Supplementary Information for

Addressing China's Wind Power Underperformance

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Supplementary Method S1. Wind Farm Database

The wind farm database used in this study covers 10,032 individual wind farms (both onshore and offshore) installed in mainland China between 1989 and 2022. It was assembled from the project-level records reported by the China Wind Energy Association (CWEA).

The CWEA records are compiled under China's official statistical reporting system, per National Energy Administration Notice No. 61 on renewable electricity generation statistics. The reported metric is installed ("erected") capacity (defined by CWEA as capacity for which turbine components have been fully assembled on-site and have passed commissioning inspection) rather than grid-connected capacity, meaning the database captures wind farms at the point of physical construction rather than the point of grid interconnection. CWEA cross-checks enterprise-submitted project lists against (i) national and provincial annual wind development plans issued by the National Energy Administration and provincial energy bureaus, (ii) turbine manufacturer shipment and commissioning records, and (iii) on-site verification conducted by CWEA-commissioned inspectors (*1*). CWEA's capacity statistics have been widely used as a primary data source in the peer-reviewed literature on China's wind sector, including studies published in Nature and other leading energy journals (*2-4*).

For each farm the database records farm name, geographic coordinates, installation year, administrative location (province and county), installed capacity, turbine model, rotor diameter, hub height, per-turbine rated capacity, and an onshore-offshore classification. Records sharing the same wind farm name but differing in project phase, commissioning date, or turbine model were treated as distinct wind farms in the database. This project-level representation preserves differences in turbine characteristics, commissioning timing, and meteorological conditions, thereby improving the accuracy of generation assessment. Where appropriate, records sharing the same wind farm name can be aggregated after assessment to recover wind farm-level statistics.

Quality control of the records was performed in three stages:

(i) Missing-field completion. For records with missing attributes - such as turbine model, hub height, or coordinates - values were manually supplemented on a case-by-case basis using publicly available sources, including corporate disclosures, project announcements, and tender/bidding documents associated with the corresponding wind farm. The Wind Power Database (*5*) and Global Wind Power Tracker (*6*) were further referenced to cross-check and ensure project-level consistency.

(ii) Aggregated capacity cross-referencing. Aggregated provincial capacities were compared with official wind capacity statistics published annually by the National Energy Administration (*7*), the China Electric Power Yearbook (*8*), and CWEA's China Wind Power Installation Statistics Briefing (*9*). Provincial grid-connected capacity was smaller than installed capacity in all years except 2020; the 2020 comparison is provided in Table

S3. Cumulative installed capacity summed across individual records in our database matched the totals reported by CWEA.

(iii) Coordinate validation. For every wind farm in the database, turbine coordinates were manually verified against Google Earth satellite imagery to confirm the presence of turbine structures at the reported location. For records with inconsistent or uncertain coordinates, project announcements and other publicly available sources were further consulted to identify project boundary coordinates, center coordinates, or location descriptions (e.g., relative geographic references). Coordinates were then manually corrected and re-validated using satellite imagery to ensure alignment with the actual turbine locations.

Supplementary Method S2. Meteorological Data Inputs

S2.1 China Meteorological Administration Wind Resource Dataset

The primary meteorological input for estimating theoretical wind generation is the high-resolution wind energy resource dataset developed by the National Climate Center (NCC) of the China Meteorological Administration (CMA). The dataset is a nationally authoritative product with independent intellectual property, referred to officially as "Big Data of China's Four-Dimensional Wind Energy Resources" (*10*).

The foundational 3-km dataset was produced using a mesoscale numerical model driven by large-scale atmospheric forcing fields and coupled with a three-dimensional variational data assimilation (3DVAR) system that ingests observations from approximately 2,400 surface meteorological stations and 169 upper-air sounding stations. The numerical simulations were performed on the Sunway TaihuLight supercomputer (at the time ranked as the world's fastest), consuming over 15 billion core-hours of computation over more than one year.

The original dataset provides hourly meteorological fields at 3 km × 3 km horizontal resolution with 38 vertical layers, including 10-m spacing below 200 m above ground level, covering the period 1995-2016. Variables include wind speed, wind direction, air temperature, air density, and turbulence intensity, among other meteorological parameters.

For 2018-2022, an extended version of the dataset was used. This product was generated using the same modelling framework with dynamical downscaling to 1 km × 1 km horizontal resolution and provides hourly meteorological fields at 10-m vertical intervals from the surface to 300 m above ground level across mainland China.

The hourly wind speeds for 2017 were reconstructed by bias-correcting MERRA-2 wind speeds using the site-specific relationship between the two datasets established during their overlapping period from 2011 to 2016. Specifically, hourly wind speeds from MERRA-2 were scaled by correction factors derived for each wind farm from the ratio between CMA and MERRA-2 wind speeds over 2011-2016, following the bias-correction approach proposed by Gruber et al (*11*). MERRA-2 was selected because its interannual variability and long-term trends showed better agreement with the CMA dataset than ERA5 (see Fig. 2b in main text). The calibration period was restricted to 2011-2016 because the more recent CMA and MERRA2 product provide more reliable wind fields than earlier years.

S2.2 Global Reanalysis Datasets (comparison benchmarks)

Two widely used global reanalysis datasets, MERRA-2 and ERA5, were additionally employed.

MERRA-2 (Modern-Era Retrospective Analysis for Research and Applications, Version 2) is produced by the NASA Global Modeling and Assimilation Office (GMAO). The dataset provides hourly meteorological fields at a horizontal resolution of 0.5° × 0.625° (~50 km) from 1980 to the present.

ERA5, the fifth-generation global atmospheric reanalysis produced by the European Centre for Medium-Range Weather Forecasts (ECMWF), provides hourly meteorological fields at 0.25° × 0.25° (~25 km) horizontal resolution from 1940 to the present.

Both datasets are publicly available and have been extensively used in global and regional wind resource assessments. However, comparisons with the CMA high-resolution product reveal that MERRA-2 and ERA5 systematically underestimate wind resources in southern, central, and southwestern China (Fig. 3a-c in main text).

S2.3 Wind Speed and Air Density Extraction

For each of the 10,032 wind farms, hourly wind speed and air density were extracted from the nearest meteorological grid cell at the recorded turbine hub height.

For the CMA dataset, hub-height wind speeds and air density were obtained by linearly interpolating the multi-level meteorological fields (10-200 m) to the recorded turbine hub height.

For ERA5, hub-height wind speeds and air density were obtained using its 138 model-level pressure interfaces and 137 atmospheric layers with the interface coefficients (a_i, b_i). The interface pressures (p_i) and layer thickness (Δz_k) were computed using the hybrid coordinate formulation and the hypsometric equation:

$$p_i = a_i + b_i \cdot p_s, \quad i = 1, \ldots, 138 \tag{1}$$

$$\Delta z_k = -\frac{R \cdot T_k}{g} \cdot \ln\left(\frac{p_k}{p_{k+1}}\right), \quad k = 1, \ldots, 137 \tag{2}$$

where p_s is the surface pressure; p_k and p_{k+1} are pressures at the upper and lower interfaces of the 137 layers; R is the specific gas constant for dry air and g is gravitational acceleration; T_k is the mid-point temperature provided directly by ERA5.

The (mid-level) AGL height of each layer used for interpolation was then calculated as:

$$Z_k^{agl} = \sum_{i=1}^{k-1} \Delta z_i + 0.5 \cdot \Delta z_k \tag{3}$$

Based on the reconstructed mid-level heights and the corresponding ERA5 variables at each layer, the values of wind speed, wind direction, vertical wind shear, and air density at the turbine hub height were obtained through linear interpolation between the two layers that bound the hub height.

For MERRA-2, hub-height wind speeds were estimated from the 10 m and 50 m wind fields using a power-law wind profile. Our previous comparisons using the multi-level ERA5 dataset and the 3-km HRRRv4 dataset showed that the power-law approach more closely reproduces hub-height wind speeds obtained by vertical interpolation than the logarithmic wind profile. Detailed comparisons are provided in Supplementary Fig. S6. Here, the power-law profile was

adopted throughout this study for MERRA-2. The power law wind profile as detailed by Archer and Jacobson (*12*), is:

$$V_h = V_r \cdot \left(\frac{h}{r}\right)^{\alpha} \tag{4}$$

where V_h is the wind speed at height h; V_r is the known wind speed at a reference height r; the exponent α (friction coefficient) is determined by hourly wind speeds derived from the meteorological datasets.

The bottom layer of the AIRDENS variable in MERRA-2 was interpolated into hourly data to represent ρ for each plant following Millstein et al. (*13*).

For comparison, the logarithmic law wind profile, described by Oke (14), is:

$$V_h = \frac{V_*}{k} \cdot \left[\mathrm{In}\left(\frac{h-d}{h_0}\right)\right] \tag{5}$$

where V_* is the friction velocity (m s^{-1}), k is the Von Kármán constant, d is the zero-plane displacement (in meters) and h_0 is the surface roughness (in meters). This is simplified to:

$$V_h = A \cdot \left[\mathrm{In}\left(\frac{h-d}{h_0}\right)\right] = A \cdot \mathrm{In}(h-d) - A \cdot \mathrm{In}(h_0) \tag{6}$$

where the log law assumes a constant A, equal to the friction velocity divided by the Von Kármán constant (*15*). For ERA5, wind speeds at heights of 10, and 100 m were used to compute A and h_0 and were applied then to obtain wind speeds at the hub height.

Supplementary Method S3. Economic Assessment for Utilizing Unrealized Wind Power

S3.1 Construction of Hourly Unrealized Wind Generation Profiles

For each province (r), an hourly profile of unrealized wind electricity was constructed from the provincial hourly electricity demand and simulated hourly wind generation. Let $L_{r,t}$ denote the provincial hourly electricity demand and $W_{r,t}$ the corresponding hourly wind generation. The demand profile was multiplied by a scaling factor α_r, and unrealized wind generation was defined as the portion of wind generation exceeding the scaled demand:

$$U_{r,t} = \max\left(W_{r,t} - \alpha_r \cdot L_{r,t}, 0\right) \quad (7)$$

where $U_{r,t}$is the hourly unrealized wind electricity. The scaling factor $\alpha_r$was determined iteratively using a bisection algorithm. Starting from the interval [0,1], α_r was iteratively updated until the annual unrealized electricity matched the estimated annual generation gap:

$$\sum_{t=1}^{8760} U_{r,t} = G_{r,gap} \quad (8)$$

where $G_{r,gap}$ is the province-specific annual unrealized wind generation between 2018-2020 estimated in the main analysis. This procedure preserves the annual generation-gap magnitude while producing a highly intermittent hourly profile representative of unrealized wind generation for subsequent techno-economic assessment. The hourly provincial demand curve is adopted from Chen et al. (*16*).

S3.2 Model Descriptions for Each Flexibility Option

For each province, utilization pathway, and target reuse ratio, the required technology capacity was optimized to minimize annualized system cost while satisfying the prescribed utilization of unrealized wind generation. The target reuse ratio specifies the fraction of annual unrealized wind generation to be recovered by a given pathway.

S3.2.1 Battery Storage

For the battery storage pathway, the installed battery power capacity (C_P) and energy capacity (C_E), together with hourly charging, discharging, and state-of-charge (SOC), were jointly optimized to minimize the annualized system cost while achieving a prescribed utilization ratio of unrealized wind generation.

The optimization variables include the installed battery power capacity ($C_{r,P}$), energy capacity ($C_{r,E}$), battery charging power ($P_{r,t}^{\mathrm{cha}}$), discharging power ($P_{r,t}^{\mathrm{dis}}$) and battery state of charge ($SOC_{r,t}$), the utilized wind generation ($W_{r,t}^{\mathrm{use}}$) and unmet demand ($L_{r,t}^{\mathrm{cur}}$). Hourly power balance was enforced as

$$W_{r,t}^{\mathrm{use}} + P_{r,t}^{\mathrm{dis}} - P_{r,t}^{\mathrm{cha}} = \alpha_r \cdot L_{r,t} - L_{r,t}^{\mathrm{cur}} \quad (9)$$

Hourly wind generation satisfies

$$W_{r,t} - U_{r,t} \le W_{r,t}^{\text{use}} \le W_{r,t} \tag{10}$$

Hourly unmet demand satisfies

$$0 \le L_{r,t}^{\text{cur}} \le \alpha_r \cdot L_{r,t} - (W_{r,t} - U_{r,t}) \tag{11}$$

For a prescribed utilization ratio r_{reuse}, the annual unrealized wind generation remaining after storage is constrained by

$$\sum_{t=1}^{8760} W_{r,t} - W_{r,t}^{\text{use}} = (1 - r_{\text{reuse}}) \cdot G_{r,gap} \tag{12}$$

Battery charging was permitted only during hours with surplus wind generation, whereas discharging was allowed only during hours when electricity demand exceeded wind generation. Battery operation followed

$$0 \le P_{r,t}^{\text{cha}}, P_{r,t}^{\text{dis}} \le C_{r,P} \tag{13}$$

$$0 \le SOC_{r,t} \le C_{r,E} \tag{14}$$

$$0 \le P_{r,t}^{\text{cha}} \le U_{r,t} \tag{15}$$

$$0 \le P_{r,t}^{\text{dis}} \le \alpha_r \cdot L_{r,t} - (W_{r,t} - U_{r,t}) \tag{16}$$

$$SOC_{r,t+1} = (1 - \lambda) SOC_{r,t} + \eta P_{r,t}^{\text{cha}} - \frac{P_{r,t}^{\text{dis}}}{\eta} \tag{17}$$

$$SOC_{r,1} = SOC_{r,8760} \tag{18}$$

where η is the battery round-trip efficiency (0.93) and λ is the hourly self-discharge rate (0.001/h). A cyclic annual boundary condition was imposed by requiring the final-hour SOC to equal the initial-hour SOC after accounting for charging, discharging, and self-discharge.

The optimization objective minimizes the annualized investment cost,

$$\min C_{r,ann} = c_P \cdot C_{r,P}(a + f_{\text{OM}}) + c_E \cdot C_{r,E}(a + f_{\text{OM}}) \tag{19}$$

$$a = \frac{\rho(1+\rho)^n}{(1+\rho)^n - 1} \tag{20}$$

where c_P and c_E are the unit capital costs of battery power and energy capacity, respectively, a is the capital recovery factor, ρ is the discount rate (0.08), n is the lifetime (15 years), and f_{OM} is the fixed operation and maintenance rate (5%).

After the optimal battery configuration for each province was obtained, alternative battery cost scenarios were evaluated by applying projected battery capital-cost to the optimized capacities

while maintaining the same operating schedule. The levelized cost of electricity delivered from storage was calculated as

$$LCOE_{r,bat} = \frac{C_{r,ann}}{\sum_{t=1}^{8760} P_{r,t}^{\mathrm{dis}}} \tag{21}$$

where the denominator is the total annual electricity discharged from the battery.

Provincial utilization-cost results were aggregated to construct a national utilization supply curve. For each province, the estimated annual unrealized wind generation was divided into ten equal energy blocks corresponding to successive utilization intervals. Each block was assigned the levelized cost obtained for the corresponding provincial utilization level. All provincial energy blocks were then pooled nationally and ranked from lowest to highest cost. The cumulative utilized energy was normalized by total unrealized wind generation to obtain the national utilization ratio, thereby yielding the national cost-utilization panel for each technology and year (in main text Fig.5c).

Battery cost parameters (Table. S6) were based on recent Chinese lithium iron phosphate (LFP) battery market tender prices (*17*), with future cost reductions following the medium projections of the National Renewable Energy Laboratory (NREL) (*18*). Battery lifetime, round-trip efficiency, and other technical parameters were assumed to remain constant over time (*16*).

S3.2.2 Hydrogen Production with Electrolysis and Power-to-H2-to-Power

For direct hydrogen production, unrealized wind generation was supplied directly to electrolyzers during surplus-wind hours. For each province and prescribed reuse ratio r_{reuse}, the electrolyzer capacity $C_{r,el}$ and hourly electricity consumption $P_{r,t}^{\mathrm{el}}$ were optimized such that the target fraction of annual unrealized wind generation was utilized.

Electrolysis was only permitted during hours with surplus wind generation,

$$0 \le P_{r,t}^{\mathrm{el}} \le C_{\mathrm{r,el}} \tag{22}$$

$$0 \le P_{r,t}^{\mathrm{el}} \le U_{r,t} \tag{23}$$

The annual consumed unrealized wind generation satisfied

$$\sum_{t=1}^{8760} P_{r,t}^{\mathrm{el}} = r_{\mathrm{reuse}} \cdot G_{r,gap} \tag{24}$$

Because the required electrolyzer capacity depends only on the utilization target rather than the unit investment cost, the optimization first minimized the installed electrolyzer capacity subject to the hourly operating constraints.

$$\min C_{r,ann} = c_{el} \cdot C_{r,el}(a + f_{\mathrm{OM}}) \tag{25}$$

where c_{el} is the unit capital costs of electrolyzer, a is the capital recovery factor following equation (20), the lifetime is 25 years and the fixed operation and maintenance rate is 4% (*19*).

The levelized cost of hydrogen (LCOH) was calculated as

$$LCOH_r = \frac{C_{r,ann}}{\sum_{t=1}^{8760} P_{r,t}^{\mathrm{el}} \eta_{\mathrm{el}}} \tag{26}$$

where η_{el} is the electricity-to-hydrogen conversion factor.

Provincial LCOH-cost results were aggregated to construct a national utilization supply curve following the same procedure as S3.2.1.

Electrolyzer cost parameters (Table. S6) were based on recent Chinese alkaline electrolysis system (AEC) market tender prices (*20, 21*), with future cost reductions following the medium projections (*22, 23*).

For power-to-hydrogen-to-power (P2H2P), unrealized wind generation was converted to hydrogen by electrolysis, compressed and stored, and subsequently reconverted to electricity through either fuel cells or hydrogen combustion in thermal power plants. The optimization simultaneously determined the capacities of the electrolyzer ($C_{r,el}$), compressor ($C_{r,comp}$), hydrogen storage ($C_{r,sto}$), and power-generation unit ($C_{r,gen}$) together with their hourly operation.

Hourly electricity balance was represented as

$$W_{r,t}^{\mathrm{use}} + P_{r,t}^{\mathrm{gen}} - P_{r,t}^{\mathrm{el}} - P_{r,t}^{\mathrm{com}} = \alpha_r \cdot L_{r,t} - L_{r,t}^{\mathrm{cur}} \tag{27}$$

where $P_{r,t}^{\mathrm{comp}}$ denotes compressor electricity consumption and $P_{r,t}^{\mathrm{gen}}$ is electricity generated from stored hydrogen. Hourly wind generation, unmet demand and reuse ratio follow the same constraints as equations (10-12). Power consumption and generation satisfy

$$0 \le P_{r,t}^{\mathrm{el}} + P_{r,t}^{\mathrm{com}} \le U_{r,t} \tag{28}$$

$$0 \le P_{r,t}^{\mathrm{gen}} \le \alpha_r \cdot L_{r,t} - (W_{r,t} - U_{r,t}) \tag{29}$$

Hydrogen production and reconversion were represented by

$$H_{r,t}^{\mathrm{prod}} = P_{r,t}^{\mathrm{el}} \eta_{\mathrm{el}} \tag{30}$$

$$P_{r,t}^{\mathrm{comp}} = H_{r,t}^{\mathrm{prod}} \eta_{\mathrm{comp}} \tag{31}$$

$$P_{r,t}^{\mathrm{gen}} = H_{r,t}^{\mathrm{out}} \eta_{\mathrm{gen}} \tag{32}$$

$$0 \le P_{r,t}^{\mathrm{el}} \le C_{r,el} \tag{33}$$

$$0 \le P_{r,t}^{\mathrm{comp}} \le C_{r,comp} \tag{34}$$

$$0 \le P_{r,t}^{\mathrm{gen}} \le C_{r,gen} \tag{35}$$

where $\eta_{\mathrm{comp}}$and η_{gen}denote the compressor (1.14kWh/kg-H2) and electricity-generation conversion factors (20kWh/kg and 15.33kWh/kg for fuel cell and co-combustion), respectively.

Hydrogen storage followed the inventory balance

$$SOC_{r,t} = SOC_{r,t-1} + H_{r,t}^{\mathrm{prod}}\eta_{\mathrm{sto}} - H_{r,t}^{\mathrm{out}}/\eta_{\mathrm{sto}} \tag{36}$$

subject to

$$0 \le SOC_{r,t} \le C_{\mathrm{r,sto}} \tag{37}$$

$$SOC_{r,1} = SOC_{r,8760} \tag{38}$$

The total annualized system cost was minimized,

$$\min C_{\mathrm{r,ann}} = \sum_{k} (c_k C_k a_k + OM_k C_k) \tag{39}$$

where k includes the electrolyzer, compressor, hydrogen storage, and electricity-generation unit (fuel cell or thermal hydrogen combustion), a_k is the capital recovery factor following equation (20). Lifetime for compressor, hydrogen storage, fuel cell and thermal combustion are 15, 30, 15 and 20 years; their fixed operation and maintenance rate are 0.04, 0.01, 0.02 and 0.03, respectively.

Finally, the levelized cost of electricity from the P2H2P pathway was calculated as

$$LCOE_{\mathrm{r,P2H2P}} = \frac{C_{\mathrm{r,ann}}}{\sum_{t=1}^{8760} P_{r,t}^{\mathrm{gen}}} \tag{40}$$

Hydrogen compressor and storage costs were estimated from publicly available Chinese tender prices together with cost projections reported by the U.S. Department of Energy (DOE) and NREL (*24-26*). Current Chinese hydrogen compressor and storage costs were assumed to be approximately 40% of the corresponding U.S. costs (*27*) , and the same relative scaling was applied to future cost projections. Proton-exchange membrane (PEM) fuel cells were considered for hydrogen-to-power conversion. The current capital cost was based on recent Chinese tender prices (*28*), while future costs followed the same projection framework. For hydrogen co-combustion in natural gas plant, additional retrofit costs for natural-gas plants was adopted from Ref. (*29*) and adjusted to Chinese conditions.

S3.2.3 Ammonia Synthesis and Power-to-Ammonia-to-Power

For ammonia production, unrealized wind generation was first converted to hydrogen through electrolysis, compressed and stored, and subsequently synthesized into ammonia. For the power-to-ammonia-to-power (P2A2P) pathway, stored ammonia was further converted back to electricity through ammonia-fired power generation. The optimization simultaneously determined the capacities of the electrolyzer, hydrogen compressor, hydrogen storage, ammonia synthesis unit, ammonia storage, and ammonia power-generation unit together with their hourly operation.

The hourly electricity balance was expressed as the following, similar to equation (27):

$$W_{r,t}^{use} + P_{r,t}^{NH_3} - P_{r,t}^{el} - P_{r,t}^{comp} - P_{r,t}^{syn} = \alpha_r \cdot L_{r,t} - L_{r,t}^{\mathrm{cur}} \tag{41}$$

where $P_{r,t}^{syn}$ denote the electricity consumed by ammonia synthesis, and $P_{r,t}^{NH_3}$ represents electricity generated from ammonia combustion. Hourly wind generation, unmet demand and reuse ratio follow the same constraints as equations (10-12). Power consumption and generation followed equations (28-29). Hydrogen production and reconversion followed equations (30-35).

Electrolysis, hydrogen compression, and ammonia synthesis were restricted to surplus-wind hours, whereas ammonia-fired generation was allowed only during hours with electricity deficits.

Ammonia production was represented as

$$NH_{3,r,t} = H_t^{out} \times \eta_{syn} \times 0.97 \tag{42}$$

where η_{syn}denotes the hydrogen-to-ammonia conversion factor (5.67kg/kg H2) and 0.97 accounts for the ammonia synthesis yield. The electricity required for ammonia synthesis was calculated as

$$P_{r,t}^{syn} = NH_{3,r,t} e_{syn} \tag{43}$$

where e_{syn} is the specific electricity consumption of ammonia synthesis (3.68kWh/kg).

Hydrogen storage followed equations (36-38) and ammonia storage inventory followed hourly mass-balance equations,

$$SOC_{r,t}^{NH_3} = SOC_{r,t-1}^{NH_3} + NH_{3,r,t} - NH_{3,r,t}^{out} \tag{44}$$

$$SOC_{r,1}^{NH_3} = SOC_{r,8760}^{NH_3} \tag{45}$$

Electricity generation from stored ammonia was calculated as

$$P_{r,t}^{NH_3} = NH_{3,r,t}^{out} \eta_{NH_3} \tag{46}$$

where $\eta_{NH_3}$is the ammonia-to-electricity conversion efficiency (2.538kWh/kg ammonia).

The annualized total system cost included the electrolyzer, hydrogen compressor, hydrogen storage, ammonia synthesis unit, ammonia storage, and ammonia-fired generation unit,

$$C_{r,ann} = \sum_{i} (c_i C_i a_i + OM_i C_i) \tag{47}$$

where a_i is the annualization factor defined in Eq. (20). The lifetime for ammonia synthesis, storage and co-combustion are all 20 years.

The levelized cost of ammonia (LCOA) was calculated as

$$LCOA_r = \frac{C_{r,ann}}{\sum_{t=1}^{8760} NH_{3,r,t}} \tag{48}$$

while the levelized cost of electricity for the P2A2P pathway was

$$LCOE_{r,P2A2P} = \frac{C_{r,ann}}{\sum_{t=1}^{8760} P_{r,t}^{NH_3}} \tag{49}$$

Ammonia synthesis and storage costs were estimated from Li et al.(*30*) and the New Energy and Industrial Technology Development Organization (NEDO) report (*31*). The ammonia-fired generation pathway considered additional retrofit costs for ammonia co-firing in thermal power plants based on Ref. (*32*), adjusted to Chinese conditions.

Supplementary Text. S1

The determination of wind power overall reduction coefficient (ORC) is based on three comprehensive methodological approaches. First, precise calculations of power loss are performed using wind measurement data and wind farm design schemes, encompassing seven major factors including extreme weather shutdowns, line losses, and high wind speed hysteresis (*33*). Second, assessment values are derived by combining historical data statistics with actual post-evaluation analyses of operational wind farms. For instance, the reduction coefficient for icing shutdowns is calculated by identifying and removing icing data from wind measurements, evaluating the impact of icing in similar regions, and determining the proportion of energy loss (*34*). This assessment category includes eleven reduction factors such as wind turbine availability, planned shutdowns, and grid availability (*35*). Third, factors that cannot be precisely quantified, such as site accessibility and environmental changes, are estimated based on historical frequencies and future probabilities (*36*).

The ORCs reflect the combined influence of multiple physical, technical, and operational mechanisms. National onshore wind farms generally show reduction coefficients between 70% and 89% (*37*), with significant regional variations. Offshore wind farms exhibit higher coefficients than onshore facilities, with comprehensive reduction coefficients ranging from 72.6% to 80.4% (*38*), and some offshore wind farms in Jiangsu reaching up to 95% (*39*), primarily due to stable wind resources and reduced terrain disturbances, although they face greater challenges from salt fog corrosion and maintenance difficulties. The Northwestern region shows excellent performance, with Xinjiang onshore wind farms achieving 82% (*40*) and the Hami area in Xinjiang at approximately 70% (*41*), owing to open terrain and abundant wind resources, but grid transmission capacity emerges as a key constraint limiting power generation efficiency. The low reduction coefficients in high-altitude areas like Tibet, at only 66% (*42*), reflect decreased energy density due to lower air density, as well as challenges from extreme weather and equipment adaptability issues.

Eastern and Central regions demonstrate balanced coefficients, reflecting moderate wind resources coupled with favorable grid connection conditions, with a specific wind farm in Shanghai reaching 81.68% (*43*), an average of 82% in Shandong (*44*), and 75% in Changde, Hunan (*45*). Henan Province shows values of 76.72% in Zhumadian (*46*) and 70.1% in Zhoukou (*47*). Hebei Province displays clear terrain-based differences, with 80%-85% in plain areas and 75%-80% in mountainous regions (*48*). The Northeastern and Southern regions are primarily affected by seasonal extreme weather events (such as freezing and typhoons), resulting in additional equipment downtime, with Heilongjiang at approximately 70%. The Southwestern region, including Yunnan, Guizhou, Sichuan, and northern parts of Guangdong and Guangxi (excluding wake effects), shows reduction coefficients between 64% and 74% (*49*).

Regarding technical factors, wake effects can reduce downwind turbine efficiency by 5%-15%, while blade contamination and icing cause performance losses of 2%-5% and 3%-7%,

respectively. Across the country, 49 wind farms show ORCs distributed between 55% and 80% (*50*), with some specific regions as low as 69% (*51*). In terms of management factors, wind turbine availability (typically 93%-98%) and grid availability (90%-99%) constitute the fundamental components of reduction coefficients, reflecting the impact of equipment reliability and grid dispatch. These regional differences in mechanisms and their systematic interactions collectively shape the complex landscape of wind power reduction coefficients across China.

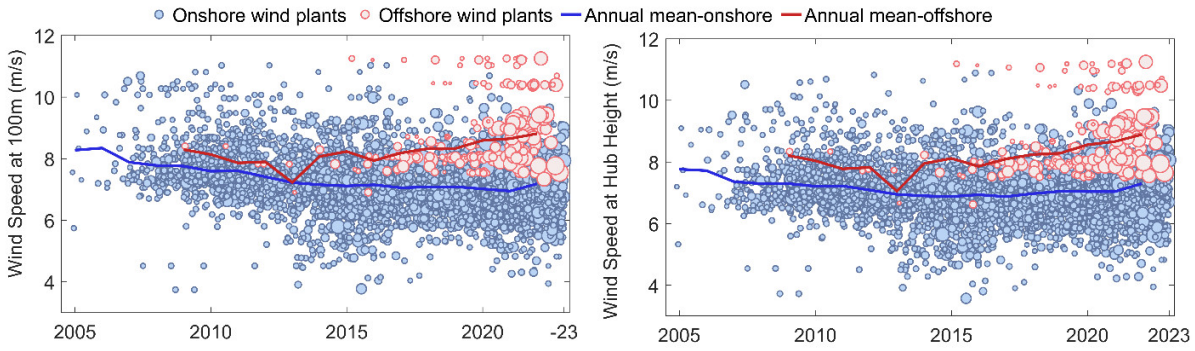


Fig. S1. Long-term wind resources at newly commissioned wind farms in China. Mean annual wind speeds at 100 m (left) and estimated hub height (right) for newly commissioned onshore and offshore wind farms by commissioning year. Solid lines indicate capacity-weighted annual mean values. Wind speed is estimated using turbine installation data from 1989 to 2022 and high-resolution (3 km) meteorological data from the China Meteorological Administration.

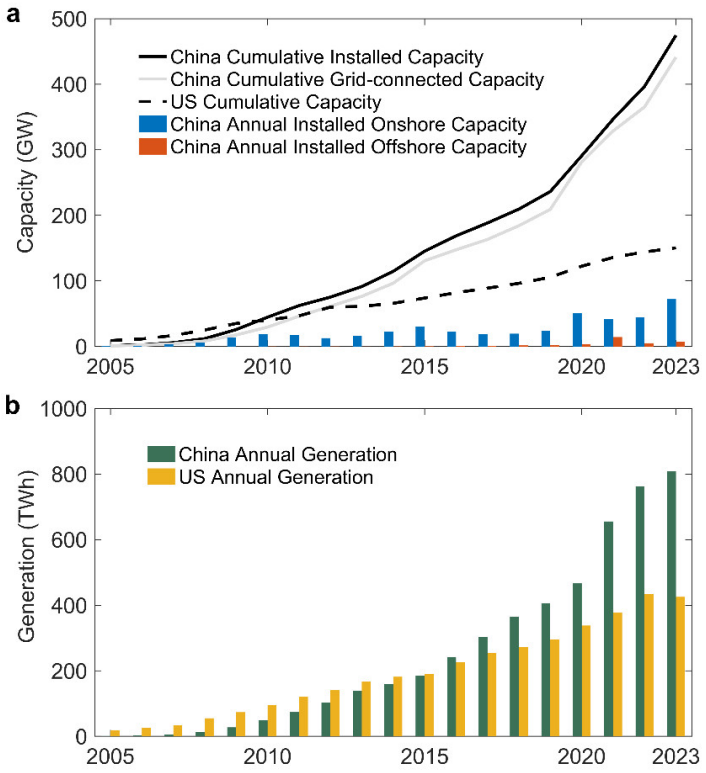


Fig. S2. Wind power deployment in China and the US from 2005 to 2023. a, Comparison of cumulative installed and grid-connected wind power capacity between China and the US, with annual onshore and offshore installations in China represented by colored bars. b, Annual wind-generated electricity in China and the US.

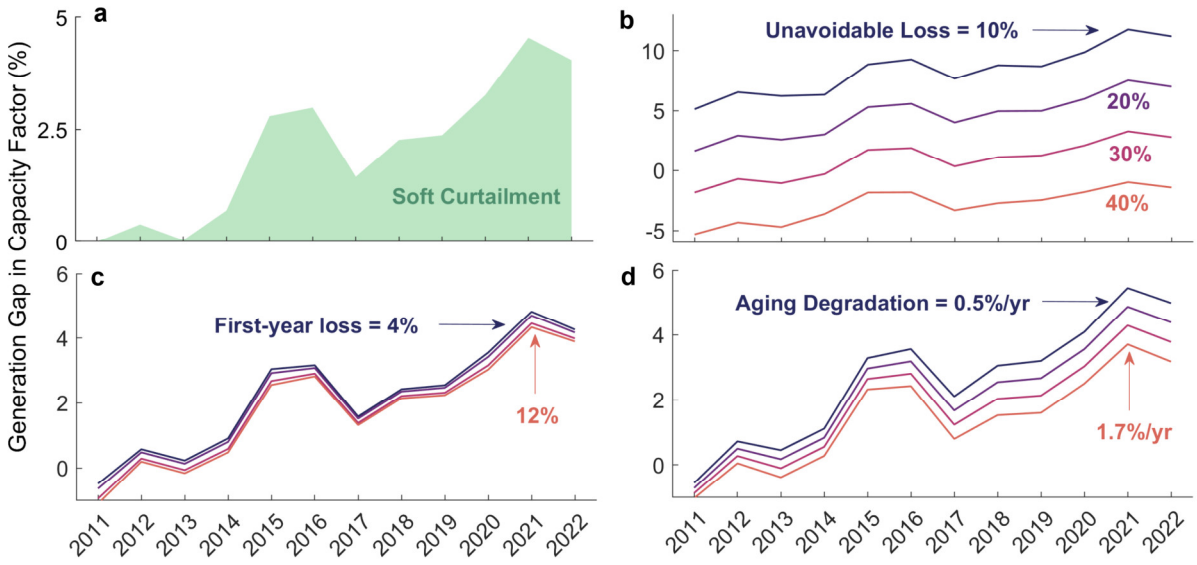


Fig. S3. Generation gap expressed as capacity factor (CF, %). a, Estimated soft curtailment under the default assumptions. **b-d**, Sensitivity of estimated soft curtailment to the assumed fixed loss factor (**b**, 10%, 20%, 30%, and 40%), first-year commissioning loss (**c**, 4%, 6%, 10%, and 12%), and annual turbine aging degradation rate (**d**, 0.5%, 0.9%, 1.3%, and 1.7% yr^{-1}), respectively. The default assumptions are a fixed loss factor of 27%, a first-year commissioning loss of 8%, and an annual aging degradation rate of 1.1% yr^{-1}.



Fig. S4. Provincial overall reduction coefficient (ORC) trajectories, 2011-2020. Annual ORC for each province from 2011 to 2020 (blue lines with markers), with the national average ORC shown as a grey dashed reference in every panel.

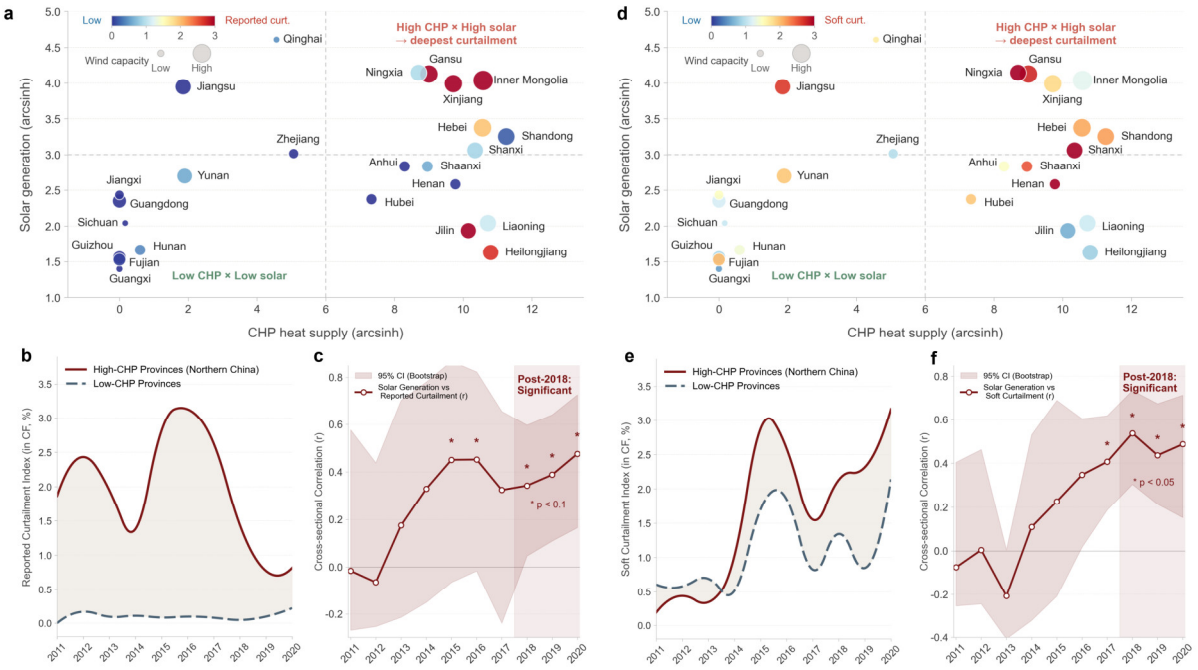


Fig. S5. Separate analyses of reported and soft wind curtailment. a, Province-level CHP-solar space for reported curtailment, with wind capacity shown by bubble size and reported curtailment indicated by color. **b**, Divergence in reported wind curtailment between high- and low-CHP provinces. **c**, Annual cross-sectional correlations between solar generation and reported wind curtailment; shaded ribbon indicates the 95% bootstrap confidence interval. **d-f**, Same analyses as in a-c but for soft curtailment.

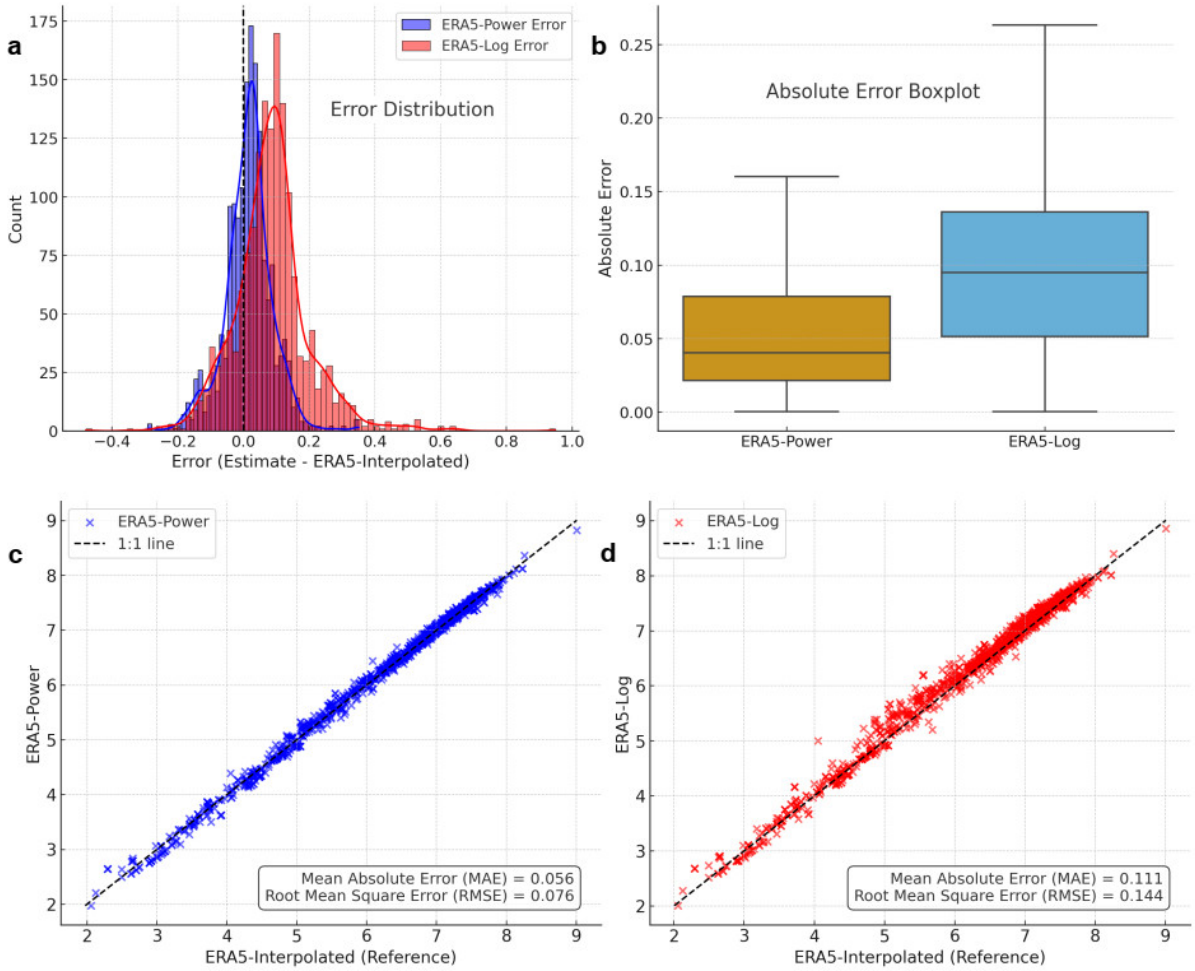


Fig. S6. Comparison of power-law and logarithmic-law extrapolations for ERA5 hub-height wind speeds. (**a**) Error distribution of extrapolated wind speeds relative to the interpolated ERA5 reference. (**b**) Boxplot of absolute errors for the power-law and logarithmic-law methods. (**c-d**) Scatter plots comparing extrapolated and interpolated hub-height wind speeds using the power-law (**c**) and logarithmic-law (**d**) approaches.

Table. S1. Comparison of Wind Turbine Attributes in China and the US. Attributes of newly installed onshore wind turbines in China and the US for 2005 and 2022, as well as cumulative values up to 2022. The attributes include Blade Diameter (meters), Rated Power (MW), Hub Height (meters), and Specific Area (m^2/kW), highlighting advancements in China's wind turbine technology and how it compares to the US over time.

		China	US
Hub Height (meters)	2005 (New Installations)	58.2	75.5
	2022 (New Installations)	110.8	99.6
	2022 (Cumulative)	90.8	85.1
Blade Diameter (meters)	2005 (New Installations)	55.4	84.5
	2022 (New Installations)	170.5	134.7
	2022 (Cumulative)	118.3	105.9
Rated Power (MW)	2005 (New Installations)	0.9	1.6
	2022 (New Installations)	4.6	3.5
	2022 (Cumulative)	2.5	2.3
Specific Area (m^2/kW)	2005 (New Installations)	2.7	3.5
	2022 (New Installations)	5.0	4.1
	2022 (Cumulative)	4.4	3.8

Table. S2. Key Policies and Plans Affecting Onshore and Offshore Wind Power in China 1994-2022. Adopted from Huenteler et al (*52*) and extended with more recent detail.

Highlights are summarized as follows:

- Strong subsidy incentives for the wind power development (installation and localization rate) from the state level
- Heavily rely on each five-year plan with careful state planning
- Multiple ministries and department coordination, mainly led by the economic and technology bureaus
- NDRC became the major decision-making body in 2005, indicating the economic incentive behind the development of wind power in China
- Each round of decreasing subsidies led to another round of installation rush

Year	Name	Content	Authority
1994	Regulation on wind farm grid connection management	Wind power purchase price set at 'reasonable profit' levels; Incremental cost borne by grid corporations	Ministry of Electric Power (MEP)
1995	Wind Farm Grid Connection and Operation Management Regulations (Trial)	Power grid companies should allow wind farms to connect to the grid locally, purchase the full amount of electricity generated by wind farms, and distribute the portion that exceeds the average grid price across the entire network.	MEP
	Double Increase Program	1.2 billion RMB of preferential loans to install 120 MW (reached ca. 25 MW); plan to develop two manufacturing bases for towers, hubs and later nacelle, braking and yaw systems	MEP
1996	National High Tech R&D Program (863 Program) - 9th Five-Year Plan	Over RMB 60 million was made available for renewable energy R&D. R&D programs included a focus on developing 600 kW wind turbines with 40 percent local content for all new wind power projects.	MOST and SDPC
	Loans for Wind Farm Development	This program gave priority access to reduced interest domestic loans for wind farms with rates up to 50 percent lower than current commercial rates, with a preference given to projects using locally manufactured wind turbines. It was used to develop several small demonstration wind projects.	MOST and SDPC
1997	Ride the Wind Program	400 MW by the end of 2000; Develop 300 and 600 kW turbines with 60% domestic content; 23.6	SPC

		million RMB to develop two 'national teams' (domestic manufacturing and S&T bases)	
1998	Further Modifications to Import Duties on Wind Turbine Components	In 1998 further differentiation between domestic and imported turbine components was made when components were exempted from value-added taxes (VAT) and turbines were not, to further promote domestic wind turbine manufacturing. Customs duty regulations vary across components and are applied differently to firms with different ownership structures.	MOF
	Approval of Electricity Prices Begins	During this phase, the grid electricity prices are approved by local price authorities and filed with the central government. Different regions implement varying levels of electricity prices, resulting in inconsistent pricing. The lowest prices are still determined by competitive pricing and are comparable to the grid electricity prices for coal-fired power generation. However, the highest prices can reach up to 1.2 yuan per kilowatt-hour.	
1999	Notice on next steps in developing renewable energy	Reduction of 2% on bank loans for renewable energy projects; Power purchase price set at 'production cost incl. interest rates + max 3%' for projects using foreign manufacturer, '+min 5%' for projects using domestic manufacturer.	SPC and MOST
		China's first domestically produced wind turbine, the S600, has officially passed national acceptance testing. This marks the beginning of the localization of wind power equipment in China. At this time, the Chinese wind power market had already been monopolized by international giants like Vestas for more than a decade.	
2000	National Debt Wind Power Program	600 million RMB government loans to develop 73.5 MW of wind farms	State Economic and Trade Commission (SETC)
2001	10th Five Year Plan; Key points for energy development	Continuation of 'ride the wind'; target to install 500MW of wind power within 10th FYP timeframe; Plan to increase localization rate from 40% to 70%	SPC
	10th Five Year Plan for the new and renewable energy industry	Target of 1,200 MW cumulative capacity by the end of 2005, concentrated in 100 MW+ parks; target of 150-200 MW annual domestic production capacity, focus on 600 kW+ turbines	SETC

	National High Tech R&D Program (863 Program) - 10th Five-Year Plan	The continued implementation of the 863 Program as part of the 10th Five-Year Plan included support for the development of megawatt-size wind turbines, including technologies for variable-pitch rotors and variable-speed generators, and supported the RD&D of many Chinese companies' early development of MW-scale wind turbine technology.	MOST
	Value-Added Tax Reductions on Wind Electricity	Reduced the VAT for wind electricity from 17 percent to 8.5 percent, resulting in a reduction in the price of wind power electricity.	MOF; State Administration of Taxation
2003	Concession projects	Tenders for large scale (100-300 MW) wind parks, awarded based on price and localization rate; minimum localization rate set to 50% (2003) and 70% (2004-2007)	NDRC
	Dual Pricing System for Wind Power	The dual pricing system consists of bid prices formed through concession bidding and traditional approved electricity prices. During this phase, bid prices are generally determined by the state through public bidding to promote the construction of large wind farms, while approved electricity prices are still determined by the local price authorities.	
2005	Kyoto Protocol and CDM	Chinese wind projects can earn carbon credits to be sold in global carbon markets	UNFCCC
	Measures for Operation and Management of Clean Development Mechanism Projects in China	Set the domestic guidelines for CDM project development in China in line with China's role as a recipient of CDM-related carbon finance under the Kyoto Protocol for certified emissions reductions by projects that are shown to reduce GHG emissions.	State Council decision, implemented by NDRC in consultation with MOST and the MFA
	Renewable Energy Law	Requirement of compulsory grid connection and full purchase of renewable power; Electricity surcharge to cover RE cost, set at 1 RMB/MWh in 2006; 2 RMB in 2008, 4 RMB 2009 and 8 RMB since 2011	
	Notice on requirements related to wind power construction management	The localization rate of wind power equipment must reach over 70%. Wind farms that do not meet the localization rate requirement for equipment are not allowed to be constructed.	NDRC
		Clarified the project approval process and criteria for wind projects, including proximity to the grid and the percentage of domestically manufactured	

		equipment utilized. NDRC had to approve all projects greater than 50 MW, while provincial or local DRCs could approve those less than 50 MW.	
	Phase of bidding and approval methods	The end of the coexistence phase of bid and approved electricity prices marked the beginning of the implementation phase of bidding and approval methods. During this phase, wind power prices were entirely determined through the bidding process, and the electricity price standards were set based on the results of the bids.	
2006	Renewable energy price and cost-sharing management	Power pricing mechanisms: (1) tendered concessions; (2) fixed provincial feed-in tariff (FIT), or (3) government approved price per project; FIT should be equal to cost difference with local desulphurized coal price	NDRC
	National High Tech R&D Program (863 Program) - 11th Five-Year Plan	The 863 Program as updated for the 11th Five-Year Plan supported the development of MW-size wind turbines, including technologies for variable-pitch rotors, variable-speed generators, and commercialization of wind turbines of 2 to 3 MWs in size.	MOST
2007	Medium and long term RE development plan	Target of 10% of total energy use from renewable sources by 2010; 15% by 2020; targets of 5 GW wind power by 2010; 30 GW by 2020; including 1 GW of offshore power. Mandatory market share (quota) placed on power companies with more than 5 GW of generation capacity should have 3% of non-hydro RE by 2010 and 8% by 2020.	NDRC
	Interim Measures on Revenue Allocation from the Renewable Surcharge	Aimed at improving equity among provinces in bearing the costs of renewable electricity, this measure established an equalization program requiring provincial grid companies to exchange their shortfall or surplus of surcharges with grid companies from other regions.	NDRC
		China's newly installed wind power capacity reached 3.3 million kilowatts, surpassing the cumulative installed capacity of the past 20 years. Additionally, Chinese companies have made significant strides, capturing a 56% share of the new market, surpassing foreign enterprises for the first time.	
2008	11th Five Year Plan for Renewable Energy	Target of 10 GW wind power by 2010, 5 parks with 1 GW+ capacity, 1 GW of offshore; target to achieve domestic batch production capabilities of 1.5 MW+ turbines, develop 3 MW+ and offshore	NDRC

		turbine production capacity. This plan established seven wind power bases of at least 10 GW in size in Gansu, Xinjiang, Hebei, Jilin, eastern and western Inner Mongolia, and coastal Jiangsu, which together would total 138 GW by 2020.	
	Interim measures for administration of special funds for the wind power equipment industry	R&D fund for 1.5 MW+ turbines: 600 RMB/kW for the first 50 turbines produced (i.e., 45 million RMB for 50+ sets of 1.5 MW turbines); Blades, gearboxes and generators must come from Chinese controlled firm.	MOF
	Notice on the Publication of the Directory of Corporate Income Tax Incentives for Public Infrastructure Projects (2008 Edition)	Effective January 1, 2008, a policy of collecting and then refunding import duties and import value-added tax will be implemented for domestic enterprises that pay these taxes on key components and raw materials imported for the development and manufacture of high-power wind turbine units of 1.2 MW or above.	MoF, the State Administration of Taxation, NDRC
2009 First-round wind subsidies			
2009	Notice on Improving Grid-Connected Wind Power Tariff Policy	Nationally determined feed-in tariff (FIT): The program included four standardized national feed-in tariffs for wind power development with tariff levels varying by wind resource class: category I, RMB 0.51 per kWh; category II, RMB 0.54 per kWh; category III, RMB 0.58 per kWh; category IV, RMB 0.61 per kWh.	NDRC
	Amendment to Renewable Energy Law	Government system of safeguards for full purchase of RE power; Grid managers mandated to increase investment and research on grid development and its capacity to absorb RE power (smart-grid and power storage); Support from RE fund for grid connection when prohibitively expensive	NPC
	Notice on Abolishing the Localization Rate Requirement for Equipment Procurement in Wind Power Projects	This notice removed the long-standing local content requirement that favored domestic over imported wind technology in the Chinese market.	NDRC
2008-2010	Due to several disruptions caused by Sinovel, the price of 1.5 MW wind turbines dropped from 6,500 yuan per kilowatt to 4,600 yuan per kilowatt, a decline of nearly 30%. Under this low-price strategy, product quality control was lax, resulting in inferior quality and frequent		

	accidents. For example, wind turbines designed to have a lifespan of 20 years were reduced to only 7-8 years by domestic manufacturers.		
2010		China has experienced significant curtailment of wind power.	
	Interim measures for the management of development and construction of off-shore wind power		NEA; The State Oceanic Administration (SOA)
2011	The industry has reached a saturation point, and the quality of wind power has frequently led to accidents. In Gansu's Jiuquan, 598 wind turbines were disconnected from the grid, resulting in a loss of 840,000 kilowatts of output. This caused the frequency of the Northwest main grid to drop to a low of 49.854 Hz, making it the most significant incident to date of wind power impacting the grid in China.		
	Provisional Management Methods for Wind Power Forecasting	Aimed at improving wind power integration by better predicting when wind power will be available to the grid, required all grid-connected wind farms to install forecasting systems.	NEA
	Interim Measures for the Administration of Wind Power Development and Construction	According to the project approval management authority, wind farm projects approved by provincial government investment authorities must follow the wind farm construction plans and annual development plans filed with the national energy authority. The measures clarify the application process and management requirements for onshore wind power projects and revoke local independent approval rights for wind power projects under 50 MW. Wind power project approvals are incorporated into the national unified planning system.	NEA
	Notice on Strengthening the Management of Wind Power Plant Grid Integration and Operation	This notice was directed at reported problems with wind integration resulting in frequent wind power curtailments. The regulation included the establishment of new grid codes to address challenges with the interconnection of wind turbines. It also requires all wind farms to obtain NEA approval in order to receive the feed-in tariff subsidy.	NEA and the China National Standardization Commission
2012	12th Five Year Plan for Renewable Energy	Target of 100 GW wind capacity and 190 TWh wind generation by 2015, and 200 GW wind capacity and 390 TWh wind generation by 2020; Development concentrated in the 7 'wind bases'	State Council

		established by the 11th Five Year Plan with 5 GW per park to be installed by 2015; Encourage distributed wind generation.	
	12th Five Year Plan: Special Plan for the Development of Wind Power Science and Technology	This special plan aimed at: 1) improving the capacity in large-size wind turbine manufacturing (i.e. 3-5 MW direct drive turbines, and 7-10 MW turbines and components); 2) improving the capacity in development and operation of very large-scale wind farms, including grid integration and large-scale power storage; and 3) establishing national R&D and pilot center to improve wind power standards, testing, and personnel training.	MOST
2013	Notice on Strengthening the Management of Wind Power Integration and Utilization for year 2013	This notice set increasing wind power utilization rate as an important criteria for the energy department at all levels of government. It also includes detailed plans on wind power integration and utilization for provinces that have high level of wind installed capacity.	NEA
	Notice on Utilizing Wind Power for Clean Heating	To increase the utilization of wind generation and improve the winter air quality in Northern China, this notice promotes the deployment of wind power heating technologies in Northern provinces.	NEA
	Notice on Improving Monitoring, Forecasting, and Evaluating System for Wind Power Industry	Aimed at coordinating National Renewable Energy Center, other national level associations in electric power planning and renewable energy, grid companies, and energy department in local governments to establish information system for monitoring, forecasting and evaluating wind industry development, project construction and operation, wind power integration, and wind equipment quality.	NEA
	Notice on Adjustment of Electricity Surcharge for Renewable Energy	Increased the electricity surcharge to cover RE cost from 8RMB/MWh (since 2011) to 15RMB/MWh (from September 25, 2013). This was used to subsidize wind projects and grid-connection projects.	NEA
	Decision of the State Council on Canceling and Delegating a Batch of Administrative Approval Items	The National Energy Administration announced that the authority to approve “enterprise investment wind power station projects” would be delegated to local investment authorities.	NEA
2014 First-round FIT reduction			

2014	Notice on Adjustment of feed-in tariff for offshore wind power	Reduced the feed-in tariffs for wind projects located in wind: categories I, II, and III by 0.02RMB/kWh (for wind projects approved after Jan 1, 2015, and wind projects approved before 2015 but operating after Jan 1, 2016). The feed-in tariffs for wind projects in category IV was unchanged.	NDRC
	National offshore wind power development plan (2014-2016)	A total of 44 projects, with a combined capacity of 10.53 million kilowatts, are included in the National Offshore Wind Power Development and Construction Plan (2014-2016). Projects included in the development and construction plan are considered to be part of the approval plan and must be approved within the valid period (2 years). Projects that are not approved within the valid period must provide an explanation and reapply to be included in the development and construction plan.	NEA
2015	Notice on Further Improving the Management of Annual Wind Power Development Plans	Regions with a wind curtailment rate exceeding 20% are not permitted to arrange new construction projects and must take effective measures to improve grid integration of wind power. They should develop technical solutions to promote wind power grid integration and consumption. These measures will serve as the basis for assessing and supervising the construction and operational responsibilities of local energy authorities.	NEA
	Opinions on further deepening the reform of the electric power system	Further refine the separation of government and enterprise functions, the separation of power plants and grid companies, and the separation of main and auxiliary operations. Follow the framework of "controlling the middle and liberalizing both ends" to gradually liberalize the prices of competitive segments outside of transmission and distribution. Gradually open the distribution and retail electricity business to social capital. Gradually liberalize electricity generation and consumption plans, except for those related to public welfare and regulatory purposes.	Central Committee of the Communist Party of China; State Council
2014-2015 First installation rush		The newly installed capacity increased significantly, primarily due to the regulatory authorities issuing policies to reduce subsidies, which led to an industry-wide "installation rush."	

2016	Notice on Adjusting the Benchmark On-Grid Tariffs for Photovoltaic Power Generation and Onshore Wind Power	Reduce the benchmark on-grid tariffs for photovoltaic power generation and onshore wind power. Clarify the benchmark on-grid tariffs for offshore wind power. For offshore wind projects that were not included in a tendering process, two feed-in tariffs have been decided, for offshore and inter-tidal wind power. The benchmark feed-in tariff for offshore wind power projects will be 0.85 RMB/kWh; the benchmark feed-in tariff for inter-tidal wind power projects will be 0.75 RMB/kWh	NDRC
2018 5% curtailment restriction	Clean Energy Consumption Action Plan (2018-2020)	The plan sets targets for a national average wind power utilization rate above 88% and a photovoltaic power utilization rate above 95% in 2018, ensuring that the amounts of curtailed wind and solar power further decrease compared to 2017. By 2020, the national wind power utilization rate is aimed to be around 95%, and the photovoltaic power utilization rate should be above 95%.	NDRC, NEA
2019 Second-round FIT reduction			
2019	Notice on Actively Promoting Subsidy-Free Grid Parity for Wind Power and Photovoltaic Power Generation	Carry out the construction of grid parity projects and low-price grid connection pilot projects. Ensure priority power generation and full guaranteed purchase. Encourage grid parity and low-price grid connection projects to obtain reasonable profit compensation through green certificate trading. Strictly implement the responsibility of grid enterprises for grid connection engineering construction. Promote the subsidy-free development of wind power and photovoltaic power generation through market-based electricity transactions.	NDRC
	Notice on Improving the On-Grid Tariff Policy for Wind Power	1. Onshore wind power projects approved before the end of 2018 that are not connected to the grid by the end of 2020 will no longer receive state subsidies. 2. Onshore wind power projects approved from January 1, 2019, to the end of 2020 that are not connected to the grid by the end of 2021 will no longer receive state subsidies.	NDRC

		3. Starting from January 1, 2021, newly approved onshore wind power projects will achieve grid parity without state subsidies. For 2019, the onshore wind power guiding prices for new projects in resource areas I to IV, which are in line with planning and included in the annual scale management for financial subsidies, are adjusted to 0.34 yuan, 0.39 yuan, 0.43 yuan, and 0.52 yuan per kilowatt-hour, respectively.	
2020 Third-round FIT reduction			
2020	For 2020, the guiding prices are adjusted to 0.29 yuan, 0.34 yuan, 0.38 yuan, and 0.47 yuan per kilowatt-hour, respectively. In regions where the guiding prices are lower than the local benchmark on-grid tariffs for coal-fired units (including desulfurization, denitrification, and dust removal tariffs), the benchmark on-grid tariff for coal-fired units will be used as the guiding price.		
2019-2020 Second installation rush			
2021	Notice on Relevant Matters of the 2021 New Energy On-Grid Tariff Policy by the National Development and Reform Commission	Starting in 2021, the central government will no longer provide subsidies for newly filed centralized photovoltaic power stations, industrial and commercial distributed photovoltaics, and newly approved onshore wind power projects. In 2021, for the electricity generated within the guaranteed purchase hours of new projects, the on-grid tariff will continue to be formed through the "guiding price + competitive allocation" method.	NDRC

Table. S3. Cumulative Installed and Grid-Connected Wind Power Capacity by Province as of the end of 2020. Cumulative installed capacity is sourced from the Chinese Wind Energy Association (*53*), while grid-connected capacity data comes from the National Energy Administration and the China Electricity Council (*54*). In the generation calculation process, if grid-connected capacity exceeds installed capacity, the installed capacity is used instead to prevent negative grid connection delay values.

Unit: 10,000 KW	Grid-connected Capacity	Installed Capacity		Grid-connected Capacity	Installed Capacity
Heilongjiang	686	746	Jiangsu	1547	1636
Qinghai	843	865	Xinjiang	2361	2394
Shaanxi	892	835	Guangxi	653	662
Chongqing	97	92	Guangdong	565	689
Liaoning	981	1064	Shanxi	1974	1961
Guizhou	580	585	Shandong	1795	1960
Tibet	1	1	Anhui	412	395
Fujian	486	512	Ningxia	1377	1389
Gansu	1373	1395	Tianjin	85	80
Hunan	669	745	Sichuan	426	469
Hubei	502	584	Jilin	577	621
Hainan	29	35	Beijing	19	25
Zhejiang	186	198	Inner Mongolia	3786	3859
Henan	1518	1427	Yunnan	881	936
Hebei	2274	2370	Shanghai	82	82
Jiangxi	510	466	National	28165	29075

Table. S4. Provincial-Level Weighted Average Turbine Attributes for Installed Wind Capacity (Cumulative to 2022). Turbine attributes for all installed wind capacity in each Chinese province as of 2022, calculated using capacity-weighted averaging for each wind farm. The table includes hub height, rotor diameter, per-turbine capacity, and specific area, defined as the ratio of rotor swept area (m^2) to nameplate capacity (kW), an inverse measure of "specific power."

	Hub Height (meters)	Rotor Diameter (meters)	Turbine Rated Power (MW)	Specific Area (m^2/kW)
Heilongjiang	90.1	107.7	2.2	16.8
Qinghai	89.1	131.0	2.4	22.5
Shaanxi	94.0	130.5	2.5	21.4
Chongqing	89.3	134.7	2.7	21.4
Liaoning	86.2	110.8	2.4	17.0
Guizhou	83.8	113.8	2.1	19.6
Tibet	84.1	122.5	2.3	20.9
Fujian	88.9	122.6	4.0	13.7
Gansu	86.2	121.4	2.7	17.9
Hunan	88.7	127.1	2.5	20.7
Hubei	97.5	127.7	2.4	21.9
Hainan	72.3	82.4	1.7	12.4
Zhejiang	92.7	138.8	4.4	15.1
Henan	115.8	135.3	2.6	22.2
Hebei	89.4	113.3	2.4	17.2
Jiangxi	88.6	123.2	2.3	20.9
Jiangsu	101.2	135.3	3.4	18.0
Xinjiang	80.6	106.8	2.4	16.0
Guangxi	94.0	136.4	2.8	21.1
Guangdong	96.4	141.2	4.6	15.3
Shanxi	87.0	121.0	2.4	19.6
Shandong	97.3	123.7	2.7	18.9
Anhui	110.8	131.5	2.6	21.6
Ningxia	82.9	109.9	2.0	19.0
Tianjin	106.0	128.8	2.8	19.7
Sichuan	88.1	126.8	2.5	20.4
Jilin	92.6	123.0	2.7	18.5
Beijing	76.2	90.8	1.8	14.6
Inner Mongolia	84.0	115.5	2.7	16.2
Yunnan	84.5	115.8	2.6	17.0
Shanghai	93.5	133.7	4.1	14.4
National	90.8	121.6	2.7	18.3

Table. S5. Wind Power Reduction Coefficients in Different Regions of China. The reduction coefficient represents the ratio of actual power generation to theoretical power generation, with higher values indicating power generation efficiency closer to theoretical values.

Region/Type	Reduction Coefficient Range (%)	Average Reduction Coefficient (%)
North China (Hebei, Shanxi, etc.)	75-85	77.5
Northeast China (Liaoning, Jilin, Heilongjiang)	70-75	72.5
East China (Jiangsu, Zhejiang, Fujian)	72-85	78.5
South China (Guangdong, Guangxi)	70-75	72.5
Central China (Hunan, Hubei, Jiangxi)	73-83	78.0
Southwest China (Sichuan, Yunnan)	64-80	77.0
Northwest China (Shaanxi, Gansu, Qinghai, Xinjiang)	70-85	80.5
Special Region (Tibet)	66	66.0
Onshore Wind Farms (National Average)	55-89	74.0
Offshore Wind Farms	72.6-95.0	81.5

Table. S6. Key techno-economic parameter for technologies during 2025-2060. The battery parameters were adopted from Refs. (*16-18*), with lifetime (15 years), round-trip efficiency (0.93), self-discharge (0.001/h) assumed to remain constant over time. The alkaline electrolyzer parameters were adopted from Refs. (*20-23*), with 25 years lifetime assumed to be constant. The power-to-hydrogen-to-power parameters were adopted from Refs. (*24-29*), with compression, storage, fuel cell and co-combustion lifetime to be 15, 30, 15 and 20 years, respectively. The power-to-ammonia-to-power parameters were adopted from Refs. (*30-32*), with the lifetime of the ammonia units to be 20 years.

Items	2025	2030	2040	2050	2060
Battery: power cost (CNY/kW)	1036	881	673	570	518
Battery: energy cost (CNY/kWh)	616	524	400	339	308
Water electrolyzer (CNY/kW)	2121	1610	1274	987	910
Water electrolysis efficiency	0.65	0.675	0.7	0.725	0.75
Hydrogen compression (CNY/kW)	7770	6216	5051	4274	3885
Hydrogen storage tank (CNY/kg in H_2)	2380	2121	1883	1785	1715
H_2 geological storage (CNY/kg in H_2)	50	50	50	50	50
Fuel cell (CNY/kW)	7000	5600	4550	3850	3500
H_2 co-combustion (CNY/kW)	1500	1335	1185	1125	1080
Ammonia synthesis (CNY/kg/h in H_2)	151200	147000	142100	137200	133000
Ammonia storage (CNY/kg in H_2)	38.5	38.5	38.5	38.5	38.5
Ammonia co-combustion (CNY/kW)	1800	1602	1422	1350	1296

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