The influence factors of interprovincial power transmission on China’s CO2 emissions

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Abstract
Electric power system is a major source of CO2 emission in China. Understanding the evolution of power-related CO2 emission is an important step to both emission reduction and a sustainable energy transition. Here, we assess the CO2 emission of power production in China, finding that it increased by 47% from 2008 to 2017 despite a significant decrease in CO2 emission intensity of power production. The CO2 emission intensity of power production differs greatly across provinces, with the highest provincial CO2 emission intensity 11 times the lowest. To understand the evolution of power-related CO2 emission, this study quantified the embodied CO2 emissions of power transmission, and then use decomposition analysis to explore the influencing factors of it. We found that China’s embodied CO2 emissions from power transmission increased from 315 to 523 Mt between 2008 and 2017, and the increase in electricity consumption and the dependence on power transmission networks are the important reasons for the increase in embodied CO2 emissions. Nationally, power transmission reduced CO2 emission by 78 Mt. because, compared to the east, the west generally has a larger CO2 emission factor. These dynamics will become important for policymakers and energy planners to achieve carbon neutrality.

Keywords
Energy transition, electricity generation, electricity transmission, CO2 emissions, decomposition analysis

Introduction
Since China’s reform and opening up, the country has enjoyed rapid economic development followed by an accelerated and continuous urbanization process. Yet this has come at a high cost: high carbon emissions. Indeed, in recent years, China’s total carbon emissions have consistently been ranked first in the world. Despite the government’s goal of
carbon peak and carbon neutrality, China’s total energy consumption and CO₂ emissions are still increasing year on year. Research on this issue has shown that China is experiencing a geographical mismatch between the power demand in the economically developed east coastal areas and the power production capacity in the less developed inland regions. As a tool to connect upstream power production and downstream power consumption, power transmission is particularly important for China, where the power sector is composed of multiple regional power grids. For this reason, power is frequently traded among China’s regional power grids.

The surface temperature of the earth has risen by nearly a degree over the past century, with numerous negative impacts on human health, the ecosystem, and the supply of food, water, and energy. In response, the international community reached the world’s most significant agreement to address climate change (the Paris Agreement) in December 2015, calling for reducing anthropogenic greenhouse gas (GHG) emissions, particularly CO₂ emissions. Thus, China, the world’s largest emitter of CO₂, contributing 27% of the world’s total emissions, has promised to become carbon neutral before 2060, and to reach peak emission before 2030. Currently, energy combustion accounts for 88% of total CO₂ emissions in China, and the electric power sector accounts for 41% of CO₂ emissions from energy combustion. China’s roadmap for carbon reduction heavily relies on the decarbonization of the power sector. Under the warming limit of 1.5 °C, as the most widely used energy type, the power sector needs to spend a lot of costs and resources to achieve complete decarbonization by 2050. Understanding the CO₂ emission from power production is essential to Chinese and global CO₂ emission reduction.

This paper uses the logarithmic mean division index (LMDI) decomposition method to quantify the CO₂ emission data for China’s provincial level production from 2008 to 2017. This method is widely used in academia to explore the driving factors of embodied CO₂ emissions, measure CO₂ emissions from electricity transmission over consecutive years, and analyze the driving factors behind them. The findings reveal that China’s power transmission still depends on many provinces with high CO₂ emission intensity, resulting in an increase in CO₂ emissions. However, reducing power production can significantly reduce the total amount of CO₂ emissions in most provinces, which to some extent provides unique insights for the current research on CO₂ emission reduction in the world. The specific theoretical framework is shown in Figure 1.

**Literature review**

In China’s energy system, interprovincial power transmission is playing an increasingly important role and has grown rapidly in the past decade (1.5 times from 2008 to 2017). However, with the continuous expansion of the scale of transactions, power transmission is having several marked negative environmental impacts from power consumption provinces to power output provinces. At the same time, at the provincial level, there are also great differences in China’s energy intensity and structure. Therefore, understanding the differences in provincial power production and related emissions is of great significance for policymakers and regulators to determine the implementation of relevant local and national policies.
The academic research on CO2 emissions from power production is quite fruitful, but most studies have focused on the embodied emissions in one or several discontinuous years rather than continuous years. Therefore it is impossible to investigate the changes in embodied CO2 emissions with a more precise time resolution. In addition, the embodied CO2 emissions are also affected by many factors, such as emission intensity, emissions, energy use, and so on.

Duan et al. used the kaya identity to decompose the overall structure of CO2 emissions and established an integrated assessment model to explore the impact of 1.5 °C temperature control requirements on China’s CO2 emission reduction. The research shows that the decarbonization of the power sector is of great significance to China’s CO2 emission reduction, and under the 1.5 °C temperature control requirements, the implementation cost of China’s relevant policies will also increase.15 Su et al. showed that China’s CO2 emission in interprovincial power transmission was 532 Mt in 2012, increasing by 94% compared with 2007.18 Qu et al. showed that approximately 13% of the total CO2 emission from power production was embodied in interprovincial power transmission in China in 2013.1 Li et al. indicated that the GHG embodied in the cross-province electricity trade was 607 Mt in 2017.19 Wang et al. showed that CO2 emission from power production in China increased from 935 to 3511 Mt during the period 1997–
Li et al. found that the CO2 emission intensity of China’s thermal power differed across provinces in 2016. Magazzino et al. discussed the relationship between economic growth, CO2 emissions, and energy use in Turkey and the Caucasus from 1992 to 2013. The results showed that the increase in energy use is mostly due to the increase in renewable energy use, which does not necessarily increase CO2 emissions, and that the policies related to energy use will not have a significant impact on urban economic growth. Yang et al. discussed the CO2 emission of China’s power industry with the help of an LMDI model, finding that economic growth will both increase energy consumption and energy intensity. What’s more, improving energy efficiency can also effectively promote CO2 emission reduction in the power sector.

Unlike previous studies, the present paper calculates the CO2 emissions generated by electricity in China’s provinces in a continuous range. Under the background of increasingly close transmission network connection, to reveal the impact of China’s provinces on CO2 emissions, this paper mainly studies the driving factors of CO2 emissions. Thus, relevant conclusions are drawn about urban emission reduction to a certain extent. At the same time, it also provides some unique insights for policymakers and energy planners to help China achieve carbon neutrality as soon as possible.

Methods and data

Methods

CO2 emission from power production. We applied the guidelines of the Intergovernmental Panel on Climate Change (IPCC) to calculate the CO2 emission from power production in year \( t \) (\( C_t \)) using the following equation:

\[
C_t = \sum_{j=1}^{19} C_j = F_{E_j} \cdot E_{F_j} \cdot N_{C_j} \cdot O_j \ast 10 \tag{1}
\]

where: \( C_j \) is the provincial CO2 emission from fossil fuel type \( j \) in year \( t \) (tCO2); \( F_{E_j} \) is the fossil fuel type \( j \) consumption for power production in year \( t \) (10⁴ t) (various gases are measured by 10⁸ m³); \( E_{F_j} \) is the carbon content of fuel type \( j \) (tCO2/TJ); \( N_{C_j} \) refers to the net calorific value of fuel type \( j \) (TJ/10³ t or MJ/10 m³); and \( O_j \) is the carbon oxidation rate of fuel type \( j \). Note that these three variables are fuel-specific but not time-dependent (i.e. they are the same for all years). The detailed data for \( E_{F_j}, N_{C_j}, \) and \( O_j \) can be found in Supplemental Table 1.

Subsequently, the provincial CO2 emission intensity of power production (\( EI \)) can be obtained by dividing the total CO2 emission by the total power production in the province:

\[
EI_t = \frac{C_t}{PP_t} \tag{2}
\]

where: \( EI_t \) is the provincial CO2 emission intensity of power production in year \( t \) (gCO2/kWh); and \( PP_t \) is the provincial power production in year \( t \) (GWh).
Embodied CO$_2$ emissions in power transmission. The embodied CO$_2$ emissions across provinces can be estimated by:

$$EE_{i,j}^t = EIt_i \cdot PT_{i,j} \cdot EE_{i,j}^t = EIt_i \cdot PT_{i,j}$$

(3)

where: $EE_{i,j}^t$ denotes the embodied CO$_2$ emissions exported from province $i$ to $j$ through power transmission (tCO$_2$) in year $t$; $EIt_i$ is the CO$_2$ emission intensity of power production in province $i$ in year $t$ (gCO$_2$/kWh); and $PT_{i,j}$ denotes the yearly power transmission from province $i$ to $j$ in year $t$ (MWh). Power-importing provinces reduce emissions, which can be estimated by using a counterfactual scenario where a province does not import power but satisfies the local demand by producing power itself:

$$ER_j^t = EIt_j \cdot \sum_i PT_{i,j}$$

(4)

where $ER_j^t$ denotes the import of embodied emissions (tCO$_2$) by province $j$. The impact of power transmission on provincial emissions can now be estimated:

$$NER_j^t = \sum_i EE_{i,j}^t - ER_j^t$$

(5)

where $NER_j^t$ denotes the net CO$_2$ emission reduction in province $j$ due to power transmission (tCO$_2$). A negative value of $NER_j^t$ indicates that in province $j$ the CO$_2$ emission reduction achieved by importing power is larger than the embodied CO$_2$ emission export by exporting power, thus province $j$ reduces emission through power transmission; a positive value of $NER_j^t$ indicates that there is an emission increase in province $j$.

Power production is a large CO$_2$ emitter, but its role differs across provinces due to the differences in power-generating technologies. The proportion of the power-related emission ($EP$) to the total emission is estimated at the province level using:

$$EP_j^t = C_j^t / TC_j^t$$

(6)

where: $EP_j^t$ denotes the proportion of the power-related emission ($EP$) to the total emission in province $j$ in year $t$; and $TC_j^t$ denotes the total emission in province $j$ in year $t$ (tCO$_2$). To assess the impact of power transmission on provincial emissions, we calculated the power-related emission in the counterfactual scenario:

$$CEP_j^t = C_j^t - NER_j^t / TC_j^t$$

(7)

where $CEP_j^t$ denotes the proportion of the power-related emission ($EP$) to the total emission in province $j$ in year $t$ without power transmission.

The descriptive statistics for the relevant data are shown in Table 1.

Drivers of embodied CO$_2$ emissions in power transmission. To quantify the embodied CO$_2$ emissions, this paper uses LMDI decomposition analysis to explore the driving factors behind it. In 1990, Kaya first proposed the Kaya identity, used by the IPCC, which can be improved using Ang’s LMDI decomposition method. Thanks to its advantages of no residual error and strong practicability, decomposition analysis has been widely
used to analyze the factors that lead to changes in pollution emissions.\textsuperscript{25–27} Since there is a value of 0 in the data, this paper adopts the Divisia decomposition method improved by Ang (the variables equal to 0 can be replaced with very small numbers, such as $10^{-10}$,\textsuperscript{28} while eliminating the residuals)\textsuperscript{25,26} to decompose the $EE_i$ of China’s power system to explore the driving factors of implicit CO$_2$ emission:

$$ EE = \sum_i EE_i = \sum_i EE_i \cdot \frac{PT_i}{PC_i} \cdot \frac{PC_i}{PC} \cdot PC \quad (8) $$

where: $EE_i$ is the emission induced by the power import of province $i$ (Mt); $PT_i$ is the total power import of province $i$ (TWh); $PC_i$ is the total power consumption of province $i$ (TWh); and $PC$ is the national power consumption (TWh).

Ang’s\textsuperscript{29} research proved that there are production effects, structure effects, and intensity effects in CO$_2$ emission. Therefore, this paper puts forward reasonable assumptions:

$$ EP_i = \frac{EE_i}{PT_i}, \quad PTC_i = \frac{PT_i}{PC_i}, \quad PCC_i = \frac{PC_i}{PC}, \quad P = PC $$

Equation (8) can be transformed into:

$$ EE = \sum_i EP_i \cdot PTC_i \cdot PCC_i \cdot P \quad (9) $$

where: $EP_i$ represents the emission intensity of the power import of province $i$; $PTC_i$ represents the proportion of power import in the total power consumption of province $i$, that is, the dependence of province $i$ on the power transmission network; $PCC_i$ represents the proportion of the power consumption of province $i$ in the national power consumption, that is, the spatial distribution of power consumption; and $P$ represents the national power consumption. The above four decomposition factors represent the energy intensity effect, energy structure effect, and energy production effect, respectively.

### Table 1. Descriptive statistics.

| Variable | Description                                                                 | Minimum  | Maximum  | Average   | Standard deviation |
|----------|-----------------------------------------------------------------------------|----------|----------|-----------|--------------------|
| $C_t$    | The CO$_2$ emission from power production in year $t$                        | 118      | 5162.74  | 1676.08   | 1116.24            |
| $Elt$    | The provincial CO$_2$ emission intensity of power production in year $t$    | 83.48994 | 1148.93  | 648.9829  | 220.7807           |
| $EE_{ij}^t$ | The embodied CO$_2$ emissions exported from province $i$ to $j$ through power transmission in year $t$ | 0        | 14542.97 | 1476.494  | 2465.858           |
| $ER_{ij}^t$ | The import of embodied emission                                             | 0        | 7532.73  | 1476.49   | 1851.08            |
| $Ner_{ij}^t$ | The net CO$_2$ emission reduction in province $j$ due to power transmission | 7532.726 | 14,456.24| 0.00000628| 3450.32            |
According to the LMDI model, changes in the total embodied emissions from 0 period (base period) to $t$ period (report period) can be expressed as:

$$
\Delta EE = EE^t - EE^0 = \Delta EE_{EP} + \Delta EE_{PTC} + \Delta EE_{PCC} + \Delta EE_P
$$

(10)

The four effects of embodied emission changes are entitled emission intensity of power import ($\Delta EE_{EP}$), dependence on the transmission network ($\Delta EE_{PTC}$), the spatial distribution of power consumption ($\Delta EE_{PCC}$), and the power consumption scale ($\Delta EE_P$).

The decomposition equations for each effect are expressed as follows:

$$
\Delta EE_{EP} = \sum_i L(EE^t_i, EE^0_i) \cdot \ln \left( \frac{EP^t_i}{EP^0_i} \right)
$$

(11)

$$
\Delta EE_{PTC} = \sum_i L(EE^t_i, EE^0_i) \cdot \ln \left( \frac{PTC^t_i}{PTC^0_i} \right)
$$

(12)

$$
\Delta EE_{PCC} = \sum_i L(EE^t_i, EE^0_i) \cdot \ln \left( \frac{PCC^t_i}{PCC^0_i} \right)
$$

(13)

$$
\Delta EE_P = \sum_i L(EE^t_i, EE^0_i) \cdot \ln \left( \frac{P_i}{P_0} \right)
$$

(14)

Here:

$$
L(EE^t_i, EE^0_i) = \begin{cases} 
\frac{EE^t_i - EE^0_i}{\ln EE^t_i - \ln EE^0_i}, & (EE^t_i \neq EE^0_i) \\
EE^t_i, & (EE^t_i = EE^0_i)
\end{cases}
$$

(15)

**Materials**

This study includes 30 provincial-level administrative regions (provinces, autonomous regions, and municipalities). For simplicity, they are referred to as provinces (names and locations are shown in Supplemental Figure 1). The provincial power production and consumption during 2008–2017 were obtained from the China Electric Power Yearbook. The fossil fuel consumption for power production was obtained from the Energy Statistic Yearbook. The related emission coefficients of each energy type were obtained from the IPCC. The interprovincial power transmission during 2008–2017 was obtained from the China Electricity Council. Most of them are provincial-to-provincial power transmission data and can be used directly; a small amount of data are provincial-to-local city transmission data, so we have summed up them at the provincial level. The provincial total CO2 emission was obtained from Shan et al.

However, the calculation method in this paper has some limitations: the interprovincial transmission volume does not take into account the carbon dioxide emissions
reflected in the transmission infrastructure and only involves the CO₂ emission data of fuel combustion in the power plant, although it can be high.34

Results

CO₂ emissions and intensities of power production

From Figure 2, it can be found that the CO₂ emissions of urban power production in China showed an upward trend from 2008 to 2017, but the CO₂ emission intensity decreased steadily. Industrial production is the main source of CO₂ emissions. However, in recent years, China has vigorously advocated technological innovation. On the one hand, production technological innovation effectively ensures that industrial enterprises maintain production efficiency. On the other hand, the Chinese government’s series of energy-saving policies for the industrial system have also reduced the intensity of CO₂ emissions.

Further, by comparing the CO₂ emissions of power production in provincial-level cities in China in 2008 and 2017 (Figure 3), it can be found that the central and western provinces have changed dramatically in the past decade, and the CO₂ emissions of power production in some provinces have even changed to several times that of 10 years ago. Since most of the power production emissions of these provinces are used to transmit power to other provinces, the increase in power demand in the eastern region has exacerbated the power production burden of central and western provinces. For example, in Inner Mongolia, Xinjiang, and other places in 2017, the total CO₂ emissions from power production in the province even reached more than 50%.

In terms of CO₂ emission intensity, this paper summarizes the CO₂ emission intensity of 30 provinces in China (Figure 4). It is not difficult to see that, although China’s overall CO₂ emission intensity has decreased within the study range, the CO₂ emission intensity

![Figure 2. Trend chart of CO₂ emissions and intensities of power production in China.](image)
Figure 3. CO₂ emission of power production in China in 2008 and 2017.

Figure 4. CO₂ emission intensities of power production in China.
of power production in each province is also quite different. For example, the emission intensity of Yunnan decreased significantly (–84%), while Guangxi was the only province where the emission intensity increased (+2%). In 2017, the emission intensity of power production in Yunnan Province was the lowest (83 gCO₂/kWh), while that in Inner Mongolia was the highest (905 gCO₂/kWh). We statistically analyzed the relative standard deviation of emission intensity for each province and found that the total relative standard deviation increased from 30% to 39% from 2008 to 2017. The CO₂ emission intensity of China’s power production is extremely uneven.

**CO₂ emission embodied in power transmission**

Interprovincial power transmission increased rapidly, from 0.4 in 2008 to 1.1 (10³ TWh) in 2017. Xinjiang did not export electricity in 2008 but exported large amounts (44 TWh) in 2017. In addition to the increased amount of transmission, the coverage of the transmission network also expanded. During 2008–2017, the number of large power transmission corridors (more than 1 TWh/year) increased from 46 to 66. Consequently, the CO₂ emission embodied in interprovincial power transmission increased from 315 to 523 Mt. The number of large, embodied CO₂ emission transmission corridors (more than 1 Mt/year) increased from 42 to 58. Nationally, the average emission intensity of power transmission decreased from 741 to 512 g/kWh. Inner Mongolia was the largest exporter of embodied CO₂ emissions both in 2008 (95 Mt) and 2017 (139 Mt) (Figure 5). In contrast, Hebei was the largest importer of embodied CO₂ emissions both in 2008 (46 Mt) and 2017 (61 Mt) because it imported electricity from Inner Mongolia, Shanxi, and Shaanxi, where CO₂ emission intensities were relatively high (larger than 600 gCO₂/kWh). The largest corridor of embodied CO₂ emissions was Inner Mongolia–Henan in 2008 (33 Mt) and Inner Mongolia–Liaoning in 2017 (41 Mt). Despite their large

![Figure 5. CO₂ emissions embodied in interprovincial power transmission in 2008 and 2017.](image-url)
amounts of power export, Yunnan and Sichuan provinces exported limited embodied CO₂ emissions because they mainly exported hydropower. Guangdong was the largest power importer, but its imported CO₂ emission was not the largest because it mainly consumed the hydropower from Yunnan province.

**Impact of power transmission on provincial CO₂ emission**

The power transmission network changes provincial CO₂ emissions. We examined the impact of power transmission on CO₂ emission with the value of the power-to-total ratio (PTT), which is the ratio of CO₂ emission of power production to the total provincial emission. We assessed the present and counterfactual PTT in 2017. At present, in Inner Mongolia and Ningxia, approximately 60% of the provincial emission is from power production (Figure 6). Power transmission exacerbates issues when the PTT is larger at present than in the counterfactual scenario where there is no power transmission network and thus a province does not import power but satisfies the local demand by producing power itself. Our results show that CO₂ emission was slightly more unequally distributed through power transmission. The relative standard deviations of provincial PTT (from 37.5% to 38%) increased due to power transmission. The impact of power transmission on CO₂ emission differs across provinces. Without a transmission network, Inner Mongolia could reduce emissions by 137 Mt. In contrast, Guangdong increased emissions by 97 Mt. If Beijing and Shanghai were to satisfy their power demand themselves, they would see an increase in emissions of 28% and 26%, respectively. Because of the differences in emission intensity in the power-exporting and -importing provinces, present power transmission reduced CO₂ emission by 78 Mt compared with the counterfactual scenario.

**The changing trend of CO₂ emission driving factors in power transmission**

Table 2 shows the increment of various factors of specific CO₂ emissions at the national level from 2008 to 2017. It can be seen from the table that during the study period, the
expansion of China’s power consumption was the main driving factor for the increase in actual CO$_2$ emissions. At the same time, the dependence on the transmission network usually leads to an increase in emissions. This is due to the high dependence of eastern regions of China on power imports from the midwest regions, increasing overall CO$_2$ emissions. It is worth noting that in 2011 and 2017, China’s CO$_2$ emission intensity factor turned positive, resulting in an increase in total carbon dioxide emissions. This is because, in July 2011 and January 2017, China carried out the first and third batches of low-carbon city pilot projects, respectively. As these two batches of pilot projects involve a wide range of urban angles and areas, energy consumption and CO$_2$ emissions increased in the initial stage of implementation of the policy.

To make the data more observable, this paper further draws the change decomposition diagram of embodied CO$_2$ emissions (Figure 7). It is not difficult to see that the main factor causing the change in embodied CO$_2$ emissions is the change in CO$_2$ emission intensity. Due to the demands of production, consumption, infrastructure construction, and other aspects, these eastern provinces generally have a large demand for electricity. Therefore, the power demand of such provinces has a great impact on China’s overall CO$_2$ emissions and emission intensity.

**Discussion**

**The role of power transmission in the low-carbon energy transition**

China has issued a series of policies to reduce CO$_2$ emissions at the provincial and national levels. Fairness is an important issue that requires much attention and needs to be adequately addressed before implementing emission-reduction actions. For most provinces, power production is mainly for meeting the demand of other provinces. The western provinces convert resources (e.g. fossil fuels, hydro-energy) to electric power and export it to support development in the east, increasing emissions and the pressure for emission reduction in the west. Issues will arise if only the local power demand is considered when reducing CO$_2$ emissions. For example, Inner Mongolia can reduce CO$_2$ emissions by 22% by curtailing power production to only meet the local demand (Figure 7). In that case, however, the provinces (Beijing, Hebei, Liaoning, Shandong, Tianjin) that rely on the power from Inner Mongolia would face power gaps.

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| Year | EE | ΔEP | ΔPTC | ΔPCC | ΔP |
|------|----|-----|------|------|----|
| 2009 | 43.23 | −14.17 | 37.13 | −0.95 | 21.22 |
| 2010 | 41.87 | −2.42 | −5.03 | −2.63 | 51.94 |
| 2011 | 70.59 | 26.87 | 6.09 | −10.97 | 48.61 |
| 2012 | −5.37 | −30.82 | 6.50 | −6.50 | 25.44 |
| 2013 | −4.75 | −38.37 | 39.01 | −6.33 | 35.06 |
| 2014 | −8.97 | −21.82 | −8.06 | −1.00 | 21.90 |
| 2015 | −30.24 | −33.30 | −1.58 | −6.24 | 10.88 |
| 2016 | 43.23 | −14.17 | 37.13 | −0.95 | 21.22 |
| 2017 | 71.83 | 10.77 | 36.31 | −5.62 | 30.37 |
Power transmission promotes the development of low-carbon renewables in the west and allows this power to be transmitted to where power is needed, reducing CO₂ emission on the national scale. However, the emission reduction is not significant because, currently, the main power exporters are the provinces with a high capacity in coal power. Wind and solar power are low-carbon technologies, but they have not played the main roles in China’s energy system because of low efficiency and high curtailment compared to other technologies. To meet the increasing power demand in the east, power transmission is expected to increase. The future impacts of power transmission on CO₂ emission depend on the further development of low-carbon energy in the power-exporting provinces, for example, wind and solar in Inner Mongolia and hydropower in Yunnan province.

Limitations and implications

Mi et al. measured the leading and lagging cities in energy emission reduction through the climate change index and found that industrial structure was the decisive factor to distinguish a city from a leading city. Therefore, there is likely to be an intrinsic relationship between emissions in power transmission and regional climate change mitigation performance. This is also the limitation of this paper.

The increasing power consumption and the dependence on power transmission indicate that reducing the emission intensity is the only way to reduce CO₂ emission. Shifting fossil-fuel-fired power to renewables (e.g., wind, solar, and hydropower) is an effective approach. However, the curtailment of renewables in the west is high because of the low local demand. Further construction of power transmission corridors for renewables can facilitate the development of renewables and the reduction of CO₂ emissions. Our results show that reducing power production can significantly

Figure 7. Decomposition of the changes in embodied CO₂ emissions during 2008–2017.
reduce the total CO₂ emission for most provinces. However, the power reduction of a certain province can affect the power supply of others via the power transmission network.

Comparison with previous research

Compared with the previous literature, the focus of this paper is different. Hu et al. pointed out that, from 1995 to 2014, the alternative energy efficiency of fossil fuel power generation in China was low, and the efficiency of imported power transmission alternative fuel power generation was much higher than alternative energy. From the perspective of alternative energy types, the supply of alternative energy in China’s regional power grid has increased, which has led to a rebound of 10–50% in fossil fuel power generation consumption. Due to the strong demand for imported power transmission, China’s CO₂ emissions have increased to a certain extent. Wang et al. mainly analyzed the difference in CO₂ emissions from power production in China’s provinces during 1997–2017. Li et al. studied the inter-provincial difference in CO₂ emission intensity of China’s thermal power in 2016. Our results show that the difference in emission intensity among provinces has increased from 2008 to 2017, and the relative standard deviation has increased from 30% to 39%. Unlike previous studies that have evaluated specific emissions in a year or over several years, based on state-of-the-art transmission data, our results show that specific emissions increased by 66% between 2008 and 2017. We further studied the driving factors of realizing specific CO₂ emissions through power transmission and found that the current power transmission still depends on many provinces with high emission intensity, resulting in an increase in CO₂ emissions.

Conclusions and policy recommendations

Since the reform and opening up, China’s economy has developed rapidly and has gradually shifted from a planned economy to a market economy. However, this rapid economic development has also led to the economic gap between developed and underdeveloped regions in China widening. As the most widely used energy type in the world, electric energy can not only empower urban development but also lead to an increase in urban CO₂ emissions due to its extensive production mode. The transmission network is an important means of energy allocation among provinces to meet the energy demand of provinces with weak resource endowments. At present, most of China’s power output provinces are concentrated in the central and western provinces, while the input provinces are concentrated in the southeast coastal provinces. The economic strength of the central and western provinces is generally weaker than that of the southeast coastal provinces. However, to support the development of the eastern provinces, such provinces are still overproducing electricity to support the eastern provinces while meeting their power demand, which has increased their CO₂ emission burden to a certain extent. Therefore, optimizing and improving China’s power transmission network has great practical significance for China’s urban CO₂ emission reduction.
This study has evaluated the CO₂ emissions of China’s provincial power production from 2008 to 2017, as well as investigating CO₂ emissions and driving factors embodied in cross-provincial power transmission with the help of the LMDI decomposition method.

Three key results were found. First, nationwide, although the emission intensity of power production decreased significantly during the whole period, from 2008 to 2017, the rapid growth of inter-provincial transmission led to an increase of 47% in CO₂ emissions from power production, and the proportion of CO₂ emissions from power production in some provinces even exceeded 50% of the total emissions.

Second, the power transmission network meets the power demand of some provinces, but at the same time intensifies the difference in CO₂ emission intensity between power input and output provinces. At the same time, the CO₂ emission intensity of power production in different provinces varies greatly, and the relative standard deviation increased from 30% to 39% from 2008 to 2017.

Third, increased electricity consumption and reliance on the transmission network have led to an increase in embodied CO₂ emissions. Nationwide, power transmission has reduced CO₂ emissions by 78 Mt, because compared with the east, the west usually has a larger CO₂ emission factor, showing a general trend of power transmission from the west to the east. Although most of these provinces can significantly reduce local CO₂ emissions by reducing power generation, considering the power demand of developed provinces in the east, reducing power production may affect the power supply of transmission networks in other provinces, leading to the power supply of the transmission networks not being reduced.

Based on the above research conclusions, this paper puts forward the following policy recommendations.

First, the central and western regions need to optimize and improve the high-voltage transmission network. Through research, the Federal Energy Regulatory Commission (FERC) of the United States found that thanks to its advantages in the long-distance transmission of electric energy, high-voltage transmission lines can efficiently transmit a large amount of clean energy, such as wind energy and solar energy, to areas with large power demand, and improve the utilization rate of carbon-free energy to a certain extent. In recent years, China’s renewable energy has developed rapidly. However, because the development speed of new energy in some provinces is far faster than its actual demand, a large number of “wind and power abandonment” phenomena have occurred in China, especially in northwest China. The establishment of a high-voltage line transmission network would not only help these provinces to absorb excess power and to optimize and improve the power transmission platform based on new energy but would also relieve the pressure of CO₂ emissions caused by traditional energy transmission.

Second, the eastern region needs to accelerate the research and development of low-carbon and zero-carbon technologies and reduce their dependence on the transmission network in the central and western regions. The central and western regions, such as Inner Mongolia, Yunnan, and other places, have great transmission pressure. Due to technical limitations, these regions still use more traditional methods to produce electric energy, which consumes more energy. If the power transmission for the eastern region continues, it will not only be difficult for the local technology to break through but
will also entail more serious CO2 emissions. Therefore, in the eastern region, China should give full play to the advantages of location and resource endowment, focus on the development of renewable energy technology, and focus on promoting the power substitution industry to reduce power demand.

**Author contribution**

Wenchao Li: conceptualization, funding acquisition, project administration, supervision. Lingyu Xu: writing—original draft. Yi Jin: data curation, formal analysis.

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**Supplemental material**

Supplemental material for this article is available online.

**References**

1. Qu S, Liang S and Xu M. CO2 emissions embodied in interprovincial electricity transmissions in China. *Environ Sci Technol* 2017; 51: 10893–10902.
2. Rong Y, Rodrigues J, Arnold T, et al. The impact of the expansion in non-fossil electricity infrastructure on China’s carbon emissions. *Appl Energy* 2018; 20: 872–897.
3. Borg MA and Peng B. The impact of climate change on kidney health. *Nat Rev Nephrol* 2021; 17: 294–295.
4. Karoline K, Matthias M, Christian P, et al. Impact of climate change on the Baltic Sea ecosystem over the past 1,000 years. *Nat Clim Change* 2012; 2: 871–874.
5. Liu L, Hejazi M, Li H, et al. Vulnerability of US thermoelectric power generation to climate change when incorporating state-level environmental regulations. *Nat Energy* 2017; 2: 17109.
6. Flörke M, Schneider C and McDonald RI. Water competition between cities and agriculture driven by climate change and urban growth. *Nat Sustainability* 2018; 1: 51–58.
7. Ortiz-Bobea A, Ault TR, Carrillo CM, et al. Anthropogenic climate change has slowed global agricultural productivity growth. *Nat Clim Change* 2021; 11: 306–312.
8. Ernest T, Wang D and Zhou X. Tackling air pollution and extreme climate changes in China: implementing the Paris climate change agreement. *Environ Int* 2016; 95: 152–156.
9. Tanaka K and O’Neill BC. The Paris agreement zero-emissions goal is not always consistent with the 1.5°C and 2°C temperature targets. *Nat Clim Change* 2018; 8: 1–6. doi:
10. Li J, Tian Y, Deng Y, et al. Improving the estimation of greenhouse gas emissions from the Chinese coal-to-electricity chain by a bottom-up approach. *Resour Conserv Recycl* 2020; 167: 105237.
11. Energy Research Club. The carbon intensity of the global power industry has been reduced in an orderly manner, and the carbon emission of China’s power industry is still relatively high, www.cspplaza.com/article-15947-1.html (2019, accessed 1 September 2021).
12. The State Council of the People’s Republic of China. China will formulate an action plan this year to peak its carbon emissions by 2030, www.mee.gov.cn/zwj/gwywj/202110/t20211026_957879.shtml (2020, accessed 7 September 2021).
13. National Energy Administration. Digital Grid: The “best Partner” of New Energy, www.nea.gov.cn/2021-06/11/c_1310001918.htm (2021, accessed 7 September 2021).
14. Mallapaty S. How China could be carbon neutral by mid-century. Nature 2020; 586: 482–483.
15. Duan H, Zhou S, Jiang K, et al. Assessing China’s efforts to pursue the 1.5°C warming limit. Science 2021; 372: 378–385.
16. China Electricity Council. Annual development report of China’s power industry in 2020. www.ceppea.net/n/i/198243 (2020, accessed 10 September 2021).
17. Li J, Zhang Y, Tian Y, et al. Reduction of carbon emissions from China’s coal-fired power industry: insights from the province-level data - science direct. J Cleaner Prod 2020; 242: 118518.
18. Su S, Fang X, Zhao J, et al. Spatiotemporal characteristics of consumption-based CO2 emissions from China’s power sector. Resour Conserv Recycl 2017; 121: 156–163.
19. Li W, Yang M, Long R, et al. Assessment of greenhouse gases and air pollutant emissions embodied in cross-province electricity trade in China. Resour Conserv Recycl 2021; 171: 105623.
20. Wang J, Song C and Yuan R. CO2 Emissions from electricity generation in China during 1997-2040: the roles of energy transition and thermal power generation efficiency. Sci Total Environ 2021; 773: 145026.
21. Magazzino C. CO2 Emissions and energy use in the South Caucasus and Turkey: a PVAR analyses. Econ Growth 2016; 4: 153–162.
22. Yang L, Lin B, et al. Carbon dioxide-emission in China’s power industry: evidence and policy implications. Renewable Sustainable Energy Rev 2016; 60: 258–267.
23. IPCC. IPCC Fourth Assessment Report of IPCC. Report, Cambridge University Press, UK, September 2007.
24. Kaya Y. Impact of carbon dioxide emission control on GNP growth: interpretation of proposed scenarios IPCC energy and industry subgroup, response strategies working group, Report, IPCC, UK, January 1990.
25. Chen J, Wang P, Cui L, et al. Decomposition and decoupling analysis of CO2 emissions in OECD. Appl Energy 2018; 231: 937–950.
26. Tang X, Jin Y, McEllan BC, et al. China’s coal consumption declining—impermanent or permanent? Resour Conserv Recycl 2018; 129: 307–313.
27. Xie P, Yang F, Mu Z, et al. Influencing factors of the decoupling relationship between CO2 emission and economic development in China’s power industry. Energy 2020; 209: 118341.
28. Zhang C, Zhong L and Wang J. Decoupling between water use and thermoelectric power generation growth in China. Nat Energy 2018; 3: 792–799.
29. Ang BW, Zhang F and Choi K. Factorizing changes in energy and environmental indicators through decomposition. Energy 1998; 23: 489–495.
30. Ang BW. LMDI Decomposition approach: a guide for implementation. Energy Policy 2015; 86: 233–238.
31. Zhang C, Zhong L, Liang S, et al. Virtual scarce water embodied in inter-provincial electricity transmission in China. Appl Energy 2017; 187: 438–448.
32. Shan Y, Huang Q, Guan D, et al. China CO2 emission accounts 2016–2017. Sci Data 2020; 7: 54.
33. Shan Y, Guan D, Zheng H, et al. China CO2 emission accounts 1997–2015. *Sci Data* 2018; 5: 170201.
34. Wei W, Li J, Chen B, et al. Embodied greenhouse gas emissions from building China’s large-scale power transmission infrastructure. *Nat Sustainability* 2021; 5: 739–747.
35. Zhang Q and Chen W. Modeling China’s interprovincial electricity transmission under low carbon transition. *Appl Energy* 2020; 279: 115571.
36. Xinhuanet. The CPC Central Committee’s proposals for formulating the 14th Five-Year Plan (2021-2025) for National Economic and Social Development and the Long-Range Objectives Through the Year 2035, www.xinhuanet.com/2021-03/13/c_1127205564.htm (2021, accessed 20 February 2022).
37. Mi Z and Sun X. Provinces with transitions in industrial structure and energy mix performed best in climate change mitigation in China. *Commun Earth Environ* 2021; 2: 182.
38. Hu Y and Cheng H. Displacement efficiency of alternative energy and trans-provincial imported electricity in China. *Nat Commun* 2017; 8: 14590.