Geography and Sustainability 7 (2026) 100489

Contents lists available at ScienceDirect

Geography and Sustainability

journal homepage: www.elsevier.com/locate/geosus

Research Article

Wind energy expansion in China produces substantial CO_2 reductions and climate benefits

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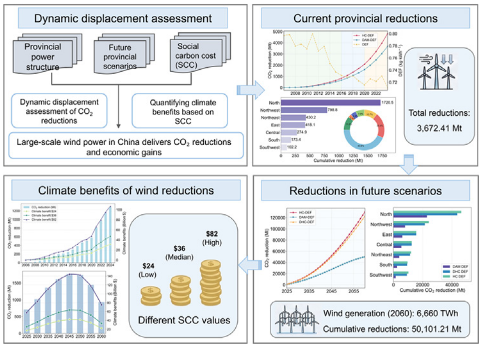
HIGHLIGHTS

- China's wind power has reduced 3,672.41 Mt CO_2, generating up to $273.26 billion in climate benefits.
- By 2060, wind power cumulative could reduce 50,101.21 Mt CO_2 and deliver $1,803.64 billion in total benefits.
- Prioritizing coal-fired power displacement with wind power increases CO_2 mitigation by >50 %.

GRAPHICAL ABSTRACT



ARTICLE INFO

Article history:
Received 5 November 2025
Received in revised form 1 April 2026
Accepted 27 April 2026
Available online 8 May 2026

Keywords:
Wind energy
CO_2 reduction
Displacement emission factor
Social cost of carbon
China

ABSTRACT

Wind power is central to decarbonizing China's power sector, yet its CO_2 reduction benefits are often evaluated using static assumptions that overlook the dynamic evolution of the energy system. To address this limitation, we established a dynamic assessment framework taking two distinct approaches: the Dynamic High-Carbon Displacement Emission Factor (DHC-DEF), which assumes the priority displacement of high-carbon baseloads, and the Dynamic All Mix Energy Displacement Emission Factor (DAM-DEF), which reflects the system-wide average emission intensity of the evolving power mix. Leveraging this framework, we quantified wind power's mitigation benefits and conducted a monetized assessment of its climate–economic value in different Social Cost of Carbon (SCC) scenarios. The results show that, owing to wind power's leapfrog development over the past two decades, China has achieved a cumulative carbon dioxide (CO_2) reduction of 3,672.41 Mt in the DAM-DEF case, generating around $273.26 billion in climate benefits. By 2060, an annual wind generation of 6,660 TWh is expected to abate at least 931.25 Mt of CO_2, achieving a climate–economic value of around $33.52 billion. Cumulative reductions over the entire period are forecasted to reach 50,101.21 Mt, delivering economic returns of around $1,803.64 billion. Spatially, the mitigation contributions have been largely concentrated in North (45.7 %) and Northwest (15.8 %) China. Notably, our analysis results show that the strategic prioritization of displacing high-carbon or coal-fired technologies holds the potential to boost mitigation benefits by over 50 %. Moreover, given the high sensitivity of economic valuation to SCC, policymakers should incorporate SCC into dynamic shadow pricing mechanisms and energy planning to support high-quality wind power development.

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https://doi.org/10.1016/j.geosus.2026.100489

1. Introduction

According to the Intergovernmental Panel on Climate Change (IPCC) Sixth Assessment Report, the increase in greenhouse gas emissions due to human activity is the main driver of global climate change, causing a 1.1 °C rise in the global surface temperature between 2011 and 2020, compared with the period from 1850 to 1900 (Grose et al., 2023). To address the negative impacts of global warming, countries worldwide have set ambitious targets for limiting the global temperature rise to below 2 °C—and ideally to 1.5 °C—by the end of this century (Nieto, 2022). Specifically, China has pledged to reach peak carbon emissions before 2030 and to achieve carbon neutrality by 2060. However, realizing these dual goals will require the gradual phasing out of fossil fuel-based power generation, especially coal, and energy sector decarbonization (Demetriou and Hadjistassou, 2021). As a clean and renewable energy source, wind power is anticipated to be vital in enabling the global low-carbon energy transition and supporting both the 2060 net-zero emission target and China's carbon neutrality goal (Keyßer and Lenzen, 2021). Wind power's CO_2 mitigation benefits largely stem from its substitution for fossil fuel-based electricity generation and the related emissions. The value of these avoided emissions reflects the potential environmental and social damages that would have been incurred in the absence of such substitution (Millstein et al., 2024). Thus, systematically and comprehensively evaluating and quantifying wind power's emission reduction benefits have become critical tasks in research related to energy transition and climate change mitigation strategies.

Previous studies have comprehensively evaluated wind power's CO_2 emission reduction benefits across global, regional, and national scales, but notable disparities remain concerning research scales, assessment frameworks, and methodological assumptions (Kuang et al., 2022; Kumar and Madlener, 2016; Li et al., 2020; Su et al., 2026). Globally, recent studies have widely recognized wind energy as a key pillar for achieving this century's climate targets, with long-term cumulative mitigation potential estimated at the multi-gigaton scale (Barthelmie and Pryor, 2021; Long et al., 2023). In early-adopter regions such as Europe and the United States, wind power's ongoing expansion over the past two decades has already afforded stable and notable abatement outcomes. For example, wind generation in Europe avoids approximately 129.1 Mt of CO_2 emissions annually (Ortega-Izquierdo and del Río, 2020). In the United States, the synergistic development of wind and solar power totally reduced emissions by roughly 900 Mt between 2019 and 2022 (Millstein et al., 2024). These empirical results highlight wind power's critical role in power sector decarbonization.

Moreover, emerging economies such as those of China and India have seen rapid growth in their wind power industries in recent years, placing renewable energy at the core of future energy planning (Chabhadiya et al., 2021; Li et al., 2024). Relevant studies have shown that in high-wind-penetration and high-solar-penetration scenarios, India's power sector CO_2 emissions by mid-century are projected to be approximately 85 % lower than in a coal-dominated baseline scenario (Lu et al., 2020). Further, in the Chinese context, life cycle assessment (LCA) results show that wind power generation's greenhouse gas emission intensity is approximately 19.88 g CO_2-eq kWh^{-1}, resulting in an abatement efficiency of about 98 % relative to standard fossil fuel-based electricity generation (Xu et al., 2025). Assessment based on technical potential showed that cumulative reductions may reach approximately 21.7 Gt by 2030 (Liu et al., 2023), while analyses based on operational data from actual wind farms revealed substantial wind power contributions of over 300 Mt CO_2 reductions in 2020 alone (Li et al., 2020). Further research projected that by 2050, onshore wind technologies will yield cumulative climate mitigation benefits of approximately 74.2 Gt, contributing 17.2 %–45.5 % toward achieving national carbon neutrality targets (Li et al., 2024).

However, most existing assessments have depended on static displacement emission factors, which assume that wind power consistently displaces carbon-intensive coal-fired generation throughout its operational lifetime (e.g., using a fixed value of approximately 0.9–1.0 kg CO_2 kWh^{-1}) (Barthelmie and Pryor, 2014; Ma et al., 2013). While such static assumptions are logical in the early wind power deployment stages, when coal dominates the electricity system, their applicability becomes increasingly limited as the energy transition accelerates (Ahmed et al., 2025; Chen et al., 2020; Thomson et al., 2017). Previous studies have shown that, with rising penetration of renewable energy, the background generation mix of power systems undergoes substantial decarbonization, causing a continuous decline in the relative proportion of high-carbon technologies (Fell et al., 2022; Williams et al., 2021; Zhang and Chen, 2022; Dong et al., 2025; Lu et al., 2026; Wang et al., 2026). Also, thermal power plants are gradually transitioning from baseload providers to more flexible, load-following roles, causing the technologies displaced by wind power—and the related mitigation effect per unit of generation—to change over time, not remain constant (Zhu et al., 2025). Under such conditions, ignoring the dynamic evolution of the power system and continuing to employ fixed high-carbon emission factors may not capture the "dilution effect" stemming from system-wide decarbonization and may cause an overestimation of wind power's long-term CO_2 mitigation benefits (Millstein et al., 2021). Therefore, evaluating wind power's mitigation potential in carbon neutrality scenarios necessitates the adoption of dynamic displacement perspectives that overtly consider electricity system structure changes.

The most direct way to assess wind power's emission reduction benefits is to monetize the emission reduction (Wang et al., 2025). The Social Cost of Carbon (SCC) is used to assess the quantifiable cost of CO_2 emissions (expressed in monetary value), and it has been widely applied by policymakers to evaluate the benefits of climate mitigation measures and compare them with the emission reduction costs (Wang et al., 2022a). SCC estimation typically uses Integrated Assessment Models (IAMs), which combine simplified representations of the climate system and the global economy to forecast the economic impact of incremental CO_2 emission pulses (Caesary et al., 2025; Rennert et al., 2022). SCC estimation largely relies on the damage functions within IAMs, with key parameters such as climate sensitivity, intergenerational discount rates, and regional equity making a significant impact on the final SCC result (Pizer et al., 2014). These uncertainties contribute to much debate over SCC's valuation, and considerable differences exist in the carbon prices employed by various organizations. For instance, an analysis by Ricke et al. (2018) found relatively high global SCC value, with the median reaching \$417/t CO_2 (66 % confidence interval), but a more uneven SCC distribution nationally. Likewise, Rennert et al. (2022) estimated an average SCC value of \$185/t CO_2 for the United States, which is 3.6 times higher than the current U.S. government value of \$51/t CO_2. In China, the median SCC is around \$36/t CO_2 (Wang et al., 2022a), and it is projected to rise to an average of \$471/t CO_2 by 2100.

Based on the existing research and its limitations, this study aimed to address several key research questions regarding wind power's mitigation potential, given China's evolving energy structure. Specifically, this study sought to answer the following questions: (1) How do estimates of CO_2 emission reduction benefits vary between traditional static substitution emission factor approaches and dynamic displacement methods in changing power system structures? (2) How do these differences change over historical and future energy transition scenarios in China? (3) How sensitive are wind power abatement's climate benefits to different SCC assumptions? To address these questions, we systematically analyzed the evolution of China's current and future energy structure and established an improved dynamic assessment framework. This framework integrates two dynamic substitution emission factor approaches with traditional static factor methods, enabling a comparative evaluation of emission reduction estimates. Moreover, wind power mitigation's climate–economic value was monetized using three SCC estimates representative of the Chinese context, and the results' sensitivity to SCC assumptions was examined.

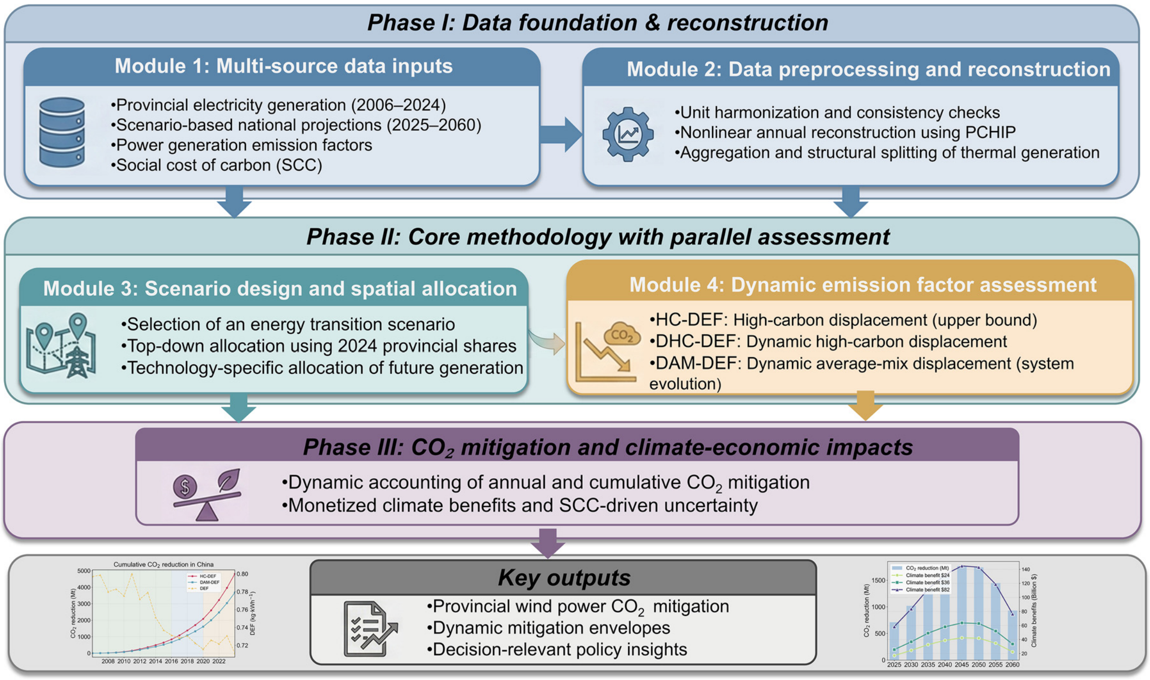

Fig. 1. Overall technical roadmap of the study, illustrating the framework for dynamic displacement emission factor assessment and climate benefit evaluation.

2. Materials and methods

To systematically assess the carbon reduction potential and climate benefits of wind power in China over the period 2006–2060, this study develops an integrated assessment framework. As illustrated in Fig. 1, the methodological workflow consists of three main phases:

(1) Data foundation and reconstruction, in which historical observations and scenario-based projections are combined to construct continuous annual power generation time series using a nonlinear PCHIP interpolation approach;
(2) Core methodological framework, which applies a tri-partite displacement emission factor system—HC-DEF, DHC-DEF, and DAM-DEF—to represent alternative substitution logics under an evolving power system; and
(3) CO_2 mitigation valuation and output, where the resulting emission reductions are monetized using a China-specific SCC gradient to derive policy-relevant indicators.

2.1. Data and pre-processing

The historical provincial electricity generation data used in this study were obtained from the public database of the National Bureau of Statistics of China (https://data.stats.gov.cn/easyquery.htm?cn=E0101). This database provides monthly electricity generation statistics for 31 provincial-level administrative regions (excluding Hong Kong, Macau, and Taiwan), covering various energy sources including thermal power, hydropower, nuclear power, wind power, and solar energy. The data is regularly updated, with the most recent data available up to the previous month. To ensure data completeness for the early years of renewable energy development, wind power data for 2006–2012 and solar power data for 2006–2015 were supplemented using the *China Electric Power Statistical Yearbook*. The historical analysis begins in 2006, which coincides with the implementation of China's Renewable Energy Law and marks the onset of large-scale, policy-driven expansion of wind power. In addition, provincial-level wind power generation statistics became increasingly standardized and systematically reported from this year onward, providing a consistent and reliable basis for long-term and cross-regional comparative analysis.

Future simulation data for different scenarios adopts a comprehensive energy forecasting model that integrates macro-level top-down control with sector-specific bottom-up end-use analysis. The projected power generation data (2025–2060) are derived from the *China Energy Outlook 2060* (SINOPEC Economics, Development Research Institute, 2025). This report, based on systematic energy system modeling and multi-scenario analysis, outlines the future trends in energy structure and electricity generation in China under the goal of achieving carbon neutrality. It is highly authoritative and scientifically sound, providing a solid data foundation for the long-term electricity generation projections in this research. In this study, we selected the electricity generation forecast under the Coordinated Transition scenario. This scenario aims to peak carbon emissions by 2030 and achieve carbon neutrality by 2060, assuming a stable international situation, orderly restructuring of global industrial supply chains, and limited impact from localized conflicts on bulk commodity trade. It also envisions high-quality domestic economic development, accelerated improvement of the modern industrial system, and enhanced living standards. In this scenario, natural gas serves as a transition bridge, and by around 2035, low-carbon technologies such as green hydrogen, energy storage, and carbon capture are expected to achieve cost competitiveness, ensuring the timely realization of green and low-carbon goals. The electricity generation forecasts based on this scenario provide a reliable long-term reference for this study.

To construct annual power generation time series for the period 2025–2060 and to avoid the potential loss of nonlinear transition dynamics caused by linear interpolation between five-year scenario intervals, this study adopts a nonlinear time-series reconstruction approach that integrates historical observations with scenario-based anchor points. Specifically, for power generation technologies with consistent classification definitions across both the historical period and future scenario projections—namely wind power, solar power, hydropower, and nuclear power—annual generation series are reconstructed by jointly using historical year-by-year statistical data and five-year-interval scenario projections as anchor points. A monotonicity-preserving Piecewise Cubic Hermite Interpolating Polynomial (PCHIP) method is applied to interpolate annual values. This approach constructs smooth interpolation curves that are continuous in both function value and first derivative between adjacent anchor points, effectively avoiding the overshooting artifacts commonly associated with conventional spline interpolation while preserving the nonlinear growth or decline characteristics inherent in energy transition processes. The interpolation can be expressed as:

$$E_k(t) = \mathrm{PCHIP}\left\{t_m, E_k\left(t_m\right)\right\}_{m=1}^{M} \tag{1}$$

where $E_k(t)$ denotes the electricity generation of technology k in year t, and $\{t_m\}$ represents the set of historical observation years and future scenario anchor years.

In historical statistics, thermal power generation is not further disaggregated into coal-fired, gas-fired, and other fossil-fuel-based generation, whereas future scenario projections provide a more detailed classification of fossil-based technologies. To ensure consistency between historical and future data, we adopt a “total interpolation–structural disaggregation” approach. First, the total thermal power generation—defined as historical thermal generation and the sum of coal-fired, gas-fired, and other fossil-fuel-based generation in future scenarios—is interpolated using the PCHIP method to obtain an annual thermal power generation series $E_{\mathrm{thermal}}(t)$. Subsequently, this total is disaggregated into individual fossil fuel technologies according to their proportional shares in the future scenario projections:

$$E_j(t) = E_{\mathrm{thermal}}(t) \times \frac{E_j^{\mathrm{scen}}(t)}{\sum_{l \in \{\mathrm{coal,\ gas,\ other}\}} E_l^{\mathrm{scen}}(t)} \tag{2}$$

where $E_j(t)$ denotes the electricity generation of coal-fired, gas-fired, or other fossil-fuel-based power in year t, and $E_j^{\mathrm{scen}}(t)$ represents the corresponding projected generation from the future scenario data.

For other non-fossil power generation, a stable and comparable standalone technology classification is not available in historical statistics. Therefore, historical backcasting is not performed for this category. Instead, only future scenario anchor points are used, and annual values are smoothed using the PCHIP method to avoid introducing speculative or physically unjustified historical estimates.

To derive provincial-level future electricity generation, we adopted a top-down proportional disaggregation approach based on the most recent observed generation structure, applied separately to each power generation technology. Specifically, national projections of electricity generation by technology from the *China Energy Outlook 2060* were used as control totals, and spatial allocation weights were constructed based on provincial shares of national generation in 2024 for each technology. Let $P^k_{\mathrm{national},y}$ denote the projected national electricity generation of technology k (e.g., coal, hydropower, nuclear, wind, solar, natural gas) in year y. Provincial electricity generation for province i and technology k, P_i^k is calculated as:

$$P_i^k = P^k_{\mathrm{national},y} \times \omega_i^k \tag{3}$$

where ω_i^k represents the allocation weight of province i for technology k, defined as:

$$\omega_i^k = \frac{P^k_{i,2024}}{\sum_{i=1}^{N} P^k_{i,2024}} \tag{4}$$

where, $P^k_{i,2024}$ denotes electricity generation of technology k in province i in 202, and N is the total number of provinces. This procedure ensures consistency between provincial estimates and national projections while preserving the observed spatial distribution patterns of different generation technologies. The resulting allocation weights for all technologies and provinces are provided in Table S1 in the Supplementary materials.

The carbon emission factor data for various power generation technologies used in this study are sourced from the 2023 Electricity Carbon Footprint Factor Bulletin jointly released by the Ministry of Ecology and Environment, the National Bureau of Statistics, and the National Energy Administration (Ministry of Ecology and Environment of the People’s Republic of China, 2023). This data, based on both international and domestic carbon footprint accounting standards, systematically calculates the unit carbon emissions for different power generation types (including coal, natural gas, hydropower, nuclear power, wind power, photovoltaics, biomass, etc.). It reflects the average emission levels of various power generation technologies currently used in China, filling a gap in the domestic data on electricity carbon footprint factors. Accordingly, they are adopted in this study to construct displacement emission factors (DEFs), ensuring that the estimated mitigation outcomes are well aligned with China’s energy structure characteristics and institutional context. The datasets used in this study are summarized in Table 1.

2.2. *Dynamic displacement assessment of CO_2 reductions*

Unlike the static displacement emission factor approaches commonly adopted in previous studies—which assume that wind power persistently and exclusively displaces coal-fired power or other specific high-carbon generation—this study builds upon the dynamic displacement estimation framework proposed by (Vázquez Hernández et al., 2019) and related studies to establish a comprehensive comparative assessment framework. From a bottom-up perspective, we systematically assess the annual and cumulative CO_2 mitigation potential of wind power generation in China under an evolving power system structure.

To explicitly capture the uncertainties associated with different substitution assumptions during the energy transition, we construct one static scenario and two dynamic displacement emission factor scenarios. This comparative framework enables us to rigorously quantify how alternative substitution pathways influence estimated mitigation outcomes, identify the systematic bias inherent in conventional static approaches, and provide a robust range (from lower to upper bounds) for wind power abatement benefits under long-term decarbonization pathways.

(1) High-Carbon Displacement Emission Factor (HC-DEF). This scenario assumes that wind power generation displaces coal-fired power only. The associated CO_2 reductions are calculated as the product of wind electricity generation and a fixed coal-fired power emission factor. This scenario represents the conventional static coal substitution assumption widely adopted in existing literature.
(2) Dynamic High-Carbon Displacement Emission Factor (DHC-DEF). Under this scenario, wind power is assumed to dynamically displace all high-carbon power generation technologies within the electricity mix, including coal-fired power, natural gas–fired power, and other fossil fuel–based generation. The high-carbon displacement emission factor is calculated as a dynamically weighted average based on the annual generation shares of these fossil fuel technologies, thereby reflecting temporal changes in the high-carbon power structure. This approach reflects the merit-order dispatch logic where zero-marginal-cost wind power typically prioritizes the displacement of fuel-intensive thermal generation, thereby representing the upper bound of mitigation benefits.
(3) Dynamic All Mix Energy Displacement Emission Factor (AM-DEF). This scenario assumes that wind energy can displace all types of power generation technologies within the energy mix, including both fossil and non-fossil energy sources. The corresponding displacement emission factor is dynamically determined as the weighted average emission factor of the entire power generation mix in a given year. This approach captures the “dilution effect”—where wind power competes with other low-carbon sources at high penetration levels—thus representing the conservative lower bound of the mitigation potential.

The calculation steps for the dynamic displacement estimation method are as follows:

Calculate the substitution emission factor $\mathrm{DEF}_{p,y}$ for province p and year y:

$$\mathrm{DEF}_{p,y} = \frac{\sum_{t \in T_y \setminus \mathrm{Wind}} E_{t,p,y} \cdot \mathrm{EF}_t}{\sum_{t \in T_y \setminus \mathrm{Wind}} E_{t,p,y}} \tag{5}$$

Table 1
Summary of datasets used in this study.

Data name	Source	Spatial / Temporal resolution	Preprocessing	Purpose
Provincial electricity generation	National Bureau of Statistics of China	Province / Monthly	Aggregation, consistency check	Historical energy structure
Provincial electricity generation	*China Electric Power Statistical Yearbook*	National / Yearly	Aggregation, consistency check	Historical energy structure
Future power generation	*China Energy Outlook 2060*	National / 5-year	Provincial disaggregation	Scenario analysis
Power emission factors	MEE–NBS–NEA (China)	National / Static	-	DEF construction
Social cost of carbon estimates	Ricke et al. (2018); Wang et al. (2022a); Estrada et al. (2025)	China-specific	Scenario selection	Monetization

where $T_y \backslash \mathrm{Wind}$ represents the set of all technologies displaced by wind energy in year y (excluding wind power itself). $E_{t,p,y}$ is the electricity generated by technology t in province p during year y. EF_t is the emission factor (in terms of CO_2 emissions per unit of electricity) for technology t.

Calculate the CO_2 emissions avoided by wind power generation in province p for year y as $\mathrm{EM}_{p,y}$:

$$\mathrm{EM}_{p,y} = E_{\mathrm{Wind},p,y} \cdot \mathrm{DEF}_{p,y} \tag{6}$$

where, $E_{\mathrm{Wind},p,y}$ is the electricity generated by wind power in province p during year y.

Therefore, the national cumulative emission reductions are then expressed as:

$$E_y^{\mathrm{Total}} = \Sigma_{p \in N_p} \mathrm{EM}_{p,y} = \Sigma_{p \in N_p} E_{\mathrm{Wind},p,y} \cdot \mathrm{DEF}_{p,y} \tag{7}$$

where N_p represents the set of all provinces.

The national weighted average alternative emission factor is:

$$\mathrm{DEF}_y^{\mathrm{Total}} = \frac{\Sigma_{p \in N_p} E_{\mathrm{Wind},p,y} \cdot \mathrm{DEF}_{p,y}}{\Sigma_{p \in N_p} E_{\mathrm{Wind},p,y}} \tag{8}$$

2.3. Quantifying the climate benefits of carbon reduction

In this study, we adopted the SCC indicator to monetize the CO_2 reductions attributable to wind power generation, thus quantifying the climate benefits of wind energy deployment. The SCC represents the marginal economic damage of emitting 1 ton of additional CO_2 into the atmosphere, and it is widely used as a key metric for assessing expected climate damages and informing climate policy design (Ricke et al., 2018). Currently, most SCC estimates are obtained from IAMs, which couple socioeconomic development, climate system processes, and damage functions. However, SCC estimates are highly sensitive to assumptions about discount rates, damage function specifications, risk treatment, and regional heterogeneity, giving rise to substantial uncertainty (Peng et al., 2021). Furthermore, existing studies have reported a wide range of SCC values, spanning from approximately \$10 to \$1000 per ton of CO_2 (Anthoff and Tol, 2013; Moyer et al., 2014; Wang et al., 2019), with the majority of estimates concentrated between \$30 and \$250 (Liu et al., 2022).

Against this backdrop, this study selected three representative SCC values to characterize a plausible uncertainty range in the Chinese context. Specifically, the low-end scenario (\$24/t CO_2) was based on (Ricke et al., 2018), who extended global IAM frameworks to estimate country-level SCC and report a median SCC of approximately \$24 (4–50) per t CO_2 for China. The high-end scenario (\$82/t CO_2) is derived from recent assessments based on the CLIMRISK framework (Estrada et al., 2025), which explicitly incorporate climate risk and extreme-damage tail events, yielding substantially higher SCC estimates for China under high-impact scenarios and thus representing an upper-bound estimate. For the mid-range scenario, recent China-focused studies have shown that SCC estimates in moderate socioeconomic development and emission scenarios generally cluster around \$40/t CO_2, while fossil fuel–intensive scenarios yield markedly higher values (Wang et al., 2022b). Accordingly, the value of \$36/t CO_2 adopted in this study (Wang et al., 2022a) was deemed a reasonable central estimate for China, positioned between conservative lower-bound and high-risk upper-bound scenarios.

Consistent with the dynamic displacement emission factor framework employed in this study, the adoption of these three SCC scenarios explicitly captures the uncertainty of China's SCC estimates, thus enhancing the robustness and policy relevance of the monetized assessment of wind power's emission reduction benefits. By utilizing this SCC gradient (\$24–\$82/t CO_2), this study provides a plausible monetized range reflecting varying levels of climate risk and socioeconomic assumptions. Note, however, that these values represent the long-term social damage costs associated with CO_2 emissions, rather than short-term regulatory carbon prices (e.g., ETS spot prices). This distinction ensures the robustness of the long-term economic assessment and avoids distortions stemming from short-term market fluctuations.

3. Results

3.1. Evolution power structure and wind power's emission reduction benefits in China

China's current energy structure is still largely dependent on traditional fossil fuel power generation. However, over the past two decades, wind power generation in China has witnessed rapid growth. As shown in Fig. 2a and 2b, in 2006, China's wind power generation was only 2.83 TWh, constituting 0.1 % of the total national power generation. By 2010, wind power proportion had exceeded 1 % for the first time, reaching 49.5 TWh. Since 2015, renewable energy proportion (hydropower, wind power, and solar energy) in China's power structure has steadily fallen, with the total power generation reaching 1,203.25 TWh by 2015, or 21.55 % of the national total. Of this amount, hydropower contributed 996 TWh (17.84 %), wind power contributed 168.09 TWh (3.01 %), and solar power contributed 39.16 TWh (0.7 %). In later years, hydropower generation gradually declined, while wind and solar power generation steadily increased, with wind power seeing notable growth. By the end of 2024, wind power generation had reached 936.02 TWh, constituting 9.94 % of the total national generation and 35.6 % of the total renewable energy generation.

Regionally (Fig. 2c–f), the highest wind power generation in 2024 was seen in North China (332.62 TWh), Northwest China (173.27 TWh), and East China (111.71 TWh), accounting for 13.99 %, 12.48 %, and 5.95 % of their regional total generation, respectively. Notably, despite the relatively high total wind power generation in East China, the region's power structure is still dominated by thermal power, with thermal power generation reaching 1,455.46 TWh, constituting 77.47 % of the total generation. Nuclear power follows as the second largest source, generating 208.78 TWh, or 11.11 % of the total. Of all regions, Northeast China has the largest wind power proportion, at 18.77 % (86.32 TWh). Moreover, Southwest China is the only region where the proportion of thermal power is below 40 %, with thermal power constituting only 31.42 %. The main power source in this region is hydropower,

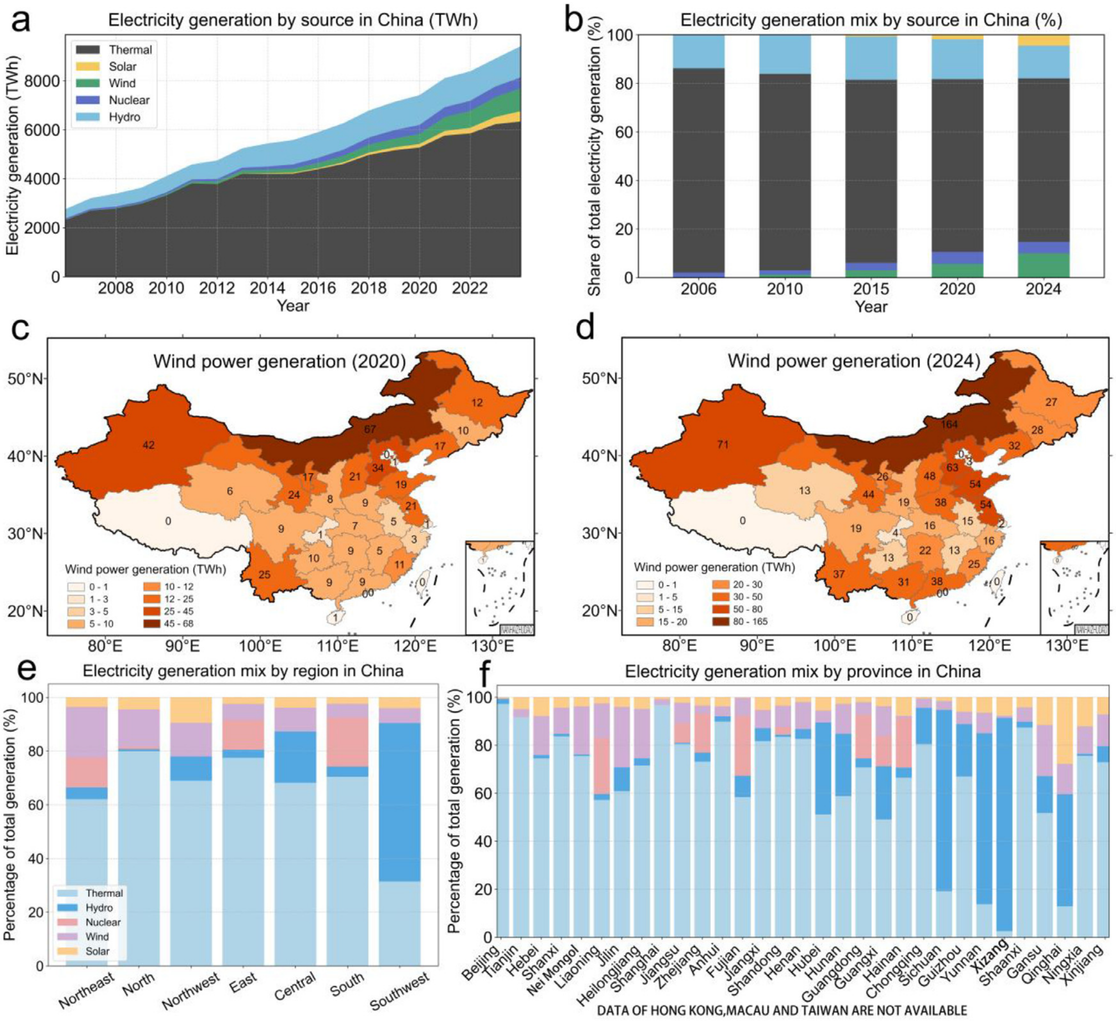

Fig. 2. Overview of the evolution of China's power structure over the past two decades. (a)–(b) Evolution of China's power structure over 2006–2024, and the change in the proportion of each energy source in total installed capacity; (c)–(d) Map of wind power generation distribution across Chinese provinces in 2020 and 2024; (e)–(f) Major energy structure compositions of China's seven power grid regions and provinces.

which generates 775.48 TWh, making up 58.97 % of the region's total power generation.

Over the past 5 years, wind power generation has witnessed considerable growth across all provinces, with more than 60 % of provinces experiencing a wind power growth rate exceeding 100 %. Specifically, Nei Mongol, Xinjiang, and Hebei were the top three provinces in wind power generation in 2024, with 164.3 TWh, 70.79 TWh, and 63.47 TWh, respectively. Together, these three provinces account for about one-third of the total national wind power generation. Notably, according to our previous research (Long et al., 2025), Xizang has ample wind and solar resources, but the province currently depends largely on hydropower (88.83 %), generating 12.83 TWh, with wind power contributing only 0.13 TWh, or less than 1 % of the national wind power generation.

Using wind power to replace coal-fired power generation results in a certain degree of overestimation of wind power's emission reduction potential, with the cumulative overestimation reaching approximately 31 %. Fig. 3a shows the cumulative CO_2 emission reductions over 2006–2024, computed using two methods: wind power replacing coal-fired generation (HC-DEF) and wind power replacing all power generation technologies (DAM-DEF). The results show a rapid increase in wind power's emission reductions with both methods, with the gap between the two gradually widening.

Specifically, in 2006, the wind power emission reductions were only 2.58 Mt (HC-DEF) and 2.16 Mt (DAM-DEF), translating to a difference of 19.25 %. By 2015, the emission reductions had grown to 646.01 Mt (HC-DEF) and 518.87 Mt (DAM-DEF), with the difference widening to 24.5 %. Over 2016–2020, owing to national policy support, renewable energy rapidly developed. Wind power's cumulative CO_2 emission reductions rose from 838.39 Mt and 666.31 Mt to 2,083.09 Mt and 1,609.47 Mt, respectively, with the gap expanding to 29.43 %. After nearly five years of rapid development, by the end of 2024, the cumulative CO_2 emission reductions from wind power had reached 4,812.93 Mt and 3,672.41 Mt, with the difference between the two methods reaching 31.06 %. This overestimation is largely due to the dynamic nature of the substitution emission factor in the DAM-DEF method. As the renewable energy proportion in the energy mix increases, the DEF value gradually falls. In contrast, the HC-DEF method assumes a fixed emission factor for coal-fired power generation at 0.944 kg CO_2e kWh^{-1}, which causes an overestimation of wind power's emission reduction potential.

Regionally (Fig. 3b–d), regardless of the calculation method used, over 50 % of the wind power emission reductions nationwide are contributed by the North China and Northwest regions. In North China, provinces such as Nei Mongol, Hebei, Shandong, and Shanxi lead in cumulative wind power emission reductions. According to the DAM-DEF method, the cumulative emission reductions in North China are 1,720.5 Mt, accounting for 43.9 % of the total reductions. Moreover, with the HC-DEF method, the reduction is 1,792.2 Mt, representing 37.2 %, with a difference of 4.17 %. The Northwest region (represented by Xinjiang,

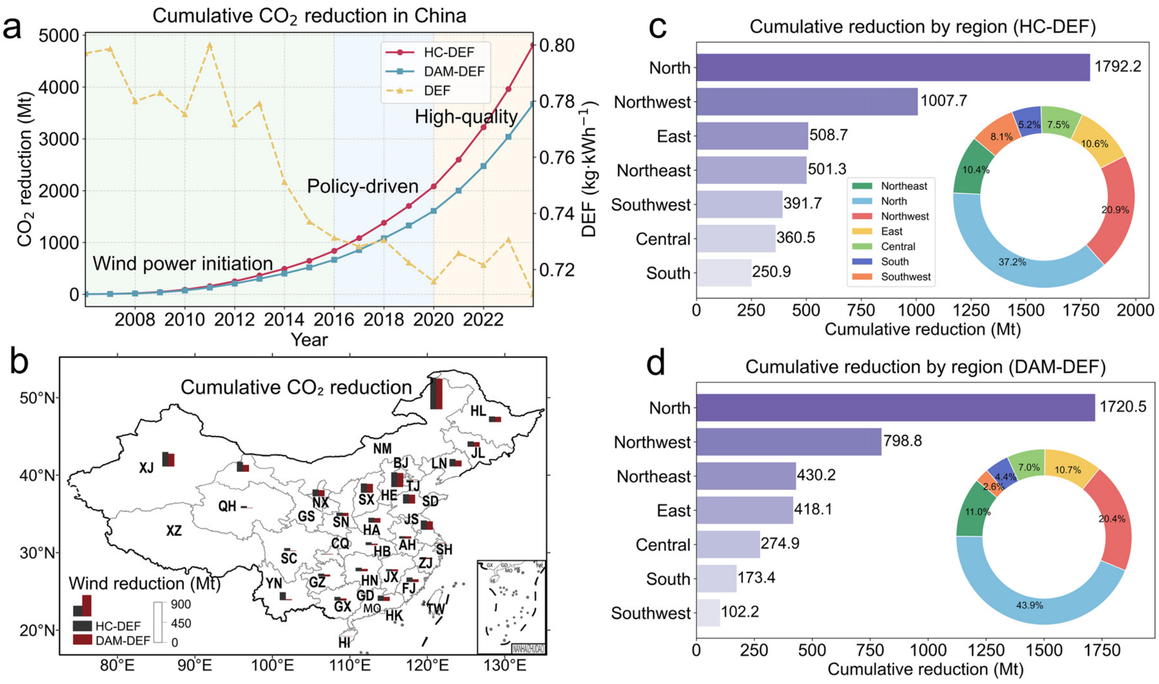

Fig. 3. Cumulative CO_2 reduction from wind power generation over the past two decades. (a) Cumulative CO_2 reductions from wind power in China over 2006–2024 (based on the results from two calculation methods); (b) Distribution of cumulative CO_2 reductions from wind power across provinces in 2024; (c)–(d) Regional reductions calculated using the HC-DEF and DAM-DEF methods, with small pie charts showing the proportion of each region in the national cumulative reduction. *Note*: See Table S2 in the Supplementary materials for the full names and codes of provincial abbreviations used in this figure.

Gansu, and Ningxia) follows, with notable wind power reductions. Using the DAM-DEF method, we found that the total emission reductions in Northwest China amount to 798.8 Mt. However, with the HC-DEF method, this value rises to 1,007.7 Mt, which is 26.15 % higher than the DAM-DEF method. The main reason for this difference is that the Northwest region has the largest renewable energy proportion, producing a larger variation in the emission factor with energy structure changes. However, owing to the relatively lower renewable energy proportion in North China, the emission factor evolves more gradually, resulting in smaller differences between the two methods.

The Southwest region shows the largest discrepancy in emission reductions of the two evaluation methods. With the DAM-DEF method, the cumulative reduction in the Southwest is 102.15 Mt, while with the HC-DEF method, the reduction is more than three times higher, or 391.72 Mt. This considerable difference is largely due to hydropower, the main power source in the Southwest, having a carbon emission factor of only 0.0143 kg CO_2e kWh^{-1}. Therefore, the dynamic emission factor in this region is lower, causing reduced emission reductions with the DAM-DEF method.

3.2. Wind power reduction potential under future power structure transition in China

In the Coordinated Transition Scenario, China's future energy structure reflects a profound transformation characterized by the rapid expansion of renewable energy and the deep phase-down of high-carbon energy sources, as shown in Fig. 4. According to the forecast, China's total electricity generation will increase from 10,580 TWh in 2025 to 18,860 TWh in 2060, marking a growth rate of 78.2 %. Of this amount, renewable energy generation (i.e., hydropower, wind power, solar power) is projected to rise from 3,850 TWh in 2025 to 14,940 TWh in 2060, accounting for nearly 80 % of the total electricity mix. Wind power (44.58 % in 2060) and solar power (33.94 % in 2060) are the main contributors to the growth of renewable energy, with their generation expected to rise from 1,140 TWh and 1,040 TWh in 2025 to 6,660 TWh and 5,070 TWh in 2060, respectively. In contrast, hydropower's growth is projected to be more moderate, increasing by only about 26.2 %.

Concerning high-carbon energy, the generation of coal, natural gas, and other fossil fuels is expected to decrease from 6,270 TWh in 2025 to 1,610 TWh in 2060, translating to a decline of about 74.3 %, with their proportion in the power mix falling to 8.54 %. This shift will be largely driven by the accelerated decarbonization of China's electricity structure. During this period, coal-fired power generation is predicted to decrease from 5,630 TWh in 2025 to 1,080 TWh in 2060, or a decline of approximately 80.9 %, with coal's proportion in the electricity mix expected to fall to just 5.73 % by 2060.

Regionally, North China and Northwest China, the areas with the richest renewable energy resources in China, will play a key role in the country's future energy transition. By 2030, the renewable energy generation in North China and Northwest China is forecasted to reach 1,128.4 TWh and 1,008.24 TWh, respectively, constituting for 21.25 % and 18.99 % of the total renewable energy generation in China, respectively. By 2060, the renewable energy generation in North China and Northwest China will increase to an estimated 3,979.29 TWh and 3,047.81 TWh, respectively, with their proportion in the total generation of their respective regions rising to 87.85 % and 90.22 %, indicating their future dominance of the regional energy mix.

Wind power, an important component of renewable energy, will see particularly considerable growth, being expected to range from 324.18 TWh to 2,366.67 TWh in various regions, or from 22 % to 63 % of their regional renewable energy generation mix. Specifically, by 2030, provinces such as Nei Mongol, Xinjiang, Hebei, Jiangsu, and Shandong will all exceed 100 TWh in wind power generation, with Nei Mongol leading at 312.44 TWh. In these provinces, the wind power proportion in the total energy generation mix will surpass 10 %, with the highest reaching 27.61 %. By 2060, China's wind power generation will also see a considerable increase. Except for Beijing, Tianjin, and Hainan, all provinces will have wind power making up more than 10 % of their energy structure. Among them, Nei Mongol's wind power generation is

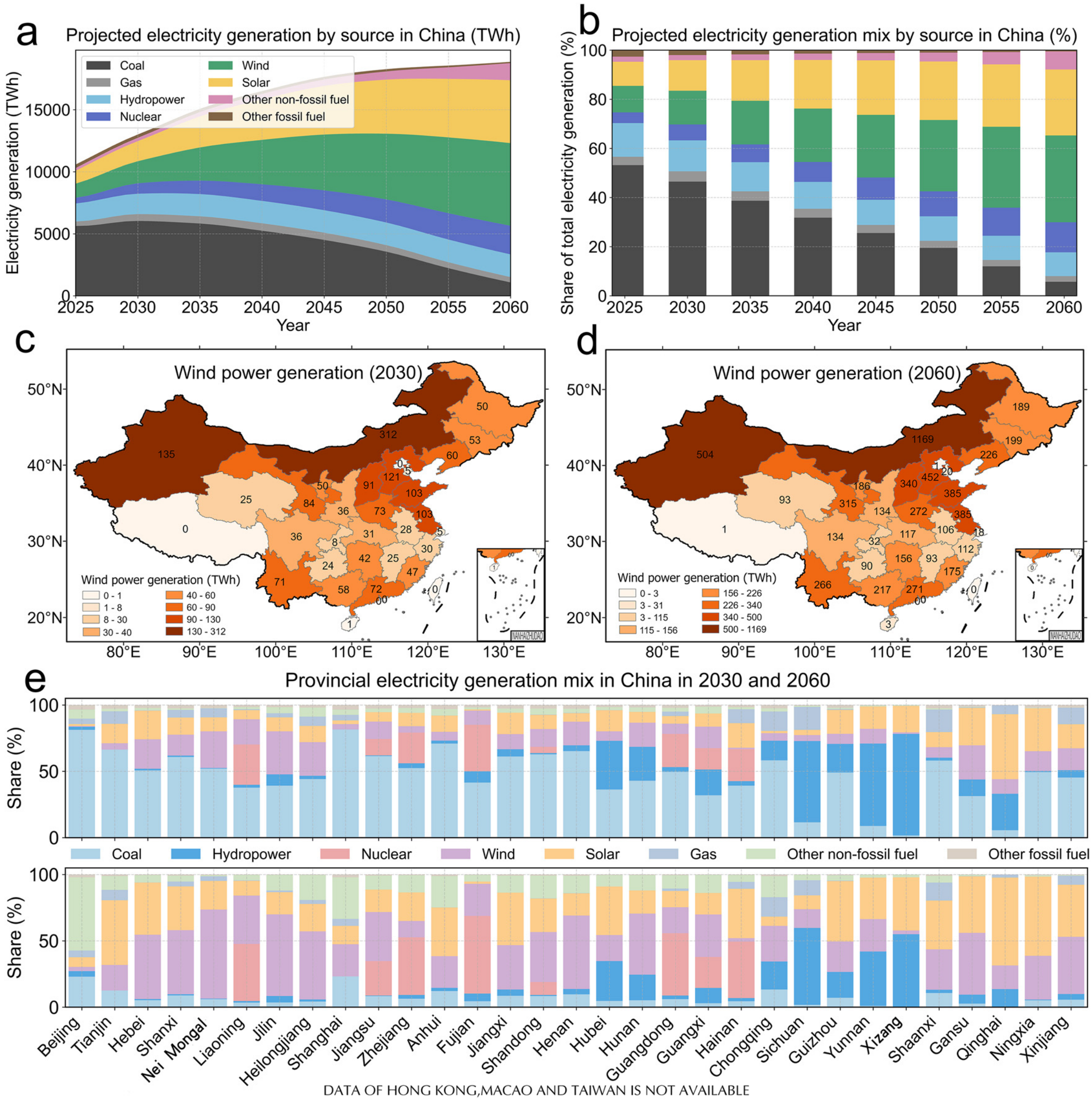

Fig. 4. Evolution of China's power structure over 2025–2060. (a)–(b) Evolution of China's power structure over 2025–2060 and the changes in the proportion of each energy source in the total installed capacity. (c)–(d) Wind power generation distribution across provinces in China for 2030 and 2060. (e) Major energy structure composition across provinces in China for 2030 and 2060.

projected to reach 1,169.03 TWh, accounting for 67.18 % of its total electricity generation, underscoring the central role of wind energy in the region's energy structure.

With the rapid growth in the renewable energy proportion in the future power mix, the difference in cumulative CO_2 reduction benefits in different wind power displacement scenarios will become increasingly pronounced. With 2030 taken as a benchmark, the cumulative reduction with the DAM-DEF scenario will stand at 5,214.95 Mt. In contrast, in the DHC-DEF and HC-DEF scenarios, cumulative reductions will reach 77,225.49 Mt and 8,005.71 Mt, respectively, representing increases of 48.14 % and 53.51 %, respectively, relative to the DAM-DEF scenario. By 2060, this gap will widen further, with the mitigation volumes in the DHC-DEF and HC-DEF scenarios exceeding the DAM-DEF baseline by 145.21 % and 160.33 %, respectively (Fig. 5a). These margins markedly exceed the differences seen during the historical period (2006–2024). This projection indicates that as the renewable energy proportion keeps rising and growing, the trend of divergence in CO_2 emission reductions in different scenarios will also become more pronounced.

Furthermore, as shown in Fig. 5b, with the annual increase in wind power generation, the overall CO_2 reductions across all three scenarios exhibit an upward trend. However, with the DAM-DEF scenario, the reduction will peak in 2047 (1,780.63 Mt) and subsequently decline, dropping to 931.25 Mt by 2060. This inversion trend is fundamentally driven by the rapid decarbonization of the background power grid. As China hurtles toward its carbon neutrality goal, the power structure will undergo profound transformation. According to our projections, the proportion of coal-fired power will plummet from 53.21 % in 2025 to just 5.73 % by 2060. Moreover, the shares of low-carbon power sources such as solar and nuclear energy will soar from 9.83 % and 4.35 % to 26.88 % and 12.25 % by 2060, respectively. This structural shift will produce a continuous decline in the grid's average carbon intensity. In the later stages (post-2047), the "dilution effect" generated by the large injection of clean energy—where the background grid becomes inherently clean—will outweigh wind power capacity growth's positive impact. Therefore, in the DAM-DEF scenario, the marginal displacement benefit per unit of wind power will fall over time, leading to an observed decline in the theoretical CO_2 reduction potential during this phase.

Regionally (Fig. 5c–e), North China, leveraging its rich wind resource endowment and long-standing function as a large-scale energy supply base, exhibits significantly higher total CO_2 reductions in all

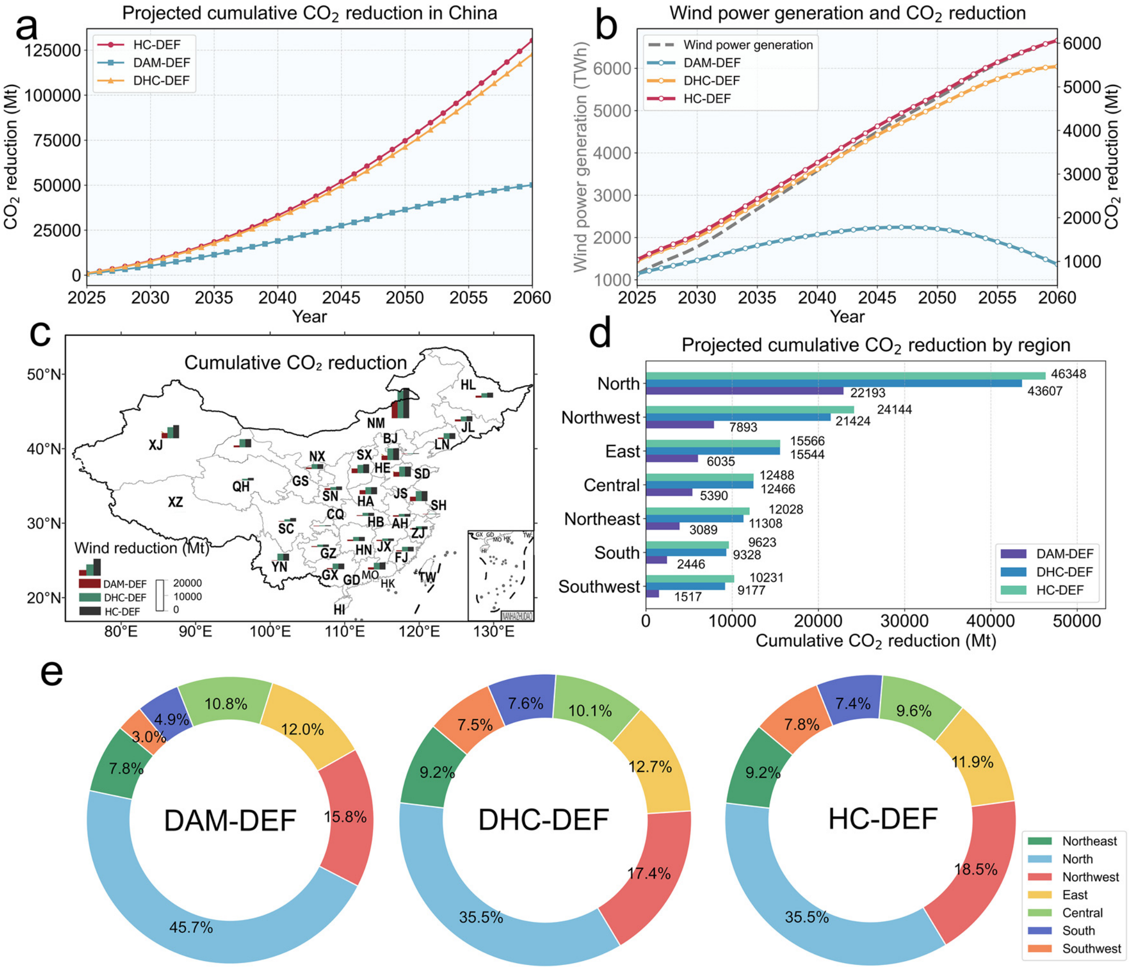

Fig. 5. Cumulative CO_2 emission reductions from wind power generation over 2025–2060. (a) Cumulative CO_2 emission reductions from China's wind power over 2025–2060 (calculated using three methods); (b) Yearly changes in wind power CO_2 reductions in China over 2025–2060; (c) Distribution of CO_2 emission reductions from wind power across provinces in 2060; (d) Regional reductions calculated based on the DAM-DEF, DHC-DEF, and HC-DEF scenarios; (e) Proportion of each region in the total national cumulative reductions with the three methods. *Note*: See Table S2 for the full names and codes of provincial abbreviations used in this figure.

three (35.5 %–45.7 %), ranging from 22,913.05 Mt to 46,347.99 Mt. This forecast is mainly driven by Nei Mongol, where the vast wind potential and flat terrain enable large-scale wind power deployment, contributing 54.12 % of the regional total in the DAM-DEF scenario (compared to 47.57 % and 49.4 % in the DHC-DEF and HC-DEF scenarios, respectively). Additionally, Hebei, Shandong, and Shanxi, known for their relatively high industrial electricity demand, each contribute approximately 15 %. Notably, in the DHC-DEF scenarios, Hebei's contribution increases, even exceeding 20 %.

The Northwest and East China regions rank next in terms of cumulative CO_2 reductions, contributing between 11.9 % and 18.5 %. In the DAM-DEF scenario, the reductions are 7,893.04 Mt and 6,034.63 Mt, respectively. However, when considering high-carbon emission replacements, these figures skyrocket, exceeding 24,000 Mt and 15,000 Mt, respectively. In the Northwest, which has vast land resources and wind corridors, Xinjiang's contribution accounts for approximately 50 % of the regional total. Conversely, in East China, in spite of its relative land constraints, Jiangsu Province dominates (~50 %) because of its backdrop of high power demand and rapid offshore wind development. In Central China, the reduction ranges from 5,390.00 Mt to 12,487.84 Mt, with the populous province of Henan playing a dominant role (42.6 % to 57.38 %). In South China, Guangdong leads, contributing between 55.18 % and 65.92 %. The northeastern provinces exhibit relatively balanced reductions, with no single province dominanting.

Specifically, the Southwest region, characterized by a high proportion of hydropower, shows the lowest total reduction under the DAM-DEF scenario (only 1,517.18 Mt). However, under the HC-DEF scenario, this figure surges dramatically, to 10,230.5 Mt, which is approximately sixfold the amount in the DAM-DEF baseline. This pronounced discrepancy is mainly due to the region's heavy reliance on hydropower. Notably, hydropower is projected to make up as much as 51.61 % of the regional power mix in 2030. Although this proportion will decrease to 43.22 % by 2060, it will remain the structurally dominant power generation source. Given the near-zero emission intensity of hydropower (0.013 kg CO_2e kWh^{-1}), substantial low-carbon hydro markedly reduces the background grid's average carbon intensity in the DAM-DEF scenario. Therefore, the marginal mitigation space corresponding to unit wind generation is severely compressed. In contrast, the HC-DEF scenario assumes that wind power prioritizes the displacement of high-carbon sources such as coal power. This mechanism prevents the dilution effect imposed by the low-carbon background grid, thus fully harnessing the theoretical mitigation potential of the Southwest region and yielding a substantial rise in reduction volumes in this scenario.

3.3. Climate benefits of wind power reduction: based on the SCC

The SCC is commonly used to measure the economic loss caused by CO_2 emissions. Specifically, SCC refers to the socioeconomic damage as-

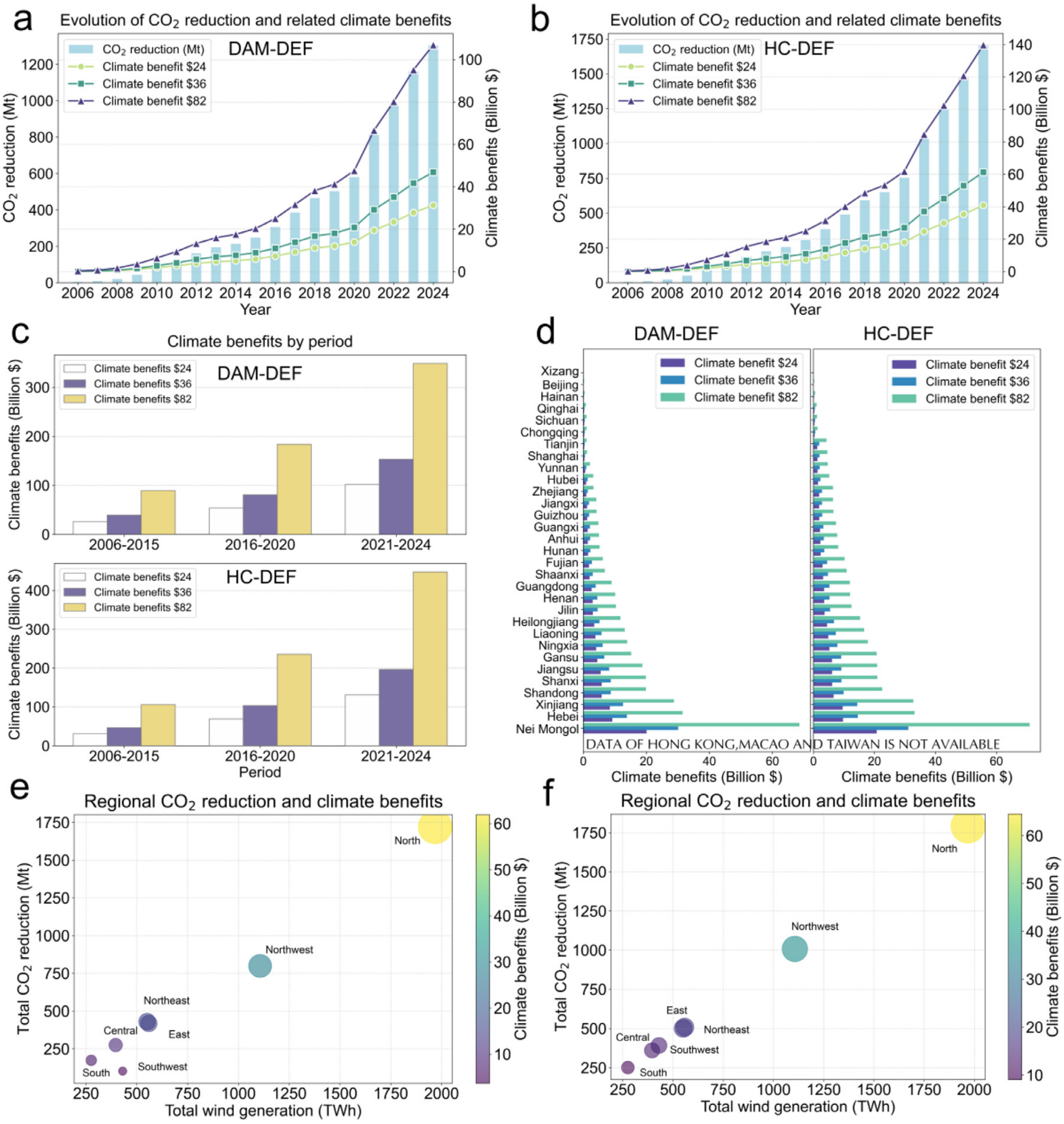

Fig. 6. Climate benefits from wind power between 2006 and 2024. (a) Annual benefits based on DAM-DEF wind power emission reductions; (b) Annual benefits based on HC-DEF wind power emission reductions; (c) Cumulative climate benefits for different time periods with the two CO_2 reduction methods; (d) Cumulative climate benefits by province; (e)–(f) Climate benefits by region with the DAM-DEF and HC-DEF methods, represented as bubble charts.

sociated with the emission of 1 ton of CO_2, which is largely driven by the negative impacts of climate change on the environment and economy. Wind power reduction's climate benefits can be expressed as the product of two factors. Based on the wind power carbon reduction estimates discussed earlier, this study used three different SCC estimates—low (\$24/t CO_2), medium (\$36/t CO_2), and high (\$82/t CO_2)—to quantify wind power emission reduction's climate benefits. We assessed wind energy's climate benefits in both historical and future periods for different regions, considering the total national benefits as the sum of regional contributions. For the subsequent analysis, the medium SCC estimate (\$36/t CO_2) was used as the primary reference, with the results compared against the low and high SCC estimates to capture the uncertainty in wind power reduction benefits under different SCC assumptions.

The CO_2 reductions driven by wind power translate into substantial climate benefits—a trend that has been particularly pronounced in the last five years. As shown in Fig. 6, over 2006–2024, with the median SCC valuation, the total climate benefits generated by wind power in China were estimated at approximately \$273.26 billion in the DAM-DEF scenario, and reaching up to \$346.53 billion in the HC-DEF scenario. Notably, during wind power's high-quality development phase (2021–2024), the mitigation benefits in the HC-DEF and DAM-DEF scenarios reached \$196.55 billion and \$153.18 billion, respectively, with both accounting for over 56 % of their respective cumulative totals. As for regional distribution, North China and Northwest China, which are rich in wind energy resources and have high installed capacities, not only hold notable emission reduction potential but also contribute to large-scale climate benefits. During the analysis period, Nei Mongol and Hebei were the top two provinces in terms of emission reduction benefits, reaching \$30.1 billion (DAM-DEF) and \$31.11 billion (HC-DEF) for Nei Mongol, and \$13.83 billion (DAM-DEF) and \$14.55 billion (HC-

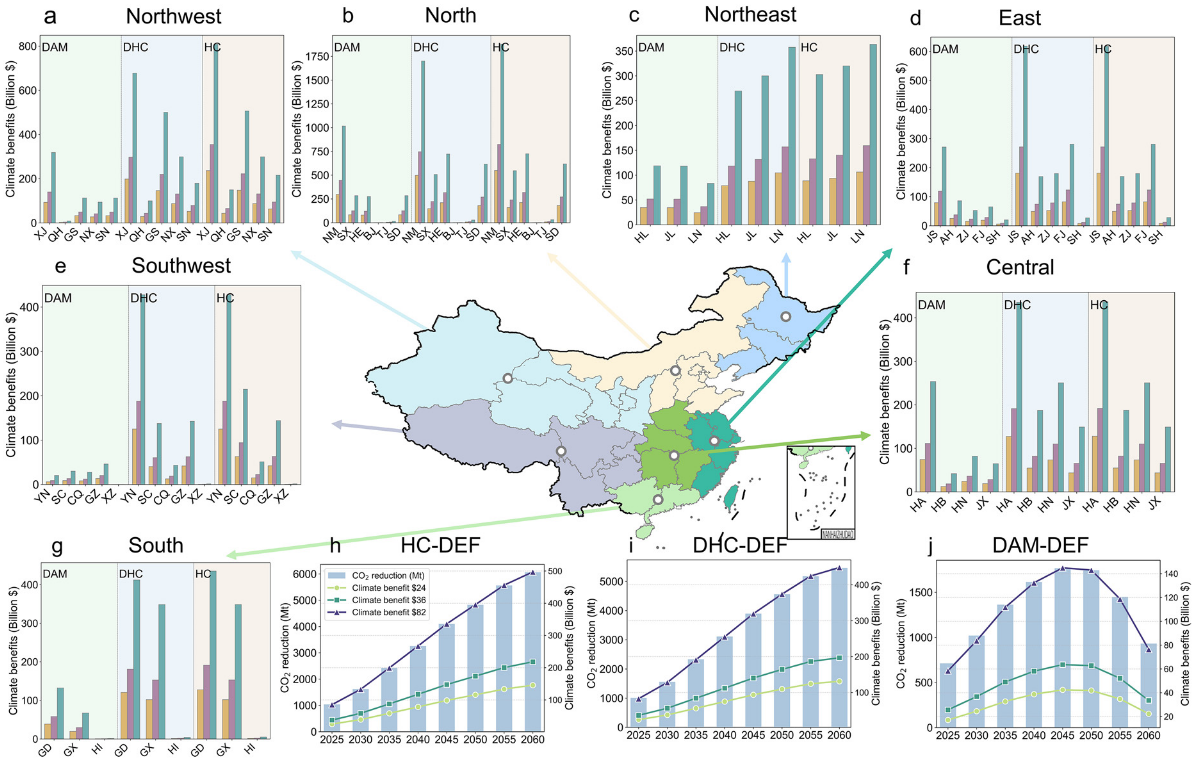

Fig. 7. Wind power's climate benefits over 2025–2060. (a)–(g) Wind power emission reduction's total climate benefits in seven Chinese regions in different scenarios. The *x*-axis in each subplot represents the provinces included in each region, with the subplots arranged from left to right for the DAM-DEF, DHC-DEF, and HC-DEF scenarios, respectively. (h)–(j) Annual climate benefits of national wind power emission reductions over 2025–2060, showing the results for DAM-DEF, DHC-DEF, and HC-DEF methods. *Note*: See Table S2 for the full names and codes of provincial abbreviations used in this figure.

DEF) for Hebei. They were followed by Xinjiang ($12.62 billion DAM-DEF; $14.38 billion, HC-DEF) and Shandong ($8.73 billion DAM-DEF; $9.18 billion, HC-DEF).

From 2025 to 2060, as the renewable energy proportion in the power mix keeps increasing, the climate benefits derived from wind power-induced CO_2 mitigation are also projected to become increasingly notable. Our estimates indicate that the total climate benefits may reach $1,803.64 billion under the DAM-DEF scenario and exceed $4,000 billion under the more aggressive mitigation scenarios (DHC-DEF and HC-DEF), as shown in Fig. 7. Moreover, these climate benefits exhibit a year-on-year upward trend. Specifically, under the HC-DEF and DHC-DEF scenarios, annual climate benefits are projected to peak in 2060, reaching $497.19 billion and $448.15 billion, respectively. In contrast, under the DAM-DEF scenario, the annual benefit is projected to peak earlier in 2047, at $146.01 billion. Regionally, under the DAM-DEF scenario, North China—benefiting from superior wind resources and large-scale development—is projected to achieve the highest total climate benefit of $824.87 billion. This is followed by Northwest and East, reaching $284.15 billion and $217.25 billion, respectively. Even in Southwest, where the mitigation potential is relatively lower, the total climate benefit is expected to reach $54.62 billion. Notably, when shifting to the DHC-DEF and HC-DEF scenarios, these climate benefits increase to approximately 2.5 times those of the DAM-DEF scenario, and by more than six times in the Southwest region.

The uncertainty surrounding the climate benefits of wind energy reductions is largely driven by variability in SCC estimates. To quantify this effect, we calculated the climate benefits under alternative SCC assumptions, with the results summarized in Table 2. The results show that SCC assumptions exert a substantial influence on the magnitude of monetized mitigation benefits. Specifically, higher SCC values lead to markedly larger estimated economic gains. For example, adopting a conservative SCC of $24/t CO_2 results in climate benefits that are 33.33 % lower than those with the median estimate. In contrast, under the high SCC scenario ($82/t CO_2), the estimated climate benefits rise by 127.78 % relative to the median baseline.

This pronounced sensitivity demonstrates that SCC valuation plays a key role in shaping the perceived economic feasibility and wind power investment prioritization. Under low SCC assumptions, wind power's social returns are relatively modest, while higher SCC valuations substantially increase its estimated economic contribution. These findings highlight the importance of adopting scientifically robust and context-appropriate SCC estimates in energy policy assessments and carbon pricing frameworks to more accurately reflect wind power deployment's long-term climate benefits.

4. Discussion

This study systematically analyzes the current and future evolution trends of China's energy structure, stablishing an improved dynamic assessment framework that integrates two dynamic alternative emission factor methodologies to evaluate the potential emission reduction benefits of wind energy. Compared to the commonly used fixed substitution emission factor method in traditional studies, the dynamic estimation method introduced in this study more accurately reflects the actual emission reductions and provides a systematic comparison with the fixed-factor approach. Additionally, to more intuitively reflect the climate-economic value of carbon reductions brought by wind power, this paper further monetizes the potential CO_2 emission reductions of wind energy based on different levels of the SCC in China.

4.1. Challenges of uneven wind power patterns and regional drivers of mitigation benefits

Our analysis of China's energy structure evolution revealed the rapid development of renewable energy, especially wind power, over the past

Table 2
Matrix of cumulative climate benefits (Billion $) under varying displacement emission factors and Social Cost of Carbon (SCC) valuations (2025–2060).

SCC scenario	Unit value ($/t CO_2)	Sensitivity to SCC (vs. Median)	DAM-DEF (base model)	HC-DEF (high-carbon)	DHC-DEF (dynamic HC)
Cumulative mitigation	Mt	–	50,101.21	130,427.04	122,853.33
Low estimate	24	−33.33 %	1,202.43	3,130.25	2,948.48
Median estimate	36	Ref.	1,803.64	4,695.37	4,422.72
High estimate	82	+127.78 %	4,108.30	10,695.02	10,073.97

Note: Cumulative mitigation quantities remain identical across SCC scenarios for each displacement emission factor (DEF) framework; variations in climate benefits reflect differences in SCC assumptions only.

two decades. However, electricity consumption is primarily concentrated east of the Hu Huanyong Line. This spatial mismatch between resource supply centers (West and North) and demand hubs (East) poses severe challenges to the power grid (Dang et al., 2024). Addressing this contradiction necessitates sustained investments in inter-regional grid infrastructure (Chen et al., 2010), especially by enhancing the capacity and efficiency of Ultra-High Voltage (UHV) transmission channels (Wang et al., 2024), while simultaneously optimizing cross-regional dispatch mechanisms and advancing smart grid technologies (Yuan et al., 2023).

Despite wind power's nationwide expansion, its contribution to CO_2 reduction exhibits notable regional heterogeneity. This disparity is not driven by a single factor but is a complex interplay of wind resource endowment, power system structure, industrial and load characteristics, and substitution pathway assumptions. North and Northwest China contribute over 50 % of the national wind power emission reductions. The chief reason is their simultaneous advantages across the "resource–installation–substitution target" dimensions. In one sense, regions like Nei Mongol and Xinjiang possess the nation's best wind resources and vast flat or desert terrains, thereby markedly reducing land and grid integration constraints for large-scale development (Gao et al., 2020). In another sense, serving as national energy bases with a massive installed base of thermal power, these regions allow wind power to displace a higher-carbon generation mix in most scenarios, thus generating a larger marginal mitigation effect. For example, the high power demand from heavy industrial provinces like Hebei and Shanxi further amplifies the benefits of substituting coal power (Li et al., 2023).

In contrast, while East China has relatively limited wind resource endowments, its mitigation contribution remains among the highest in the nation, which is mainly driven by demand-side factors. As China's critical economic and load center, East China shows high and stable electricity consumption intensity. This behavior ensures that new wind power, even if lower in proportion, achieves a substantial scale of absolute emission reductions (Wang et al., 2020). Notably, the development of offshore wind power in coastal provinces such as Jiangsu has partially compensated for the scarcity of onshore resources (Hui et al., 2021), making it a dominant contributor in multiple substitution scenarios.

The pronounced pathway disparity observed in Southwest China underscores the high dependence of wind power mitigation assessments on the background power structure. In the DAM-DEF framework, which assumes the substitution of the average generation mix, the region's long-standing dominance of high-proportion hydropower—with its near-zero emission characteristics—markedly reduces the average carbon intensity of the background grid. This effect compresses wind power's marginal abatement space under the "average substitution" assumption. In contrast, in the HC-DEF scenario, where wind power is assumed to prioritize displacing high-carbon sources like coal, this "dilution effect" driven by clean energy is effectively prevented, allowing the theoretical abatement potential to be fully unleashed. This result indicates that the sensitivity of different regions to substitution assumptions is heavily dependent on their existing energy mix features.

Overall, wind power mitigation benefits' spatial differentiation reflects a systemic coupling relationship between the resource supply side, demand structure, and the evolutionary path of the power system. This understanding not only explains current regional disparities but also underscores the necessity of adopting dynamic assessment methods. Currently, traditional evaluations are mainly based on the assumption that wind power fully replaces coal-fired generation, which carries a risk of overestimation. In our study, the CO_2 reduction from wind power in China in 2021 was 392.29 Mt, lower than the 462 Mt estimated in previous studies based on the "coal-replacement" assumption (Long et al., 2023). Thus, traditional methods fail to fully factor in changes in the energy structure (e.g., the proportion of hydro and nuclear), leading to a total overestimation of up to 31 %. Therefore, future mitigation assessments and related policy frameworks must overtly account for these regional and structural complexities to avoid systematic bias.

4.2. Physical validity of dynamic substitution and cross-regional attribution boundaries

In assessing wind power mitigation benefits, the selection of substitution targets is a critical factor determining the credibility of the results. Traditional power system studies generally posit that wind power mainly displaces the dispatchable units with the highest marginal operating costs—typically coal- or gas-fired plants—corresponding to the HC-DEF scenario defined in this study (Liu et al., 2023; Lu et al., 2020; Millstein et al., 2024). We acknowledge that from a short-term operational perspective, the HC-DEF scenario aligns more closely with marginal substitution theory and can be regarded as the theoretical ceiling of wind power's mitigation potential. However, the DAM-DEF method employed in this study is designed to evaluate wind power's impact on the carbon intensity of the overall power mix from the long-term system evolution perspective. As China progresses toward its 2060 carbon neutrality goal, the proportion of non-fossil energy will rise continuously. Consequently, wind power will evolve from a marginal supplement to a core component, with its incremental generation effectively competing for generation space at the system level. In this context, wind power's mitigation benefits should be interpreted as a systemic "dilution" effect on the carbon intensity of the background grid. Therefore, although the DAM-DEF scenario yields more conservative estimates, it captures the objective trend of diminishing marginal mitigation benefits per unit of wind generation as the grid decarbonizes, thereby providing a conservative lower bound for long-term mitigation assessment.

Furthermore, the attribution boundary of mitigation benefits warrants discussion. This study currently employs a production-based accounting approach, attributing mitigation benefits to the provinces where wind farms are located. However, given the massive scale of cross-provincial power transmission in China, adopting a consumption-based accounting framework would reveal a spatial shift of benefits from western production centers to eastern consumption hubs (Tian et al., 2024). Existing studies indicate that differences in accounting approaches can markedly affect the allocation of regional carbon responsibility, specifically highlighting potential carbon inequalities associated with capital distribution (Tian et al., 2025). Simultaneously, inter-regional transmission entails realistic costs, such as grid infrastructure investment and transmission losses, which may offset wind power substitution's net economic gains (Deng et al., 2022). Although these factors are not explicitly incorporated into our current model, they suggest that future policy-making must balance production-side incentives with consumption-side responsibilities and conduct more refined assessments that account for power flows and grid cost constraints.

4.3. Uncertainty and policy implications

While this study provides a dynamic assessment, the projections remain subject to multiple sources of uncertainty. Regarding result credibility, our model projects that by 2060, wind power will reduce CO_2 emissions by at least 931.25 Mt. This figure aligns closely with the projection range of Yang et al. (2025) (938–995 Mt), and the underlying power mix assumptions are corroborated by authoritative international scenarios. Specifically, we project that by 2060, the proportion of coal power will decline to 5.73 %, while renewable electricity—dominated by wind and solar—will account for 79.22 % of total generation. These figures correspond closely with the IEA's Announced Pledges Scenario (APS), which envisions a 5 % coal share and an 80 % renewable share for China (IEA, 2021). Furthermore, this deep decarbonization trajectory complies with the IPCC AR6 requirement for the East Asian power sector to achieve near-zero emissions by mid-century (Shukla et al., 2022). Such consistency across multiple macroscopic sources strongly supports the plausibility and robustness of our assessment in terms of both magnitude and trend.

However, it must be noted that this study relies mainly on the single Coordinated Transition scenario from China Energy Outlook 2060, which may not fully capture extreme future policy shifts, technological breakthroughs, or market fluctuations. Future research should incorporate multi-scenario analyses, such as combining Shared Socioeconomic Pathways (SSPs), to explore mitigation ranges under varying policy ambitions, breakthrough technologies (e.g., maturity of deep-sea offshore wind), or drastic market volatilities, thereby delineating a more comprehensive uncertainty envelope for long-term wind power mitigation in China. Beyond these scenario assumptions, the physical constraints of real-world power system operations constitute another critical source of uncertainty. While this study assumes full utilization of wind capacity—representing an idealized integration scenario—wind curtailment remains a critical challenge in China's actual grid operations (Xia et al., 2020). Constrained by wind power's counter-peak generation characteristics and insufficient grid flexibility, some wind farms may face forced curtailment, resulting in actual mitigation outcomes that fall below theoretical projections (Kader et al., 2022). If system flexibility—such as energy storage deployment or thermal power flexibility retrofits—cannot be effectively enhanced in the future, this loss in utilization rate will directly translate into a decline in realized mitigation benefits per unit of installed capacity (Zhang et al., 2021).

Accompanying the uncertainty in physical reduction estimates is the high sensitivity of economic valuation to parameter choices, particularly the SCC. Although this study adopts low, medium, and high scenarios to evaluate the climate benefits of wind power mitigation at the national scale, it should be noted that SCC estimates exhibit pronounced spatial heterogeneity within China, driven by differences in socio-economic development, industrial structure, and climate vulnerability (Jin et al., 2020). For instance, in economically developed eastern provinces such as Jiangsu and Guangdong, SCC values tend to be higher due to greater economic density and higher exposure to climate risks, whereas relatively lower values are observed the Northwest and Northeast regions of China (Tian et al., 2026; Wang et al., 2022b). Therefore, future research should incorporate interprovincial heterogeneity into the monetization framework to provide more region-specific policy implications.

While wind power's mitigation benefits are highly sensitive to SCC assumptions, this characteristic itself carries important policy implications. Rather than viewing SCC uncertainty as a limitation, we suggest that policymakers explicitly incorporate a dynamic shadow pricing framework into energy planning. Specifically, this framework treats SCC as a time-varying shadow price under different scenarios, reflecting the evolving marginal social cost of carbon along alternative development pathways. In practice, scenario-dependent SCC trajectories can be constructed over time and applied as weighting factors in the monetization of annual emission reductions, thereby enabling a dynamic assessment of climate benefits across different stages. Under high-SCC scenarios, the potential climate benefits associated with wind power—exceeding $4,000 billion in cumulative value—indicate that, even if grid upgrades and system flexibility investments entail substantial short-term costs, such investments remain economically justified from the perspective of long-term social welfare maximization. In this context, proactive investments in energy storage, grid flexibility retrofits, and smart grid infrastructure can be rationalized not only on technical grounds, but also on robust climate-economic criteria.

Synthesizing the spatiotemporal patterns and uncertainty analyses presented above, it is evident that a single nationwide aggregate target is insufficient to effectively address regional imbalances in wind power development and mitigation outcomes. Accordingly, differentiated energy policies tailored to regional characteristics are essential. In regions characterized by abundant wind resources but relatively low local electricity demand—such as the "Three-North" areas (e.g., Nei Mongol and Xinjiang)—policy priorities should evolve from a sole emphasis on capacity expansion toward a dual strategy combining long-distance transmission with local conversion. Beyond reinforcing UHV transmission corridors, greater emphasis should be placed on utilizing low-cost wind electricity for green hydrogen production and for enabling the low-carbon transition of energy-intensive industries, thereby enhancing local absorption capacity.

By contrast, economically developed yet resource-constrained regions in East China (e.g., Jiangsu and Shanghai) require a parallel approach that integrates technological advancement with responsibility sharing. On the supply side, accelerating the deployment of offshore wind power clusters can help overcome land and resource limitations. On the demand side, more sophisticated interprovincial green electricity trading mechanisms are needed, allowing these regions to assume an appropriate share of emission reduction responsibility through consumption-based pathways. In Southwest China, where the electricity system is dominated by hydropower, policy interventions should instead focus on strengthening wind–hydro complementary operational schemes. Leveraging the inherent flexibility of hydropower to smooth wind power variability can substantially enhance mitigation outcomes, particularly under substitution pathways that prioritize the displacement of high-carbon generation. Beyond region-specific strategies, the accounting framework itself warrants further refinement. Given the limitations of the current production-based approach, future research should advance consumption-based carbon accounting to explicitly quantify the embodied carbon transfers associated with interprovincial electricity transmission. Such efforts would provide a more robust scientific foundation for designing equitable and effective regional carbon compensation mechanisms.

Furthermore, as the share of renewables in China's energy mix continues to rise, a wind-centric perspective is no longer sufficient to capture the mitigation dynamics of future power systems. A transition toward an integrated multi-energy framework is therefore essential. Within this framework, the emission reduction benefits of wind power are shaped not only by its scale but also by its interactions with other energy sources. For example, the spatiotemporal complementarity between wind and solar enhances system stability (Lv and Tang, 2025; Yuan et al., 2025), while hydropower and pumped storage provide critical flexibility to mitigate variability in wind generation (Qiao et al., 2026). Nuclear power, as a highly reliable baseload source, further complements wind power within the overall generation mix (El-Emam et al., 2024). Such integration not only facilitates higher renewable penetration but also reduces marginal abatement costs through more efficient system operation. Accordingly, future energy policies should shift from a single-technology focus toward a system-oriented approach, with an emphasis on pricing and dispatch mechanisms that enable cross-energy coordination.

5. Conclusions

Based on the evolution of China's electricity structure over the past two decades and future scenario projections, this study established a dynamic assessment framework to quantify the CO_2 reductions and associated climate benefits of wind power within China's evolving power sector. Our results show that shifting from static to dynamic evaluation captures the progressive decarbonization of the energy mix. Notably, we find that traditional static assessments (HC-DEF) may overestimate the decarbonization potential of wind energy, as they overlook the increasing integration of other low-carbon sources into the grid.

Looking toward 2060, as wind power is projected to account for 45 % of total generation, substantial CO_2 mitigation is projected, particularly in North, Northwest, and East China. Our results indicate that under a more idealized dispatch strategy that prioritizes the displacement of high-carbon or coal-fired technologies (DHC-DEF), mitigation benefits could increase by over 50 % compared to the DAM-DEF scenario. When these reductions are monetized, they yield significant climate-economic benefits; however, these benefits are highly sensitive to the choice of SCC values. Therefore, the appropriate selection and application of SCC values are essential for estimating the emission reduction benefits of wind power. This study provides a scientific basis for Chinese provinces to formulate targeted renewable energy incentive policies and offers a dynamic assessment framework for other coal-dependent economies undergoing energy transitions worldwide.

Data availability

Data will be made available on request.

Declaration of competing interests

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.

CRediT authorship contribution statement

Yunxia Long: Writing – original draft, Visualization, Methodology, Conceptualization. **Yaning Chen:** Writing – review & editing, Supervision, Funding acquisition. **Yongchang Liu:** Writing – review & editing, Methodology. **Hongyu Wang:** Software, Data curation.

Acknowledgements

This research was supported by the Major Science and Technology Program of Xinjiang Uygur Autonomous Region (Grant No. 2024A03006-5).

Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.geosus.2026.100489.

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