wang, Y. Wang, J. Wang, R. Chang, G. He, W. Tang, Z. Gao, J. Li and C. Liu, *Renewable Sustainable Energy Rev.*, 2020, **132**, 110151.
28 J. Lazo, E. Trujillo-Baute and D. Watts, Available at SSRN 4972268.
29 J. V. Lamy, P. Jaramillo, I. L. Azevedo and R. Wiser, *Energy Policy*, 2016, **96**, 341–350.
30 Å. Lindman and P. Söderholm, *Appl. Energy*, 2016, **179**, 1351–1359.
31 M. Z. Jacobson, *Energy Environ. Sci.*, 2009, **2**, 148–173.
32 D. P. Parker, S. Johnston, B. Leonard, D. Stewart and J. B. Winikoff, *Nat. Energy*, 2024, 1–9, DOI: 10.1038/s41560-024-01617-4.
33 M. Z. Jacobson, M. A. Delucchi, G. Bazouin, Z. A. F. Bauer, C. C. Heavey, E. Fisher, S. B. Morris, D. J. Y. Piekutowski, T. A. Vencill and T. W. Yeskoo, *Energy Environ. Sci.*, 2015, **8**, 2093–2117.
34 J. van Ouwerkerk, M. Celi Cortés, N. Nsir, J. Gong, J. Figgener, S. Zurmühlen, C. Bußar and D. U. Sauer, *Nat. Commun.*, 2024, **15**, 8206.
35 J. Blazejczak, F. G. Braun, D. Edler and W.-P. Schill, *Renewable Sustainable Energy Rev.*, 2014, **40**, 1070–1080.
36 T. P. Brennand, *Energy Sustainable Dev.*, 2004, **8**, 82–92.
37 National Bureau of Statistics of China, National data, https://data.stats.gov.cn/, (accessed April, 2024).

38 OpenStreetMap contributors, OpenStreetMap (OSM), https://www.openstreetmap.org/, (accessed April 2024).
39 N. N. Davis, J. Badger, A. N. Hahmann, B. O. Hansen, N. G. Mortensen, M. Kelly, X. G. Larsén, B. T. Olsen, R. Floors, G. Lizcano, P. Casso, O. Lacave, A. Bosch, I. Bauwens, O. J. Knight, A. Potter van Loon, R. Fox, T. Parvanyan, S. B. Krohn Hansen, D. Heathfield, M. Onninen and R. Drummond, *Bull. Am. Meteorol. Soc.*, 2023, **104**, E1507–E1525.
40 Energy Sector Management Assistance Program (ESMAP), Global Solar Atlas (GSA), https://globalsolaratlas.info, (accessed April 2024).
41 E. Peri and A. Tal, *Appl. Energy*, 2020, **279**, 115829.
42 Z. Zhu, D. Zhang, X. Zhang and X. Zhang, *Energy Environ. Sci.*, 2025, **18**(8), 3699–3717.
43 A. Lopez, B. Roberts, D. Heimiller, N. Blair and G. Porro, *U.S. Renewable Energy Technical Potentials. A GIS-Based Analysis*, United States, 2012.
44 D. Mulas Hernando, W. Musial, P. Duffy and M. Shields, *Capacity Density Considerations for Offshore Wind Plants in the United States*, United States, 2023.
45 Ministry of Natural Resources of the People's Republic of China, Notice on Further Strengthening the Management of Sea Use for Offshore Wind Power Projects, https://www.gov.cn/zhengce/zhengceku/202501/content_6996439.htm, (accessed December, 2024).
46 M. Z. Jacobson and C. L. Archer, *Proc. Natl. Acad. Sci.*, 2012, **109**(39), 15679–15684.
47 L. Sun, Y. Jiang, Q. Guo, L. Ji, Y. Xie, Q. Qiao, G. Huang and K. Xiao, *Resour., Conserv. Recycl.*, 2021, **168**, 105306.
48 G. Rediske, H. P. Burin, P. D. Rigo, C. B. Rosa, L. Michels and J. C. M. Siluk, *Renewable Sustainable Energy Rev.*, 2021, **148**, 111293.
49 Y. Noorollahi, A. Ghenaatpisheh Senani, A. Fadaei, M. Simaee and R. Moltames, *Renewable Energy*, 2022, **186**, 89–104.
50 M. Elgendi, M. AlMallahi, A. Abdelkhalig and M. Y. E. Selim, *Int. J. Thermofluids*, 2023, **17**, 100289.
51 J. Lange, J. Mann, J. Berg, D. Parvu, R. Kilpatrick, A. Costache, J. Chowdhury, K. Siddiqui and H. Hangan, *Environ. Res. Lett.*, 2017, **12**, 094020.
52 R. Sayre, Global Mountains K3, (accessed April 2024).
53 J. Zhang, S. Chowdhury, A. Messac and L. Castillo, *Energy Policy*, 2012, **42**, 538–550.
54 A. Sedaghat, A. Hassanzadeh, J. Jamali, A. Mostafaeipour and W.-H. Chen, *Appl. Energy*, 2017, **205**, 781–789.
55 J. Cotrell, T. Stehly, J. Johnson, J. O. Roberts, Z. Parker, G. Scott and D. Heimiller, *Analysis of Transportation and Logistics Challenges Affecting the Deployment of Larger Wind Turbines: Summary of Results*, United States, 2014.
56 Ministry of Natural Resources of the People's Republic of China, Notice of the National Energy Administration and the National Oceanic Administration on Issuing the Implementation Rules for the Management of Offshore Wind Power Development and Construction, https://gc.mnr.gov.cn/201806/t20180619_1797507.html, (accessed April, 2024).
57 B. Wu, T. L. Yip, L. Xie and Y. Wang, *Ocean Eng.*, 2018, **168**, 121–132.
58 A. Gastli and Y. Charabi, *Renewable Sustainable Energy Rev.*, 2010, **14**, 790–797.
59 A. Barbón, P. Fortuny Ayuso, L. Bayón and C. A. Silva, *Appl. Energy*, 2023, **348**, 121524.
60 J. A. L. Stoddard and R. O'Connell, *Economic, Energy, and Environmental Benefits of Concentrating Solar Power in California*, National Renewable Energy Laboratory (NREL), 2006.
61 SOLARGIS, Solar resource maps & GIS data, https://solargis.com/resources/free-maps-and-gis-data, (accessed April 2024).
62 B. Settou, N. Settou, A. Gouareh, B. Negrou, C. Mokhtara and D. Messaoudi, *Clean Technol. Environ. Policy*, 2021, **23**, 219–234.
63 M. Jia, Z. Zhang, L. Zhang, L. Zhao, X. Lu, L. Li, J. Ruan, Y. Wu, Z. He, M. Liu, L. Jiang, Y. Gao, P. Wu, S. Zhu, M. Niu, H. Zheng, B. Cai, L. Tang, Y. Shu and J. Wang, *Appl. Energy*, 2024, **373**, 123838.
64 J. Liu, D. Song, Q. Li, J. Yang, Y. Hu, F. Fang and Y. Hoon Joo, *Energy Convers. Manage.*, 2023, **277**, 116628.
65 K. An, W. Cai, X. Lu and C. Wang, *Sci. Data*, 2025, **12**, 69.
66 Q. He, H. Chen, Z. Lin, X. Dai, Y. Huang and W. Cai, *Energy Rep.*, 2022, **8**, 147–155.
67 X. Ouyang and B. Lin, *Energy Policy*, 2014, **70**, 64–73.
68 International Energy Agency (IEA) & Nuclear Energy Agency (NEA), *Projected Costs of Generating Electricity: 2020 Edition*, Paris: OECD Publishing, 2020.
69 Ministry of Ecology and Environment of the People's Republic of China, Announcement by the Ministry of Ecology and Environment and the National Bureau of Statistics on the Release of the 2021 Carbon Dioxide Emission Factor for Power Generation, https://www.mee.gov.cn/xxgk2018/xxgk/xxgk01/202404/t20240412_1070565.html, (accessed June, 2025).
70 S. Hyun and Y. C. Park, *Energies*, 2024, **17**, 5332.
71 H. Huang, *et al.*, *Mater. Sci.: Mater. Rev.*, 2017, **1**, 1–8, DOI: 10.18063/msmr.v1i1.503.
72 J. Tian, S. Zhou and Y. Wang, *Environ. Impact Assess. Rev.*, 2023, **102**, 107161.
73 E. Byers, V. Krey, E. Kriegler, K. Riahi, R. Schaeffer, J. Kikstra, R. Lamboll, Z. Nicholls, M. Sandstad and C. Smith, 2022.
74 China Electric Power Construction Association, Annual Development Report of China's Electric Power Construction Industry 2023, https://www.cepca.org.cn/news/show-12628.html, (accessed June, 2025).
75 National Bureau of Statistics of China, The National Bureau of Statistics Announcement on the Final Verification of the 2022 Gross Domestic Product (GDP), https://www.stats.gov.cn/sj/zxfb/202312/t20231229_1946058.html, (accessed December, 2024).
76 National Energy Administration (NEA), Notice on Ensuring the Effective Integration of New Energy and Promoting Its High-Quality Development, https://www.nea.gov.cn/2024-06/04/c_1310777103.htm, (accessed December, 2024).
77 H. Guo, M. R. Davidson, Q. Chen, D. Zhang, N. Jiang, Q. Xia, C. Kang and X. Zhang, *Energy Policy*, 2020, **145**, 111717.
78 National Development and Reform Commission (NDRC), Notice on Deepening Market-Oriented Reform of

Grid-Connected Electricity Prices for New Energy and Promoting High-Quality Development of New Energy (Price Department of NDRC [2025] No. 136), https://www.ndrc.gov.cn/xxgk/zcfb/tz/202502/t20250209_1396066.html, (accessed December, 2024).
79 A. Jain, P. Das, S. Yamujala, R. Bhakar and J. Mathur, *Energy*, 2020, **211**, 118993.
80 S. K. Saraswat and A. K. Digalwar, *J. Renewable Sustainable Energy*, 2023, **15**, 066102.
81 F. E. M. Suliman, *Energies*, 2024, **17**, 1894.
82 IEA, Renewables 2024, https://www.iea.org/reports/renewables-2024, Licence: CC BY 4.0, (accessed June, 2025).
83 H. Dinesh and J. M. Pearce, *Renewable Sustainable Energy Rev.*, 2016, **54**, 299–308.