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Cost Increments of Electricity Supply to Achieve Carbon Neutrality in China

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ABSTRACT

The Chinese government has set long-term carbon neutrality and renewable energy (RE) development goals for the power sector. Despite a precipitous decline in the costs of RE technologies, the external costs of renewable intermittency and the massive investments in new RE capacities needed to achieve carbon neutrality would drive electricity costs up. Here, we develop a power system expansion model to comprehensively evaluate changes in the costs of electricity supply over a 30-year transition to carbon neutrality, including the effects on the costs of various factors. RE supply curves across China, operating security constraints, and characteristics of various generation units are modelled in detail to assess the cost variations as accurately as possible. According to our results, approximately 5.5 TW of wind and solar photovoltaic capacities would be required to achieve carbon neutrality in the power system by 2050. The electricity supply costs would increase 21.5%, or 10.4 CNY¢/kWh (1.51 USD¢/kWh), which equates to a rise in the effective marginal price of carbon to 1082.6 CNY/t (157.0 USD/t) in 2050. The major cost increments would result from substantial investments in the new RE capacities, flexible generation resources, and network expansion that would be required to achieve carbon neutrality.

1 Introduction

During the 75th UN General Assembly, the Chinese government announced that China aims to reach peak carbon emissions before 2030 and reach carbon neutrality by 2060 (the so-called "3060" targets)¹. The electricity sector in China consumes over 50% of the total coal supply leading to annual carbon dioxide (CO₂) emissions of 4.5 billion tonnes². Numerous studies indicate that the power sector must take the lead among China's sectors by achieving national carbon neutrality by 2050, in advance of the economy-wide target of 2060³. In 2019, 62.1% of China's electricity supply comes from coal-fired units. Although China already features by far the world's largest installed capacities of power generation using renewable energy (RE), a profound transformation of its power system will still be required over the next 30 years to achieve China's carbon emission goals.

The total unit capacities of the key technologies to enable decarbonization, i.e. variable renewable energy (VRE, defined here as wind and solar PV power), increased by a factor of ten in the past decade, thanks to massive feed-in tariff and other policy support⁴. The VRE investment costs per unit have decreased significantly, with those of PV and wind power dropping 68% and 27%, respectively, since 2012 in China⁵. The declining trends in costs of RE technology are clearly helping to decarbonize the power system^{6,7}.

While important, the integration of VRE brings entails considerable external costs to guarantee secure and stable power system operations. The intermittency and uncertainty of VRE output require coordinated dispatch of more flexible generation resources, such as conventional units or energy storage systems. Moreover, the significant geographic mismatch between load centres and RE generation centres requires extensive grid interconnection. As the installed capacity increases, the completion of projects in areas with the best wind and solar resources will force later development into lower-quality regions, increasing the levelized cost of energy (LCOE). Additionally the need to achieve carbon neutrality in a short time frame of 30 years may force development that strains manufacturing capacities and induces massive investment in RE units before their cost decline has been fully realized⁸. Such costs of transition to carbon neutrality are affected by many factors and the scale of their effects remains unclear. The costs of the power system transition are eventually paid by consumers through renewable surcharges in electricity bills. It is, therefore, crucial to evaluate factors driving the cost of the electricity supply that will be needed to achieve carbon neutrality, to inform effective energy policy design and implementation.

Figure 1. Modelling framework for generation and transmission expansion optimization. We generate the typical year-around hourly output data of RE plants and summarize the supply curves for each province based on the GREAN database. The GTEP model, an optimization problem solver, simulates future power system developments. The hourly RE output intermittency, the characteristics of various generation technologies, and system security requirements are all considered. The impacts of high RE penetration are analysed based on the solution results.

Previous studies have explored the wind and solar potential of China and other regions around the world^{9–11}, focusing on the natural resource endowments. Based on these results, RE investment costs at fine spatial resolution are usually presented, taking account of the integration of renewables into power systems¹². Seeking to assess impacts of low-carbon goals on the power system, studies of the resulting power system morphology^{6,13,14}, comparative development status across countries¹⁵ and associated environmental benefits^{16,17} have been conducted. However, few studies focus on the costs of the electricity supply required to achieve carbon neutrality, including detailed consideration of practical challenges of high renewable capacity shares. Simply estimating changes in electricity supply costs based on only the power balance will result in underestimation of the comprehensive effects of various factors on the costs of power system decarbonization. In particular, a fuller cost accounting must take stock of important practical considerations by integrating VRE supply curves into models, considering operational security concerns caused by strong uncertainty and low inertia of VRE units, and projecting developments of the local network.

To accomplish this fuller accounting, we modelled and optimized a power system with high RE capacities share to evaluate the impacts on the costs of electricity supply caused by China’s transition to carbon neutrality. A planning model of power system generation and transmission is formulated to study its configuration over time. The operating stability problems caused by high RE penetration, such as lower inertia and lack of peak regulation reserves, which increase requirements of transmission and storage capacity, are considered in detail via security constraints in the planning model. The supply curves of VRE based on high-resolution meteorological and geographic data are integrated into the planning model to assess costs more comprehensively. Furthermore, a simulation of the long-term development of China’s power system at the province level is conducted, as in most current studies. For within-province grids, we project their expansion based on historical network data and simulation results. Finally, modelling enables a more accurate estimation of the external costs of RE integration to the overall power system.

Results

Model and scenarios

The electricity supply cost increments caused by the carbon neutrality transformation are evaluated based on the power system expansion planning model considering RE distribution characteristics and system security constraints under high renewable penetration. The model structure is presented in Fig. 1. The model simulates the generation and transmission expansion from 2020 to 2050 while taking account of the environment constraints and energy policy goals at the macro level. The operation security and stability constraints at the micro level are also considered. The modelling formulation, assumption, and parameters are presented in the Methods and Supplementary Note 1.

China’s wind and solar PV potential and supply curves in this paper are assessed using the Global Renewable-energy Exploitation Analysis (GREAN) database. The GREAN database contains detailed geographic information, RE resource endowment data, and human activity information for quantitative evaluation of economic potential. Fig. 2 presents the spatial

(a) Wind capacity factors across mainland China

(b) PV capacity factors across mainland China

(c) Regional wind power supply curves

(d) Regional PV Power supply curves

Figure 2. Spatial RE capacity factors across China and regional VRE supply curves. Fig. 2(c) and Fig. 2(d) show wind and PV supply curves for seven regions: North China (N), Northeast China (NE), East China (E), Central China (C), South China (S), Southwest China (SW), and Southeast China (SE). See Supplementary Figs. 7 and 8 for VRE supply curves for each province. Note that the LCOE and supply curves are calculated based on the forecast of investment cost per kW in 2035.

VRE capacity factor distribution and regional VRE supply curves across China mainland. The total economic potential for wind and solar PV is 7.2 TW and 128.1 TW, respectively. The total energy potential is 200.9 PWh per year, which is 13.5 times China's maximum projected electricity demand in 2050 of 14.9 PWh yr⁻¹ (see Methods and Supplementary Note 5 for more details on evaluation methods and VRE potential).

Although the total potential is large, the spatial distribution and corresponding LCOEs are not uniform and are highly mismatched to the electricity demand. RE-rich areas for both wind and PV are located mainly in northern and northwestern China, while the load centres are chiefly in coastal areas. The VRE supply curves for each province are detailed in Supplementary Figs. 7 and 8. Along with accelerating development of RE, the LCOE increases remarkably due to the decrease in capacity factors and the increasing difficulty of construction and grid integration due to growing distance from existing transmission lines and other factors. This feature is particularly obvious for wind power. The cost distribution for onshore wind shows a "fat tail" pattern, which means the costs are distributed over a larger range. The LCOE ranges from 17.5 to 54.8 CNY¢/kWh in different regions (95% confidence level), with a nationwide average of 26.7 CNY¢/kWh. The LCOE distribution of for PV is relatively more concentrated, and varies from 11.7 to 31.5 CNY¢/kWh (95% confidence level) with a nationwide average of 19.5 CNY¢/kWh. The RE potential and supply curves in each province determine the development sequence and spatial distribution of renewable energy units, which further determines the future power system morphology under carbon neutrality targets. Thus, it is necessary to consider the supply curves across the whole country when optimizing RE investments and regional network connections.

To precisely calculate the electricity supply costs of a power system with high renewable penetration, we have considered the following critical factors in detail:

- The VRE supply curves for each province are integrated into the GTEP model in a piecewise manner (see Supplementary Note 2 for details). In addition to VRE-related data, the future development conditions and potential for other generation resources in China such as hydropower, biomass energy, and natural gas are also explored, based on regulatory reports and expert consultations.
- The model includes three kinds of power system security and stability constraints: power reserve limits, spinning reserve requirements, and minimum system inertia limits. Such constraints determine the additional flexible resources that are required to accommodate the increasing RE.
- We set potential candidate transmission lines for nationwide grid connections in the future considering the location of generation and loads. The model also accounts for the investment costs needed in provincial grids according to simulation results and historical network data (see Methods).
- The current generation mix and the inter-provincial network topology of China's power system as of 2020 are considered in the model.

Such detailed modelling of RE development costs, power system security constraints, and transmission line investments facilitates an accurate estimation of the electricity supply costs of achieving the carbon neutrality target.

Four carbon mitigation scenarios considering different government policies are designed to compare the electricity supply costs with increasing carbon mitigation. The specific descriptions for the scenarios are shown in Table 1. The carbon emission trajectories and electricity consumption of the four scenarios are presented in Supplementary Figs. 4 and 5. Note that the "3060" target for China applies to the entire economy and society. Carbon neutrality is easier to achieve in the power sector than in other sectors due to the relative maturity of low- and zero-carbon electricity generation technologies. In addition, the power sector must achieve carbon neutrality in advance of other industries, transportation and other sectors, in order to provide zero-carbon power for the anticipated increased electrification. Hence, we regard the CN2050 scenario, which achieves carbon neutrality of the power sector in 2050, as a practical translation of the "3060" target to the power sector: we set it as the base case for comparison and analysis. The electricity supply costs and variation of the power system morphology, including generation mix and transmission network topology, are calculated for each scenario.

Power system morphology under carbon neutrality

Fig.3 presents the generation mix under each scenario in 2050 according to our GTEP model. Under the carbon neutral target, the total installed capacity in 2050 will be 3.7 times the current capacity. Regarding the generation mix, the carbon emission reduction targets impact mainly the choice between coal power and RE. In BAU without emission limits, the coal capacity increases from 1104.5 GW to 1446.2 GW in 2050, when it still accounts for 46.5% of power generation. By contrast, coal power begins downscaling significantly on a large scale after 2035 and is almost completely phased out in 2050 under the CN2050 scenario. The changes in the generation mix are shown in the Supplementary Fig. 9. Under the NDC and GM2.0 scenarios, the coal power capacity remains 909.6 GW and 138.9 GW, respectively, in 2050. Coal-based CCS generation does not play an important role in the mix due to its high projected costs for CO₂ capture.

Table 1. Model scenario descriptions and settings

	Description	Carbon emission budget during 2020-2050 (billion tonne)	Electricity load demands in 2050 (TWh)
Business-as-usual (BAU)	No carbon emission reduction targets are enforced. It is set for reference.	N/A	12.3
Nationally Determined Contributions (NDC)	Based on China's NDC goals and action plans under the Paris Agreement, the past low-carbon transition trends and policies in the power sector since the Paris Agreement was enacted are continued.	104.4	12.3
Global Warming of 2.0 °C (GM2.0)	Oriented to achieve the IPCC goal of global average surface warming of no more than 2.0 °C, the carbon emissions from the power system are strictly limited while supplying the increasing electrified load of other industries.	84.2	13.1
Carbon neutrality (CN2050)	Oriented to achieve carbon neutrality in the whole power system in 2050 while serving expanded electrified load from other industries. The CN2050 scenario corresponds to requirements of the power system in China to meet the IPCC goal of global average surface warming of no more than 1.5 °C.	66.2	14.86

VRE units, specifically PV and wind, would be deployed primarily to offset the decline of coal power. For the BAU scenario, VRE would be developed only in the later years, a result of its growing unsubsidized cost-competitiveness, with total capacities of 2001.6 GW in 2050, accounting for 32.0% of all power generation. Under the CN2050 scenario, the VRE penetration reaches 70.8% in 2050 with 3163.8 GW of PV and 2302.4 GW of wind (ten times the VRE capacities in 2020). The installed capacities of VRE for the NDC and GM2.0 scenarios by 2050 are 3912.6 GW and 4830.1 GW, respectively. Fig.4(a) presents the provincial generation mix in 2050 under the CN2050 scenario. Large-scale onshore wind power capacities are located in Gansu, Xinjiang, and Inner Mongolia, and small capacities are located in the northeast and coastal provinces. Offshore wind power is concentrated in the three coastal load centres of Shandong, the Yangtze River Delta, and Guangdong. The disparities in installed PV capacities between provinces are not as significant as those for wind power because the average PV LCOEs are more similar across provinces. Although the investment costs of VRE per kW capacity are expected to continue to decrease in the future, the huge investments to expand their total installed capacities will increase the electricity supply costs.

Power system security and stability require auxiliary services from flexible generation resources to enable the integration of VRE. Currently, such service is provided mainly by coal-based units, although this cannot continue to be the case under carbon neutrality. With the forced withdrawal of coal power, the task of auxiliary services is taken over by natural gas units because of their relatively low rate of carbon emissions and generation flexibility. The NDC scenario has a relatively low gas capacity in 2050, 142.3 GW, because considerable coal capacities still remain. Under the GM2.0 scenario, the gas capacity increases from 111 GW to 516.0 GW by 2050. The installed capacities in CN2050 are slightly smaller, at 413.3 GW. To achieve carbon neutrality in CN2050, the emissions of these gas units are offset by negative emissions achieved by generation using biomass energy with CCS (BECCS). Due to its highly variable operating costs (approximately twice those of coal power), biomass power is developed at large scale only in the CN2050 scenario. Among the 234.8 GW of biomass generating capacity, 40.5% is from BECCS units, contributing 194.2 million tonnes of negative carbon emissions per year. However, the supply of natural gas and biomass fuel for power generation is relatively scarce in China, limiting the total capacities. These two types of units are distributed mainly in coastal and central China, driven by the relatively abundant primary fuel resources in those provinces. The high fuel costs of natural gas and biomass in China would also contribute to increased costs of electricity supply.

Energy storage systems (ESSs) play a critical role in accommodating high RE penetration and guaranteeing system security, as they are able to provide high-performance ancillary services including accident reserves, peak regulation, fast frequency

Figure 3. Generation mix in China under different carbon emission target scenarios Fig. 3(a) compares the generation mix between different carbon emission scenarios and the current status in 2020. Fig. 3(b) presents the energy generated and lost in 2050 under different scenarios and the current status.

regulation, and virtual inertia. Pumped hydro storage (PHS) and battery energy storage (BESS) are considered in the model. Due to the limits of both the geographical resources for PHS and the battery manufacturing capacities, BESS is developed mainly in the later stages of the simulation period. The total installed capacities of ESSs in GM2.0 and CN2050 are 845.6 GW and 1017.8 GW, respectively. The distribution of ESSs is roughly consistent with the distribution of VRE, primarily in areas of rich VRE resources and load centres. Concentrated solar power (CSP) plants with heat storage devices play a similar role as ESSs, while also serving as an RE generation resource. Because of limited by solar irradiation conditions, CSPs are located mainly in northwest China and Inner Mongolia, where particularly high-quality solar energy resources exist. The investment in ESS and CSP reflects the external costs brought about by VRE grid integration, which would be a considerable part of future electricity supply costs.

High renewable penetration also increases the demand for long-distance transmission lines, and more intensive grid interconnection is required to cope with the generation-load imbalance. Fig.4(b) presents the 2050 inter-regional and intra-regional power exchanges in the CN2050 scenario according to our results. In the CN2050 scenario, 380.4 GW of AC lines and 454.2 GW of DC lines would be newly constructed for inter-provincial transmission. Inter-provincial power delivery reaches 6634.5 TWh per year in 2050, which is 4.17 times the value in 2020 and 44.6% of the total annual demand. In comparison, the BAU scenario has only 3048.5 TWh of inter-provincial power delivery in 2050. The topological structure of China's inter-provincial transmission grid under the CN2050 scenario is presented in Supplementary Fig. 10. The distribution of power flow continues the current pattern of "from west to east" and "from north to south". North and northwest China are still the main power output regions, reflecting their abundant renewable energy potential. East and central China are still the main receiving regions, with both receiving more than 1000 TWh of external power annually. Although the main power flow pattern remains unchanged, the power flow between regions is mostly bidirectional. These increases in power transmission will also increase the electricity supply costs.

Costs of Carbon Neutrality

The dramatic changes in power system morphology will inevitably cause changes in costs of electricity supply. We find considerable but arguably affordable costs of transforming China's power system to support carbon neutrality. The total costs of the CN2050 and BAU scenarios over the 30-year period are 51.4 trillion CNY and 31.3 trillion CNY (present value in 2020, approximately 7.45 trillion USD and 4.54 trillion USD), respectively. The carbon neutrality goal imposes an aggregate additional cost to the power sector of 63.7% over BAU. The average annual additional costs would account for approximately 0.66% of China's GDP in 2020, a large but manageable value, especially recognizing that it does not account for considerable external co-benefits of fossil fuel substitution, such as reduced health and agricultural damages from air pollution.

(a) Provincial generation mix

(b) Electricity exchange between regions and provinces

Figure 4. Provincial generation mix and power flow across China in 2050 under carbon neutrality. Fig. 4(a) shows the generation mix in each province. The size of the pie charts is proportional to the cumulative generation capacities for each province in 2050. Fig. 4(b) shows the power exchange between and within seven regions.

Figure 5. Electricity supply costs and carbon mitigation costs under different scenarios. Electricity supply cost is the average cost the power system must recover per kWh of electricity load demand. The marginal carbon price is the increased power system cost per tonne of carbon reduction based on the emission targets of each year. The numbers between each pair of curves denote the average carbon mitigation costs per tonne between the more stringent scenario and the less stringent one. This value is numerically equal to the ratio of the difference between the total costs of the two scenarios and the difference between the carbon emission budget. The calculation methods are detailed in Supplementary Note 3. The marginal carbon price in the BAU scenario is zero because it includes no carbon emission constraints.

Fig.5 presents the electricity supply costs and marginal carbon prices for each scenario. In CN2050, the costs of electricity supply increase 10.4 CNY¢/kWh, or 21.5%, over the 30 years to 58.7 CNY¢/kWh (8.51 USD¢/kWh) in 2050. The process is not linear and can be roughly split into three stages. During the first five years, the cost curve is relatively flat, rising only 1.2 CNY¢/kWh. Between 2025 and 2040, the costs soar 17.6%, reaching 58.2 CNY¢/kWh (8.44 USD¢/kWh). From 2040 to 2050, the cost growth again slows due to expanded RE manufacturing capacities and further declines in per-MW capital costs. With carbon neutrality almost achieved in 2045, the costs hit the peak value of 59.1 CNY¢/kWh (8.57 USD¢/kWh) and then decrease slightly in the last five years. This trajectory of electricity supply costs is largely driven by the second “3060” target, to achieve carbon neutrality by 2050 in the power sector (and by 2060 for the entire economy), while the first target, to reach peak carbon emissions by 2030, has relatively little effect.

By comparison, electricity supply costs would decrease 6.7% from 2020 to 2050 under BAU, absent carbon controls. Annual carbon emissions would reach 5.92 billion tonnes between 2035 and 2040, and then begin to fall because the capital costs of RE would become sufficiently low to compete with conventional units, including their external costs. Specifically, declines in the per-kW investment costs of wind and PV units of 25% and 40% respectively would incentivize construction of many RE units even without carbon controls. The electricity supply costs in the other two scenarios show slight decreases in the first five years and increases in the latter years because of the tightened emission requirements. The additional costs of emission reduction in 2050 for NDC and GW2.0 are 2.4 and 5.8 CNY¢/kWh, respectively, compared with the BAU case.

The average carbon mitigation costs are the additional costs paid per tonne of carbon emission between two scenarios. The average carbon mitigation costs grow rapidly when tightening the emission limits across the four scenarios as shown in Fig. 5. The average additional cost for carbon mitigation is 730.7 CNY/t (105.9 USD/t) between GM2.0 and CN2050. This value is 17.5 times the difference between BAU and NDC of 41.9 CNY/t. The marginal carbon prices reflect the cost of carbon emission reductions under various emission limits. They represent the gradient of total costs to carbon emission reductions. With carbon neutrality requirements, the marginal price reaches 1082.6 CNY/t (159.0 USD/t) in 2050 under CN2050, while the 2020 carbon price in China’s carbon market is only 49 CNY/t (7.1 USD/t)¹⁸. As the emission reduction requirements become more stringent, the same amount of emission reduction will bring about a rapid increase in emission reduction costs. These

results reflect the tradeoff between low-carbon targets and the total costs. Hence, the less aggressive carbon reduction goals are much less expensive to achieve not only in aggregate terms but also on a per tonne basis, and the per-tonne expenditure increases rapidly under ambitious targets such as CN2050.

Composition changes of electricity supply costs

The electricity supply cost structure changes substantially over 30 years because of the carbon neutrality target. Fig.6 shows the changes in the composition of the costs of electricity supply per kWh in the CN2050 scenario. The proportion of operating costs continues to decrease while maintenance and capital costs continue to grow due to changes in the generation mix reflecting the growth of RE and the retirement of thermal generation. The maintenance costs exceed the operational costs in 2050.

Fig.6(b) shows the contribution of different factors to changes in the costs of electricity supply. The changes are driven by three factors. The phasing out of coal power naturally causes a decrease in its costs, while the installation of VRE causes an increase in capital and related external costs. A number of factors exert downward pressure on the cost of electricity supply, amounting in aggregate to 25.8 CNY¢/kWh. Almost all are related to the reduction in coal-fired installed capacity and generation. As a result, both the operating and capital costs for coal power decrease, with the latter accounting for the dominant share, 18.8 CNY¢/kWh.

Wind and PV power are the main driving factors in decarbonization. Since the two have zero operating costs, their capacity growth does not cause increases in operating costs. However, carbon neutrality requires an RE installed capacity of over 5000 GW, reflecting in part the low capacity factors of wind and PV. Therefore, the capital and maintenance costs per kWh increase, even as the VRE investment cost per kW rapidly decreases. Under the assumptions of the CN2050 scenario, the supply cost increments contributed by VRE are totally 16.4 CNY¢/kWh, although the investment costs per kW decline by approximately 60%. The fact that VRE capital costs account for a considerable fraction of the supply costs illustrates the necessity of considering the supply curves for each province in detail. Absent consideration of the spatial distribution of LCOE, the costs in 2050 will be underestimated by 2.3 CNY¢/kWh. Explanations of the calculation and comparison method are presented in Supplementary Note 2.

Security and stability constraints in a power system with very high RE capacity share require flexible generation resources and regional network expansion. Added gas power, biomass power, ESSs, CSP and transmission expansion result in additional supply cost increases of 18.4 CNY¢/kWh. This increase is a result of the requirements for optimal development and operations despite the spatio-temporal imbalances and low-inertia characteristics of VRE.

Electricity supply costs sensitivities

Sensitivity analysis is conducted on the CN2050 scenario to consider the impact of the uncertainties of five key factors: RE and ESS overnight investment costs, load growth rate, security requirements, RE and ESS manufacturing capability, and transmission capacity limits. We vary the parameters within the given intervals for each factor to assess their influence on the electricity supply cost increases in each stage (see Supplementary Note 4 for the sensitivity analysis setting and Fig. 7 for the results).

The uncertainties of RE and ESS capital costs (wind, PV, CSP, and BESS) yield the largest differences in the final electricity supply cost of approximately $\pm 7.3\%$. The electricity supply costs in 2050 under carbon neutrality vary from 54.2 to 62.8 CNY¢/kWh as VRE capital cost increases from the less stringent to more stringent scenarios. Such variation increases as the carbon emission limits tighten over the planning period, since VRE investment cost yields the largest contribution to the increase in electricity supply costs. Increasing support for the research and development of low-carbon power generation technologies would effectively reduce the costs brought about by the decarbonization target.

The uncertainties of security and inertia requirements, including power reserve constraints, spinning reserve constraints, and minimum inertia requirements, result in a $\pm 3.1\%$ difference in final supply costs. The variation increases as the penetration of VRE increases since VRE provides neither robust reserve capacity nor inertia to the power system and introduces difficulties for system security and stability. Stricter system security requirements force greater investment into ESSs, CSP, and transmission lines to accommodate VRE, which leads to rapidly rising costs. Without the three security requirements, the electricity supply cost of achieving carbon neutrality in 2050 drops by 2.4 CNY¢/kWh.

The sensitivity of the transmission capacity limits shows a similar trend as the security requirements. They impact the costs of electricity supply mainly after 2035, when greater electricity delivery is needed. The uncertainties of transmission capacity limits result in up to a $\pm 2.2\%$ difference in electricity supply cost in 2050.

The impacts of uncertainties in the rate of load growth and manufacturing capability show a different pattern. Their impacts on total costs in the early or medium-term stages are more significant than those in the later stage. For load growth rates, the impact on costs decreases from a peak value of 4.3 CNY¢/kWh in 2035 to 1.5 CNY¢/kWh in 2050 because each additional kilowatt-hour of load demand in the initial stage would cause more carbon emissions and require more RE generation, which is relatively expensive at that time. Hence, the supply costs in the early stage are more sensitive to load demands than those in the completion stage. RE and BESS manufacturing capability represents the maximum capacity that can be newly installed each

(a) Electricity supply cost variation

(b) Contributions to the cost changes of different components in power system

Figure 6. Composition variation of the electricity supply cost in the CN2050 scenario. Fig. 6(a) presents the composition variation of the electricity supply cost over 2020-2050. The electricity supply cost consists of three parts: capital costs (CAP), operating costs (OP), and maintenance costs (MAI). The total investment costs are annualized over the plant lifetime to calculate the annual capital costs (see detailed calculation method in Supplementary Note 3). Fig. 6(b) shows the cost variation caused by various factors separately. Each bar denotes the cost difference between 2020 and 2050 for the corresponding component. For example, the first bar denotes the contribution of the increase in capital cost of wind power to the net change in the total electricity supply cost. The results for the other three scenarios are presented in Supplementary Fig. 11.

Figure 7. Sensitivities of electricity supply costs in CN2050 to various assumptions. Variations of electricity supply costs in different years are compared to the CN2050 scenario defined by assumptions on RE capital cost, RE unit manufacturing capacity, transmission limits, reserve and inertia requirements, and load growth rates. A low and high scenario is set for each factor. We vary the parameters within the given intervals with five evenly sampled intermediate scenarios. See Supplementary Note 4 for detailed sensitivity analysis settings.

year, which is driven by the production capacity of RE generation units and related policy. Its sensitivity is highest in 2040, since the carbon emission limits are reduced by 78.1% from 2030 to 2040, so the ability to install RE generation becomes critical. Such capability becomes redundant in the later stage, so its sensitivity to the electricity supply costs diminishes. However, when the manufacturing capacity is too low to produce sufficient total RE units over a certain threshold (approximately 5 TW according to our results), considerable investment in coal-based CCS units would occur to meet the emission reduction goals, leading to gross increases in costs (see the outliers in Fig. 7 for RE unit manufacturing capability).

Discussion

Carbon neutrality and reduction of electricity prices are difficult to achieve simultaneously, as discussed above. Despite the influence of various uncertainties, increments in the cost of electricity supply are almost inevitable in the attempt to achieve carbon neutrality by 2050. The peak of electricity supply costs would appear around 2045. Then the costs would slightly decline thanks to the maturity of RE and ESS generation technologies. Our simulation results show that more than 5000 GW of VRE units is needed to realize carbon neutrality in China's power system. The integration of VRE power brings about not only substantial capital costs but also additional external costs because of its properties of intermittency and low inertia. Very large investments in ESSs, CSP units, and transmission lines will be needed to meet the requirements on reserve capacity, minimum system inertia, and real-time power balancing. In effect, an entirely new type of power system will be required, with wind and PV resources serving as the core generating capacity and various flexible generation resources serving as the auxiliary capacity. Moreover, the inter-provincial grid interconnection must be gradually transformed from a simple power transmission channel to a platform supporting bidirectional energy sharing between regions with different generation resources.

The electricity supply costs would increase by 10.4 CNY¢/kWh (1.51 USD¢/kWh) in the CN2050 scenario. This increment is approximately 5.4 times the current RE surcharge in electricity prices of 1.9 CNY¢/kWh^{19,20}. The RE surcharge has not been changed since 2018, despite a 49.1% increase in VRE installed capacities. In the next 30 years, the costs of the zero-carbon transformation are projected to increase rapidly. Therefore, a reasonable market mechanism is urgently needed to translate this change to the electricity price. A capacity market and ancillary service market should be established to internalize the external costs of high RE penetration and to protect the benefits of other auxiliary units, such as ESSs, which will be essential.

The capital costs of RE units are the dominant factor affecting the costs of electricity supply according to this analysis, including the sensitivity analysis. The Chinese government's support for the wind and PV industries in the past ten years has resulted in considerable cost reductions. As mentioned, the investment costs per kW of PV power dropped by 68% since 2012⁵. Similar policy support remains vital to spur technological innovation and cost reduction, especially for technologies in the early stages of development, such as BESS and CSP.

During the decarbonization transformation, carbon reduction targets have a small impact on costs in the first five years. Because of the cost decrease of RE technologies, the costs may even drop slightly if the carbon emission requirements are not

stringent. The period of 2030 to 2045 is critical for the transformation. At this stage, the installed capacities of wind, PV, and ESS would need to increase annually by at least 87.7 GW, 118.7 GW, and 43.7 GW, respectively. For comparison, the average annual growth in capacities of wind and PV in the past five years have been 30.0 GW and 41.8 GW respectively. Additionally, the total installed capacities of ESS in China were just 32.4 GW at the end of 2019. The manufacturing capabilities to produce RE and energy storage units are currently highly insufficient to support the needed energy transformation. Ensuring the integrity of the supply chain and implementing appropriate policy incentives are critical steps to achieve decarbonization of the power sector by 2050.

Methods

GREAN platform

To evaluate the factors increasing the costs of electricity supply under high wind and solar penetration to achieve carbon neutrality in the power system of China, we apply the integrated analysis platform Global Renewable-energy Exploitation ANalysis (GREAN) established by the Global Energy Interconnection Development and Cooperation Organization (GEIDCO). The key points to accurately assess the LCOE are two-fold: 1) a detailed database for weather, geographic and related infrastructure information, and 2) comprehensive assessment models that consider the costs of construction of flexible generation and grid interconnection under high wind and solar penetration.

The GREAN platform contains data on worldwide VRE resources, geographic characteristics, and human activities. The global VRE (wind and solar) energy resource data have a resolution of 9km×9km. Additionally, the wind energy resource data provided by Vortex²¹ include wind speed, wind direction, air density, temperature, and other parameters. The solar energy resource data provided by SolarGIS²² include global horizontal irradiance and direct normal irradiance. Combined with characteristics of wind turbines and PV modules, these data are applied to evaluate provincial VRE capacity factors and generate annual VRE power output. The geographic data include a global land cover map, distribution of major water bodies, terrain elevation data, and other characteristics. The human behaviour-related data include the distribution of major conservation areas, information on power grid and transportation infrastructure, and other factors. The geographic information and human behaviour data are used to evaluate the availability of RE sites, challenges of construction, and grid-connection costs. The specific data categories and sources of the database in the GREAN platform are detailed in Supplementary Fig. 6 and Supplementary Tables 7-9.

Comprehensive assessment models are established based on the databases above to conduct the systematic calculation of theoretical, technical, and economic VRE potentials. The theoretical VRE potential refers to the maximum developable capacity for VRE units considering only the VRE resources data. The technical VRE potential is obtained by excluding the areas that are unsuitable for development due to poor resource endowment, disadvantageous geographic conditions, or policy prohibitions, such as conservation area designations. Based on the technical VRE potential, economic VRE potential is calculated considering the construction constraints and grid-connection costs and is then used to calculate the overall electricity supply costs under carbon control and neutrality targets. To evaluate the economic VRE potential, the GREAN platform first calculates the year-round hourly power output of wind and solar power in each 500m×500m area based on the generation characteristics of 2.5 MW wind turbines with hub heights of 100 m that meet IEC standards and 300 W monocrystalline PV modules. The capacity factors are then calculated for each province. The LCOE is finally calculated considering the grid-connected cost and device transportation cost according to the distance between the construction location and related infrastructure. The supply curves of VRE generation potential around China can be obtained based on the LCOE with a fine spatial resolution to reveal the different characteristics of the RE resources in different regions.

With all the key factors taken into account, the GREAN platform provides LCOE and supply curve estimates that are as close as possible to the actual values based on the data available. The technical details of the platform are presented in the references²³.

Generation and Transmission Expansion Model

A generation and transmission expansion planning (GTEP) Model is formulated to simulate the long-term development roadmap of China's power system under carbon emission reduction targets in the next 30 years. The planning model is structured at the provincial level with embedded operation simulation on an hourly scale. Hourly dispatch schedules in 2050 under the CN2050 scenario are presented in Supplementary Fig. 9. Mathematically, the GTEP model is an optimization problem aiming to minimize the total costs caused by electricity generation, transmission, and low-carbon transformation over planning periods. Specifically, the total costs consist of investment, maintenance, and operating costs. Long-term investment schemes and short-term dispatch schedules are optimized simultaneously, and are subject to two sets of constraints: planning and operational constraints. The planning constraints represent resource limits and regulations of environmental policy at the macro level. Construction and retirement decisions of various generation units, ESSs, and transmission lines in different stages are made within the feasible region of the planning constraints. Because of the considerable impact of VRE capital costs

on electricity supply costs, the dynamic changes in LCOE with increasing installed capacities are considered in the GTEP model. The VRE supply curves provided by the GREAN platform are integrated into the optimization model in a piecewise manner for every province (see Supplementary Note 2). The operational constraints describe the daily power system dispatch at the micro-level with generation and transmission operational characteristics modelled from the bottom up. Eleven kinds of generation technologies are considered in the GTEP model, namely, wind, PV, CSP, nuclear, hydro, biomass, gas, coal, Biomass-CCS (BECCS), Gas-CCS, and Coal-CCS. Two kinds of ESSs, pumped hydro and battery storage, are also considered. Both high-voltage direct current (HVDC) and high-voltage alternating current (HVAC) transmission technologies are set as available candidate lines for expansion. The power system is operated under operating rules such as power balancing and spinning reserve requirements, while pursuing the minimum total operation costs. The mathematical expression of these constraints, code implementation methods, and solution algorithm are detailed in Supplementary Note 1.

The settings in the GTEP model for China's current power system are extracted from real-world data at end of 2020 for each province, including generation mix, load demands, and inter-provincial transmission capacities²⁴. The per-kW investment costs projections for generation technologies in the GTEP model refer to the results of NREL's annual technology baseline (ATB) model published in 2020⁸, which includes three trajectories: conservative, moderate, and advanced. The per-kW investment costs in the NDC, GM2.0, and CN2050 scenarios follow the moderate trajectories from 2020 to 2050. We conduct sensitivity analysis on RE capital costs, where the NREL conservative projection is set as the high-cost case and the advanced projection represents the low-cost case (see Supplementary Fig. 2). Load growth rates over the planning period are derived from the Research Report on China's "14th Five-Year" Power Development Plan²⁵ and the Report on China's Long-term Low-carbon Development Strategy and Pathway³. The load growth rate depends heavily on the degree of electrification of other industrial sectors under different carbon emission reduction targets. Sensitivity analysis is also conducted on a load growth with 10% fluctuations (see Supplementary Table 1).

Local grid development projection

The investment costs and maintenance costs of the transmission and distribution system within each province account for a considerable part of the total costs of electricity, approximately 15% according to previous research⁶. Such local grid planning is not directly optimized in the GTEP model because of the inaccessibility of data and calculation difficulties due to their spatial resolution. Hence, we project the investment of local network expansion based on the historical local network capacity and the planning results of the GTEP model.

We collect data on installed transformer capacity and transmission line length at each voltage level (750 kV, 500 kV, 330 kV, and 220 kV) in each province from 2008 to 2018²⁶. The historical electricity load demands and local power generation are collected and used to regress their relationships with installed transformer capacities and transmission line lengths. To avoid the disturbance to the regression results of abnormal historical data in several small provinces, the provinces are grouped into seven regions and the projection is conducted on a region scale. The linear regression model with L1 and L2 regularizers is used as the regression model²⁷. The regression method is implemented using the sklearn package in Python²⁸. The fitted model is then used to estimate the local transmission investment based on the electricity load demands and power generation planning results in the next 30 years obtained from the GTEP model. The goodness of fit in the training set and the projection results are presented in Supplementary Tables 5 and 6. For distribution networks, investment below 110 kV is estimated based on the proportion of total investment costs in distribution network equipment with respect to the total investment costs of the entire power grid provided by the China Electric Council (CEC) yearly reports².

Capacity factors of the whole generation mix will decrease as the VRE penetration increases, which will further reduce the utilization rate of network equipment²⁹. To consider such impacts of changes in the generation mix on local power grids, we modify the local grid investment based on historical data according to the changes in the capacity factors of the local generation mix. Assuming that the utilization rate of power grid equipment decreases by the same rate as the power supply capacity factor, the modification formula is as follows:

$$\tilde{C}_{r,y}^{local} = \frac{cf_{r,y0}}{cf_{r,y}} C_{r,y}^{local}, \forall r, y \quad (1)$$

where $C_{r,y}^{local}$ and $\tilde{C}_{r,y}^{local}$ denote the projected and modified local network investment in region r at planning stage y , respectively. $cf_{r,y0}$ and $cf_{r,y}$ denote the current capacity factors and capacity factors at planning stage y for the generation mix in region r , respectively. The investment costs and the maintenance costs for the local grid network are calculated based on the modified network capacities.

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429 **Author contributions**

430 Z.Z., E.D., N.Z., and C.K. conceived and designed the research. Z.Z., E.D., and N.Z. formulated the theoretical model. Z.Z.
431 conducted the code implements and carried out the simulations. Z.Z., N.Z., C.P.N, and X.L. conducted the data analysis and
432 led the writing of the paper. N.Z., C.P.N, and X.L. wrote the introduction. Z.Z., E.D., J.X., and J.W. contributed to the data
433 collection and figure drawing. N.Z., and C.K. conducted the policy analysis. All authors contributed to the discussions on the
434 framework and the editing of this article.

435 **Competing interests**

436 The authors declare no competing interests.

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