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Potential contributions of wind and solar power to China's carbon neutrality

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A R T I C L E I N F O

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A B S T R A C T

China's goal of being carbon-neutral by 2060 requires a green electric power system dominated by renewable energy. However, the potential of wind and solar alone to power China remains unclear, hindering the holistic layout of the energy development plan. Here, after taking temporal matching of supply and demand (60 min), land use, and government policy into account and assuming lossless transmission, we demonstrate that deploying wind and solar capacity of 2495 and 2674 GW, respectively, within flexible and optimized grids can meet ~67% of electricity demands by all society sectors for 2050 (~6.3% curtailment rate), even without other costly power sources or storage. Spatially explicit configurations of the grids are provided simultaneously to support this achievement. The resulting green electricity supply of 10.4 PWh per year help secure China's carbon-neutral goal and reduces 2.08 Mt SO_2 and 1.97 Mt NOx emissions annually. Our findings recommend policymakers accelerate exploiting complementary wind and solar power as the dominant source of energy.

1. Introduction

At the 75th United Nations General Assembly in September 2020, as the world's largest developing country, coal consumer, and carbon emitter, China announced an ambitious and stimulating goal to hit peak carbon emissions before 2030 and achieve carbon neutrality before 2060 (Mallapaty, 2020). This indicates that China aims to pursue efforts to limit the global average temperature increase to 1.5 °C above pre-industrial levels (J. He, J. et al., 2020). The 2060 carbon-neutral goal requires China to build carbon-neutral electric power systems by 2050, because rapid decarbonization of the electric power system is regarded as a prerequisite for many end-use sectors to achieve carbon neutrality (Chen et al., 2021; EFC, 2020; J. He, J. et al., 2020; IEA, 2021). Therein, renewable energy, primarily wind and solar, is anticipated to become the dominant electricity source. Wind and solar energy investments have become increasingly favorable, mainly because wind and solar power generation costs have declined sharply over the past decade(G. He, G. et al., 2020). From 2010 to 2020, the global weighted

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average levelized cost of electricity (LCOE) for solar photovoltaics (PV), onshore wind, and offshore wind fell by 85%, 56%, and 48%, respectively(IREA, 2021). Sustainable green electricity could provide considerable environmental and health benefits by reducing air pollutants and associated premature mortality(Dedoussi et al., 2020; Siler-Evans et al., 2013). If this is achieved, it will largely curb global climate change and promote human well-being around the world.

Despite China government has officially announced to prescribe renewable energy as the dominant source of power generation in the future(CFEAC, 2021), the potential contributions from wind and solar remain unclear. From the supply perspective, compared to traditional dispatchable energy such as coal or nuclear, the generation of wind and solar power is inherently variable and highly dependent on geophysical location, local terrain, and local weather(Liu et al., 2020). This creates significant challenges for current power systems that require a stable and flexible electricity supply (Lu et al., 2016; Veers et al., 2019). Many previous wind and solar resource assessments in China are performed at the site scale(He and Kammen, 2014, 2016; Liu et al., 2019; Xu et al., 2017) or using global meteorological reanalysis datasets(Davidson et al., 2016; Ren et al., 2019; Yang et al., 2019). By contrast, the newly hourly wind and solar data employed here have much higher spatiotemporal resolution and quality (See Methods and ref (Liu et al., 2020)). From the demand perspective, while previous studies have compared total electricity demand to the potential energy provided by wind and solar resources, they do not examine how fluctuations in instantaneous demand affect this balance (Chen et al., 2019; McElroy et al., 2009; Sherman et al., 2020). Unlike many previous studies that relied on artificial historical electricity loads(Davidson et al., 2016), we collected realistic historical hourly electricity loads at the province scale from the relevant agencies in China, reinforcing the reliability of our results (See Methods). To the best of our knowledge, despite there are already some efforts in investigating the possible contributions of solar (Chen et al., 2019) and wind (Davidson et al., 2016; Lu et al., 2016) separately, no studies have explored the potential of fully integrating physically available wind and solar power generations (onshore wind, offshore wind, solar PV) at the grid cell scale into power systems in China with a detailed consideration of temporal matching of supply and demand, land use and government policy.

In this study, we comprehensively considered the spatiotemporal variability of wind and solar power generation, instantaneous electricity demand by all society sectors, land use, government policy, and three development strategies to promote renewable energy: grid connection, technology improvement, and demand response (See Methods). We focus on the year of 2050 here because it is more relevant to the projected timing of the carbon-neutral electric power system. We only integrated wind and solar power into the supply side of the electric power system for five reasons: (i) we primarily focused on the full potential of wind and solar resources to constitute a green and sustainable power system; (ii) to mitigate climate change, renewables (mainly wind and solar) have already been prescribed as the dominant source of power generations officially in China's government policy(CFEAC, 2021); (iii) China's Energy Law requires the integration of wind and solar into the power system as a priority (NEA, 2020); (iv) in contrast to other power sources, wind and solar power generations are anticipated to be cheapest power source soon(IREA, 2021) and the marginal cost of wind and solar is near-zero(Blazquez et al., 2018); (v) without good understandings on the potential of wind and solar alone to power China, it will hinder the holistic layout of the energy development plan. This paper is structured as follows: Firstly, we performed the full assessments of physically available wind and solar resources and power generations at the grid cell scale. Rather than using global reanalysis climate datasets, we assessed available wind and solar resources at the grid cell scale between 2007 and 2014, based on start-of-art and validated wind and solar data with high spatial (15 km × 15 km) and temporal (60 min) resolution over China (**Figure S1**). We also projected future electricity loads based on collected realistic load for each province. Secondly, to maximize the utilization of wind and solar resources and minimize wind and solar electricity curtailments, we first applied mixed-integer linear programming and the CPLEX optimizer(IBM, 2017) to optimize the spatial configuration of the grid (plant location and installed capacity) at the provincial scale. We then considered three additional technical development strategies (i.e., grid connection, technology improvement, and demand response) to promote wind and solar utilization, resulting 8 scenarios in total. Finally, we evaluated economic costs and environmental benefits of the identified scenarios that could achieve high wind and solar penetrations in electric power systems.

2. Methods

2.1. Wind energy assessment

Wind energy was assessed using the wind profile data from the National Climate centre (NCC), China Meteorological Administration (CMA), with a horizontal resolution of 15 km × 15 km, a vertical resolution of 10 m, and a time period of 1995–2016. The wind profile data was produced using a mesoscale numerical simulation model (e.g., Weather Research and Forecasting Model) and by assimilating observational data from Fengyun Meteorological Satellites, approximately 2400 ground stations, and 169 sounding stations. Independent validation against 400 wind masts at heights of 70–120 m suggested that this CMA–NCC wind profile data had much higher accuracy and quality in China than commonly used global reanalysis datasets, such as MERRA-2 and ERA5(CMA, 2018). Taking the regional dependence of wind turbine suitability into account, onshore and offshore wind power at 100 m hub heights were calculated using four onshore turbine power curves (GW131–2.2, GW121–2.0, GW140–3.4, and GW109–2.5) and three offshore turbine power curves (GW171–6.45, GW154–6.7, and GW168–6.45), respectively. Wind turbine details have been added to the Supplementary Information. The actual wind power equals the theoretical wind power multiplied by a system efficiency coefficient that usually ranges between 20% and 30%(Zhu, 2019); we used the average value (25%). The wind capacity factor (CF) was calculated as the ratio of actual electricity generation over a year to the maximum possible electricity generation over that year.

Taking constraints of land use, government policy, and others into account, we also identify areas suitable for both onshore and offshore turbine sitting. More details are shown in supplementary information. Then, we estimated that onshore wind turbine spacing generally allowed roughly 5 × 10 rotor diameter per turbine, and offshore wind turbine spacing was a maximum of approximately 5 MW/km^2. Overly dense turbine spacing can cause turbulent wake effects on downwind turbines and decrease the total wind power output(Lundquist et al., 2019). **Table S1** displays physically available wind installed capacity.

2.2. Solar energy assessment

Solar energy was assessed using the solar radiation data from the China Academy of Sciences (CAS), with a spatial resolution of 5 × 5 km and a time period of 2007–2014. To produce this solar radiation dataset, an artificial neural network (ANN)-based algorithm was built by combining Moderate Resolution Imaging Spectroradiometer (MODIS) cloud products and Multifunctional Transport Satellite (MTSAT) imagery data to estimate cloud parameters (cloud mask, effective particle radius, and liquid/ice water path). Then, the estimated cloud parameters and other information (such as aerosols, ozone, and precipitable water) were entered into a parameterization model to calculate horizontal solar radiation(Tang et al., 2016). Independent validation against both experimental data and operational solar station data in China found that the accuracy and quality of these data were demonstrated to be comparable to or higher than two commonly used solar radiation products (GLASS and ISCCP-FD)(Tang et al., 2016).

Following previous work(Chen et al., 2019; Yan et al., 2019), the solar photovoltaic model used in this study considered the influence of ambient temperature, wind speed, optimum tilt, azimuth angel, etc., on power output efficiency. Specifically, the hourly solar photovoltaic power output was calculated using the model modified from Duffie and Bechman(Campana et al., 2015) as follows:

$$P_{pv} = \eta_{PV,STC}\left[1+\frac{\mu}{\eta_{PV,STC}}(T_a - T_{STC}) + \frac{\mu}{\eta_{PV,STC}}\frac{9.5}{5.7+3.8\nu}\frac{(NOCT-20)}{800}(1-\eta_{PV,STC})\times G_{g,t}\right]\frac{G_{g,t}}{R_{STC}}\times A_{PV}\times K\times\alpha, \quad (1)$$

where P_{pv} is the power output from the PV system (W); $\eta_{PV,STC}$ is the efficiency of the PV module under standard test conditions (STC) (10%); μ is the temperature coefficient of the output power (~0.043%/ °C); T_a is the ambient temperature (°C); T_{STC} is the standard test condition temperature (25 °C); ν is the wind speed (m/s); NOCT is the nominal operating cell temperature (45 °C); A_{PV} is the PV array area related to the PV array power peak (m^2); $G_{g,t}$ is the global solar radiation on the tilted surface (W/m^2); R_{STC} is the solar light intensity under standard test conditions, and its value is 1000 W/m^2; and K is the ratio of the optimal slope total irradiance to the global horizontal irradiance. The optimal slope total irradiance at 2461 ground stations in China was calculated using the Klein–Hay model(Hay, 1979; Klein, 1977), and the K at the 2461 ground stations were spatially interpolated to obtain values at each pixel. The system efficiency coefficient (α) takes the aging effect, shading, packing factor, ground reflectance loss, etc., into account. The value was set as 0.8 according to the China PV industry development roadmap of 2018(CCID, 2018). The 3 hourly ambient temperature data was retrieved from ERA-interim reanalysis(Dee et al., 2011) and interpolated to an hourly scale. The hourly wind speed was obtained from NCC, CMA. The solar energy data were bilinearly gridded to match the spatial resolution of the wind energy data. Similar to wind CF, the solar CF was calculated as the ratio of actual electricity generation over a year to the maximum possible electricity generation over that year.

Similar to wind power, taking constraints of land use, government policy, and others into account, we also identify areas suitable for PV panel sitting.

2.3. Electricity demand

The hourly electricity load data by all society sectors were obtained from China's State Grid and China Southern Power Grid. Unlike the modeling load data of some provinces discussed in previous studies (Davidson et al., 2016), we collected realistic electricity load data for each province, but only for the year 2017. The electricity load projection is achieved by applying an annual increasing rate to the realistic historical load for each province. The increasing rate was retrieved from the report from the China Energy Research Institute that comprehensively considers factors contributing to the load projection, including economic growth rate, carbon emissions, population size, technology costs, and environment protection (Table S6) (ERI et al., 2017).

2.4. Power grids classification in mainland China

In general, mainland China's power grids can be classified into two levels: 31 provincial grids and 7 regional grids. At the provincial grid scale, note that Inner Mongolia is divided into two sub-regions: West Inner Mongolia and East Inner Mongolia. Hebei, Beijing, Tianjin, and Tangshan are divided into Jing-Jin-Tang and Jinan. The 31 provincial grids are integrated into 7 regional power grids, including the Southwest Grid, Northwest Grid, North Grid, Northeast Grid, Central Grid, South Grid, and East Grid (Inner Mongolia is divided into two sub-regions that belong to the North and Northeast grids, respectively). Specific classifications are described in **Table S5**.

2.5. Spatial optimization of wind and solar configurations

Based on the mixed-integer linear programming in CPLEX and MATLAB, we held electricity demand and technical available capacity as constraints and assumed perfect transmission between or within grids (i.e., no losses of transmission electricity), and optimized the wind and solar power system configurations in each grid (plant location and installed capacity). The objective was to minimize the sum of the positive and negative residual demand, i.e., the difference between total electricity demand (i.e., electricity load) and total wind and solar generation. This is because positive residual demand (demand>generation) leads to costs for dispatchable backup capacity, backup energy, and possibly coal. Negative residual demand (generation>demand) results in high costs in energy storage or economic losses due to curtailments. Following previous studies(Shaner et al., 2018; Zappa and van den Broek, 2018), we treated the grid as a copper plate model, i.e., no losses or constraints on the electricity transmission, yielding a best-case scenario to exploit the benefits of wind and solar resources. The size of the grid (i.e., copper plate) depends on the scenario employed afterward.

Mathematically, the objective function and associated constraints was formulated as:

$$\begin{aligned} &min\sum_t\sum_i\sum_x\left(CFw_{t,i,x}\cdot Qw_{i,x} + CFs_{t,i,x}\cdot Qs_{i,x}\right) - \sum_i d_{t,i}, \\ &\text{such that}\left\{\begin{array}{c} 0 \le Qw_{(i,x)} \le Qw^m_{(i,x)} \\ 0 \le Qs_{(i,x)} \le Q^m_{(i,x)} \end{array}\right\}, \end{aligned} \quad (2)$$

where i is the power grid, t is the hourly time step, x is the grid cell, CFw is the wind capacity factor, Qw is the installed wind capacity, CFs is the solar capacity factor, Qs is the installed solar capacity, d is the electricity demand, Qw^{max} is the maximum installed wind capacity, and Qs^{max} is the maximum solar capacity factor. Note that as we aimed to explore the full potential of spatially optimizing solar and wind capacity, and as the information of existing or planned wind and solar farms was not publicly available, we optimized the grid without being constrained by the current system.

2.6. Penetration rate and curtailment rate

Penetration rate is the ratio of total electricity that meets instantaneous demands to total electricity demands. Curtailment rate is the ratio of curtailed electricity to total power generation which includes the curtailed electricity.

2.7. Wind and solar energy development strategies

We included three strategies (i.e., grid connection, technology improvement, and demand response) to promote wind and solar energy development. We assessed both the independent effect of each strategy and the combined effect of several strategies together. As a result, there were eight scenarios in total: Scenario I, the base scenario without any development strategy; Scenario II, grid connection; Scenario III, technology improvement; Scenario IV, demand response; Scenario V, grid connection + technology improvement; Scenario VI, grid connection + demand response; Scenario VII: technology improvement + demand response; and Scenario VIII: grid connection + technology improvement + demand response.

a Grid connection

We assumed that each regional grid allowed flexible electricity exchange internally, i.e., provincial grids are interconnected in each regional grid. The cost of electricity transmission was set as 0.1 CNY/kWh(Davidson et al., 2016).

a Technology improvement

For wind energy, the turbine hub heights were raised from 100 to 140 m. Thus, more wind energy was generated, and we assessed the increase in produced wind energy. The system costs increased by approximately 10% after consulting with the largest wind turbine manufacturer in China.

For solar energy, we considered the improvement in solar cell efficiency and the replacement of fixed systems with solar tracking systems. In this study, we assumed solar power generation increased by approximately 30%, and system costs increased by approximately 20% (Lamoureux et al., 2015).

a Demand response

We managed the hourly electricity demand to minimize the residual demand, i.e., increased demand when the net load (generation minus load) was positive, decreased demand when the net load was negative. Currently, several provinces, such as Shandong, Zhejiang, Jiangsu, and Henan, have tried to adopt the demand response strategy at several small grids. In general, they allow demand ranges from −5% to 5%. We assumed that the demand could range from −10% to 10% in 2050. The cost equaled 1.5 times that of coal feed-in tariff (DRC, 2019).

2.8. Economic cost assessment

Economic costs consisted of power generation and electricity transmission costs. For power generation cost, we assess it using Levelized cost of electricity (LCOE). LCOE measures the average costs to build and operate a power generating plant over its lifetime. LCOE is also commonly used to compare electricity costs from different energy technologies on a consistent basis. In this study, we comprehensively take value-added tax (VAT), sales tax and extra charges (SALE), operation and maintenance costs (OMC) and annual actual income tax (INC) into account to calculate LCOE. See more details in supplementary information.

2.9. Environmental benefits assessment

Unlike coal, renewable wind and solar power barely produce CO_2, SO_2, and NO_X emissions. Therefore, we calculated the compensating pollution reductions according to the emission factors. In general, compared to coal, 1 kWh of electricity from renewable wind and solar energy can offset 841 g CO_2, 0.2 g SO_2, and 0.19 g NO_X(CEC, 2019).

2.10. Limitations

Before showing our results, we first note several limitations in our analysis: (1) Despite we have clearly established the reason why we just focus on the potential of wind and solar alone to power China, we acknowledge additional modeling of storage, hydropower, nuclear and other power sources would provide other valuable insights. For instance, to address the issue of building a 100% renewable energy system for China, combining other power sources or storage into wind and solar is necessary(Lu et al., 2021); (2) power system operation is modelled in a perfect way (i.e., we assume the grid as a copper plate). This might overlook possible electricity transmission limitations but allow yields a possible scenario for achieving maximum use of benefits of geophysical-complementary wind and solar resources in China. Sufficient power transmission lines with high-voltage and high-capacity are required. (3) We do not forecast possible changes in the shape of demand profiles due to the huge uncertainties. (4) We have taken critical government policies that constrain wind and solar plant constructions into account (See Supporting Information), but the future analysis should update the latest policy. These issues should be considered in future work.

3. Results

3.1. China's current inflexible power system impedes high penetration rates of wind and solar

First, for each province, we investigated the expected fraction of its electricity demand that it could meet by utilizing its own wind and solar power in 2050, i.e., no imported electricity and no other power sources or storage. This is because flexible electricity exchange is quite limited in China's power system, and grids are generally operated on a provincial scale, even though the ambitious goal of carbon neutrality applies to China as a whole.

Physical resource assessment showed that wind and solar power potential is rich in the northwestern provinces (>3000 TWh yr^{-1}) but much smaller in the east and south (<800 TWh yr^{-1}), and the potential of solar energy is higher than that of wind in most provinces (Fig. 1a). However, the best resources are far from demand centers (Fig. 1b). The projected electricity demand in 2050 is higher in the east and south (>1000 TWh yr^{-1}) but smaller in the northwest (<600 TWh yr^{-1}) (CNREC, 2019). In total, China's physical wind and solar potential reaches up to 77.9 PWh yr^{-1}, five times the projected demand of 15.4 PWh yr^{-1} for 2050. Our modeling results showed that wind and solar penetration rates could be higher than 80% in northwestern provinces with rich wind and solar resources and low demands, including Tibet, Xinjiang, Qinghai, Gansu, and Inner Mongolia (Fig. 1c). However, wind and solar penetration rates would be lower than 50% in many coastal and central provinces that have poor wind and solar resources and high demands. For instance, Chongqing's wind and solar penetration rate is modelled to be only approximately 5.1%, despite the installation of all physically available wind and solar capacity. This contrasting pattern indicates the spatial imbalance between renewable energy supply and power demand in China. The nationally averaged wind and solar penetration rate is projected to be approximately 51.5%, and the total generated electricity is approximately 8.5 PWh yr^{-1} for 2050. This suggests that the current system is unlikely to achieve the wind and solar penetration rate (~60%).

3.2. Sensitivity of wind and solar penetration rate to development strategies

We then considered three development strategies to promote wind and solar utilization and quantified their potential impacts on raising the wind and solar penetration rate. Specifically, grid connection allows flexible electricity exchange within each regional grid; technology improvements enable the utilization of more wind and solar resources by raising hub heights to 140 m and improving solar cell efficiency and solar tracking systems (leading to a ~30% increment in energy); and managing demand responses to control the electricity load and minimize residual demand with a maximum variation ranging from −10% to 10%. We assessed the influence of each strategy, as well as the combined

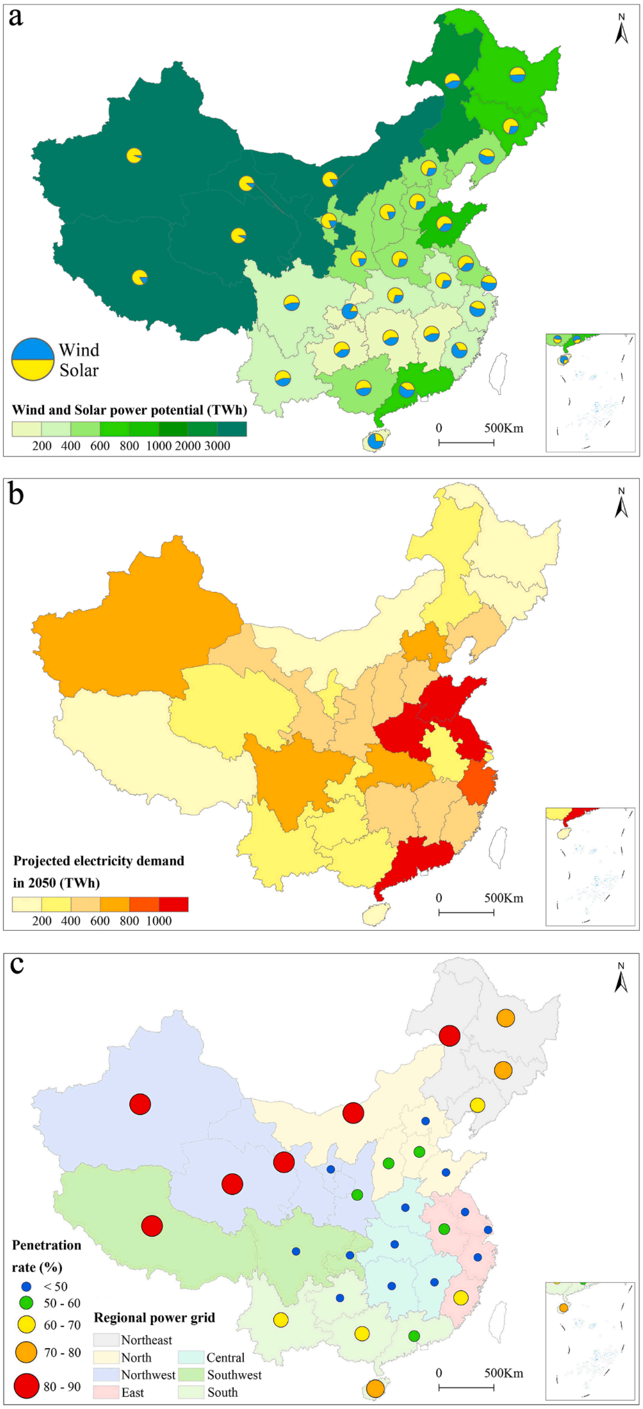

Fig.. 1. The wind and solar power potential, projected electricity demands for 2050, and simulated penetration rates across mainland China. (A) The average yearly estimate of wind power potential at the 100m hub height and solar power potential for each provincial grid using the high-resolution weather data and power-modeling algorithms for 2007–2014. Areas unsuitable for power plant siting were excluded from the analyses. The pie chart represents the respective share of wind and solar. Note that offshore wind power potential is already integrated into the relevant province. (B) Projected electricity demand for 2050 for each provincial grid. (C) Simulated penetration rates of wind and solar for 2050 for each provincial grid. The seven regional grids are indicated by different colors (North Grid, East Grid, Central Grid, Northeast Grid, Northwest Grid, Southwest Grid, and South Grid). The size of each circle corresponds to the five levels (<50%, 50–60%, 60–70%, 70–80%, and >80%) of penetration rate.

effects of multiple strategies utilized together, resulting in eight total scenarios (See Methods).

Our results showed that grid connection was the most promising strategy, as it increased rates of wind and solar penetration across all grids (Fig. 2). For example, grid connection alone increased the wind and solar penetration rates in the Southwest and North grids from 32.5% to 81.6% and 49.8% to 82.6%, respectively (Fig. 2b and 2d). This suggests that aggregating wind and solar power over large areas could reduce power variability(MacDonald et al., 2016; Shaner et al., 2018) and significantly enhance wind and solar penetration rates. Most importantly, with this change, the nationally averaged wind and solar penetration rate reached up to 67% (Fig. 2h), highlighting the remarkable potential of grid connection for improving wind and solar penetration. The importance of grid connection is further confirmed by the fact that >60% wind and solar penetration can only be met in scenarios that incorporate grid connection. Additionally, curtailment rates remained low in these scenarios, with a national average of 6.3% (Table S2). We realize that the current curtailment rates slightly exceeded the value included in the policy plan (<5%)(Ye et al., 2018), but other flexible power sources or power storage options could potentially reduce this further.

In contrast, scenarios that do not include grid connection produced little variation in the wind and solar penetration rate (Fig. 2). Technology improvement alone did not help and even decreased wind and solar penetration rates slightly in several grids, such as in the Southwest Grid (-8.4%). This was due to the increased mismatch between supply and demand (Figure S2). Likewise, managing demand response also had a minimal impact on wind and solar penetration rates, only causing an average increase of 2%. This suggested that increasing the flexibility of electricity load finitely may not be very effective in combination with highly variable wind and solar power generation.

Interestingly, in addition to the favorable increase in wind and solar penetration, grid connection also altered optimal wind and solar configurations compared to the base scenario (Fig. 3). Tremendous wind capacity could be newly installed in areas with large and stable wind power generation, such as the North, Northwest, and Southeast grids (Figures S1 and S3). Variations in solar capacity were widespread across grids and were geophysically dispersed. In the North Grid, for example, approximately 474.4 GW of wind capacity could be newly installed in West Inner Mongolia, increasing its wind capacity by approximately 26 times compared to its capacity in the base scenario (~18.3 GW). To accomplish this, almost all solar capacity would need to be removed from Beijing, Tianjin, Hebei, Shanxi, and Shandong, and approximately half would have to be re-located (~290 GW) to West Inner Mongolia. In this case, rich wind resources in West Inner Mongolia could be maximally utilized and replace solar power. The resulting total wind and solar capacity across all regional grids increased by 891.4 GW (1604.1 to 2495.5 GW) and decreased by 99.3 GW (2773.4 to 2674.1 GW), respectively. Low year-to-year variability of installed wind and solar capacity confirms that these spatial configurations are robust to interannual climate variations (Figure S4).

3.3. Wind and solar has the potential to secure the carbon-neutral goal embodying tremendous environmental benefits

Next, we examined the generated green electricity, economic costs, and environmental benefits of the four identified scenarios that could achieve high wind and solar penetration (>60%) (Table 1). The economic costs included power generation (measured by LCOE) and electricity transmission costs (See Methods and Supporting Information). It is anticipated that wind and solar power generation will be the cheapest power source soon. Based on estimated wind and solar costs , we compared the costs for four scenarios. We found the grid connection + technology improvement scenario had the lowest total and average costs (3.55 trillion CNY and 0.33 CNY/kWh) and highest investment returns (i.e., meeting 1% of the total electricity demand requires 53.4 billion

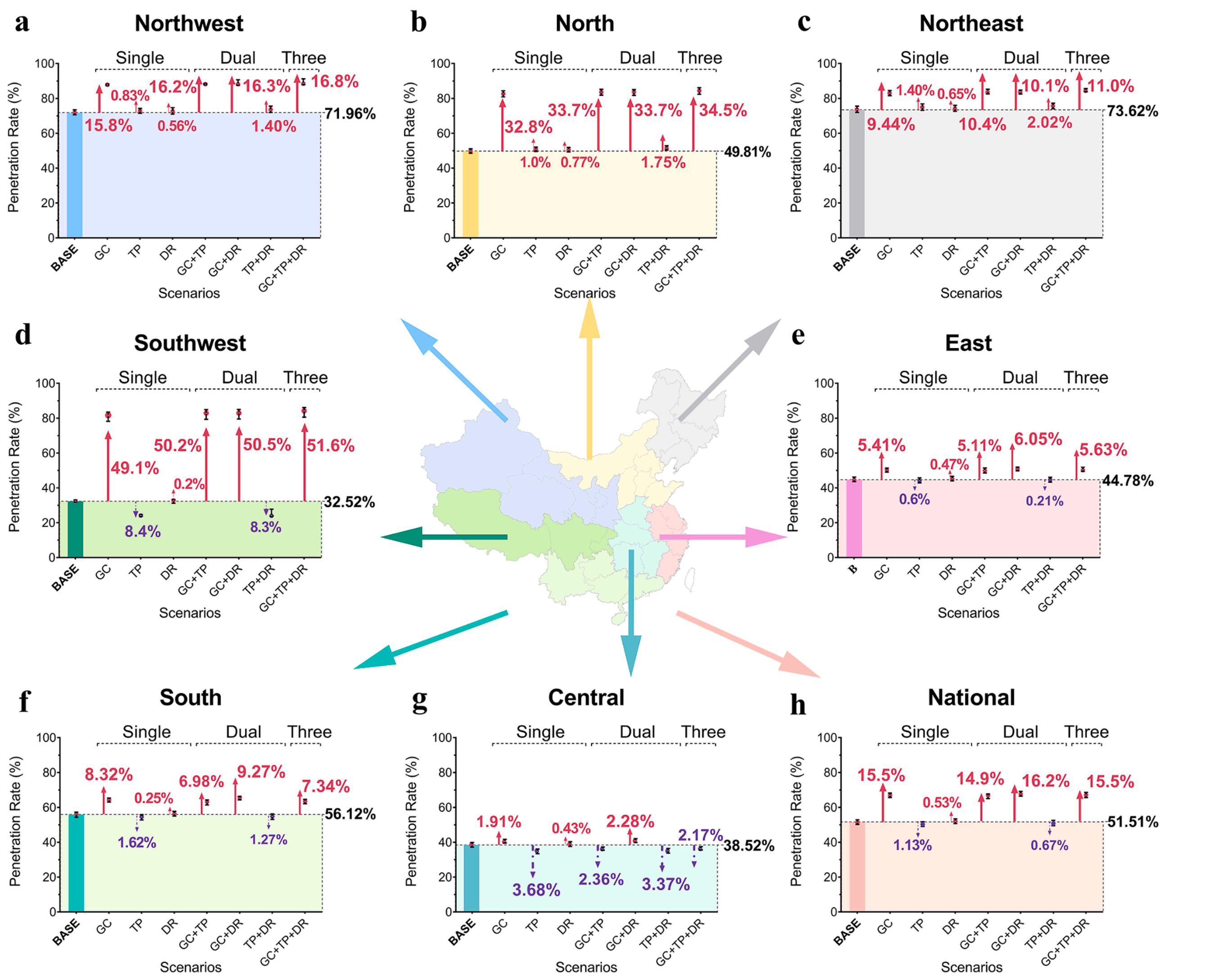

Fig.. 2. Changes in the wind and solar penetration rate as a result of three development strategies. The seven regional grids are labeled as follows: (A) Northwest Grid, (B) North Grid, (C) Northeast Grid, (D) Southwest Grid, (E) East Grid, (F) South Grid, (G) Central Grid. National average results are shown in panel (H). Eight scenarios are included as follows: B, base scenario without any development strategy; GC, grid connection; TP, technology improvement; DR, demand response; GC + TP, grid connection + technology improvement; GC + DR, grid connection + demand response; TP + DR, technology improvement + demand response; GC + TP + DR, grid connection + technology improvement + demand response. The colored bar and shaded area indicate average wind and solar penetration at the regional grid level in the base scenario without any development strategy. In each panel, the only bar shows the baseline value (i.e. the base scenario without any development strategy); arrows indicate the direction and size of changes in penetration rates caused by different development strategies, compared to the base scenario; error bars indicate the year-to-year variability (standard deviation) in penetration rates.

CNY), turning out to be the most cost-optimal scenario. In terms of climate and environmental benefits, we assessed carbon emission mitigation and reductions in air pollution (See Methods). To limit atmospheric warming below 1.5 °C, China's wind and solar power generation might need to reach approximately 5.4–9.7 PWh by 2050(CMA, 2018; Cui et al., 2020; G. He, J. et al., 2020). This would result in a reduction of 4.54–8.15 Gt of emitted CO_2 per year. Our results suggested that all four of the scenarios with grid connection could provide >10 PWh of green electricity supply, fulfilling this requirement. Of the four scenarios, the grid connection + demand response scenario produced the largest amount of green electricity, at 10.39 PWh. In comparison with coal, this would cause reductions in other pollutants as well, reducing SO_2 and NO_x emissions by 2.22 and 2.11 Mt per year, respectively, and are anticipated to prevent a great number of early deaths(Dedoussi et al., 2020).

4. Discussion and conclusion

In this study, we demonstrated that China's physically available wind and solar resources have a strong foundation for building a green and sustainable energy system (~5 times the predicted 2050's electricity demand). Taking temporal matching of supply and demand, land use, and government policy into account, deploying wind and solar capacity of 2495 and 2674 GW, respectively, could lead to a green and sustainable power system dominated by variable wind and solar energy (~67%) by 2050, even without other power sources or storage. Importantly, the nationally averaged curtailment rate of generated electricity could be limited to 6.3%. The resulting green electricity would help China to achieve its 2060 carbon-neutral goal and could generate substantial environmental and health benefits.

We picked out a particularly efficient wind and solar development strategy in China: grid connection. Instead of dispatchable energy, storage, and backup capacity, our results shed light on the remarkable role of grid connection over China in dealing with the challenge of

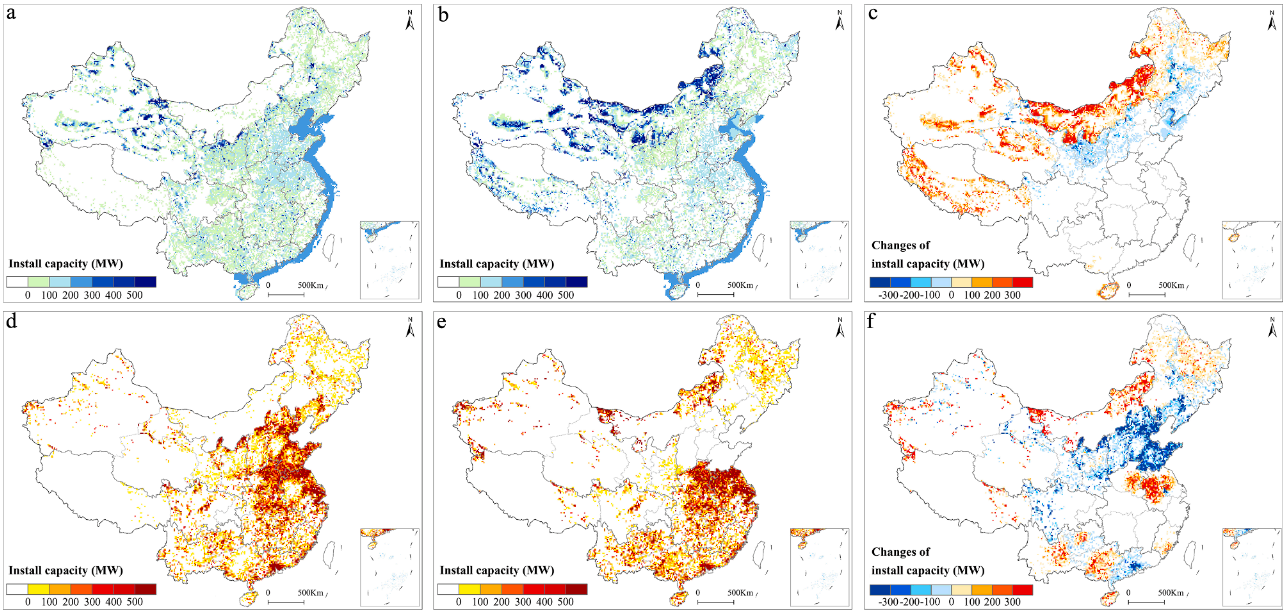

Fig.. 3. Spatial configurations of wind and solar installed capacity obtained with different scenarios. The mean installed capacity for (A) wind and (D) solar per grid cell in the base scenario (i.e., the scenario without grid connection, technology improvement, or demand response) is shown. The mean installed capacity for (B) wind and (E) solar per grid cell in the grid connection scenario is shown. The differences in mean installed capacity for (C) wind and (F) solar between the base scenario and the grid connection scenario are also shown. Only data from mainland China are shown.

Table 1

Economic costs and climate and environmental benefits of green electricity. Four scenarios where wind and solar power generation provided >60% of electricity demand for 2050: GC, grid connection; GC + TP, grid connection + technology improvement; GC + DR, grid connection + demand response; GC + TP + DR, grid connection + technology improvement + demand response. The total economic costs and average economic cost per kWh are shown. Estimated climate and environmental benefits include reductions of CO_2, SO_2, and NO_X per year, compared to coal.

Scenario	Total electricity generation consumed by the demand (PWh)	Penetration rate (%)	Total economic cost of the electricity system (trillion CNY)	Average economic cost of the electricity system (CNY/kWh)	CO_2 emission reduction (Gt yr^{-1})	SO_2 emission reduction (Mt yr^{-1})	NO_X emission reduction (Mt yr^{-1})
GC	10.29	67.01	4.12	0.37	8.65	2.06	1.95
GC+TP	10.20	66.42	3.55	0.33	8.58	2.04	1.94
GC+DR........	10.39	67.75	5.21	0.47	8.74	2.08	1.97
GC+TP+DR........	10.27	66.97	4.38	0.40	8.64	2.05	1.95

integrating highly variable renewable energy into the power system. The variability of wind and solar resources aggregated over large areas is lower(Liu et al., 2020), and the spatial-temporal imbalance between renewable supply and power demands can be alleviated. Experiences from two frontrunners in the energy transitions in Europe, i.e., Denmark (DEA, 2017) and Germany(Lund et al., 2015), also support the important role of grid connection. Patrick and Audun also found inter-regional grid connection can greatly help build a zero-carbon electricity system in the US and even reduce system cost(Brown and Botterud, 2021). Furthermore, as grid connection maximizes the utilization of wind and solar resources, the optimal wind and solar configurations are always centralized in areas with rich resources and cheap costs. As there is still significant room for wind and solar development globally, we suggest that it is best to frame future wind and solar development roadmaps over large spatial extents. We strongly recommend policymakers to unify coordination schemes across grids and even across countries.

Wind and solar power are the most popular green energy alternatives for fossil fuels, but they present distinctive advantages and could compete in the future. On the technical side, compared to solar power, wind power generally has a higher capacity factor and could still provide electricity during nights or cloudy conditions (IEA, 2016; Liu et al., 2020). On the economic side, the future evolution of solar and wind power costs could be different and affect their respective contributions to the carbon-neutral target. The cheapest power source is most cost-competitive. However, the accurate prediction of costs is always challenging. For instance, the actual wind energy cost reductions are far greater than that predicted by global experts in 2015 (Wiser et al., 2021). The learning rate is a widely used method to project cost evolutions (Arrow, 1962). It is reported that a higher learning rate would lower projected costs of wind and solar power in China (Tu et al., 2019, 2020). A more comprehensive analysis incorporating up-to-date learning rates could infer future wind and solar power costs better and thus promote the achievement of green energy transition in China. In addition, the speed and scale of wind and solar power developments can be enhanced or impeded by government economic policies (Duan et al., 2021). For instance, the green finance policies, such as carbon pricing, tradable green certificate and green credit, can provide economic incentives, lower costs of the renewable energy power, and improve the profitability of projects (Hafner et al., 2020; He et al., 2019; Tu et al., 2021). It is anticipated that implementation of these green finance policies could strongly reduce the LCOE of offshore wind power and solar power (Sherman et al., 2020; Tu et al., 2020), accelerate the coal-phase out (Mo et al., 2021), and thus accelerate green energy transition in China. Once these policies are well implemented nationally, future analyses accounting for these policies could improve the projection of future wind and solar development roadmap.

In 2050, China's electricity consumption is predicted to account for approximately one-quarter of the global electricity(BloombergNEF, 2019; IEA, 2020). That means the "green" transition of China's power system is indispensable to global carbon neutrality. Our findings demonstrate a reliable pathway for China to achieve 67% reliance on wind and solar electricity without other costly power sources or storage. Consequently, we strongly recommend China to accelerate the "green" transition of power systems by prescribing complementary wind and solar as the dominant source of energy. Given China's current coal-heavy power system, it also essential to accelerate coal phase-out. Meanwhile, we also underscore the need for other power sources or cost-affordable energy storage to fill the remaining residual demands and to ensure power system balance. Further efforts are needed to determine the optimal strategic combinations of all renewable power sources and/or storage to build a sustainable energy system with near-zero carbon emissions in China.

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Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Supplementary materials

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