Supplementary Information

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

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Supplementary Notes

Supplementary Note 1 | Wind capacity measurement

Terrain conditions significantly influence installed capacity. In flat terrain, the onshore wind installed capacity density can reach up to 5 MW per square kilometer[1, 2]. As the slope increases, the installation capacity decreases based on Table.1 below[3]. The onshore wind power installed capacity per unit grid is calculated using the following formula.

$$P_{econ} = 5MW/km^2 * n_{slope} * S_{available} \#(1)$$

Where P_{econ} is the installed capacity after excluding limiting factors, measured in kW; n_{slope} is the slope factor (refer **Table S1**), derived from nationwide slope data calculated using a 250m resolution with a 3×3 grid window, and classified into slope factors based on reclassified slope values[3]. $S_{available}$ is the effective area available for installation, which is the area within a 10 km $\times$ 10 km grid unit that remains after excluding ecological protection zones and residential areas.

The installed capacity per square kilometer of sea area for offshore wind power projects in China shall not exceed 8 MW[4].

Supplementary Note 2 | The competitive constraints on available kinetic energy among wind turbines

To address the question of whether the spatial layout results of current wind turbine installation planning account for competitive constraints on available kinetic energy among wind turbines, we drew on the methodology proposed by Jacobson & Archer.[6] We attempted to validate the rationality of our wind turbine installation planning layout through a comparative analysis of grid-level installed capacity density against theoretical saturation thresholds. The specific analytical arguments and results are as follows.

According to the study by Jacobson & Archer,[6] the upper limit of installed capacity density for kinetic energy competition among wind turbines is 11.3 MW/km². Statistical data show that the wind power installed capacity density of each grid in this study in 2022 ranges from 0.002 to 14.88 MW/km², with an average of 0.894 MW/km². Among these, 99.3% of the wind power installed grids are below 11.3 MW/km², and only two grids exceed 11.3 MW/km² (**Fig. S5**). This indicates that the current wind power installation deployment in most regions of China is far below the saturation density threshold predicted by the model, and the recovery of wind

speed and the efficiency of wind energy extraction are relatively less restricted by the competitive constraints of available kinetic energy among wind turbines.

Furthermore, we calculated the planned wind power installed capacity density for China under the policy and low-carbon scenarios from 2025 to 2060 (**Table S11**). The results show that the capacity density in future years did not exceed the upper limit (11.3 MW/km^2) recommended by the study of Jacobson & Archer[6].

In summary, the capacity density of the vast majority of wind power installation grids falls within the reasonable range. Overall, the deployment of wind turbines nationwide does not significantly affect wind speed recovery at a large-scale, and the wind energy extraction efficiency has not entered the "saturation wind power potential (SWPP)" threshold identified by Jacobson & Archer.[6] This further demonstrates that the competitive constraints of available kinetic energy among the planned wind power installations in this study remain relatively minimal.

Supplementary Note 3 | Solar capacity measurement

Solar capacity measurement is influenced by PV equipment and geographical conditions. During site selection, key terrain factors are considered, including elevation, slope, aspect, and terrain undulation. In this study, installation density was calculated for various locations within a 10 km × 10 km grid using a 10MW fixed photovoltaic panel system, 110kV grid connection conditions, and 20% power generation efficiency under three types of terrain installation scenarios.

This study selected a 10 MW fixed photovoltaic panel installation scheme, with 110 kV grid connection conditions and a 20% power generation efficiency, across three types of terrain[5]. The terrain types are described as follows:

- Area Type 1: Refers to flat areas with no significant topographical relief, where the natural ground slope is less than or equal to 3°.
- Area Type 2: Refers to areas with mild terrain undulation, where the natural ground slope is greater than 3° but less than or equal to 20°, and the relative elevation difference is within 200 meters, typically small hill areas.
- Area Type 3: Refers to areas with significant topographical relief, where the natural ground slope is greater than 20° and the relative elevation difference exceeds 200 meters, typically large hill or mountainous areas.

The **Table S5** presents the installation density under 20% photovoltaic conversion efficiency conditions for regions across the country, based on latitude and relative

terrain characteristics. For latitudes not listed in the table, installation density can be calculated through linear interpolation.

Supplementary Table S1 | Slope influence factor

Slope (°)	Slope influence factor
≤1.7	1
1.8-3.4	0.5
3.5-16.7	0.3
16.8-30	0.15
>30	0

Supplementary Table S2 | Simulation results

Grid location	**Avg. Wind speed (m/s)**	**Avg. slope (°)**	**Slope-based capacity (MW)**	**No. of wind turbines**	**Total capacity (MW)**	**Turbine spacing**	**Capacity density (MW/km²)**	**Net gen. hours**			**Net wind speed(m/s)**			**Wake-induced speed deficit**
								Min	**Max**	**Mean**	**Min**	**Max**	**Mean**	
Inner Mongolia	6.02	0.33	500											
				100	500	$24D^2$	5	1964	2560	2156	5.23	5.78	5.41	0.102
				130	650	$24D^2$	6.5	1964	2558	2137	5.23	5.76	5.39	0.105
				235	1175	$12D^2$	11.75	1537	2487	1733	4.80	5.68	5.00	0.170
				347	1735	$9D^2$	17.35	1359	2428	1546	4.61	5.62	4.81	0.202
Gansu	6.52	1.06	500											
				100	500	$24D^2$	5	2399	3030	2569	5.69	6.37	5.87	0.100
				130	650	$24D^2$	6.5	2398	3030	2561	5.68	6.37	5.86	0.101

				235	1175	$12D^2$	11.75	1891	2842	2055	5.17	6.18	5.35	0.179
				347	1735	$9D^2$	17.35	1645	2803	1811	4.91	6.13	5.09	0.219
Guangxi	3.81	13.51	75											
				15	75	$24D^2$	0.75	1124	2140	1567	4.37	5.53	4.80	-0.261
				100	500	$24D^2$	5	198	2269	972	2.66	5.66	4.01	-0.052
				130	650	$16D^2$	6.5	30	2296	953	1.54	5.68	3.97	-0.041
				235	1175	$14D^2$	11.75	30	2296	953	1.54	5.68	3.97	-0.041
				347	1735	$14D^2$	17.35	1	1703	531	0.85	5.10	3.41	0.106

Supplementary Table S3 | Sensitive analysis for onshore wind power

Installation density	Technical installation potential (GW)	Scenario	Installation grids in 2060	Installation capacity in 2060 (GW)	Electricity generation in 2060 (TWh)	Net benefits in 2060 (Trillion CNY)
5	13692.14	Policy	9707	2160.00	4666.18	1.60
		Low carbon	17171	4138.20	8951.44	4.43
8	21907.43	policy	6253	2160.00	4323.42	1.42
		Low carbon	10057	4138.20	8293.91	4.01
10	27384.29	policy	5284	2160.00	4094.92	1.31
		Low carbon	8083	4138.20	7855.55	3.73
20	54768.57	policy	4059	2160.00	2952.39	0.73
		Low carbon	4790	4138.20	5663.76	2.35

Supplementary Table S4 | Sensitive analysis for offshore wind power

Installation density	Technical installation potential (GW)	Scenario	Installation grids in 2060	Installation capacity in 2060 (GW)	Electricity generation in 2060 (TWh)	Net benefits in 2060 (Trillion CNY)
5	1615	Policy	1217	615.29	1660.18	0.38
		Low carbon	2460	1236.74	3336.96	1.18
8	2584	Policy	767	615.29	1538.23	0.33
		Low carbon	1544	1236.74	3091.84	1.04

Supplementary Table S5 | 10MW fixed photovoltaic grid connection conditions at 110kv, conversion efficiency 20%, coverage area across different latitudes

Area type	Latitude (degree)	10MW 110KV （hm^2）	Installation density (MW/km^2)
1	18	10.324	97
	20	10.701	93
	25	11.864	84
	30	13.472	74
	35	15.807	63
	40	19.456	51
	45	25.881	39
	50	39.994	25
2	18	12.936	77

	20	13.426	74
	25	14.938	67
	30	17.029	59
	35	20.064	50
	40	24.808	40
	45	33.16	30
	50	51.507	19
3	18	15.548	64
	20	16.151	62
	25	18.012	56
	30	20.585	49
	35	24.321	41
	40	30.16	33
	45	40.44	25
	50	63.02	16

Supplementary Table S6 | Cost of wind and solar farm construction in China[6]

Province	Greater administrative region	Project name	Wind/Solar	Bidding Price (Million Yuan)	Year	Installed capacity (MW)
Henan	Central China	Sanxia New Energy Beijing Tianhuacheng Xincai 19MW Distributed Wind Power Project EPC	Wind	47.99	2021	19.00
Henan	Central China	Henan Huadian Yiyang Phase IV 40MW Wind Power Project EPC Engineering	Wind	107.98	2021	40.00
Henan	Central China	Henan Anyang Huaxian 70MW Wind Power Project, Yiyang Zhangwu 50MW Wind Power Project EPC General Contract	Wind	316.85	2019	120.00
Hubei	Central China	Hubei Energy Group Xiangzhou Huangji Phase I 100MW Wind Power Project EPC General Contract	Wind	188.51	2023	100.00
Hubei	Central China	China Resources Jiayu Paizhou Bay 200MW Wind Power Project Main Engineering EPC General Contract	Wind	794.59	2023	200.00
Hunan	Central China	State Power Investment Corporation 185MW Wind Power EPC General Contract Project	Wind	1341.45	2024	185.00
Hunan	Central China	SPIC Wuling Electric Power Taoyuan Reshizhen Wind Farm Project (65MW) EPC Engineering	Wind	528.00	2023	65.00
Hunan	Central China	SPIC Wuling Electric Power Jiangyong County Baima Shangjiangwei Wind Power Phase II Project EPC	Wind	428.92	2023	55.00
Hunan	Central China	Dingcheng District Shimeitang Town, Haozigang Town Wind Farm	Wind	1464.00	2023	200.00

Province	Greater administrative region	Project name	Wind/Solar	Bidding Price (Million Yuan)	Year	Installed capacity (MW)
		Project				
Anhui	East China	Suixi County Linhuan Wind Farm Project (Phase II) EPC General Contract	Wind	220.00	2024	40.00
Anhui	East China	Huadian Huaibei Suixi Linhuan 110MW Wind Power EPC General Contract Project	Wind	920.00	2022	110.00
Anhui	East China	Anhui Province Suixi County Xinfeng Wind Power EPC General Contract Project	Wind	325.67	2021	50.00
Anhui	East China	China Resources Fengtai County Shangtang Wind Power Project	Wind	1327.19	2023	200.00
Shandong	East China	Shandong Haiwei Peninsula South U Site 450MW Offshore Wind Power Project EPC General Contract	Wind	4728.30	2024	450.00
Shandong	East China	Shandong Energy 500MW Offshore Wind Power EPC General Contract Project	Wind	5629.70	2022	500.00
Jiangsu	East China	Jiangsu Guoxin Huai'an Wind Power Project (EPC)	Wind	430.00	2020	50.00
Jiangxi	East China	Jiangxi Weiheng Niyangshan 50MW Wind Farm Project EPC General Contract	Wind	315.96	2023	50.00
Zhejiang	East China	Huaneng Yuhuan Unit 2 Offshore Wind Power Project EPC General Contract	Wind	5191.00	2024	400.00
Zhejiang	East China	Zhejiang Zhoushan Shengsi Unit 2 Offshore Wind Farm Project (EPC)	Wind	647.00	2020	200.00

Province	Greater administrative region	Project name	Wind/Solar	Bidding Price (Million Yuan)	Year	Installed capacity (MW)
Fujian	East China	Datang (Fuzhou) New Energy Co., Ltd. Minhou Qingpulian Wind Farm (EPC General Contract Tender)	Wind	400.00	2016	48.00
Inner Mongolia	North China	Manzhouli Green Power Flexibility Application Project	Wind	960.00	2024	300.00
Inner Mongolia	North China	Inner Mongolia Energy West Su 1GW Wind-Storage Project	Wind	2315.16	2024	1000.00
Inner Mongolia	North China	Inner Mongolia Energy Urad Middle Banner Ganqimaodu Port 500MW Flexible Green Power Demonstration Project	Wind	1770.00	2024	500.00
Inner Mongolia	North China	Investment Announcement for Ulanqab Daihai 1.5GW Wind Power Green Electricity to Beijing Base Project	Wind	9179.00	2022	1500.00
Beijing	North China	Beijing Luming Mountain Guanting Wind Farm Phase IV 49MW	Wind	489.00	2018	49.00
Beijing	North China	Datang Qinghuiling Wind Power Expansion Project Construction General Contract Project	Wind	71.01	2023	50.00
Tianjing	North China	Zhihui Binhai Yangjiabo 43.2MW Wind Power Project EPC General Contract	Wind	427.68	2023	43.20
Tianjing	North China	Beichen District Shuangkou Town 50MW Wind Power Project	Wind	265.60	2023	50.00
Tianjing	North China	Wuqing District Shangmatian Town 80MW Wind Power Project	Wind	350.00	2022	80.00
Shanxi	North China	Shanxi Province Taiyuan City Yangqu County Nituo Town 200MW	Wind	500.00	2023	100.00

Province	Greater administrative region	Project name	Wind/Solar	Bidding Price (Million Yuan)	Year	Installed capacity (MW)
		Wind Power Project (Phase I 100MW)				
Shanxi	North China	Datong Guangling 100MW Wind Power Project	Wind	805.00	2023	100.00
Shanxi	North China	China Resources Xinzhou Kalan 100MW Wind Power Project EPC General Contract	Wind	515.50	2023	100.00
Hebei	North China	Ren County 60MW Wind Power Project EPC General Contract Engineering	Wind	79.91	2023	60.00
Hebei	North China	Jiaotou Pingquan 300MW Wind Power Project EPC General Contract Winning Bid Announcement	Wind	490.62	2022	300.00
Hebei	North China	Beijing Haoge Energy Technology Co., Ltd. Dongguang County 200MW Wind Power Project EPC (Design, Procurement, Construction) General Contract Winning Candidate Announcement	Wind	1500.00	2023	200.00
Jiling	Northeast	Huaneng Jilin Branch Jilin Province Haoan New Energy Technology Co., Ltd. 200MW Wind Power Project EPC General Contract	Wind	719.00	2024	200.00
Liaoning	Northeast	Huaneng Dalian Power Plant In-Plant 15MW Distributed Wind Power Project EPC General Contract Winning Bid	Wind	102.68	2020	15.00
Liaoning	Northeast	Liaoning Jinzhou Heishan Changxing 300MW Wind Power Project EPC General Contract Engineering	Wind	1763.00	2023	300.00

Province	Greater administrative region	Project name	Wind/Solar	Bidding Price (Million Yuan)	Year	Installed capacity (MW)
Liaoning	Northeast	Liaoning Jianping Shahai 200MW Wind Farm General Contract (EPC) Project	Wind	1181.35	2023	200.00
Liaoning	Northeast	Guoneng Kangping Power Generation Co., Ltd. Liushutun 200MW Wind Power Project EPC General Contract	Wind	1279.00	2023	200.00
Heilongjiang	Northeast	China Power Construction New Energy Company Heilongjiang Mingshui 200MW Wind Power Project	Wind	606.50	2024	200.00
Heilongjiang	Northeast	Heilongjiang Harbin Shangzhi City Ruilong 200MW Wind Power Project (Phase II 100MW) EPC Engineering	Wind	571.00	2024	200.00
Heilongjiang	Northeast	China Energy Construction Aihui 200MW Phase I Wind Power EPC General Contract Engineering Tender Announcement	Wind	1030.00	2024	200.00
Ningxia	Northwestern China	Ningxia Sanxia New Energy Ningxia Tongxin Wind Farm (50MW) Project EPC General Contract	Wind	410.00	2018	50.00
Ningxia	Northwestern China	Sanxia New Energy Ningxia Hongsibao Wind Farm (100MW) Project EPC General Contract Engineering	Wind	249.95	2024	100.00
Xinjiang	Northwestern China	Hami City 400MW Wind Power Project EPC General Contract	Wind	1753.52	2024	400.00
Xinjiang	Northwestern China	Altay Storage Project Buerjin Region 300MW Wind Power EPC General Contract Project	Wind	188.51	2023	30.00

Province	Greater administrative region	Project name	Wind/Solar	Bidding Price (Million Yuan)	Year	Installed capacity (MW)
Gansu	Northwestern China	Dunhuang Runjian 500MW Wind Power Project EPC General Contract Engineering	Wind	2509.50	2023	500.00
Gansu	Northwestern China	Longnan Wudu District Maying 300MW Wind Power Project (Section I, Section II) EPC General Contract Project	Wind	1434.50	2023	300.00
Gansu	Northwestern China	Gao Tai Beitan Million Kilowatt Wind Power Base 400MW EPC Wind Power Project	Wind	2800.00	2023	400.00
Gansu	Northwestern China	Gansu Subai County Mazongshan Yinmaxia 100MW Wind Power EPC Project	Wind	558.82	2023	100.00
Gansu	Northwestern China	Zhangye City Ganzhou Pingshan Lake Million Kilowatt Wind Power Base 200MW Wind Power 2# Project EPC General Contract Engineering	Wind	730.00	2023	200.00
Shaanxi	Northwestern China	Baoji Longxian Guguan Wind Farm	Wind	1400.00	2023	200.00
Qinghai	Northwestern China	Sanxia New Energy Qinghai Province Gonghe Qieji Wind Farm (100MW) Project EPC General Contract	Wind	810.00	2019	100.00
Qinghai	Northwestern China	Sanxia New Energy Qinghai Province Haixi Prefecture Nomuhong 50MW Wind Power Project EPC	Wind	49.59	2020	50.00
Qinghai	Northwestern China	Sanxia New Energy Qinghai Province Xitianshan Liusha Ping Phase II Wind Farm 100MW Storage Project EPC General Contract Engineering	Wind	19.78	2020	100.00

Province	Greater administrative region	Project name	Wind/Solar	Bidding Price (Million Yuan)	Year	Installed capacity (MW)
Offshore	Offshore	SPIC Guangdong Zhanjiang Xuwen Offshore Wind Farm 300MW Capacity Expansion Project	Wind	1392.00	2023	300.00
Offshore	Offshore	Guangxi Fangchenggang Offshore Wind Power Demonstration Project A Site Section 1 EPC General Contract Engineering Winning Bid Announcement	Wind	9500.00	2023	700.00
Offshore	Offshore	Wanning 1GW Floating Offshore Wind Power Experimental Project	Wind	22500.00	2022	1000.00
Guangdong	South China	Mingyang Guangdong Shaoguan Shixing County Neishan Wind Power Phase I Project	Wind	120.96	2022	18.96
Guangdong	South China	Sanxia Shaoguan Xinfeng Fengyuan Wind Farm Project Construction	Wind	661.49	2023	100.00
Guangdong	South China	Guangdong Yue Power Nanyong Zhuancun Wind Farm Project	Wind	490.00	2016	49.90
Guangxi	South China	Babu Shangcheng Wind Farm Project	Wind	1417.95	2024	200.00
Guangxi	South China	Fuchuan Yao Autonomous County Lianshan Town Tiantangling Huaneng Jinziling Wind Farm Phase I Project	Wind	495.00	2013	49.50
Guangxi	South China	Xincheng County People’s Government and Beijing Energy International Holdings Co., Ltd. Wind Power Project	Wind	2800.00	2021	300.00
Hainan	South China	Datang Hainan Danzhou 1.2GW Offshore Wind Power Project	Wind	14595.00	2022	1200.00
Hainan	South China	Hainan Dongfang CZ8 Site 500MW Offshore Wind Power Project	Wind	6000.00	2023	500.00
Yunnan	Southwestern	Tianzhen Huaneng Xiachu 100MW Wind Power Project EPC General	Wind	516.72	2023	100.00

Province	Greater administrative region	Project name	Wind/Solar	Bidding Price (Million Yuan)	Year	Installed capacity (MW)
	China	Contract Engineering				
Yunnan	Southwestern China	Qujing Yunneng Tongquan North Power Development Co., Ltd. Plans to Invest in Tongquan Wind Farm Expansion Project	Wind	732.00	2023	131.25
Yunnan	Southwestern China	Jianshui Liangzi Wind Farm Project	Wind	311.00	2022	50.00
Sichuan	Southwestern China	CGN Releases Miyi Longjiushan 50MW Wind Power Project EPC General Contract	Wind	359.76	2021	50.00
Sichuan	Southwestern China	Liangshan Prefecture Dechang County Labashan Wind Farm Project	Wind	1500.00	2022	192.00
Sichuan	Southwestern China	Liangshan Prefecture Huidong County Tangtang Phase II Wind Power Project	Wind	871.76	2022	120.00
Xizang	Southwestern China	Naqu City Seni District Oumatingga 100MW Wind Power Project Grid-Connected Power Generation	Wind	640.00	2023	100.00
Guizhou	Southwestern China	Fenggang Huaping Phase I Wind Farm	Wind	310.00	2023	55.00
Guizhou	Southwestern China	Guizhou Huadian Qianxi Huaxi Jiangjunshan 100MW Wind Power Project Wind Farm EPC General Contract Project Commencement	Wind	141.00	2023	100.00

Province	Greater administrative region	Project name	Wind/Solar	Bidding Price (Million Yuan)	Year	Installed capacity (MW)
Guizhou	Southwestern China	Ziyun County Mazongling Wind Farm Project EPC General Contract Engineering	Wind	557.00	2023	100.00
Chongqing	Southwestern China	About Chengkou Shuanghe Phase I Wind Power Project	Wind	193.00	2023	30.00
Chongqing	Southwestern China	Qianjiang Qilin Phase II Wind Power Project Approval Content	Wind	346.95	2023	49.50
Hubei	Central China	Hubei Bangsheng New Energy Ezhou Changgang Town 100MW Fishery-Solar Hybrid Photovoltaic Project EPC General Contract	Solar	419.83	2023	100.00
Hunan	Central China	SPIC Wuling Electric Power Baojing County Shuitianhe Town Liangjia Village Tea-Light Hybrid Photovoltaic Project EPC	Solar	9.88	2023	6.00
Shanghai	East China	Shanghai Zhujiajiao Town Xianfeng Village Fishery-Solar Hybrid Photovoltaic Project EPC General Contract	Solar	82.86	2023	18.96
Shanghai	East China	Shanghai Chongming Zhongxing Town 100MW Fishery-Solar Hybrid Project EPC General Contract	Solar	474.00	2024	100.00
Shanghai	East China	Shanghai Chongming District Chenjia Town Fishery-Solar Hybrid 110MW EPC General Contract Project	Solar	407.00	2020	110.00
Shanghai	East China	Fengxian District Fengxian New City Unit 08-06-02 Area Plot Solar Photovoltaic Power Generation Project	Solar	4.97	2024	0.84

Province	Greater administrative region	Project name	Wind/Solar	Bidding Price (Million Yuan)	Year	Installed capacity (MW)
Shanghai	East China	Dishui Lake Waterfront Landscape Revitalization Demonstration Section Solar Photovoltaic Power Generation Project	Solar	0.65	2024	0.14
Shanghai	East China	Shanghai Second Branch of the People's Procuratorate Distributed Photovoltaic Power Generation Energy Management Contract Project	Solar	1.29	2024	0.07
Shanghai	East China	Shanghai Nanhui Base 2MW Distributed Photovoltaic Power Generation Project EPC General Contract	Solar	7.30	2024	2.00
Shanghai	East China	Shanghai Huadian Chongming Huaxing 62.72MW Fishery-Solar Hybrid Photovoltaic Power Generation Project	Solar	374.55	2022	81.00
Anhui	East China	SPIC Wuling Electric Power Anhui Wuhu City and Surrounding Counties 100MWp Residential Photovoltaic Project EPC General Contract	Solar	89.20	2024	100.00
Anhui	East China	Huaneng Anhui Branch Wuhu 70MW Residential Photovoltaic Project EPC Engineering	Solar	227.50	2024	70.00
Shandong	East China	Shandong Linyi 100MWp Rooftop Distributed Fishing Platform Village and Other 27MWp Photovoltaic Projects EPC General Contract	Solar	92.89	2024	27.00
Jiangsu	East China	SPIC Wuling Electric Power Jiangsu Huai'an Huaiyin District 100MWp Beautiful Countryside Tri-Network Integration Demonstration Photovoltaic Project Engineering Supervision Service Tender	Solar	500.00	2024	100.00

Province	Greater administrative region	Project name	Wind/Solar	Bidding Price (Million Yuan)	Year	Installed capacity (MW)
		Announcement				
Jiangsu	East China	Jiangsu Nantong Rugao Economic and Technological Development Zone 19.278MWp Industrial and Commercial Distributed Photovoltaic Power Generation Project EPC	Solar	66.51	2024	19.28
Jiangsu	East China	CNNC Tianwan 2GW Tidal Flat Photovoltaic Demonstration Project	Solar	10200.00	2024	2000.00
Jiangxi	East China	Jiangxi Shangrao Zuoshe Phase I 150MW Photovoltaic Power Generation Project (First Stage 50MW) EPC General Contract	Solar	194.53	2023	50.00
Jiangxi	East China	Jiangxi Xinyu 100MWp Photovoltaic Power Generation Project EPC General Contract	Solar	404.50	2021	100.00
Zhejiang	East China	Zhejiang Wenling Jiangsha 100MWp Tidal-Light Complementary Smart Photovoltaic Power Generation Project EPC General Contract	Solar	202.02	2021	100.00
Fujian	East China	Fujian Wind Power Company Quanzhou Kailian 4.26018MW Photovoltaic Power Generation Project EPC	Solar	20.40	2023	4.13
Fujian	East China	Fujian Qingtou Group 400MW Rooftop Distributed Photovoltaic Project EPC General Contract	Solar	1680.00	2023	400.00
Inner	North China	Inner Mongolia Energy Dalat Banner 1GW Mining Area Photovoltaic +	Solar	2417.68	2024	1200.41

Province	Greater administrative region	Project name	Wind/Solar	Bidding Price (Million Yuan)	Year	Installed capacity (MW)
Mongolia		Storage Project EPC Project				
Tianjing	North China	Huaneng Tianjin Haijing "Salt-Light Complementary" Photovoltaic Power Generation Project	Solar	5600.00	2023	1000.00
Tianjing	North China	Tianjin Taiping Town 450MW Photovoltaic Power Generation Project Phase I 200MWp Project	Solar	854.00	2023	200.00
Tianjing	North China	Tianjin Huadian Binhai Hangu 100MW "Green Ecological Compound" Photovoltaic Power Generation Project	Solar	275.41	2023	100.00
Shanxi	North China	China Power Construction New Energy Company Taiyuan Xinghualing District 395MWp Photovoltaic Project (Phase I 200MW) EPC General Contract	Solar	539.49	2023	200.00
Shanxi	North China	CNNC Shuocheng District 100MW Photovoltaic Power Project	Solar	114.24	2022	100.00
Shanxi	North China	CGN Xinzhou Ningwu 100MW Photovoltaic Project EPC General Contract	Solar	89.48	2023	100.00
Shanxi	North China	CGN Yuci	Solar	230.51	2020	50.00
Shanxi	North China	CGN Ningwu	Solar	195.08	2020	50.00
Hebei	North China	Huaneng Hebei Leting County Distributed Photovoltaic Project (Phase I 20MW) EPC Engineering	Solar	72.28	2023	20.00

Province	Greater administrative region	Project name	Wind/Solar	Bidding Price (Million Yuan)	Year	Installed capacity (MW)
Hebei	North China	Jingneng International Hebei Cangzhou Dongguang County Jingcang 45MW Distributed Photovoltaic EPC Engineering General Contract Tender Winning Candidate Announcement	Solar	162.00	2023	45.00
Hebei	North China	China Energy Conservation Solar Energy Hebei Unicom 150MW Distributed Photovoltaic Power Generation Project EPC Engineering General Contract	Solar	636.45	2023	150.00
Jiling	Northeast	Huaneng Jilin Branch Jilin Province 80MW Residential Photovoltaic Project EPC Engineering	Solar	263.67	2023	80.00
Jiling	Northeast	Jilin Province Liaoyuan City 180KW Photovoltaic Power Generation Project (EPC)	Solar	1.49	2017	0.18
Ningxia	Northwestern China	Ningxia Huadian Lijunbao Phase II 60MW Wind Power Project EPC	Solar	109.05	2019	60.00
Xinjiang	Northwestern China	Wuerhe Source-Grid-Load-Storage Integrated Project - Karamay Mengshi Light Storage Wuerhe 1GW Photovoltaic Power Generation Supporting 120MW/240MWh Storage Project (Phase II Photovoltaic) II Bid Section Project Design, Procurement, Construction (EPC) General Contract Engineering	Solar	378.00	2023	400.00
Xinjiang	Northwestern	China Resources Power Hetian Region 1.3GW Photovoltaic Project	Solar	4896.00	2023	1300.00

Province	Greater administrative region	Project name	Wind/Solar	Bidding Price (Million Yuan)	Year	Installed capacity (MW)
	China					
Gansu	Northwestern China	Datang Longxi 100MW Photovoltaic Project EPC General Contract	Solar	276.35	2023	100.00
Gansu	Northwestern China	Dunhuang City Shazhou Energy Photovoltaic Power Co., Ltd. 260MW Photovoltaic Power Project Phase II 150MW Photovoltaic Power Project	Solar	579.72	2023	150.00
Gansu	Northwestern China	Guangdong Water Power Lanzhou New District 100MW Centralized Photovoltaic Power Project EPC General Contract	Solar	308.29	2023	100.00
Gansu	Northwestern China	Jinta Baishuiquan 600MW Photovoltaic Power Phase II 400MW Engineering EPC General Contract	Solar	965.60	2023	200.00
Gansu	Northwestern China	Public Aviation Travel Liangzhou District Jiuduntan 100MW Photovoltaic Power Project EPC General Contract	Solar	368.79	2023	100.00
Qinghai	Northwestern China	Qinghai Guoluo Agro-Solar Complementary Photovoltaic Project	Solar	960.00	2022	200.00
Qinghai	Northwestern China	Qinghai Qilian County 155MW Photovoltaic Project Commencement	Solar	1120.00	2023	155.00
Qinghai	Northwestern China	Dulan 30MW Grid-Connected Photovoltaic Power Project (EPC) (Qinghai Zhongzhu Photovoltaic Power Co., Ltd.)	Solar	176.00	2022	30.00

Province	Greater administrative region	Project name	Wind/Solar	Bidding Price (Million Yuan)	Year	Installed capacity (MW)
Qinghai	Northwestern China	Gaomi East Station Distributed Photovoltaic Power Project Construction Engineering EPC General Contract Tender Announcement	Solar	11.73	2024	3.50
Guangdong	South China	Guangzhou Development Yangshan Taiping Photovoltaic Composite Phase II Expansion Project EPC General Contract	Solar	99.82	2023	50.00
Guangdong	South China	Qingyuan City Fogang County CNNC Rural Revitalization Agri-Solar Complementary Photovoltaic Power Station (Phase I) EPC General Contract	Solar	326.85	2023	200.00
Guangdong	South China	CGN Poyang 500MW Agri-(Forest, Fishery)-Solar Complementary Photovoltaic Phase I 250MW Project EPC General Contract	Solar	803.35	2021	250.00
Guangdong	South China	Shaoguan City Zhenjiang District Fishery-Solar Complementary Photovoltaic Power Comprehensive Utilization Project	Solar	1289.00	2024	300.00
Guangxi	South China	Shanglin County Baiwei Town 40MW (Phase III) Photovoltaic Power Generation Project EPC General Contract	Solar	77.48	2022	45.06
Guangxi	South China	Tantou Township Photovoltaic Power Generation Project is a Major Advancement Project in Rong'an County	Solar	420.00	2022	100.00
Guangxi	South China	CNNC Huanjiang 100MW Agricultural Photovoltaic Project	Solar	507.00	2020	100.00
Yunnan	Southwestern China	Yunnan Zhujiazai Photovoltaic Power Project EPC General Contract Project	Solar	178.90	2023	80.00

Province	Greater administrative region	Project name	Wind/Solar	Bidding Price (Million Yuan)	Year	Installed capacity (MW)
Yunnan	Southwestern China	Total Investment of 57.2964 Million Yuan! Yunnan Energy Investment Plans to Build an 11MW Photovoltaic Project	Solar	57.30	2023	11.00
Yunnan	Southwestern China	Guangnan County Duimenzhai Photovoltaic Power Project	Solar	124.45	2023	94.71
Yunnan	Southwestern China	Guangnan County Donazhai Photovoltaic Power Project	Solar	213.21	2023	135.00
Yunnan	Southwestern China	Guangnan County Nanongzhai Photovoltaic Power Project	Solar	305.76	2023	229.40
Yunnan	Southwestern China	Guangnan County Nanongzhai Photovoltaic Power Project	Solar	86.93	2023	54.00
Yunnan	Southwestern China	Guangnan County Zigan Village Photovoltaic Power Project	Solar	179.06	2023	198.00
Sichuan	Southwestern China	Sichuan Liangshan Prefecture Muli County	Solar	97.99	2023	240.00
Xizang	Southwestern China	Tibet Changdu Mangkang Angdu 1.8GW Photovoltaic Power Project	Solar	603.98	2023	1800.00
Xizang	Southwestern China	Tibet Changdu Gongjue Latuo Phase I 800MW Photovoltaic Power Project	Solar	1119.26	2023	1800.00

Province	Greater administrative region	Project name	Wind/Solar	Bidding Price (Million Yuan)	Year	Installed capacity (MW)
Guizhou	Southwestern China	Winning Bid for Guizhou Guanling Photovoltaic Power Project	Solar	2650.00	2023	1050.00
Guizhou	Southwestern China	Guizhou Huadian Dafang Sheep Farm 90MW Agricultural Photovoltaic Power Project EPC General Contract Engineering	Solar	116.00	2023	90.00
Chongqing	Southwestern China	Chongqing Wanzhou District Wuling Town, Nangdu Town 24.6MW Centralized Photovoltaic Power Project EPC General Contract	Solar	58.08	2023	24.60

Supplementary Table S7 | The share of capital expenditures in lifecycle cost in China

Type	Share of Capital expenditures in lifecycle cost	Notes	Published year	Source
Wind - offshore	83.0%	-	2025	An *et al.*[8]
Wind - offshore	75-95% (85%)	-	2022	He *et al.*[9]
Wind - onshore	62.9%	Overnight cost/LCOE	2014	Ouyang *et al.*[10]
Solar	69.1%			

Solar	83.7%	Investment/LCOE Discount Rate 7%	2021	International Energy Agency (IEA) & Nuclear Energy Agency (NEA)[11]
Wind - onshore	76.9%			
Wind - offshore	76.6%			

Supplementary Table S8 | Carbon emissions price[7]

	Policy Scenario (CNY/Tons)							Low-carbon Scenario (CNY/Tons)						
Province	**2022**	**2025**	**2030**	**2035**	**2040**	**2050**	**2060**	**2022**	**2025**	**2030**	**2035**	**2040**	**2050**	**2060**
Shanghai	65.42	100	150	200	300	600	800	65.42	130	240	300	400	800	1000
Yunnan	65.42	100	150	200	300	600	800	65.42	130	240	300	400	800	1000
Inner Mongolia	65.42	100	150	200	300	600	800	65.42	130	240	300	400	800	1000
Beijing	65.42	100	150	200	300	600	800	65.42	130	240	300	400	800	1000
Jilin	65.42	100	150	200	300	600	800	65.42	130	240	300	400	800	1000
Sichuan	65.42	100	150	200	300	600	800	65.42	130	240	300	400	800	1000
Tianjin	65.42	100	150	200	300	600	800	65.42	130	240	300	400	800	1000
Ningxia	65.42	100	150	200	300	600	800	65.42	130	240	300	400	800	1000
Anhui	65.42	100	150	200	300	600	800	65.42	130	240	300	400	800	1000
Shandong	65.42	100	150	200	300	600	800	65.42	130	240	300	400	800	1000
Shanxi	65.42	100	150	200	300	600	800	65.42	130	240	300	400	800	1000
Guangdong	65.42	100	150	200	300	600	800	65.42	130	240	300	400	800	1000
Guangxi	65.42	100	150	200	300	600	800	65.42	130	240	300	400	800	1000
Xinjiang	65.42	100	150	200	300	600	800	65.42	130	240	300	400	800	1000
Jiangsu	65.42	100	150	200	300	600	800	65.42	130	240	300	400	800	1000

Jiangxi	65.42	100	150	200	300	600	800	65.42	130	240	300	400	800	1000
Hebei	65.42	100	150	200	300	600	800	65.42	130	240	300	400	800	1000
Henan	65.42	100	150	200	300	600	800	65.42	130	240	300	400	800	1000
Zhejiang	65.42	100	150	200	300	600	800	65.42	130	240	300	400	800	1000
Offshore	65.42	100	150	200	300	600	800	65.42	130	240	300	400	800	1000
Hainan	65.42	100	150	200	300	600	800	65.42	130	240	300	400	800	1000
Hubei	65.42	100	150	200	300	600	800	65.42	130	240	300	400	800	1000
Hunan	65.42	100	150	200	300	600	800	65.42	130	240	300	400	800	1000
Gansu	65.42	100	150	200	300	600	800	65.42	130	240	300	400	800	1000
Fujian	65.42	100	150	200	300	600	800	65.42	130	240	300	400	800	1000
Xizang	65.42	100	150	200	300	600	800	65.42	130	240	300	400	800	1000
Guizhou	65.42	100	150	200	300	600	800	65.42	130	240	300	400	800	1000
Liaoning	65.42	100	150	200	300	600	800	65.42	130	240	300	400	800	1000
Chongqing	65.42	100	150	200	300	600	800	65.42	130	240	300	400	800	1000
Shaanxi	65.42	100	150	200	300	600	800	65.42	130	240	300	400	800	1000
Qinghai	65.42	100	150	200	300	600	800	65.42	130	240	300	400	800	1000
Heilongjiang	65.42	100	150	200	300	600	800	65.42	130	240	300	400	800	1000

Supplementary Table S9 | Wind and solar potential capacities by Policy Scenario

	Policy Scenario*											
	Wind (GW)						Solar (GW)					
Province	**2025**	**2030**	**2035**	**2040**	**2050**	**2060**	**2025**	**2030**	**2035**	**2040**	**2050**	**2060**

Xinjiang	29.30	42.30	61.06	88.15	183.71	382.88	35.62	59.17	98.29	163.27	450.54	1243.25
Tibet	0.04	0.05	0.06	0.07	0.10	0.15	10.00	17.98	32.31	58.09	187.70	606.51
Inner Mongolia	89.00	113.43	144.57	184.26	299.31	486.20	45.00	64.54	92.56	132.74	273.03	561.57
Qinghai	19.77	21.75	23.93	26.33	31.88	38.60	23.46	35.62	54.07	82.09	189.22	436.14
Gansu	38.53	43.02	48.03	53.61	66.82	83.28	42.36	56.55	75.49	100.78	179.60	320.06
Sichuan	10.00	12.05	14.53	17.51	23.70	23.70	12.00	19.07	30.30	48.15	121.58	306.99
Yunnan	11.03	13.29	16.02	19.31	28.06	40.76	53.93	68.55	87.13	110.76	178.96	289.15
Guangxi	10.76	12.56	14.65	17.10	23.30	31.74	14.90	22.41	33.72	50.71	114.73	259.58
Heilongjiang	16.86	23.37	32.39	44.90	86.26	165.73	8.68	13.90	22.28	35.71	91.72	235.58
Hunan	12.00	13.17	14.46	15.88	19.14	23.07	13.00	19.60	29.56	44.58	101.39	230.57
Guangdong	8.91	10.56	12.51	14.82	20.81	29.21	27.97	37.59	50.53	67.91	122.68	221.62
Henan	27.00	30.00	33.32	37.02	45.69	56.39	25.00	33.52	44.94	60.25	108.29	194.64
Hubei	10.02	11.71	13.68	15.98	21.82	29.79	22.00	29.87	40.56	55.06	101.51	187.13
Jiangxi	7.00	7.80	8.70	9.69	12.04	14.96	24.00	31.94	42.50	56.56	100.18	177.41
Shandong	24.05	27.58	31.62	36.25	47.64	62.62	65.00	74.91	86.32	99.48	132.12	175.46
Anhui	7.41	9.59	12.41	16.07	26.92	45.12	23.04	30.47	40.29	53.28	93.19	162.97
Shaanxi	13.68	16.48	19.87	23.95	34.80	50.55	25.98	33.69	43.69	56.66	95.29	160.27
Hebei	41.23	49.70	59.90	72.20	104.90	152.41	54.00	62.44	72.21	83.50	111.66	149.31
Guizhou	10.80	13.02	15.69	18.91	27.48	39.92	31.00	38.64	48.15	60.02	93.22	144.81
Shanxi	30.00	36.16	43.59	52.54	76.33	110.90	50.00	57.12	65.25	74.54	97.27	126.94
Jiangsu	19.06	21.38	23.99	26.92	33.89	42.67	35.00	41.95	50.27	60.25	86.55	124.32
Jilin	22.00	25.73	30.09	35.19	48.14	65.85	8.00	11.82	17.46	25.79	56.28	122.80

Liaoning	17.08	19.58	22.43	25.71	33.76	44.33	15.93	20.92	27.47	36.08	62.23	107.32
Fujian	9.00	10.85	13.08	15.76	22.90	33.27	5.00	7.69	11.82	18.17	42.94	101.48
Zhejiang	1.49	1.95	2.56	3.35	5.75	9.87	27.62	32.44	38.11	44.76	61.75	85.19
Chongqing	2.68	3.23	3.89	4.69	6.82	7.66	1.02	1.84	3.32	5.99	19.46	63.25
Hainan	0.35	0.55	0.85	1.33	3.19	7.69	2.51	3.84	5.87	8.98	21.00	49.11
Ningxia	17.50	21.09	25.43	30.65	44.53	64.69	32.50	34.24	36.07	38.01	42.18	46.82
Tianjin	3.19	3.85	4.64	5.59	8.13	11.81	5.60	6.14	6.74	7.39	8.89	10.69
Shanghai	0.83	0.99	1.18	1.41	2.02	2.89	10.00	10.99	12.07	13.26	16.01	8.90
Beijing	0.30	0.37	0.46	0.56	0.85	1.30	1.30	1.68	2.17	2.80	4.66	7.76
Offshore**	87.07	200.00	250.00	300.00	432.00	615.29	-	-	-	-	-	-

Note: *The provincial scenario projections do not include Hong Kong, Macao, and Taiwan; **The photovoltaic installation potential projections do not include offshore areas.

Supplementary Table S10 | Wind and solar potential capacities by Low-carbon Scenario

	Low-Carbon Scenario*											
	Wind (GW)						**Solar (GW)**					
Province	**2025**	**2030**	**2035**	**2040**	**2050**	**2060**	**2025**	**2030**	**2035**	**2040**	**2050**	**2060**
Xinjiang	29.30	46.73	74.54	118.89	302.49	769.59	35.62	67.17	126.67	238.87	849.50	3021.09
Tibet	0.04	0.05	0.07	0.09	0.16	0.25	10.00	20.41	41.64	84.98	353.91	1473.82
Inner Mongolia	89.00	125.33	176.49	248.52	492.82	977.25	45.00	73.27	119.28	194.21	514.80	1364.61
Qinghai	19.77	24.03	29.22	35.52	52.50	77.59	23.46	40.43	69.69	120.11	356.78	1059.83
Gansu	38.53	47.53	58.63	72.31	110.02	167.39	42.36	64.20	97.29	147.44	338.63	777.76

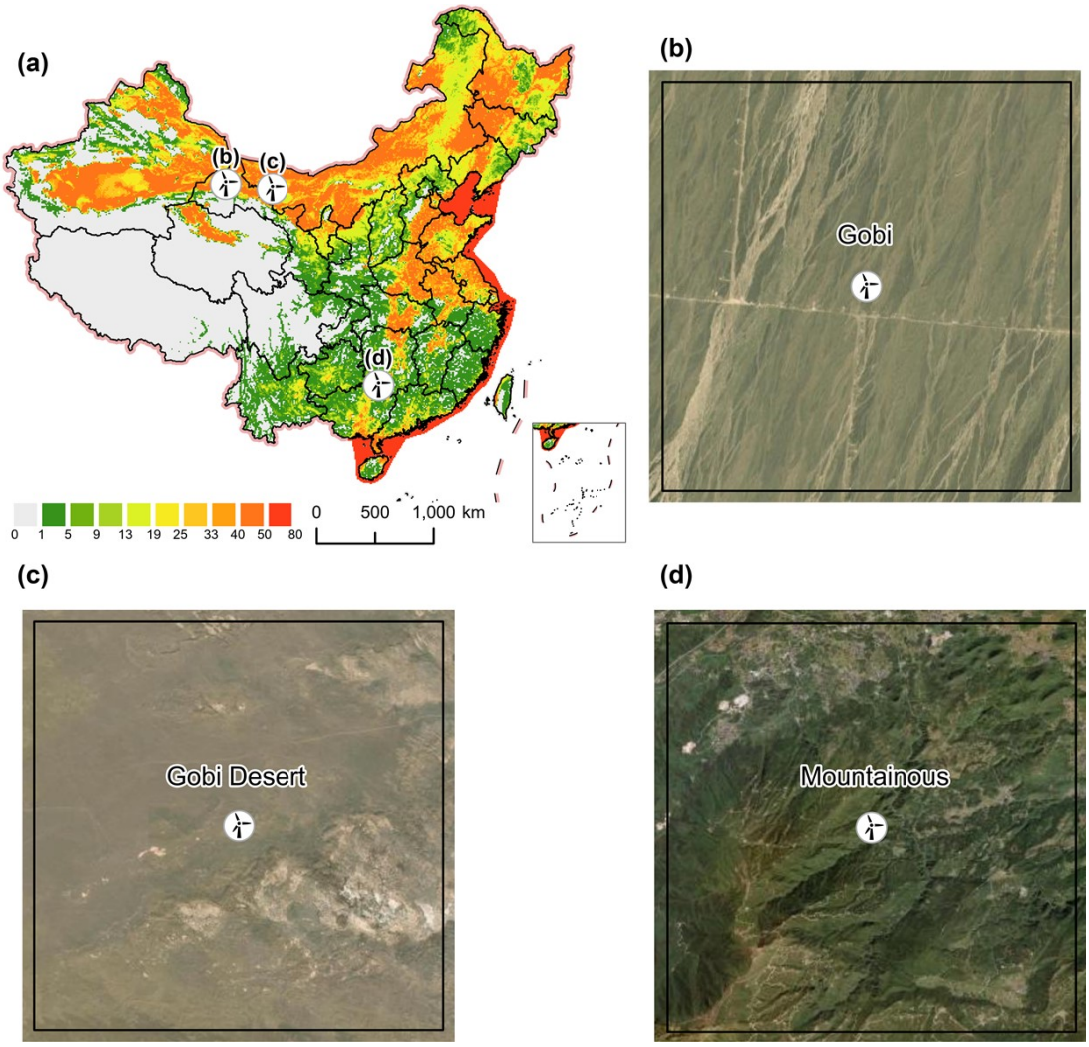
Sichuan	10.00	13.14	17.26	22.67	23.70	23.70	12.00	21.65	39.05	70.44	229.24	745.98
Yunnan	11.03	14.49	19.03	25.00	43.14	74.44	53.93	77.82	112.29	162.04	337.43	702.64
Guangxi	10.76	13.87	17.89	23.07	38.36	63.79	14.90	25.45	43.45	74.19	216.33	630.77
Heilongjiang	16.86	25.82	39.54	60.55	142.03	333.11	8.68	15.79	28.72	52.25	172.95	572.47
Hunan	12.00	14.56	17.66	21.42	31.51	46.37	13.00	22.26	38.10	65.23	191.17	560.28
Guangdong	8.91	11.66	15.27	19.99	34.26	58.72	27.97	42.68	65.12	99.36	231.32	538.55
Henan	27.00	33.14	40.68	49.93	75.23	113.35	25.00	38.05	57.91	88.14	204.18	472.97
Hubei	10.02	12.93	16.70	21.56	35.93	59.88	22.00	33.91	52.27	80.56	191.40	454.71
Jiangxi	7.00	8.62	10.62	13.07	19.83	30.07	24.00	36.26	54.78	82.76	188.89	431.12
Shandong	24.05	30.47	38.59	48.89	78.44	125.86	65.00	85.04	111.25	145.55	249.11	426.37
Anhui	7.41	10.60	15.15	21.67	44.33	90.68	23.04	34.59	51.93	77.96	175.70	396.02
Shaanxi	13.68	17.97	23.60	31.00	53.50	92.32	25.98	38.25	56.31	82.90	179.68	389.45
Hebei	41.23	54.16	71.15	93.46	161.28	278.31	54.00	70.89	93.06	122.16	210.53	362.81
Guizhou	10.80	14.19	18.64	24.48	42.25	72.90	31.00	43.86	62.06	87.81	175.78	351.89
Shanxi	30.00	39.41	51.77	68.01	117.35	143.78	50.00	64.84	84.09	109.05	183.41	308.47
Jiangsu	19.06	23.62	29.29	36.31	55.80	85.77	35.00	47.62	64.79	88.15	163.19	302.10
Jilin	22.00	28.43	36.74	47.47	79.26	132.35	8.00	13.42	22.50	37.73	106.11	298.42
Liaoning	17.08	21.63	27.39	34.67	55.58	89.10	15.93	23.75	35.41	52.79	117.33	260.80
Fujian	9.00	11.82	15.53	20.40	35.21	51.26	5.00	8.73	15.23	26.58	80.96	246.60
Zhejiang	1.49	2.16	3.12	4.52	9.47	19.84	27.62	36.83	49.11	65.48	116.43	207.01
Chongqing	2.68	3.52	4.62	6.07	7.66	7.66	1.02	2.09	4.28	8.76	36.69	153.69
Hainan	0.35	0.61	1.04	1.79	5.26	15.47	2.51	4.36	7.57	13.14	39.59	119.33

Ningxia	17.50	22.99	30.20	39.67	68.46	107.43	32.50	38.87	46.49	55.60	79.54	113.78
Tianjin	3.19	4.20	5.51	7.24	12.50	21.57	5.60	6.97	8.68	10.81	16.75	25.97
Shanghai	0.83	1.09	1.45	1.91	3.33	5.80	10.00	11.17	12.47	13.92	17.35	21.63
Beijing	0.30	0.41	0.56	0.76	1.41	2.61	1.30	1.90	2.79	4.09	8.78	18.85
Offshore**	87.07	223.60	306.39	403.04	697.43	1236.74	-	-	-	-	-	-

Note: *The provincial scenario projections do not include Hong Kong, Macao, and Taiwan; **The photovoltaic installation potential projections do not include offshore areas.

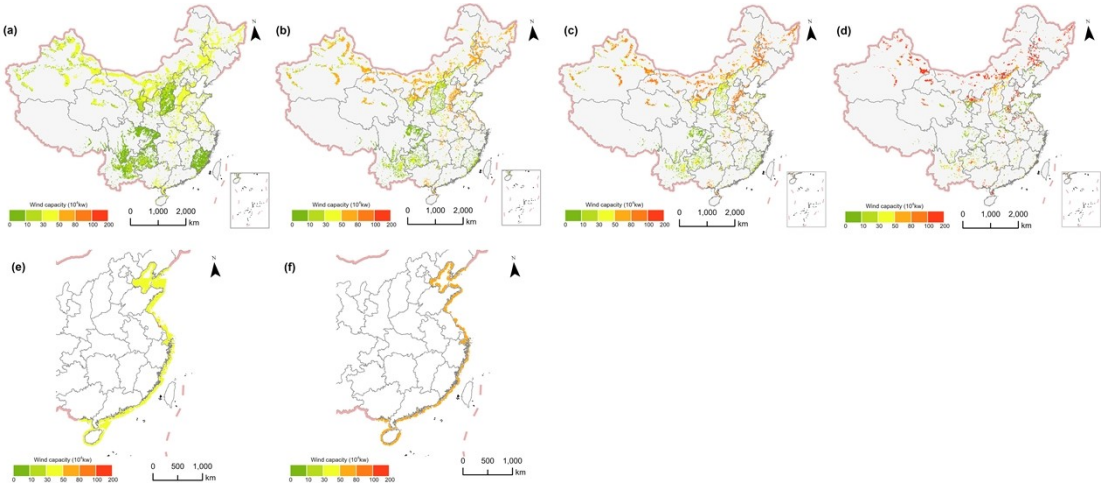
Supplementary Table S11 | Planned installed capacity density of wind power in China (MW/km²)

	2025	**2030**	**2035**	**2040**	**2050**	**2060**
Policy scenario	1.47	1.90	2.17	2.32	2.40	2.65
Low carbon scenario	1.47	2.03	2.34	2.43	2.72	2.87



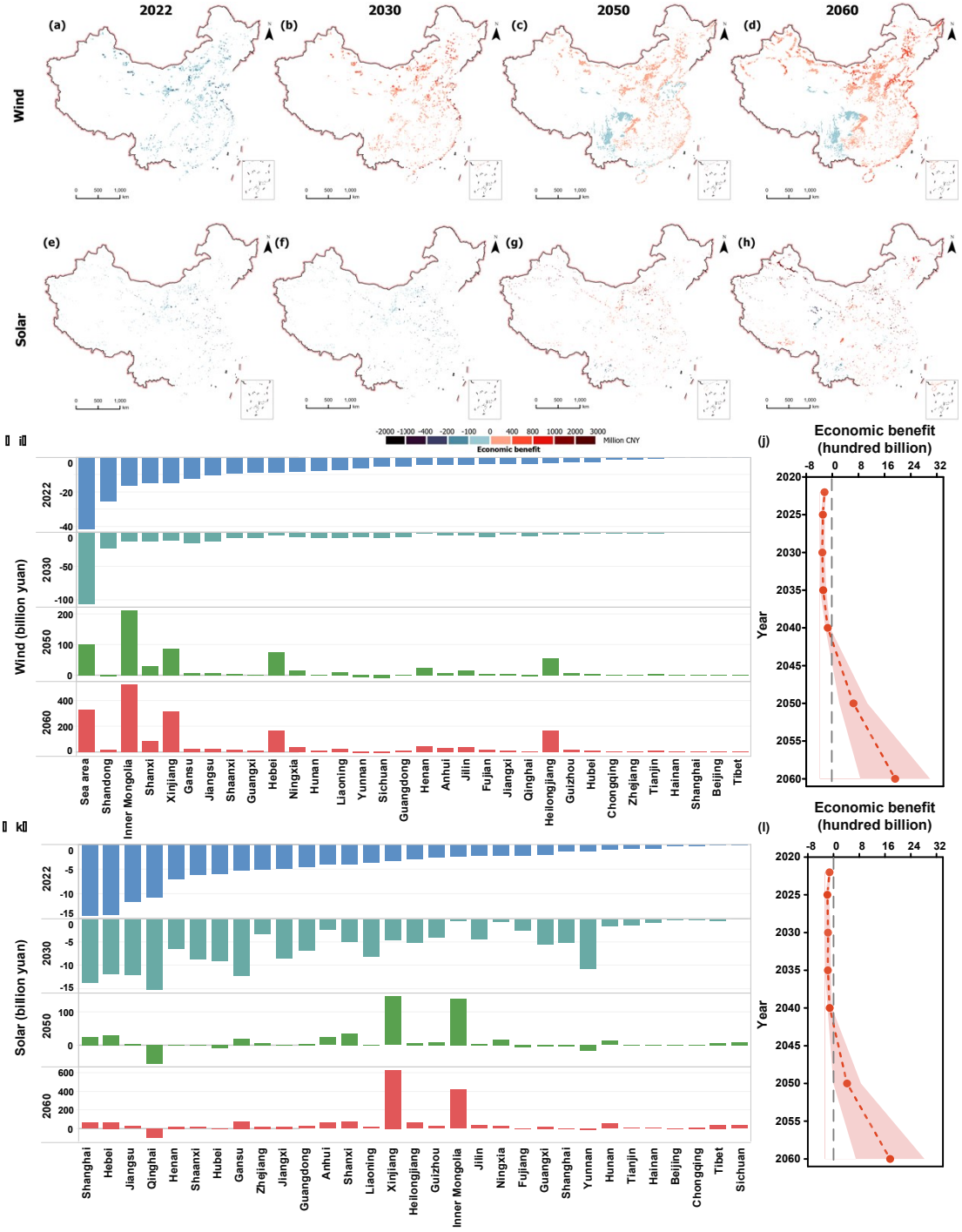
Supplementary Fig.S1 | Site selection for power generation simulating

(a) National distribution and technical potential in China; **(b)** Gansu; **(c)** Inner Mongolia; **(d)** Guangxi.



Supplementary Fig.S2 | Simulated distribution of onshore and offshore wind power installed capacity in China under the low-carbon development scenario for 2060.

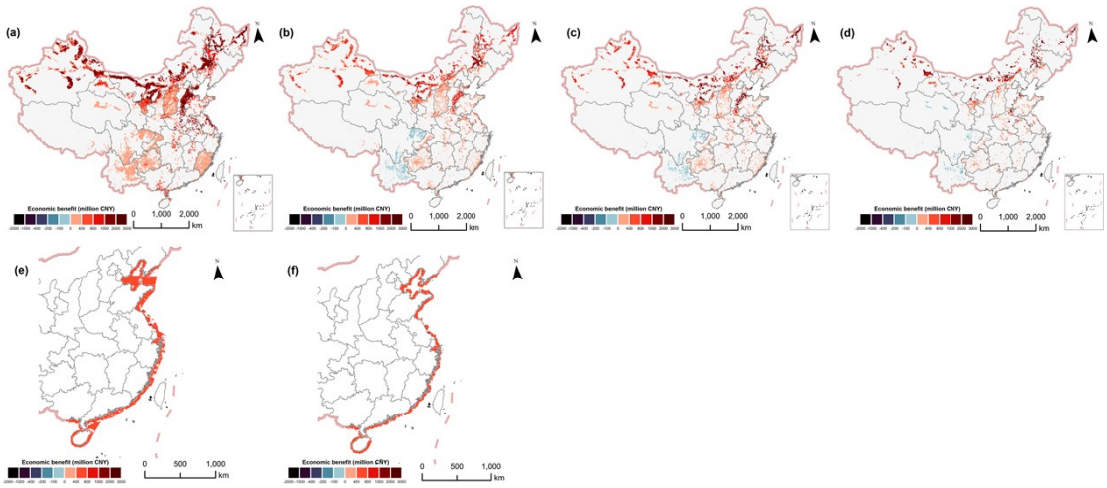
Panels **(a)–(d)** show the planning results for onshore wind power under capacity density assumptions of 5, 8, 10, and 20 MW/km², respectively; **(e)** and **(f)** present the installed capacity distribution for offshore wind power under capacity densities of 5 and 8 MW/km².



Supplementary Fig.S3 | Cost-benefit analysis from 2022 to 2060 under the Policy Scenario.

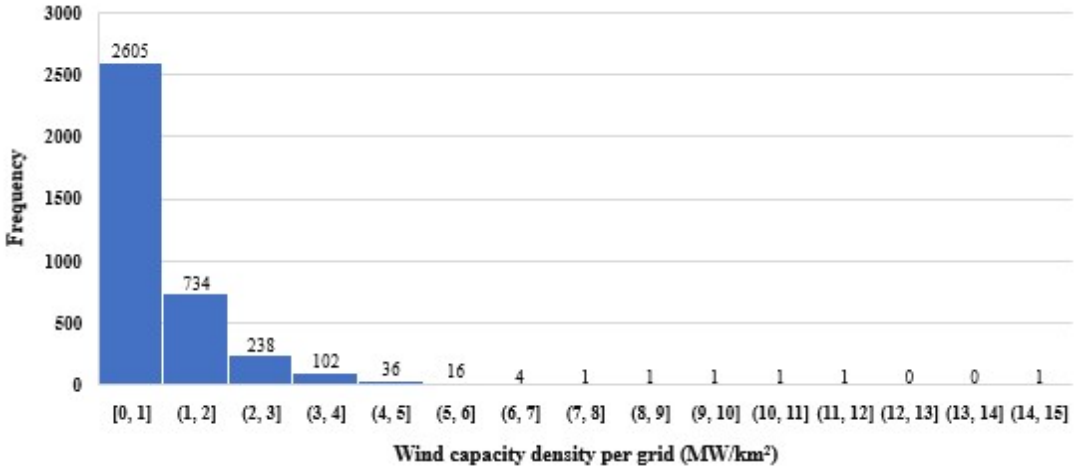
a-h, Cost-benefit for gridded level wind power (**a-d**) and solar photovoltaic (**e-h**). **i-l**, Cost-benefit analysis for provincial wind power (**i**) and solar photovoltaic (**k**). Insets show the corresponding national cost-benefit (**j, l**) from 2022-2060. The pink shaded

area indicates the 95% confidence interval, reflecting the uncertainty of the data. The gray dashed line at the zero scale serves as the division between positive and negative economic benefits, clearly differentiating between gains and losses.



Supplementary Fig.S4 | Projected Revenues of Onshore and Offshore Wind Power under Different Capacity Densities in a 2060 Low-Carbon Scenario.

Panels **(a)–(d)** show the revenue outcomes for onshore wind power under capacity densities of 5, 8, 10, and 20 MW/km², respectively; **(e)** and **(f)** illustrate the revenue distribution for offshore wind power at capacity densities of 5 and 8 MW/km², respectively.



Supplementary Fig.S5 | Frequency statistics of grid capacity density in 2022.

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