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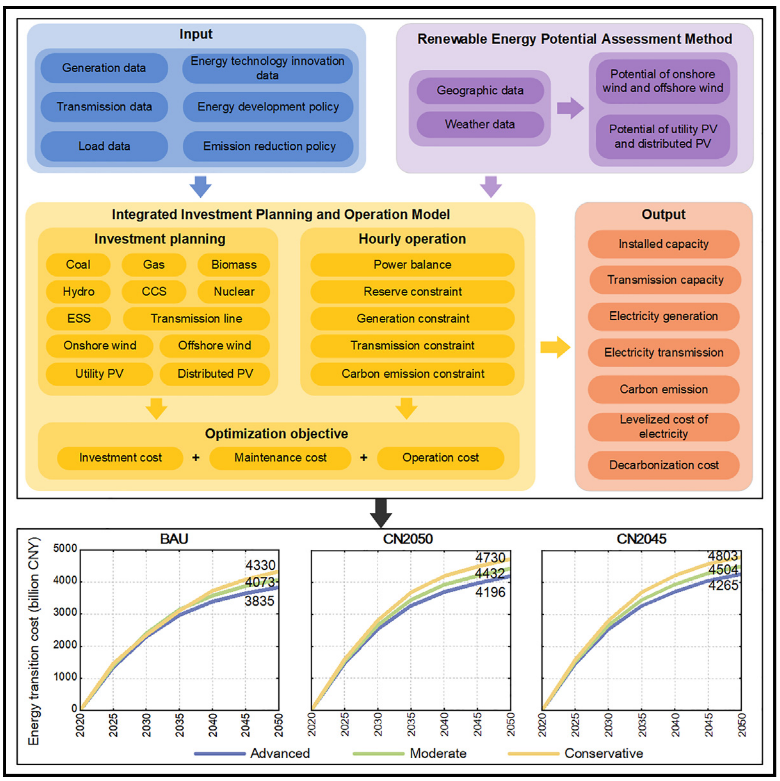
Accelerating carbon neutral power systems through innovation-driven cost reduction and regional collaboration

Graphical abstract



Highlights

- An integrated model was developed to simulate the transition pathway from 2020 to 2050
- Learning curves were incorporated in the model to represent different innovation scenarios
- Carbon neutrality can be achieved earlier and cheaper in the advanced innovation scenario
- Inter-regional and intra-regional transmission expansions facilitate carbon neutrality

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In brief

Wu et al. investigate the impacts of energy technology cost reduction driven by innovation on advancing carbon neutrality in the electric power system. Their study projects that an advanced innovation scenario can achieve carbon neutrality in the electric power system earlier and more cost effectively. Additionally, the expansion of both inter-regional and intra-regional transmission capacities is essential for achieving carbon neutrality in the electric power system at a reduced cost.

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Accelerating carbon neutral power systems through innovation-driven cost reduction and regional collaboration

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SCIENCE FOR SOCIETY Reducing carbon emissions and achieving carbon neutrality is a critical global challenge. Previous studies have formulated pathways for energy transition in the electric power system to meet carbon reduction targets. However, many of them overlook the role of energy technology cost reduction driven by innovation in advancing carbon neutrality in the electric power system. In this study, an integrated investment planning and operation model is developed to simulate the transition pathway in the electric power system from 2020 to 2050 toward carbon neutrality under different innovation scenarios. Our results reveal that carbon neutrality can be achieved earlier and more cost effectively in the advanced energy technology innovation scenario. Furthermore, expanding both inter-regional and intra-regional transmission capacities can facilitate the achievement of carbon neutrality in the electric power system at a reduced cost.

SUMMARY

Prioritizing electric power system decarbonization is crucial for meeting global carbon neutrality targets. However, the role of energy technology cost reduction driven by innovation in advancing carbon neutrality in the electric power system has not been well studied. To fill this gap, an integrated investment planning and operation model is developed to simulate the carbon neutral pathway in the electric power system over a 30-year period from 2020 to 2050. The learning curves with different learning rates are incorporated into the model to represent different energy technology innovation scenarios. According to our results, the advanced innovation scenario is projected to achieve carbon neutrality in the electric power system five years earlier compared with the conservative innovation scenario, with a cost savings of 465 billion CNY. In addition, both inter-regional and intra-regional collaboration facilitate the achievement of carbon neutrality in the electric power system at a reduced cost.

INTRODUCTION

According to the Paris Agreement,[1] the increase in global mean temperature must be limited to no more than 2°C or even 1.5°C at the end of this century, and possibly as early as 2050.[2,3] This ambitious goal necessitates a substantial reduction in carbon emissions. Therefore, achieving carbon neutrality has become the target of energy and emission policies around the world, and a transition of the energy system is critical to accomplish this target.[4] As a vital constituent of the energy system, the electric power system contributes to over half of the energy-related CO_2 emissions.[5] Hence, research on the energy transition in the electric power system is essential to achieve carbon neutrality worldwide.

As the second-largest economy of the world, China accounts for 30% of global anthropogenic CO_2 emissions.[6] During the 75th United Nations Global Assembly (UNGA) in 2020, the Chinese government declared to peak carbon emission by 2030

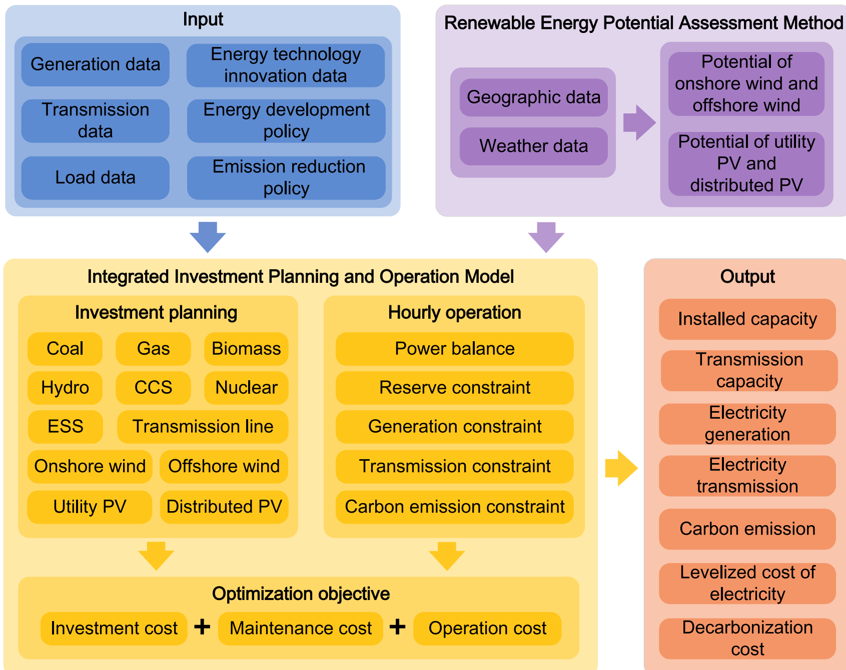

Figure 1. Framework of integrated investment planning and operation model

The potential of PV and wind power is obtained by the renewable energy potential assessment method. Then the integrated investment planning and operation model is supplied with the data on the potential of renewable energy and other input information. The model projects the transition pathway in the electric power system toward carbon neutrality over a 30-year period, considering both long-term investment planning and hourly operation.

and achieve carbon neutrality by 2060, which motivates the decarbonization of the electric power system.[7] Accelerated decarbonization of the electric power system drives electrification of other sectors, which is essential for achieving the national carbon neutrality target by 2060.[8,9] Thus, it is crucial for China to design a realistic pathway to decarbonize the electric power system.

Over the past decades, energy technology innovation has driven the development of renewable energy, resulting in a decrease of the costs,[10] especially for solar photovoltaic (PV)[11] and wind power.[12] Massive feed-in tariffs and supportive policies further promote the installed capacity of renewable energy.[13] In addition, the rapid evolution of battery technology creates opportunities for large-scale installation of renewable energy.[14,15] Besides, the development of biomass energy and carbon capture and storage (CCS) technology reduces the atmospheric carbon emissions intensity.[16–18] With the rapid development of the aforementioned energy technologies, the realization of carbon neutrality becomes feasible.[19] Previous studies have formulated pathways for energy transition in the electric power system with carbon reduction target in India,[20] Europe,[21] and China.[8,22–24] Several results have established the year 2050 as the anticipated time frame for the electric power system to achieve carbon neutrality in China, which surpasses the overall target of 2060. However, the role of energy technology cost reduction driven by innovation in advancing carbon neutrality in the electric power system has not been well studied. Disregarding the influence of energy technology innovation may result in either overestimate or underestimate of the costs of energy technologies, thereby affecting the energy transition pathway in the electric power system. Motivated by reduced costs of energy technologies due to advanced innovation, certain developed regions may pioneer achieving carbon neutrality, thereby inspiring neighboring areas to follow suit. In addition, the impacts of regional transmission and uncertain policies on carbon neutral pathway in the electric power system have not been thoroughly explored.

To address the above issues, an integrated investment planning and operation model for the regional electric power system is developed to assess the influence of energy technology cost reduction driven by innovation on advancing carbon neutrality in the electric power system. The learning curves with different learning rates are incorporated into the model to represent different energy technology innovation scenarios. The long-term expansion and hourly dispatch of energy technologies are simultaneously determined in the model. This study focuses on the Guangdong-Hong Kong-Macao Greater Bay Area, an economically advanced region with ambition for early achievement of carbon neutrality. Three scenarios with different carbon emission policies are analyzed. Energy transition costs and transition pathway in the electric power system over 30 years are obtained in the model. In addition, the impacts of regional collaboration and uncertain policies on the energy transition are also analyzed in the model.

The results of our model show that the advanced innovation scenario is projected to achieve carbon neutrality in the electric power system 5 years earlier than the conservative innovation scenario, with a cost savings of 465 billion CNY. This indicates that carbon neutrality can be achieved earlier and more cost effectively in the advanced energy technology innovation scenario. Furthermore, expanding both inter-regional and intra-regional transmission capacities can facilitate the achievement of carbon neutrality in the electric power system at a reduced cost. In addition, uncertainty analysis results demonstrate that policies play a critical role in enabling a cost-effective transition to carbon neutrality in the electric power system.

RESULTS

Model and scenarios

The framework of the integrated investment planning and operation model used in this paper is presented in Figure 1. The potential of PV and wind power is obtained by a renewable energy potential assessment method. Then the integrated investment

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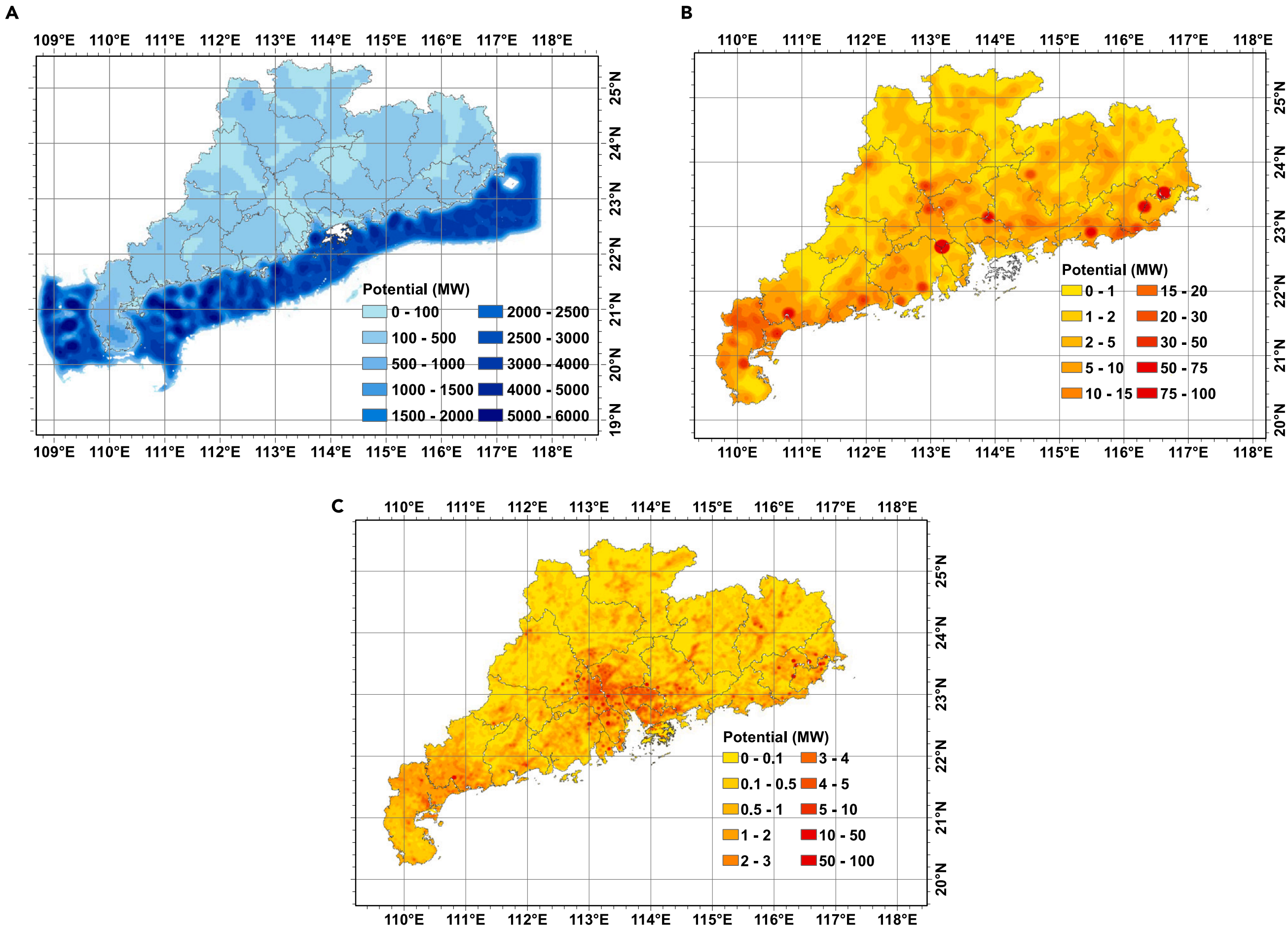


Figure 2. Spatial distribution of renewable energy potential across Guangdong-Hong Kong-Macao Greater Bay Area
(A) Potential of wind power. The onshore wind power potential of Hong Kong and Macao is not considered due to their high urbanization.
(B) Potential of utility PV, except for Hong Kong and Macao because of high urbanization.
(C) Potential of distributed PV.

planning and operation model is supplied with data concerning the potential of renewable energy and other relevant inputs. The model simulates the long-term investment planning and hourly operation of the electric power system from 2020 to 2050, taking into account different levels of energy technology innovation. Energy technology innovation is primarily reflected in the future costs of emerging energy technologies, which are influenced by learning rates. In addition, the energy development and emission reduction policies of the studied region are also considered in the model. The specific modeling formulation is shown in the "experimental procedures" section and Note S1.

The potential of PV and wind power is assessed based on the geographic and weather data. Specifically, the data such as land occupation, solar radiation and wind speed, etc. are used to select the areas suitable for renewable energy installation. Then the renewable energy potential in a specified region is calculated by aggregating all suitable areas in the region. The potential of renewable energy is represented by the maximum installed capacity in each region. The spatial distribution of renewable energy potential across Guangdong-Hong Kong-Macao Greater Bay Area is presented in Figure 2. Figure S1 illustrates the spatial distribution of potential for distributed PV in Hong Kong and Macao. The potential of onshore wind power and utility PV in Hong Kong and Macao is excluded from this study because their high level of urbanization limits the development of concentrated renewable energy.

The total potential of offshore wind power and onshore wind power of the Bay Area is 456.4 and 41.5 GW, while the potential of utility PV and distributed PV of the Bay Area is 967.8 and 82.6 GW. The substantial potential of renewable energy in the region paves the way for achieving decarbonization of the electric power system prior to 2050. The detailed assessment methods of the renewable energy potential are shown in "experimental procedures" section and Note S2.

Although the Bay Area accounts for approximately 10% of the nation's electricity consumption, the utilization of renewable energy in the region is inadequate. Especially in Hong Kong and Macao, the high level of urbanization restricts the development of renewable energy, with only a limited portion of land being suitable for distributed PV installation. The potential of

Table 1. Carbon reduction scenarios in the Guangdong-Hong Kong-Macao Greater Bay Area

Scenario	Description	Carbon emission budget (billion tons)	Time to carbon neutrality
Business-as-usual (BAU)	no carbon mitigation targets are set in the scenario, which is considered a reference	–	–
Carbon neutrality in 2050 (CN2050)	achievement of carbon neutrality in electric power system in 2050	6.29	2050
Carbon neutrality in 2045 (CN2045)	achievement of carbon neutrality in electric power system in 2045, which is used to compare and analyze the impact of energy technology innovation on pathway toward carbon neutrality	6.29	2045

distributed PV in Hong Kong and Macao is 829.8 and 46.6 MW, respectively.

To better demonstrate how the energy technology cost reduction driven by innovation accelerates the carbon neutrality in the electric power system, the following critical factors are considered in detail:

(1) The Guangdong-Hong Kong-Macao Greater Bay Area is a highly prosperous region with ambition for early achievement of carbon neutrality. In addition, the region possesses significant renewable energy potential, notably in the form of offshore wind, which provides the basis for achieving carbon neutrality. Therefore, the region is selected in this study to analyze the impacts of energy technology cost reduction driven by innovation on the pathway toward carbon neutrality in the electric power system. Other regions of the world can be similarly analyzed using the integrated investment planning and operation model after obtaining the renewable energy potential of the region, such as Northwest China,[24] India,[25] etc. Furthermore, the Bay Area exhibits imbalance between generation and load, indicating that Hong Kong and Macao cannot achieve carbon neutrality with only local generation. Thus, this study also illustrates the significance of intra-regional transmission among Guangdong Province, Hong Kong, and Macao in achieving carbon neutrality within the Bay Area. It offers valuable insights for global regions facing similar challenges of imbalanced generation and load.

(2) The learning curves with different learning rates[26,27] are incorporated into the model to represent different energy technology innovation scenarios. This study exclusively considers the impacts of learning rates on emerging energy technologies including coal-CCS, gas-CCS, biomass, biomass-CCS, offshore wind, onshore wind, utility PV, distributed PV, and battery energy storage system (BESS). The future costs of these emerging energy technologies are determined by the learning rate and capacity increment. Advanced, moderate, and conservative innovation scenarios correspond to the maximum, average, and minimum learning rates of the emerging energy technologies. The specific prediction methods are described in the "experimental procedures" section and Note S1.

(3) Energy technologies in this study encompass twelve generation technologies and two energy storage systems: coal, coal-CCS, gas, gas-CCS, biomass, biomass-CCS, hydropower, nuclear, offshore wind, onshore wind, utility PV, distributed PV, pumped hydro storage (PHS), and BESS. The transmission expansion within and outside the region is also considered in the model to represent the intra-regional and inter-regional generation and transmission synergies.

Three carbon reduction scenarios with different emission reduction policies are presented in Table 1. In addition, different energy technology innovation scenarios are considered in each carbon reduction scenario, e.g., carbon neutrality in 2045 (CN2045)-A, CN2045-M, and CN2045-C represent the advanced, moderate, and conservative energy technology innovation scenario within the CN2045 framework. The purpose of the scenario design is to demonstrate whether advanced energy technology innovation can enable electric power system to achieve carbon neutrality earlier, without exceeding the allocated budget. The annual electricity loads in the Bay Area are listed in Table S2.

Different from the carbon neutrality target of China in 2060, it is easier to achieve carbon neutrality in the electric power system than other sectors because of the rapidly development of renewable energy and carbon reduction technologies. Additionally, achieving early carbon neutrality in the electric power system can supply zero-carbon electricity to other sectors such as the transportation sector.[28] Therefore, the CN2045 and CN2050 scenarios are considered in the study, which indicate that the carbon neutrality in the electric power system is achieved in 2045 and 2050. The energy transition costs and transition pathway in the electric power system, including generation technology portfolio and transmission network topology, are obtained in each scenario.

Energy transition costs of the electric power system

Energy transition costs of the electric power system are affected by different levels of energy technology innovation. The cumulative cost of energy transition of the electric power system is shown in Figure 3A. With the development of energy technology, the cumulative cost of energy transition is gradually decreasing. The cumulative cost in the CN2045-A scenario over a 30-year period is 4,265 billion CNY (present value in 2020, ∼618 billion

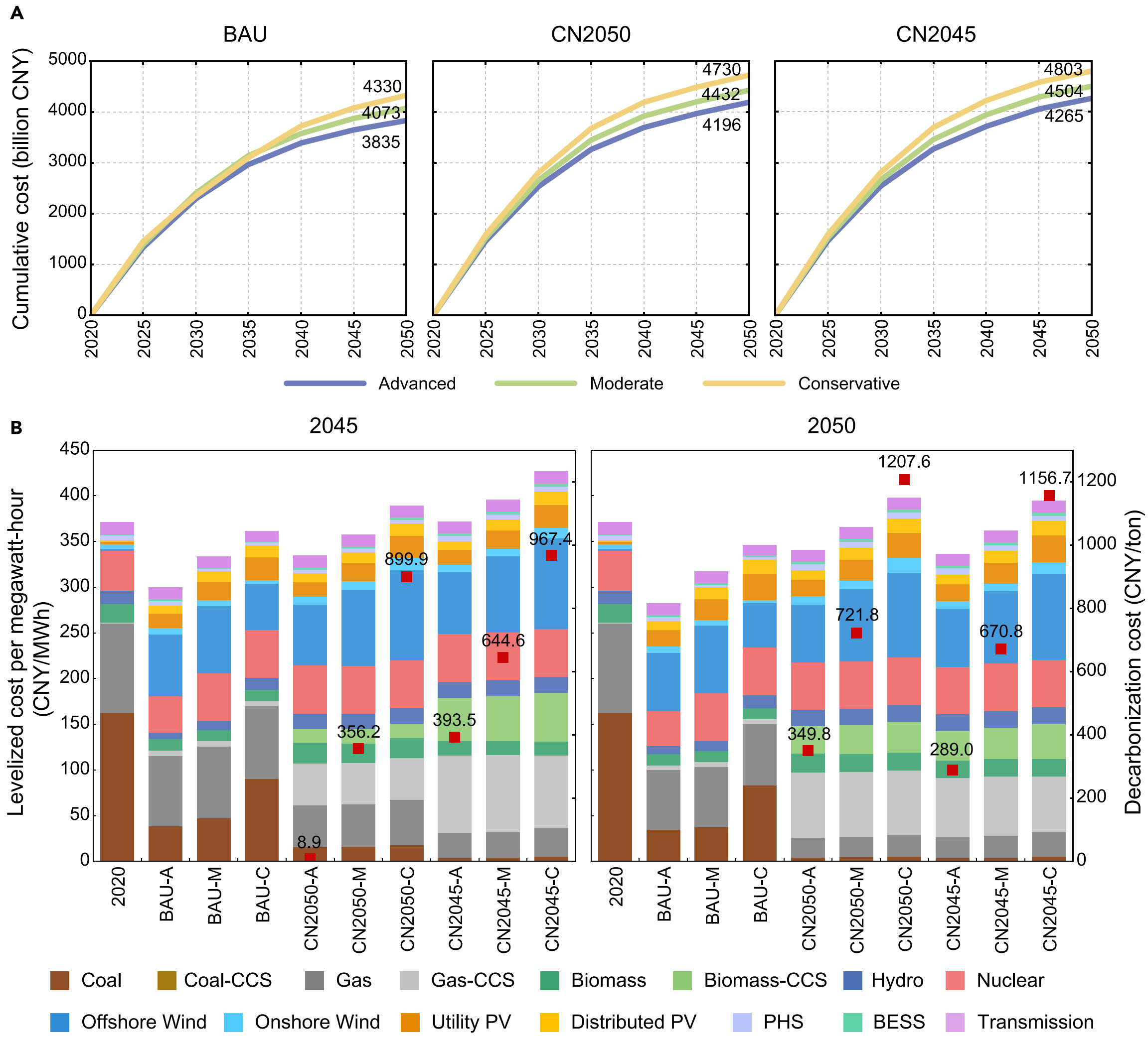


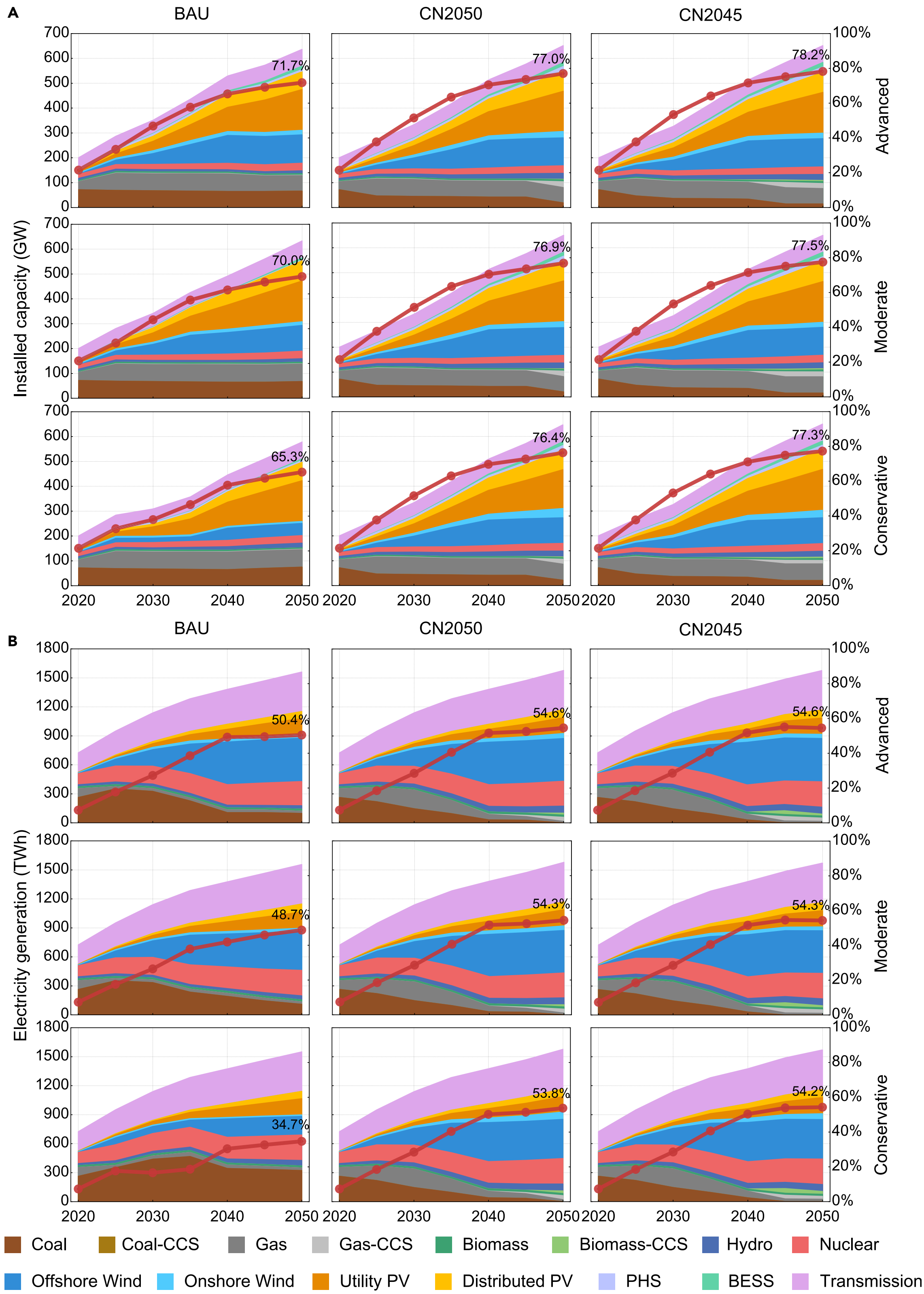
Figure 3. Energy transition costs of the electric power system under different scenarios

(A) Cumulative cost over 30 years from 2020 to 2050. The numbers in each subgraph are the cumulative cost in 2050 under different innovation scenarios.

(B) Levelized cost and decarbonization cost in 2045 and 2050. The little red square is the decarbonization cost of the scenario. Without the carbon emission constraints, the decarbonization costs are not calculated for the BAU scenarios. Energy technologies include twelve generation technologies and two energy storage systems: coal, gas, biomass, hydro, nuclear, offshore wind, onshore wind, utility PV, distributed PV, PHS, BESS, and CCS units. CCS units include coal-CCS, gas-CCS, and biomass-CCS. The cost of transmission line is also included.

USD), which is 538 billion CNY (present value in 2020, ~78 billion USD) less than 4,803 billion CNY (~696 billion USD) in the CN2045-C scenario. Importantly, the cumulative cost in the CN2045-A scenario is 3.9% and 10.9% less than the CN2050-M and CN2050-C scenarios. If the regional government allocates a budget of 4,800 billion CNY for a low-carbon energy transition, the CN2045-A scenario would achieve carbon neutrality five years earlier than the CN2050-C scenario at a cost saving of 465 billion CNY. This demonstrates that carbon neutrality can be achieved earlier and more cost effectively with a given budget in the advanced energy technology innovation scenario. In addition, the CN2045-M scenario incurs an additional cost of 4.7% compared with the business-as-usual (BAU)-M scenario. This is because stringent carbon reduction policies increase the installation of renewable energy, thereby raising the overall expense of energy transition.

Figure 3B shows the levelized cost and decarbonization cost for energy transition of the electric power system in 2045 and 2050. The decarbonization cost is the additional cost per ton of carbon reduction for each scenario relative to the BAU-M scenario. Without the carbon emission constraints, the decarbonization costs are not calculated for the BAU scenarios. Advanced energy technology innovation decreases both the levelized cost and decarbonization cost of the electric power system. In CN2045-A scenario, the levelized cost and decarbonization cost in 2050 are 336.5 CNY/MWh (~48.8 USD/MWh) and 289.0 CNY/ton (~41.9 USD/ton), which are 8.6% and 149.7% less than the CN2050-M scenario. It illustrates that carbon neutrality can be achieved earlier in the electric power system



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with lower levelized cost and decarbonization cost under the advanced energy technology innovation scenario.

Transition pathway in the electric power system from 2020 to 2050

Figure 4 demonstrates the installed capacity and electricity generation from 2020 to 2050 under different scenarios. The red dot line in the figure indicates the penetration rate of renewable energy. The carbon emission and carbon emission intensity under different scenarios over 30 years are shown in Figure S2. The penetration rate of renewable energy in electricity generation under the CN2045-A scenario is 54.6%, which is 0.4% higher compared with the CN2045-C scenario. The reduction in the capital cost of renewable energy, driven by energy technology innovation, results in an increase in both the proportion of installed capacity and electricity generation of the renewable energy. The subsequent section analyzes the impacts of different emission reduction policies based on the conservative innovation scenario.

In the CN2045-C scenario, the total installed capacity is projected to reach 582.2 GW by 2050, which is 3.78 times of the current capacity. Nevertheless, the total installed capacity in the BAU-C scenario is only 510.7 GW. The selection between conventional generation and renewable energy generation is primarily influenced by different carbon reduction targets. In the BAU-C scenario without emission limits, the generation of coal power gradually declines after peaking 466.3 TWh in 2035 due to the rapid decrease in the capital cost of renewable energy. In 2050, coal power continues to play a substantial role in the total power output, accounting for 28.2% of the overall electricity generation. By contrast, coal power gradually declines after 2020 and reaches 20.6 GW by 2050 under the CN2045-C scenario. The residual coal power is primarily utilized as flexible reserve rather than the primary source of generation.

Renewable energy generation will replace the conventional generation in the future. For the CN2045-C scenario, the installed capacities of wind power and PV are projected to reach 134.4 and 246.0 GW in 2050, accounting for 23.1% and 42.3% of the total installed capacity. For the BAU-C scenario, the installed capacities of wind power and PV are projected to reach 56.7 GW and 238.8 GW in 2050. The high cost of offshore wind power limits the installed capacity of wind power under the scenario without carbon emission constraints. The projected installed capacities of wind power and PV under the CN2050-C scenario are expected to reach 140.7 and 235.3 GW in 2050, respectively.

The anticipated high penetration of renewable energy in the future poses challenges to the security and stability of the electric power systems. Therefore, reserves must be provided by conventional generation technologies. Natural gas power is selected to replace coal power due to their lower carbon emissions and high flexibility. According to the 14th Five-year Plan for Energy Development of Guangdong Province,[29] 36 GW gas power is planned to be installed in the province from 2020 to 2025. The installed capacity of gas power in the BAU-C scenario in 2050 is only 72.0 GW due to the considerable coal power. Under the CN2045-C and CN2050-C scenarios, the installed capacities of gas power increase to 80.8 and 84.3 GW, respectively. Coal power capacities reduce to 21.9 and 20.5 GW in the two scenarios. The results suggest that gas power is used as replacements for coal power to provide reserve capacity under the scenarios with limited carbon emissions.

Biomass with CCS (bio-CCS) power is vital for achieving carbon neutrality in the electric power system due to its potential for negative carbon emissions. However, the high cost of bio-CCS power restricts their installation in the scenarios without carbon reduction constraints. In the BAU-C scenario, the installed capacity of bio-CCS power is 0 GW. As a comparison, the capacities of bio-CCS power increase to 5.6 and 3.2 GW by 2050 in the CN2045-M and CN2050-M scenarios. The findings indicate that an increased deployment of bio-CCS power is essential for achieving carbon neutrality under strict carbon reduction constraints.

Impact of inter-regional and intra-regional transmission

The power flow distribution in China can be summarized as a "from west to east" pattern, transmitting electricity from western regions to load centers on the eastern coast.[30] As a major load center of the coastal region in China, Guangdong-Hong Kong-Macao Greater Bay Area accounts for 10% of the nation's electricity. More than 20% of the electricity in the Bay Area is imported. Intra-regional transmission is defined as the electricity transmission between Guangdong Province, Hong Kong, and Macao. While inter-regional transmission is defined as the electricity transmission between the Bay Area and external regions. To determine the impacts of inter-regional and intra-regional transmission on achieving carbon neutrality in the electric power system, four scenarios are designed to compare based on the CN2045-M scenario: (1) base: CN2045-M scenario with expansion in both inter-regional and intra-regional transmission capacities; (2) R1: CN2045-M scenario with expansion of the inter-regional transmission capacity but no expansion of the intra-regional transmission capacity. (3) R2: CN2045-M scenario with expansion of the intra-regional transmission capacity but no expansion of the inter-regional transmission capacity. (4) R3: CN2045-M scenario with existing transmission infrastructure and no expansion of the transmission capacity.

The generation and transmission results under the four scenarios above are shown in Figures 5 and S3–S5. Figure 5A shows the installed capacity mix and transmission capacity results of the Guangdong-Hong Kong-Macao Greater Bay Area in 2050 under the base scenario. By 2050, 3.52 GW of DC lines and 18.00 GW of AC lines will be constructed for transmission. The intra-regional transmission capacities between Hong Kong and Macao to Guangdong Province are projected to reach 4.76 and 2.11 GW, respectively. In addition, renewable energy is anticipated to become the primary energy source in Guangdong

Figure 4. Installed capacity and electricity generation from 2020 to 2050 under different scenarios
(A) Installed capacity from 2020 to 2050. Twelve generation technologies and two energy storage systems as well as the transmission are included. The red dot line shows the penetration rate of renewable energy over years. The percentage in the graph represents the penetration rate of renewable energy in 2050.
(B) Electricity generation from 2020 to 2050.

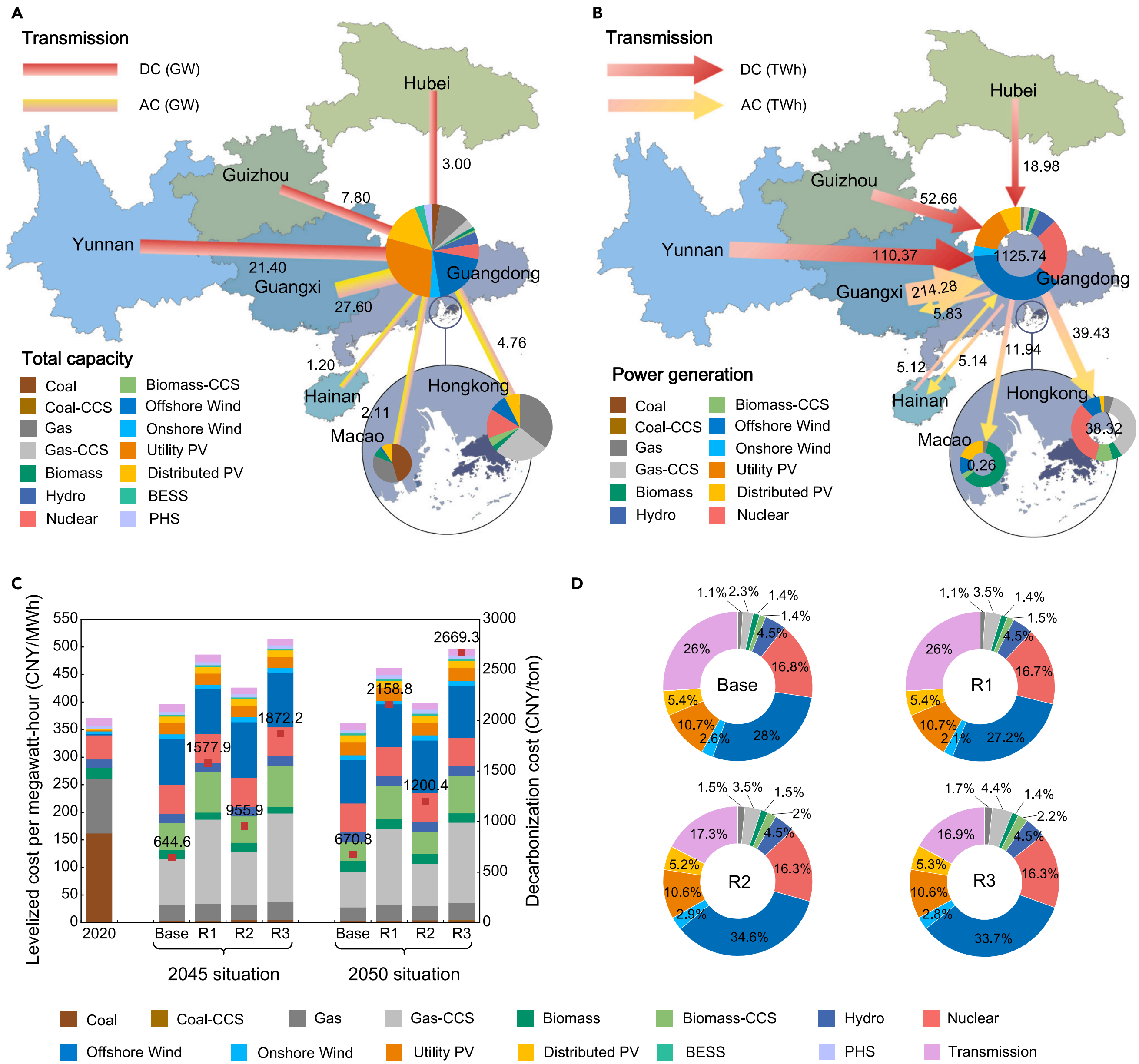

Figure 5. Generation and transmission results under different scenarios

(A) Installed capacity mix and transmission capacity results in 2050 under the base scenario. The pie charts represent the installed capacity mix in each region, and the red and yellow lines between regions represent the DC and AC transmission lines. The size of the pie charts and lines is proportional to the installed capacity and transmission capacity.

(B) Generation mix and transmission results in 2050 under the base scenario. The ring graphs represent the electricity generation mix in each region, and red and yellow arrows between regions indicate the DC and AC power flow.

(C) Levelized cost and decarbonization cost in 2045 and 2050 under four different scenarios.

(D) Electricity generation mix in 2050 under four different scenarios.

Province by 2050. However, conventional generation technologies continue to dominate in Hong Kong and Macao because limited land space restricts the development of renewable energy.

The generation mix and transmission results of the Guangdong-Hong Kong-Macao Greater Bay Area in 2050 under the base scenario are demonstrated in Figure 5B. Inter-regional electricity transmission is projected to reach 408.58 TWh per year by 2050, which is 2.03 times of the value in 2020. The transmission will continue the existing from west to east pattern, with the major electricity supplied from Yunnan, Guangxi, and Guizhou. Although the electricity transmission from Hubei Province to Guangdong Province is not part of the West-to-East power transmission project, it still plays a significant role in the

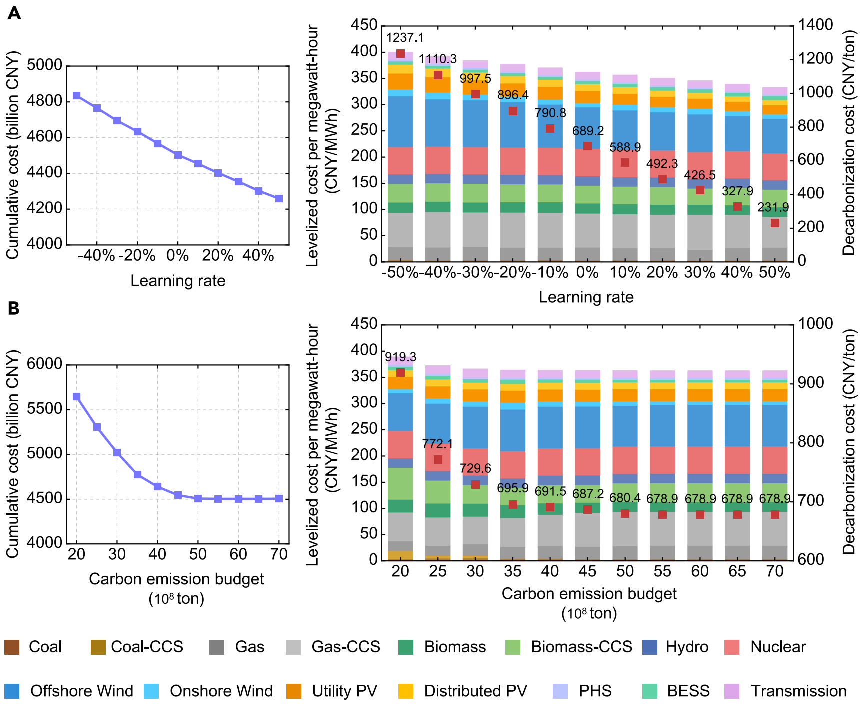

Figure 6. Uncertainty analysis results under different learning rates and carbon emission budgets

(A) Cumulative cost, levelized cost, and decarbonization cost in 2050 under different learning rates.

(B) Cumulative cost, levelized cost, and decarbonization cost in 2050 under different carbon emission budgets.

electricity supply of the study region. Intra-regional transmission from Guangdong Province to Hong Kong will increase to 39.43 TWh by 2050, accounting for 54.7% of Hong Kong's annual electricity demand. Macao, heavily relying on external electricity supplies, will receive 11.94 TWh electricity from Guangdong Province by 2050. The results indicate that the increase of electricity demand in the Bay Area leads to increased inter-regional and intra-regional electricity transmission.

The levelized cost and decarbonization cost in 2045 and 2050 under different scenarios are compared in Figure 5C. The levelized cost and decarbonization cost of the base scenario in 2050 are 365.0 CNY/MWh (~52.5 USD/MWh) and 670.8 CNY/ton (~97.2 USD/ton), both of which are lower than those projected under the scenarios with limited transmission capacity expansion. The reason is that the expansion of transmission network significantly reduces the demand for new installations of renewable energy and CCS units in the region. Figure 5D shows the electricity generation mix under four different scenarios in 2050. In the base scenario, electricity transmission accounts for 26% of the total annual electricity demand, which is 8.7% and 9.1% higher than in the R2 and R3 scenarios, respectively. Without expanded intra-regional transmission capacity, additional gas-CCS units are installed in Hong Kong and Macao to compensate for the insufficient external transmission of low-carbon electricity, which increases costs in these regions. Furthermore, to compensate for the limited expansion of inter-regional transmission capacity, additional offshore wind power and CCS units are installed in Guangdong Province. In summary, the expansion of both inter-regional and intra-regional transmission capacities can facilitate the achievement of carbon neutrality in the electric power system in a cost-effective way.

Uncertainty analysis

To assess the impact of uncertain policies on the energy transition in the electric power system, an uncertainty analysis is conducted based on the CN2045-M scenario. The analysis considers different learning rates and carbon emission budgets to represent uncertain energy technology innovation and carbon emission policies.

The uncertainty analysis results under different learning rates and carbon emission budgets are presented in Figure 6. As shown in Figure 6A, the cumulative cost, levelized cost, and decarbonization cost all decrease with the increase of learning rate. This indicates that advanced energy technology innovation drives electric power system to achieve carbon neutrality at a lower cost. Figure 6B shows that the cumulative cost, levelized cost, and decarbonization cost are inversely proportional to the carbon emission budget. Moreover, when the carbon emission budget exceeds 5 billion tons, the costs no longer decrease. This is because the carbon emission budget surpasses the optimal carbon emissions for the scenario, eliminating the need for additional CCS units installation. According to the uncertainty analysis results, it can be inferred that policies are critical in facilitating a cost-effective transition to carbon neutrality in the electric power system.

DISCUSSION

Advanced energy technology innovation increase the future cost reductions in emerging energy technologies, providing the potential for early realization of carbon neutrality in the electric power system. The Guangdong-Hong Kong-Macao Greater Bay Area is selected to analyze the impacts of energy technology cost reduction driven by innovation on the pathway toward carbon neutrality in the electric power system. Our simulation results show that the cumulative cost of the electric power system under the CN2045-A scenario is 3.9% and 10.9% less than the CN2050-M and CN2050-C scenarios. This indicates that carbon neutrality can be achieved earlier and more cost effectively in the advanced energy technology innovation scenario. In addition, the outcomes also reveal that stringent carbon reduction policies increase the installation of renewable energy, thereby raising the energy transition cost of the electric power system.

The implementation of carbon neutrality target is expected to significantly change the installed capacity and electricity generation of the electric power system by 2050, relative to 2020. Under the CN2045-C scenario, the install capacity of renewable energy is projected to reach 393.6 GW by 2050, constituting 77.3% of the total capacity. Renewable energy is anticipated to become the primary electricity provider in the electric power system, while conventional generation technologies, such as natural gas and coal power, will primarily serve to provide ancillary services. Additionally, the reductions in capital costs of renewable energy, driven by energy technology innovation, result in an increase in the proportion of installed capacity and electricity generation of renewable energy.

The expansion of both inter-regional and intra-regional transmission capacities is essential for achieving carbon neutrality in the region in a cost-effective manner. The inter-regional transmission continues the existing ‘‘from west to east’’ pattern, with the major electricity supplied from Yunnan, Guangxi, and Guizhou. Expanding intra-regional transmission within the Bay Area ensures a reliable electricity supply to Hong Kong and Macao. In addition, the expansion of transmission network significantly decreases the demand for new installations of renewable energy and CCS units, thereby reducing the energy transition costs of the electric power system. Therefore, both inter-regional and intra-regional collaboration are imperative to achieve carbon neutrality in the electric power system by 2050 at a reduced cost.

The research has been focused on the impacts of innovation-driven energy technology cost reduction on advancing carbon neutrality in the regional electric power system. However, it does not consider the correlation of energy technology innovations among regions in the world and their impact on energy technology cost reduction. It will be studied in future work.

EXPERIMENTAL PROCEDURES

Resource availability

Lead contact

Requests for further information should be directed to the lead contact, Zepeng Li (lizp22@mails.tsinghua.edu.cn).

Materials availability

No materials were used in this study.

Data and code availability

All the source data used in this analysis are available from supplemental information or cited publicly available sources. Codes used in MATLAB for this study can be made available from the lead contact upon reasonable request.

Methods

Renewable energy potential assessment

In order to assess the potential of renewable energy, different methodologies are adopted, mainly for PV and wind power. Geographic and weather data are used in the assessment. The geographic data include land occupation, altitude, slope, and marine data. The land occupation is derived from the Environmental Systems Research Institute (ESRI).[31] Altitude and slope data are obtained from the Global Enhanced Slope Database.[32] Marine data consist of ocean boundary, water depth, and marine reserves. The ocean boundary represented by locations within China’s exclusive economic zones (EEZs) is obtained from the Maritime Boundaries Geodatabase.[33] Water depth data are drived from the General Bathymetric Chart of the Oceans (GEBCO).[34] The marine reserves data are obtained from the National Maritime Data.[35] The weather data include solar irradiation and wind speed. Solar irradiation data are obtained from the SolarGIS,[36] and wind speed data are drived from the Global Wind Atlas.[37] All the geographical resolution of the data is 1 * 1 km.

The assessment of renewable energy potential is conducted based on the datasets above. For utility PV and distributed PV, the potential is assessed on the basis of land occupation, altitude, slope, and solar irradiation. Restrictions such as altitude above 3 km or slope greater than 3% are not included in the available area for PV.[38] And only the built-up areas can be used to install distributed PV. The constraints of onshore wind potential are wind speed, land occupation, altitude, and slope. For offshore wind power, potential is assessed based on the wind speed and marine data. The typical 5 MW onshore wind turbine with hub heights of 100 m and 8 MW offshore wind turbine with hub heights of 200 m above the sea level are selected to assess the potential of onshore wind power and offshore wind power. The assessment procedures of different renewable energy potential are detailed in Note S2.

Integrated investment planning and operation model

An integrated investment planning and operation model is developed to simulate the transition pathway in the electric power system toward carbon neutrality over 30 years under different scenarios. Each period of the investment planning is 5 years, which is consistent with the five-year development plan in China.[39] The long-term investment plannings and hourly operations are simultaneously optimized in the model to minimize the total cost over 30 years. Specifically, the total cost includes investment costs, maintenance costs, and operation costs. The construction and retirement of energy technologies in different stages are determined by long-term investment planning. The potential of renewable energy obtained above is considered in investment planning to constrain the installed capacity of renewable energy. To comprehensively consider the annual operating conditions and reduce the computational burden, twelve typical days are selected in the annual dataset to describe the hourly dispatch of energy technologies, which is consistent with the Zhuo et al.[8] Operation constraints such as power balance, reserve, and carbon emissions are also considered.

Hourly dispatch of the electric power system in 2050 under the BAU-M, CN2050-M, and CN2045-M scenarios is presented in Figures S6–S8. Energy technologies include twelve types of generation technologies and two energy storage systems: coal, gas, biomass, hydro, nuclear, offshore wind, onshore wind, utility PV, distributed PV, PHS, BESS, coal-CCS, gas-CCS, and biomass-CCS. To determine the impacts of regional transmission on energy transition in the electric power system, all AC and DC transmission lines are considered for expansion. The specific mathematical formulation of the integrated investment planning and operation model is detailed in Note S1. Further information of different generation technologies and energy storage systems is given in Tables S3 and S4. The parameters of transmission line are presented in Table S5.

Energy technology innovation scenarios

The learning curves with different learning rates[26,27] are incorporated into the integrated investment planning and operation model to represent different energy technology innovation scenarios. Twelve generation technologies and two energy storage systems are divided into emerging energy technologies and traditional energy technologies. Emerging energy technologies include coal-CCS, gas-CCS, biomass, biomass-CCS, offshore wind, onshore wind, utility PV, distributed PV, and BESS. The future costs of these emerging energy technologies are calculated based on the region’s actual costs in 2020 along with learning rates and capacity increments. Advanced, moderate, and conservative innovation scenarios correspond to the maximum, average, and minimum learning rates of the emerging energy technologies, respectively. While traditional energy technologies encompass coal, gas, hydro, nuclear power, and PHS. Due to the maturity of traditional energy technologies, their future costs are projected based on widely accepted annual technology baseline (ATB) electricity data from NREL.[40] The percentage trajectories from ATB data are extracted and combine with the region’s actual costs in 2020 to project the future costs of traditional energy technologies.[8] To ensure the study is based on valid data in the region, we use the actual costs of the region in 2020 from the China Electric Power Planning and Engineering Institute and China Electricity Council to project the future costs of all energy technologies in the region.[41,42] The costs of generation technologies and energy storage systems in the Bay Area in 2020 are shown in Table S3. The learning rates corresponding to different energy innovation scenarios are shown in Table S6.

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The cost projections of traditional energy technologies over 30 years are presented in Table S7. The cost projections of emerging energy technologies over 30 years under different scenarios are shown in Tables S8–S16.

SUPPLEMENTAL INFORMATION

Supplemental information can be found online at https://doi.org/10.1016/j.crsus.2024.100176.

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AUTHOR CONTRIBUTIONS

Q.W., Z.L., and X.Z. constructed the analytical framework. Z.L., C.N., and D.L. developed the original model. Q.W., Z.L., and C.N. ran the simulations and provided formal analyses. All authors contributed to the analyses and writing.

DECLARATION OF INTERESTS

The authors declare no competing interests.

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