



CO₂ emissions of constructing China's power grid towards carbon-neutral target: Based on top-down and bottom-up integrated model

Yan Liu¹

Received: 18 April 2023 / Accepted: 2 June 2023 / Published online: 15 June 2023
© The Author(s), under exclusive licence to Springer-Verlag GmbH Germany, part of Springer Nature 2023

Abstract

Power sector is the largest industrial emitter in China, and renewable energy development would contribute to the large-scale construction of power grid. Mitigating carbon emissions of power grid construction is extremely important. So, the objective of this study is to understand embodied carbon emissions of power grid construction under carbon neutrality target, and then put forward to policy implications of carbon mitigation. This study, based on top-down and bottom-up integrated assessment models (IAMs), investigates carbon emissions of power grid construction towards 2060, through identifying the key driving factors and forecasting their embodied emissions in line with China's carbon neutrality target. Our results show that, the increase of Gross Domestic Product (GDP) dominates the increase in embodied carbon emissions of power grid construction, while energy efficiency and energy structure improvement contribute to the decrease. Large scale renewable energy development promotes the power grid construction. In 2060, total embodied carbon emissions would increase to 1105.7 Million tons (Mt) under the carbon neutrality target. However, the cost and key carbon-neutral technologies should be re-considered to ensure the sustainable electricity supply. The results could provide data reference and decision-making of designing power construction and mitigating carbon emissions of power sector in future.

Keywords Carbon neutrality · Embodied carbon emissions · Power grid construction · Driving factors · Global Change Assessment Model

Introduction

China has promised to peak its emissions before 2030 and achieve carbon neutrality target by 2060. However, due to heavy-industry-dominated production structure with young plants of thermal power, steel and iron, cement, China is faced with huge mitigation pressure towards carbon neutrality target. Power sector is the key sector to mitigate its emission through power structure adjustment (Bistline and Blanford 2021). Power grid, as the transmitter of the electricity, become more and more important to plan its construction and layout among China, in order to freely dispatch the electricity in future (Santos Silva et al. 2021, Eichner

and Pethig 2015). The scientific and reasonable plan of the grid construction contribute to optimize the allocation of electricity among different regions. Also, CO₂ emissions of power grid construction is also another important point for mitigation, because most of researchers focus more on the emissions of power generation in particular to the thermal power (Tang et al. 2018; Tao et al. 2019; Wei et al. 2021).

In 2020, China generate electricity about 7626.5 billion kWh, an increase of 4.1% than that of 2019. Growing by 4.6% than the previous year, total transmission loop lines of above 220 kV reach 794×10³ km, twice of that in Europe, and corresponding capacity of substation equipment is about 4.53 billion KVA. Meanwhile, the cross-region transmission capacity of electricity is 156.16 million kW, and the transmitted electricity reach 647.4 billion kWh with a growth of 13.3%, 8.9% of total electricity generation (Wei et al. 2021). However, due to the commitment of carbon neutrality target with large-scale deployment demand for renewable energy and unequal renewable energy resource such as solar and wind, future power transmit situation would

Responsible Editor: George Z. Kyzas

✉ Yan Liu
sgccliuyan@163.com

¹ State Grid Shaoxing Power Supply Company, Shaoxin 312000, China

change significantly from traditional “West to East power transmission” to “All around to the Southwest”. So, how to design future power structure and conduct research on accounting of CO₂ emissions, is an urgent problem for us to tackle with it.

Recently, most studies focused on the development and CO₂ emissions of power generation sector. Power generation produce about 40% of national CO₂ emissions in China, and many literatures investigate how to reduce its emissions and turn to low-carbon or clean power generation relied on solar, wind and water etc. For example, Peng et al. (2018) explored how to manage China’s coal power plants to address multiple environmental objectives. Wang et al. (2021) investigated location-specific co-benefits of carbon emissions reduction from coal-fired power plants in China. Liu et al. (2020) conduct near-real-time daily estimates of fossil fuel CO₂ emissions including power generation sector from major high-emission cities in China. Qiu et al. (2022) find that electricity sector decarbonization and DAC technology improvements are both indispensable to avoid environmental problem-shifting. Zhang et al. (2023) optimize the operation strategy of a combined cooling, heating and power system based on energy storage technology. Liang and You (2023) indicated that reshoring silicon photovoltaics manufacturing contributes to decarbonization and climate change mitigation. Thus, existing studies paid more attention to the mitigation of power generation sector, and less were involved in power grid construction.

Several studies conduct static analysis of power transmit sector even the accounting of its CO₂ emissions. However, current literatures seldom systematically analyze CO₂ emissions embodied in power grid construction, in particular related to the planning of its construction under carbon neutrality target. Cao et al. (2016) conduct a comprehensive study on low-carbon impact of distributed generations on regional power grids: A case of Jiangxi provincial power grid in China. Wei et al. (2021) calculated embodied greenhouse gas emissions from building China’s large-scale power transmission infrastructure during 1990–2017, and compiled the detailed facility-level and transmission-line emissions. Li et al. (2022) conduct research on Energy storage reduces costs and emissions even without large penetration of renewable energy in the case of China Southern Power Grid. Manojlovic et al. (2023) indicated that decarbonizing the national power grid to reduce the complete replacement of the fleet with EVs for achieving net zero emissions requires all the available solar, wind, and hydropower resources of the Republic of Serbia. In the foreseeable future, China’s power transmission infrastructure will expand rapidly, due to the significant demand to support the fast-growing renewable power generation. However, rarely studies have explored the building of power transmission infrastructure and consequent emissions to achieve carbon neutrality target towards

2060. Especially, the power demand will double by 2060 compared with that of 2020, and would be reached to 16.67 PWh. Meanwhile, trans-regional transmission of electricity would increase by 2.5~4 times than that in 2020. So, uncovering the development of power transmission sector and quantifying the emissions towards 2060 is very important as an important supplement for zero-carbon power system.

Integrated assessment model (IAM) for energy economics and climate change is the main method to simulate decarbonization development pathway of power, industry or building etc. (Wu et al. 2020; Zhang et al. 2019; Zhao et al. 2021). The most popular IAM model includes Global Change Assessment Model, Computable General Equilibrium model, Dynamic Integrated model of Climate and the Economy and Greenhouse Gas and Air Pollution Interactions and Synergies, and Long-range Energy Alternatives Planning System. Specifically, they could be divided into bottom-up IAM model and top-down IAM model. Bottom-up IAM model pay more attention to technology-related policies or measures, and can reveal more detailed technological process of production. More importantly, although Greenhouse Gas—Air Pollution Interactions and Synergies (GAINS) and Long-range Energy Alternatives Planning System (LEAP) have highly integrated framework for simulation, they could also have no fixed framework and accordingly reduce the model complexity of calculation in which model could be restructured as needed. However, top-down model aims at characterizing feedback relationships among economic development, energy demand, CO₂ emissions and climate change and land use. They could be very complex even in basic model framework, and focus on policy- or single-technology-related simulation to reveal general GDP loss, sectoral output, energy demand or temperature rise. Nowadays, top-down and bottom-up models are integrated to explore the effects of policies, market and technologies for low-carbon development. In this case, fairness for intersectoral low-carbon development and efficiency for minimum investment could be balanced (Qu et al. 2017).

However, existing studies have not conduct accounting for embodied emissions of power grid construction towards carbon neutrality target. In this case, policy design and power grid planning could be even biased to achieve the carbon mitigation target because the contribution and key factors of emissions in power grid sector is unclear. Therefore, this study adopts integrated top-down model of Global Change Assessment Model (GCAM) and bottom-up model of Logarithmic Mean Divisia Index (LMDI), in order to simulate the development of power transmission network and corresponding CO₂ emissions. We first, based on GCAM model, explore the electricity demand, installed capacity and power structure of China towards carbon neutrality target. Then, improved LMDI model, coupled with GDP growth, population expansion and income increase, is applied to identify

the key factors of CO₂ emissions and forecast future CO₂ emissions by 2060 (Lin and Du 2014). Our contribution lies in that: (1) as far as our knowledge, we are the first to quantify CO₂ emissions of power transmission grid construction towards carbon neutrality target through identifying key driving factors and forecast their future changes; (2) the top-down and bottom-up models are integrated to simulate the demand for electricity and then as a factor input to explore the changes of CO₂ emissions in power grid construction. Our results could provide insight into policy implications of power grid design and zero-carbon power system. So, our study aims at providing data reference, decision-making and policy implications for future power grid construction toward carbon neutrality target. Meanwhile, the top-down and bottom-up IAM could be used to analyze mitigation pathway for achieving carbon neutrality target in other countries or sectors.

The remaining part is organized as follows: “[Methodology and data source](#)” section displays the overview situation of power grid construction, and “[Overview of embodied CO₂ emissions of 226 China’s power grid construction](#)” section is Methodology and data source. Results and discussions are showed in “[Results and discussions](#)” section, and we conclude and provide policy implications in “[Discussions](#)” section.

Methodology and data source

GCAM model

GCAM model, i.e., global change assessment model, is a comprehensive assessment model of global climate change. It is developed by the Global Change Research Institute,

jointly built by Pacific Northwest National Laboratory of the United States and the University of Maryland, and as one of the integrated assessment models adopted by “[Specific Report on Emission Scenarios](#)” of Intergovernmental Panel on climate change (IPCC). The model includes five models of energy, agriculture and land use, regional climate and global climate, and is divided into 14 regions, with a base year of 1990, a time step of 5 years, and a time span of 2100, covering more than 10 major greenhouse gases. The first use of GCAM (then MiniCAM) and Monte Carlo uncertainty analysis was published in Reilly et al. (1987). GCAM model, with multi-regional, high integration, multivariable features, has advantage in exploring the effects global climate change, energy and water use, and land allocation, and offers detailed results on these factors in terms of production, consumption, sectors and sub-sectors, technologies, costs, etc. However, the current version of GCAM 6.0 is not for solving China’s resource and environmental problems, and multi-provincial GCAM-China is not public for all academic fields. The simulation for China’s power grid construction is thus limited to the national level.

The model formwork is shown in Fig. 1.

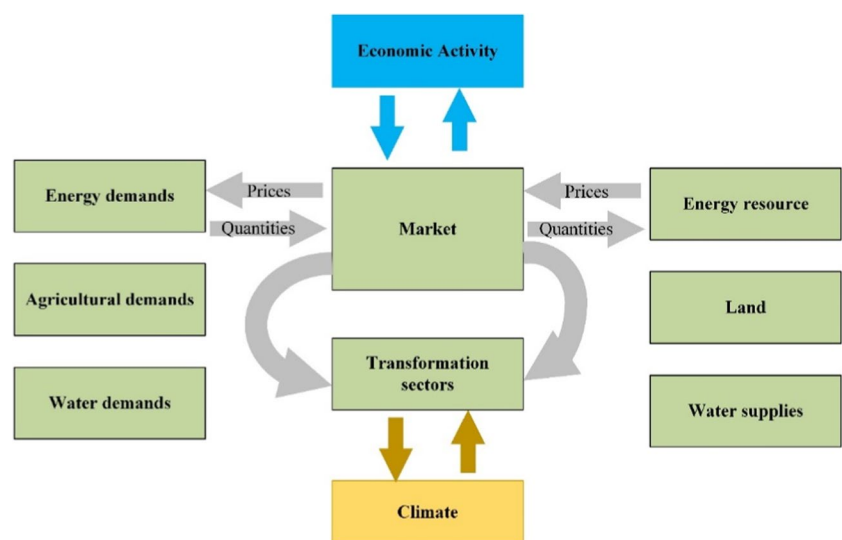
LMDI model

Accordingly, we build the improved Kaya identity of embodied carbon emissions of China’s power grid (Ang 2004, 2005, 2015), as shown in Eq. (1).

$$C = \frac{C1}{ELE1} \cdot \frac{ELE1}{E1} \cdot \frac{E1}{GDP} \cdot GDP + \frac{C2}{ELE2} \cdot \frac{ELE2}{E2} \cdot \frac{E2}{GNP} \cdot \frac{GNP}{P} \cdot P \quad (1)$$

where, *C*, *C1* and *C2* indicates total embodied carbon emissions, production-related embodied carbon emissions and daily life related embodied carbon emissions of power grid

Fig. 1 GCAM model framework



construction. *ELE1* and *ELE2* indicates production- and daily life- related electricity consumption. *E1* and *E2* indicates production- and daily life- related energy consumption. *GDP* indicates the gross domestic product and *GNP* is gross national product. *P* indicates the total population.

LMDI model is a preferred index decomposition analysis approach because of the advantages of path independence, residue free, ability to handle zero values, and consistency in aggregation, and is widely used to analyze the variations in energy usage and emissions (Li et al. 2017, 2020). However, LMDI follows the fixed frame structure, and variable adoption is limited in this frame work. Then aggregate embodied carbon emissions of power transmission between the base year 0 and the target year T could be decomposed into nine parts, expressed as Eq. (2):

$$\Delta C = C^T - C^0 = (\Delta C_{PI} + \Delta C_{PS} + \Delta C_{PEI} + \Delta C_{PG}) + (\Delta C_{HI} + \Delta C_{HS} + \Delta C_{HEI} + \Delta C_Y + \Delta C_P) \quad (2)$$

where, ΔC_{PI} and ΔC_{PI} represent carbon intensity effects of electricity production, ΔC_{PS} and ΔC_{HS} represent electricity structure effect of production sector and household sector, ΔC_{PEI} and ΔC_{HEI} represent energy intensity of production sector and household sector, ΔC_{PG} represents production scale effect, ΔC_Y represents income improvement effect, and ΔC_P represents population scale effect.

The effects of various driving factors of embodied CO₂ emissions in China's power grid industry are calculated using the following equations:

$$\Delta C_{PI} = L(C^0, C^t) \cdot \ln(PI^t / PI^0) \quad (3)$$

$$\Delta C_{PS} = L(C^0, C^t) \cdot \ln(PS^t / PS^0) \quad (4)$$

$$\Delta C_{PEI} = L(C^0, C^t) \cdot \ln(PEI^t / PEI^0) \quad (5)$$

$$\Delta C_{PG} = L(C^0, C^t) \cdot \ln(PG^t / PG^0) \quad (6)$$

$$\Delta C_{HI} = L(C^0, C^t) \cdot \ln(HI^t / HI^0) \quad (7)$$

$$\Delta C_{HS} = L(C^0, C^t) \cdot \ln(HS^t / HS^0) \quad (8)$$

$$\Delta C_{HEI} = L(C^0, C^t) \cdot \ln(HEI^t / HEI^0) \quad (9)$$

$$\Delta C_Y = L(C^0, C^t) \cdot \ln(Y^t / Y^0) \quad (10)$$

$$\Delta C_P = L(C^0, C^t) \cdot \ln(P^t / P^0) \quad (11)$$

where $L(C^0, C^t) = \frac{C^T - C^0}{\ln(C^T) - \ln(C^0)}$ is the logarithmic mean weight.

Embodied carbon emissions forecast

The embodied carbon emissions of power grid construction, using the equation transformation of Eq. (2), could be forecasted. The following equations display how the effects of various driving factors are calculated (Su and Ang 2016).

$$\begin{aligned} \Delta C = C^T - C^0 &= (\Delta C_{PI} + \Delta C_{PS} + \Delta C_{PEI} + \Delta C_{PG}) \\ &+ (\Delta C_{HI} + \Delta C_{HS} + \Delta C_{HEI} + \Delta C_Y + \Delta C_P) = \frac{C^T - C^0}{\ln(C^T) - \ln(C^0)} \\ &\cdot [\ln(PI^t / PI^0) + \ln(PS^t / PS^0) + \ln(PEI^t / PEI^0) \\ &+ \ln(PG^t / PG^0) + \ln(HI^t / HI^0) + \ln(HS^t / HS^0) \\ &+ \ln(HEI^t / HEI^0) + \ln(Y^t / Y^0) + \ln(P^t / P^0)] \end{aligned} \quad (12)$$

The growth rate of various variables between the base year 0 and the target year T can be expressed with $\alpha, \beta, \gamma, \delta, \rho, \epsilon, \theta, \vartheta, \tau$. In this way, Eq. (12) can be rewritten as Eq. (13).

$$\ln(C^t) - \ln(C^0) = \ln(\alpha) + \ln(\beta) + \ln(\gamma) + \ln(\delta) + \ln(\rho) + \ln(\epsilon) + \ln(\theta) + \ln(\vartheta) + \ln(\tau) \quad (13)$$

$$\ln(C^t / C^0) = \ln(\alpha \cdot \beta \cdot \gamma \cdot \delta \cdot \rho \cdot \epsilon \cdot \theta \cdot \vartheta \cdot \tau) \quad (14)$$

$$C^t = C^0 \cdot (\alpha \cdot \beta \cdot \gamma \cdot \delta \cdot \rho \cdot \epsilon \cdot \theta \cdot \vartheta \cdot \tau) \quad (15)$$

where,

$$W = \frac{C^0 \cdot [(1 + \alpha) \cdot (1 + \beta) \cdot (1 + \gamma) \cdot (1 + \delta) \cdot (1 + \rho) \cdot (1 + \epsilon) \cdot (1 + \theta) \cdot (1 + \vartheta) \cdot (1 + \tau) - 1]}{\ln[(1 + \alpha) \cdot (1 + \beta) \cdot (1 + \gamma) \cdot (1 + \delta) \cdot (1 + \rho) \cdot (1 + \epsilon) \cdot (1 + \theta) \cdot (1 + \vartheta) \cdot (1 + \tau)]} \quad (16)$$

Therefore, CO₂ emissions in the target year can be predicted using Eqs. (2) and (12)–(16). Where, *W* represents logarithmic mean weight.

Data source and processing

GDP, population, per capita income, electricity consumption and energy use during 2017–2020 are collected from

Table 1 Key factors used in this study in 2020, 2030 and 2060

Variables	2017	2030	2060
C (Mt)	890	-	-
C1 (Mt)	124.56	-	-
C2 (Mt)	765.44	-	-
ELE1 (Billion kWh)	5574.9	8362.35	13,937.25
ELE2 (Billion kWh)	907.2	1632.96	3628.8
E1 (Mtce)	3910.09	5060	4730
E2 (Mtce)	576.2	1000	2000
GDP (Billion RMB)	82,712.17	170,000	420,000
P (Million persons)	1390.08	1442	1283.14

China Statistical Yearbook (2018–2021). Embodied carbon emissions of power grid construction are from Wei et al. (2021). Future changes of above factors in 2030 and 2060 are collected from existing studies. For example, future population of China refers to “Report on China’s population and labor problems”.

The detail of the factors is in Table 1:

Overview of embodied CO₂ emissions of China’s power grid construction

As shown in Fig. 2, China’s total embodied carbon emissions increased from 121.5 million tons (Mt) in 1990 to 890 Mt in 2017, increased by 632.5% during the study period. Among regions, North China are largest Embodied carbon emitter of 187.3 Mt, followed by Eastern China (177.6 Mt) and Central China (151.4 Mt). In contrast, Northeast and Northwest are relatively small, and their embodied carbon emissions were 79.2 Mt and 86.4 Mt in 2017, respectively. Embodied carbon emitter of cross-regional power grid construction is 30.6 Mt in 2017. In

terms of growth rate, Southern grid experienced the most rapid growth of 959.8% from 1990 to 2017, while North-east grid has the lowest growth rate of 237.9.

As to cross-regional power grid construction, embodied carbon emissions increased from 5.8 Mt in 2000 to 30.6 Mt, with a growth rate of 424.4%; however, locally regional embodied carbon emissions maximum increased by 296.2% during the same period. This indicates the higher growth of cross-regional power grid development, and support the power development planning of “West to East Power Transmission” and regional economic development in China. Trans-provincial and trans-regional power transmission is an important means to ensure the safety of national energy strategy and solve the contradiction between energy resources and load centers in China. The establishment of inter provincial and inter regional power trading markets has promoted the optimal allocation of resources in a wider range, and played an important role in ensuring power supply, promoting the development of clean energy, maintaining power grid security, and efficient utilization of resources.

Figure 3 shows that embodied CO₂ emissions by facility of power grid construction during 1990–2017. We can conclude that the construction of direct current (DC) transmission line and alternating current (AC) substations started since 2005 and then increased significantly. In contrast, AC transmission lines and AC substations were observed a rapid increase especially before 2010. Specially, cumulative embodied CO₂ emissions of AC transmission lines and AC substations raised by 32.5% and 61.3% during 2010–2017, increasing to 811.6 Mt and 843.3 Mt in 2017; while cumulative embodied CO₂ emissions of DC transmission lines and DC convertor stations increased by 428.1% and 341.1% in this time span, reaching 19.5 Mt and 34.0 Mt of emissions in 2017. Overall, DC transmission lines and DC convertor stations jointly dominated CO₂ emissions of power grid lines

Fig. 2 Embodied CO₂ emissions of China’s power grid system

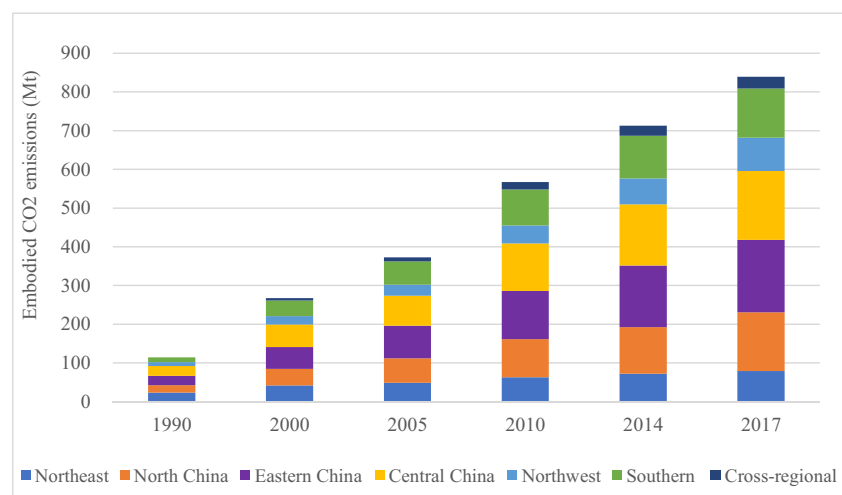
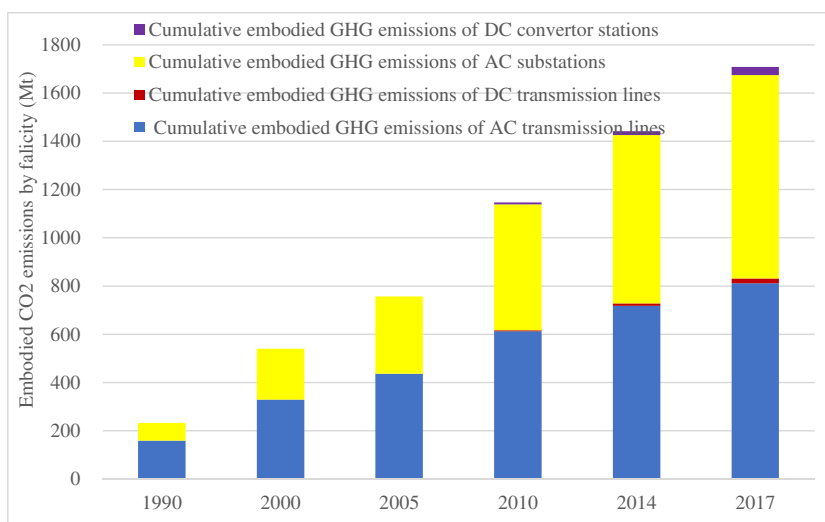


Fig. 3 Embodied CO₂ emissions by facility of power grid construction



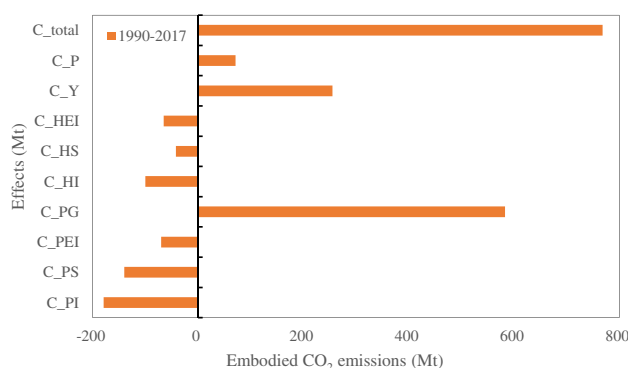
and station. Since 2005, the construction of transmission and transformation lines of the Three Gorges project has made China become the world’s largest High Voltage Direct Current transmission country. The main reason lies the higher electricity loss of AC in the long-distance transmission process although it has large transport capacity and is more convenient through voltage rise and fall. So, to avoid large loss of electricity from the West to East in China, high voltage direct current system develops considerably especially after 2005.

Results and discussions

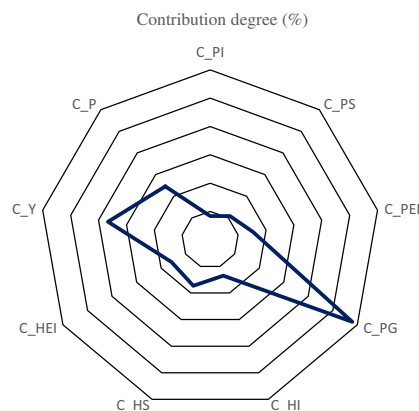
Decomposition analysis of embodied carbon emission change

Based on LMDI method, we quantified the contributions of various factors, (i.e., C_{PI}, C_{PS}, C_{PEI}, C_{PG}, C_{HI}, C_{HS}, C_{HEI}, C_Y, and C_P) to the increase of CO₂ emissions embodied in power grid construction from 1990–2017, as shown in Fig. 4. In general, carbon intensity effect of electricity generation and power structure effect contributed most to the inhibition of embodied carbon emissions of power grid construction, and their effect were -279.5 Mt, -181.8 Mt, respectively. Meanwhile, contribution degree of both of them reached -36.4% and -23.7%. Also, energy intensity effect in production and household sector play significant role in reducing the embodied carbon emissions, during which they curb embodied carbon emissions by 70.0 Mt and 65.1 Mt from 1990 to 2010 with the contribution degree of 9.1% and 8.5%.

As to the positive contribution to embodied carbon emissions of power grid construction, production scale effect, i.e., the



(a)



(b)

Fig. 4 Total effects of embodied CO₂ emissions of power grid construction during 1990–2017. Note: C_{total} represents total changes of CO₂ emissions between base year and target year; C_{PI}, C_{PS}, C_{HS}, C_{PEI}, C_{HEI}, C_{PG}, C_{HI}, C_Y, and C_P represent carbon intensity effects of electricity production, electricity structure effect of production sector and household sector, energy intensity of production sector and household sector, production scale effect, income improvement effect, and population scale effect

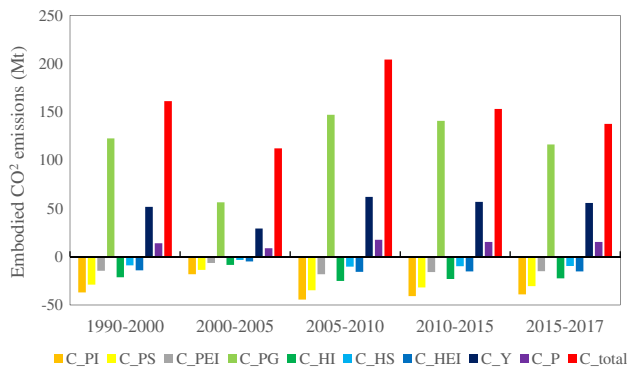


Fig. 5 Interval effects of embodied CO₂ emissions of power grid construction during 1990–2017

increase of GDP, dominated the increase, with a contribution of 583.0 Mt during 1990–2017 (Contribution degree: 75.9%). Furthermore, both income improvement and population scale have a positive effect on the embodied carbon emissions of power grid construction. Specially, income improvement effect increases embodied carbon emissions by 255.2 Mt, with a growth rate of 33.2%, while population increase have a minor effect on the increase, with a contribution of 71.1 Mt from 1990–2017 (Fig. 5).

Generally, embodied CO₂ emissions of power grid construction and their driving factors experienced an inverted U-shaped changing trend from 1990–2017. This is related to the large-scale construction of power plant and grid during 2000–2015, in order to meet the increasing demand for electricity due to rapid industrialization and urbanization. Especially during 2005–2015, China's power capacity increased from 516.79 million kW to 1524.67 million kW, power generation increased from 2.5 trillion kW·h to 5.81 trillion kWh. Meanwhile, the circuit length of transmission lines of 220 kV and above increased from 0.25 million km to 0.6 million km, and the capacity of substation equipment increased from 866.8 million KVA to 3366 million KVA. The increase in embodied carbon emissions of electricity transmission construction during 2005 to 2010 reached the largest of 204.3 Mt during 1990–2017 among different time intervals. Also, contribution degree of various effects fluctuated relatively small, less than 5%, among different time intervals. So, the positive driving factor of GDP growth and income improvement remained the significant contribution to the increase of embodied carbon emissions of power transmission infrastructure.

Future embodied emissions of power grid construction under carbon neutrality

Future electricity production based on GCAM model

We integrated the bottom-up LMDI model into top-down GCAM model to calculate the embodied emissions of power

grid construction under carbon neutrality. First, we showed the electricity production of China during 2020–2060 under the carbon neutrality target. As showed in Table 2, total electricity production or consumption is 12.16 trillion kwh in 2030 and 21.49 trillion kwh in 2060, because GCAM model assume the equilibrium electricity market. In this case, our model predicts that the growth rate of electricity consumption in 2030 and 2060 are 76.6% and 156.5%, and is bound to drive the rapid growth of power grid construction from 2020 to 2060. Specifically, the share of thermal power of coal, oil and natural gas would decline to 25.5% in 2030 and 17.1% in 2060, while wind and solar power would increase to 34.2% in 2030 and 43.9% in 2060, accounting for approximately half of total non-fossil energy power generation. Meanwhile, the share of power generation with CCS reach to 17.9% in 2030 and 23.3% in 2060. Obviously, another important mode is the nuclear power generation, contributing of 26.8% to total power generation. Because the model has high expectation for the development of nuclear power and CCS deployment, carbon pricing is 600\$ in this study, higher than that of 450\$ in IEA report.

All in all, electricity development pathway is approximately in line with the mainstream trend in most studies. More importantly, the high growth of electricity consumption promotes the rapid increase in power grid construction and then embodied carbon emissions of China. Large-scale development of renewable energy power generation requires high share and capacity of electricity storage system. Subsequently, it maybe increases the embodied carbon emissions for maintaining the high stability of power grid and energy safety. As known to all, recent large-scale black-out of power supply in Sichuan and Northeast, due to high share of renewable energy and insufficient power supply in extreme weather.

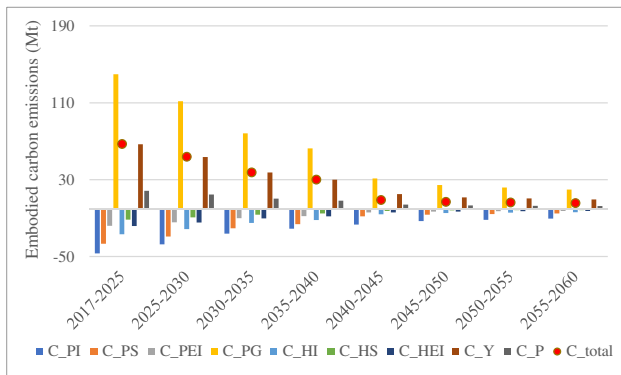
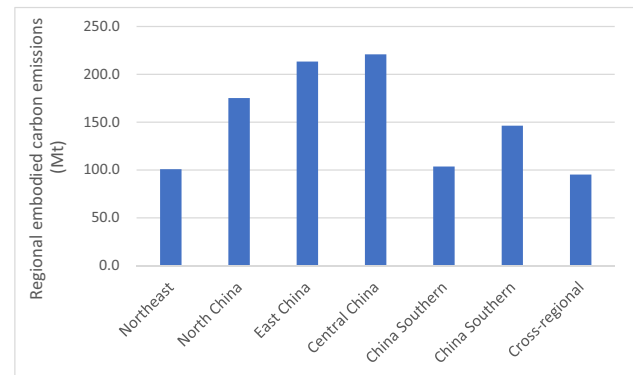
Future embodied carbon emissions of power grid construction

As shown in Fig. 6, we calculated future various effects of embodied carbon emissions of power grid construction from 2017–2060, according to the growth rate of key driving factors to the embodied emissions. We can conclude the decreasing effects of various factors to the increase in the emissions. The increased embodied emissions of decrease from 67.1 Mt during 2017 to 2025 to 5.5 Mt during 2055 to 2060, during which the rapid increase of GDP and income improvement also play the significant role in the increase in the embodied emissions, and decreasing energy intensity and energy structure improvement jointly contributed to the decrease in the emissions. More importantly, the relative size of various effects remains unchanged from 2017–2060. This is attributed to our assumption that we follow the historical change trend of various factors. In this case, total embodied

Table 2 Electricity production or consumption of China under carbon neutrality target

Million tce	2020	2025	2030	2035	2040	2050	2060
biomass (IGCC CCS)	0.0	0.8	6.1	11.5	15.3	20.9	30.8
biomass (IGCC)	0.0	0.6	0.8	0.4	0.2	0.0	0.0
biomass (conv CCS)	0.0	3.8	52.6	86.9	100.4	112.5	130.6
biomass (conv)	8.5	11.0	7.7	1.5	0.4	0.0	0.0
coal (IGCC CCS)	0.0	9.5	55.9	92.9	114.8	137.5	158.8
coal (IGCC)	0.0	9.1	9.6	3.4	1.6	0.2	0.0
coal (conv pul CCS)	0.0	17.5	83.1	126.1	148.1	164.9	169.8
coal (conv pul)	584.9	517.7	198.2	46.2	19.1	2.3	0.2
gas (CC CCS)	0.0	4.1	17.7	28.8	35.5	44.1	56.1
gas (CC)	6.5	6.8	6.3	5.2	4.2	2.2	0.6
gas (steam/CT)	12.5	7.5	3.5	1.7	1.0	0.3	0.0
geothermal	2.1	3.9	3.8	3.8	3.9	3.9	3.8
hydro	136.9	136.9	136.9	136.9	136.9	136.9	136.9
refined liquids (CCS)	0.0	0.6	2.1	1.9	1.5	1.3	1.8
refined liquids (CC)	0.2	0.1	0.1	0.1	0.0	0.0	0.0
refined liquids (steam)	0.6	0.3	0.2	0.1	0.1	0.0	0.0
rooftop_pv	2.1	31.7	41.1	62.1	91.1	138.0	177.4
CSP	0.0	0.0	0.0	0.0	0.0	0.0	0.0
CSP_storage	0.0	0.1	0.8	2.7	5.0	11.0	24.0
PV	12.5	51.4	155.6	222.9	261.5	293.5	326.1
PV_storage	0.0	0.0	0.3	1.0	1.9	4.1	9.0
wind	37.2	84.9	212.0	300.3	353.4	385.8	430.7
wind_offshore	0.0	0.5	4.4	10.2	16.2	29.3	50.5
wind_storage	0.0	0.2	1.6	3.5	5.2	8.3	13.1

IGCC represents Integrated Gasification Combined Cycle technology; CCS represents Carbon Capture and Storage technology; PV represents Photovoltaic Solar Power Generation technology; CSP represents Concentrating Solar Power Generation technology

**Fig. 6** Interval effects of embodied CO₂ emissions of power grid construction during 2017–2060**Fig. 7** Regional and cross-regional embodied CO₂ emissions of power grid construction during 2055–2060

carbon emissions would increase to 1105.7 Mt during 2055 to 2060 under the carbon neutrality target Fig. 7.

Furthermore, we classified six regional embodied carbon emissions and cross-regional embodied carbon emissions under carbon neutrality target. Obviously, central China has the largest growth rate of embodied carbon emissions

of power grid construction. Northeast, southern China and eastern China increase slowly. However, cross-regional power grid construction would experience a rapid increase in the future due to the expansion of cross-regional electricity transmission from the change of energy supply system. In the future, considering the abundant solar and wind resource,

electricity transmission situation of West–East Electricity Transmission Project transmits to that of North, West and South-Central China Electricity Transmission Project. All in all, Northeast, North China, East China, Central China, China Southern, China Southern, Cross-regional embodied carbon emissions of power grid construction are 100.8 Mt, 175.1 Mt, 213.2 Mt, 220.8 Mt, 103.6 Mt, 146.2 Mt and 95.3 Mt in 2060.

Discussions

This study explores the roadmap of electricity grid construction in China, and focus on the embodied carbon emissions and electricity consumption under the carbon neutrality target. We display the detail change of embodied carbon emissions and electricity consumption based on top-down and bottom-up integrated assessment model.

Compared with only a few existing studies, we draw both similar and different conclusions. First, Wei et al. (2021) calculated embodied emissions of China's power grid construction in detail during 1990–2017. However, the study is to explore the historical condition, and is not considered future carbon neutrality target. So, influencing factors identification from 1990–2060 could enhance significance and necessity for future the design of power grid development. Chen et al. (2022) design a two-phase market clearing framework for inter-provincial electricity trading in Chinese power grids. Ma et al. (2023) constructed an interprovincial power transmission framework to measure the seasonal carbon emissions embodied in regional electricity consumption over the period of 2008–2015 based on quarterly data. Chen et al. (2023) simulated the decarbonization of China's regional power grid by 2050, and investigated the effects of government development planning scenario. They mainly focused on how a single policy or measure affect power grid decarbonization. However, our study is in line with the carbon neutrality target, quantifying the influencing factors of embodied energy during 1990–2060. The most difference between our study and existing studies lies in that our study is not limited in the accounting for embodied CO₂ emissions of power grid construction but simulate climate target and the emissions of power grid construction, from both historical and future perspectives.

Some limitations also exist in our study that need us to investigate in future study.

First, we do not consider the cost of power grid construction under the carbon neutrality target. In the future, large scale deployment of power storage is necessary, and the capacity of the storage would account for about 1/3 of total renewable energy installation. For example, most studies reveal the lower leveling cost of solar, almost as lower as the thermal power generation; however, more power storage

capacity need to install to maintain safe and stable operation and then the total system cost would increase. In this case, the real cost of renewable energy is expected to be higher than current consideration. So, we should further conduct the cost accounting of renewable energy construction, and promote sustainable development of renewable energy through system planning and supporting policies or measures.

Second, the overall planning of power grid construction should be explored systematically. There exists large difference in ideal and reality of renewable energy deployment. For example, existing studies evaluate the PV installation potential in which building roof and wasteland could be make full use for power generation. In fact, maybe limited space could be employed because waterproof material, sloping roof, and cooling tower takes up a lot of roof space. The real share of PV installation only accounts for below 10% in total roof space, let alone the facade. To what degree the building roof could be utilized should be investigated to assess the accurate renewable energy supply potential. So, scientific model and field investigation would be necessary, not limited to satellite remote sensing measurement.

Conclusions and policy implications

Conclusions

In this study, we focus on the construction of power grid and embodied carbon emissions in China. Through integrating the bottom-up and top-down models, we predict embodied carbon emissions of power grid construction from 2017–2060. First, we identify the key factors of the increase in embodied carbon emissions. Economic growth has the largest contributions of 75.9% to the increase in the embodied carbon emissions of power grid construction, followed by income improvement effect of 33.2%. In the past thirty decades, China's rapid economic growth and income improvement have promoted power grid construction, dominated the increase in CO₂ emissions. Under carbon neutrality target, their contributions remain to be large above 30% and 15%, respectively, although the growth rate continues to decline owing to the continuously improving power grid. However, both energy efficiency and energy structure improvement played significant role in reducing embodied carbon emissions, with contributions of -36.4% and -23.7%, respectively. The two energy factors refer to both direct and indirect energy use and CO₂ emissions. Although their contribution direction is obvious, the contribution degree has great reference value for policy design and mitigation planning of power sector to achieve carbon mitigation target.

Accordingly, we predict embodied carbon emissions of power grid construction under the carbon neutrality target. We find that cross-regional and central China has the largest

growth in embodied carbon emissions of power grid construction. In-depth, local power grid is relatively perfect, and cross-regional power grid of ultra-high voltage power system need to further constructed to improve electricity transmission rate and allocate the uneven inter-regional renewable energy resource. Additionally, the construction cost of power grid should be attracted attention due to considering the system cost of renewable energy for sustainable and safe electricity supply. Top-level governmental design for power grid construction and renewable energy development should be strengthened. Especially, fiscal and taxation, and market mechanism should be improved to promote the sustainable development of renewable energy and complete set service. More importantly, the key technologies for low-carbon development should be developed diligently.

As to research direction in future, the CO₂ emissions embodied in provincial power grid construction could be quantified for regional power sector design. Driven by differentiated development trajectory, power grid construction and their embodied in CO₂ emissions would have significant differences, especially under the carbon neutrality target. Plant-to-plant or station-to-station analysis is encouraged to find out targeted and operational policy suggestions. Also, economic cost of power grid construction should be considered and calculated to increase the scientific and accuracy of our results.

Policy implications

Based on our research results, the following policy implications are provided:

- (1) Government and power grid enterprises should continuously expand the scale of long-distance transmission. The large power grid will still be the basic structural form of the power system in future, and the distributed power system will form an effective supplement, combined with the large power grid to form the basic form of the power system, flexible regulation capability of power system. Also, a service platform supporting market-oriented operation of electricity is formed by the flexible adjustment ability of the power system.
- (2) Power grid enterprise should ensure the safe and reliable supply of electricity in promoting "dual carbon". On the one hand, we should provide good power grid connection services and scientific scheduling, coordinate and support the energy-saving and carbon reduction transformation, flexibility transformation, and heating transformation of existing coal-fired power units, as well as the development of new and clean energy. On the other hand, we should fully leverage the platform role of the large power grid in optimizing resource allocation, optimizing power grid scheduling and electricity trading, deeply tapping the potential of cross regional

and cross provincial channels for power transmission, increasing the mutual assistance between provinces, and maximizing the balance of electricity and electricity. At the same time, we will cooperate with the government to strengthen demand side management of electricity, guide users to reasonably avoid peak loads, and ensure stable and orderly electricity supply.

- (3) Government should encourage to intensify the construction of ultra-high voltage and supporting power grids, and vigorously promote the construction of a new energy supply and consumption system. The power grid enterprise should strive to increase the cross regional and cross provincial transmission capacity of the State Grid of China from the current 240 million kilowatts to over 370 million kilowatts by 2030 through the efforts of the 14th and 15th Five Year Plan periods, fully serving the construction of large-scale wind power and photovoltaic bases in the desert and Gobi Desert, and providing strong grid support for the development of various clean energy sources. In response to the major technical challenges faced by the development and safe operation of the power system under the "dual carbon" scenario, we will deeply implement the Science and Technology Innovation Action Plan, vigorously carry out major technological breakthroughs such as flexible DC transmission, virtual power plants, large power grid safety and stability control, and ultra-high voltage tap changer.

Acknowledgements This study was supported by the National Natural Science Foundation of China (72104023).

Author's contributions Mrs Liu Yan independently conduct the design, modelling and manuscript writing of this study.

Data availability Data presented in this study are available upon request by the corresponding author.

Declarations

Ethical approval Not applicable.

Consent to participate Not applicable.

Consent for publication Not applicable.

Competing interests The authors declare no competing interests.

References

- Ang BW (2004) Decomposition analysis for policy making in energy: which is the preferred model? *Energy Policy* 32(9):1131–1139. [https://doi.org/10.1016/S0301-4215\(03\)00076-4](https://doi.org/10.1016/S0301-4215(03)00076-4)
- Ang BW (2005) The LMDI approach to decomposition analysis: a practical guide. *Energy Policy* 33(7):867–871. <https://doi.org/10.1016/j.enpol.2003.10.010>

- Ang BW (2015) LMDI decomposition approach: a guide for implementation. *Energy Policy* 86:233–238. <https://doi.org/10.1016/j.enpol.2015.07.007>
- Bistline JET, Blanford GJ (2021) Impact of carbon dioxide removal technologies on deep decarbonization of the electric power sector. *Nat Commun* 12:3732. <https://doi.org/10.1038/s41467-021-23554-6>
- Cao Y, Wang XF, Li Y et al (2016) A comprehensive study on low-carbon impact of distributed generations on regional power grids: A case of Jiangxi provincial power grid in China. *Renew Sustain Energy Rev* 53:766–778. <https://doi.org/10.1016/j.rser.2015.09.008>
- Chen Y, Wang H, Yan Z et al (2022) A two-phase market clearing framework for inter-provincial electricity trading in Chinese power grids. *Sustain Cities Soc* 85:104057. <https://doi.org/10.1016/j.scs.2022.104057>
- Chen R, Xu P, Yao H (2023) Decarbonization of China's regional power grid by 2050 in the government development planning scenario. *Environ Impact Assess Rev* 101:107129. <https://doi.org/10.1016/j.eiar.2023.107129>
- da Santos Silva SR, Hejazi MI, Iyer G et al (2021) Power sector investment implications of climate impacts on renewable resources in Latin America and the Caribbean. *Nat Commun* 12:1276. <https://doi.org/10.1038/s41467-021-21502-y>
- Eichner T, Pethig R (2015) Unilateral consumption-based carbon taxes and negative leakage Recourse. *Energy Econ* 40:127–142. <https://doi.org/10.1016/j.reseneeco.2015.03.002>
- Li H, Zhao Y, Qiao X et al (2017) Identifying the driving forces of national and regional CO₂ emissions in China: Based on temporal and spatial decomposition analysis models. *Energy Econ* 68:522–538. <https://doi.org/10.1016/j.eneco.2017.10.024>
- Li H, Zhao Y, Wang S, Liu Y (2020) Spatial-temporal characteristics and drivers of the regional residential CO₂ emissions in China during 2000–2017. *J Clean Prod* 276:124116. <https://doi.org/10.1016/j.jclepro.2020.124116>
- Li M, Shan R, Virguez E et al (2022) Energy storage reduces costs and emissions even without large penetration of renewable energy: the case of China Southern Power Grid. *Energy Policy* 161. <https://doi.org/10.1016/j.enpol.2021.112711>
- Liang H, You F (2023) Reshoring silicon photovoltaics manufacturing contributes to decarbonization and climate change mitigation. *Nat Commun* 14:1274. <https://doi.org/10.1038/s41467-023-36827-z>
- Lin B, Du K (2014) Decomposing energy intensity change: a combination of index decomposition analysis and production-theoretical decomposition analysis. *Appl Energy* 129:158–165. <https://doi.org/10.1016/j.apenergy.2014.04.101>
- Liu Z, Ciais P, Deng Z et al (2020) Near-real-time monitoring of global CO₂ emissions reveals the effects of the COVID-19 pandemic. *Nat Communications* 11:5172. <https://doi.org/10.1038/s41467-020-18922-7>
- Ma Y, Song S, Li C et al (2023) Germanium-enriched double-four-membered-ring units inducing zeoliteconfined subnanometric Pt clusters for efficient propane dehydrogenation. *Nat Catal*. <https://doi.org/10.1038/s41929-023-00968-7>
- Manojlovic AV, Medar OM, Andelkovic AS et al (2023) Environmental impact assessment of the electric vehicles: A case study. *Energy Sources Part A-Recovery Util Environ Eff* 45(1):1007–1016. <https://doi.org/10.1080/15567036.2023.2173342>
- Peng W, Wagner F, Ramana MV et al (2018) Managing China's coal power plants to address multiple environmental objectives. *Nat Sustain* 1:693–701. <https://doi.org/10.1038/s41893-018-0174-1>
- Qiu Y, Lamers P, Daioglou V et al (2022) Environmental trade-offs of direct air capture technologies in climate change mitigation toward 2100. *Nat Commun* 13:3635. <https://doi.org/10.1038/s41467-022-31146-1>
- Qu S, Liang S, Xu M (2017) CO₂ emissions embodied in inter-provincial electricity transmissions in China. *Environ Sci Technol* 51:10893–10902. <https://doi.org/10.1021/acs.est.7b01814>
- Reilly JM, Edmonds JA, Gardner RH, and Brenkert AL (1987) Uncertainty analysis of the IEA/ORAU CO₂ emissions model. *Energy J* 8(3):1–29. <https://doi.org/10.1016/j.enpol.2021.112711>
- Su B, Ang BW (2016) Multi-region comparisons of emission performance: the structural decomposition analysis approach. *Ecol Ind* 67:78–87. <https://doi.org/10.1016/j.ecolind.2016.02.020>
- Tang BJ, Li R, Yu BY et al (2018) How to peak carbon emissions in China's power sector: a regional perspective. *Energy Policy* 120:365–381. <https://doi.org/10.1016/j.enpol.2018.04.067>
- Tao Y, Wen ZG, Xu LN et al (2019) Technology options: can Chinese power industry reach the CO₂ emission peak before 2030? *Resour Conserv Recycl* 147:85–94. <https://doi.org/10.1016/j.resconrec.2019.04.020>
- Wang P, Lin CK, Wang Y et al (2021) Location-specific co-benefits of carbon emissions reduction from coal-fired power plants in China. *Nat Commun* 12:6948. <https://doi.org/10.1038/s41467-021-27252-1>
- Wei W, Li J, Chen B et al (2021) Embodied greenhouse gas emissions from building China's large-scale power transmission infrastructure. *Nat Sustain* 4:739–747. <https://doi.org/10.1038/s41893-021-00704-8>
- Wu F, Huang NY, Liu GJ et al (2020) Pathway optimization of China's carbon emission reduction and its provincial allocation under temperature control threshold. *J Environ Manag* 271:111034. <https://doi.org/10.1016/j.jenvman.2020.111034>
- Zhang YQ, Liu CG, Chen L et al (2019) Energy-related CO₂ emission peaking target and pathways for China's city: a case study of Baoding City. *J Clean Prod* 226:471–481. <https://doi.org/10.1016/j.jclepro.2019.04.051>
- Zhang Y, Deng Y, Zheng Z et al (2023) Optimizing the operation strategy of a combined cooling, heating and power system based on energy storage technology. *Sci Rep* 13:2928. <https://doi.org/10.1038/s41598-023-29938-6>
- Zhao MX, Lü LH, Wang S et al (2021) Meta regression analysis of pathway of peak carbon emissions in China. *Chinese Res Environ Sci* 34(9):2056–2064

Publisher's note Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.

Springer Nature or its licensor (e.g. a society or other partner) holds exclusive rights to this article under a publishing agreement with the author(s) or other rightsholder(s); author self-archiving of the accepted manuscript version of this article is solely governed by the terms of such publishing agreement and applicable law.