Life cycle analysis of greenhouse gas emissions of China's power generation on spatial and temporal scale

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Abstract
In this study, the “cradle-to-gate” greenhouse gas (GHG) intensities of six types of power generation in China are analyzed using a life cycle assessment approach, including wind power, solar photovoltaic power, nuclear power, hydropower, biomass power, and thermal power. According to the mix of regional power grids in China and GHG intensities of various types of power generation, the GHG intensities of hybrid power on regional power grid scale are calculated. The results show that they are closely corresponding to the grid mix of each region. Besides, the value of northeast China is the highest and the largest variation between regions is about twice. Furthermore, the efforts made by the Chinese government promoting energy shift are expected to accelerate the decrease of the electricity system GHG intensity to 376.9 gCO₂eq/kWh by 2035, about 51.0% lower than that in 2017. And the total GHG emissions are predicted to reach 4.5 × 10⁹ tCO₂eq in 2035, while in “below 2°C” scenario this value will decrease to 3.6 × 10⁹ tCO₂eq. This study compiles the life cycle inventory of China’s electricity generation on spatial and temporal scale, and can provide suggestions on the development of regional and national electricity systems.

Keywords
greenhouse gas emissions, life cycle assessment, power generation, regional power grid

1 | INTRODUCTION

As an important part of the national energy system, the electricity system plays a key role in greenhouse gas (GHG) emissions and policy making¹ in China. At present, the GHG emissions from electricity system account for about 40% of total GHG emissions from energy activities. Thermal power is still the main component of China’s electricity generation, and the use of a large amount of fossil fuels leads to high energy consumption and high pollution in the electricity system.² In the past few decades, renewable power generation technologies have gradually developed in China and around the world.³ The development and utilization of renewable energy can reduce the dependence on fossil fuels and meet the growing energy demand.⁴ It is the future energy development trend and will also become an effective means for China to mitigate GHG emissions and achieve carbon emission neutrality.⁵

Life cycle assessment (LCA) is a powerful tool for evaluating the environmental performance of products, processes, and production systems,⁶ and has been used
by many researchers to assess the environmental impacts of power generation. LCA studies on power generation can be divided into two categories. At present, most studies focus on the evaluation and calculation of single type or multiple types of power, and highlight the environmental advantages of specific power types. Including thermal power, solar photovoltaic (PV) power, hydropower, wind power, biomass power, and nuclear power. The second type of study aims to provide a basis for energy conservation and some policy suggestions on the development of electricity system based on the national data. Ding et al. assessed several major types of power and calculated the average power supply GHG intensities for each province in China in 2013 through LCA. They found that the GHG intensity of power generation varies greatly between regions. And compared with thermal power, renewable power has more environmental advantages. Wang et al. established a database of power plants above 6 MW in China based on the data in 2014, calculated the total emissions of \( \text{CO}_2/\text{SO}_2/\text{NO}_x \) for different types of power generation through LCA, and proposed possible emission reduction paths based on the results.

In the context of a carbon-neutral era, this study aims to combine these two types of LCA, and make a comprehensive analysis of the electricity system on spatial and temporal scale based on relatively new data. The main contributions of this study are as follows:

1. The GHG intensities of the six major types of power in China are fully considered.
2. On spatial scale. During the literature review, we found that there are few LCA studies focusing on regional grid scale. This study explores the key points affecting GHG emissions and the regional distribution characteristics of GHG emissions on regional grid scale.
3. On temporal scale. From the perspective of LCA, this study quantitatively explores the impacts of stated policies (SPs) and enhanced policies on the GHG emissions from the electricity system in the future, and studies the emission reduction impacts of renewable power development and power generation efficiency improvement. This study could provide reference for the development of the electricity system on the basis of existing policies.

## 2 | OVERVIEW OF CHINA’S GRID MIX

Table 1 describes the characteristics of China’s grid mix in 2017, with data from China Electric Power Yearbook and Energy Bureau Report. Among them, thermal power generation occupies an absolutely dominant position. As for renewable power, wind power and solar PV power take up about 4.7% and 1.8%, respectively, and a very small amount of geothermal energy, tidal power, and other types of power are included in other types.

China’s power grid is divided into six major regional grids: North China Grid, Northeast China Grid, East China Grid, Central China Grid, Northwest China Grid, and China Southern Grid. The regional power grid mix in 2017 is shown in Figure 1. Thermal power is the main type of power in the areas covered by the North China Grid, Northeast Grid, and East China Grid. In some provinces, such as Shandong, Shanxi, Heilongjiang, and Jiangsu, thermal power accounts for 90% of the total power generation while Shandong even accounts for more than 95%. In the Central China Grid and China Southern Grid regions, hydropower and thermal power.
equally contribute, with hydropower accounting for nearly 50% in the Central China Grid region and about 40% in the China Southern Grid region. Moreover, Yunnan and Sichuan are overwhelmingly dominated by hydropower, contributing 85% to total power generation.

Figure 2 shows the overview of China's grid mix from 2007 to 2017. China's total power generation increased year by year from 3264.4 billion kW h in 2007 to 6417.1 billion kW h in 2017, among which thermal power increased year by year. However, the proportion of power generation showed a downward trend. The proportion of hydropower was stable, and ranking the second, fluctuating between 14% and 20%. The proportion of wind power and nuclear power continued to increase, and solar PV power has been gradually paid attention to since about 2010. In recent years, solar PV power generation has developed rapidly, with the annual power generation of up to 116.6 billion kW h in 2017.

3 | METHODS AND DATA

The application of LCA follows the ISO14040 and ISO14044 standards, which usually includes four phases: the goal and scope definition, the inventory analysis, the impact assessment, and the interpretation.

3.1 | Research purpose and system boundary

The main objectives of this study are as follows:

1. Compile a life cycle inventory (LCI) of six types of power generation in China on “cradle-to-gate” basis, including wind power, solar PV power, nuclear power, hydropower, biomass power, and thermal power. Analyze the GHG intensities and the contributions of various life cycle stages.

2. Estimate the GHG intensities on regional grid scale, explore the relationship between regional characteristics and the results. And provide suggestions on regional power development.

3. Forecast the GHG intensities and total GHG emissions of China electricity system in 2035 in the SPs and below 2°C scenarios. Explore the way of low-carbon development of the whole electricity system.

The selection of system boundary has a significant influence on LCI input and evaluation results. Figure 3 shows the system boundary of power generation, which includes infrastructure construction, fuel supply, and power generation stages. The transmission and dispatching of electricity are not considered in this study. The system boundaries of all types of power are set in the same way except for thermal power. Its infrastructure construction stage is not included in the system boundary due to the very small proportion of overall GHG emissions over the plant's lifetime. In the end, the functional unit is 1 kW h of electricity generation.

3.2 | LCI data sources

The inventory analysis stage of LCA includes the data of all materials, energy flows, and environmental emissions
within the boundary of the system, and data close to the real production should be used as much as possible.\textsuperscript{25} Therefore, in terms of data availability and reliability, 2017 was chosen as the reference year in this study.

OpenLCA used in this study is an open source LCA software developed by Greendelta,\textsuperscript{26} which has a friendly interaction interface and comprehensive functional modules, and has been recognized and used by many researchers. Ecoinvent v3.7 is currently one of the most comprehensive and widely used database sets in the world. Its data are mainly derived from statistical data and technical literature, and it has units and aggregated data sets covering many countries in the world. Its data are mainly derived from statistical data and technical literature, and it has units and aggregated data sets covering many countries in the world.\textsuperscript{27,28} Therefore, basic data for upstream energies and raw materials are derived from the Ecoinvent v3.7 database. The Chinese data in the database are the main choices for this study, and the global average data will be used if Chinese data are not provided.

3.2.1 Wind power

China’s wind farms are mainly distributed in the northwest and coastal areas, such as Inner Mongolia, Xinjiang, Shandong, and other provinces. Although the coastal areas are very rich in wind energy resources, for technical, geographical, and economic reasons, the proportion of offshore wind power in China’s wind power generation is relatively small and there are few available data sources.\textsuperscript{29} Among onshore wind farms, 1.5 MW wind turbine is the most common generator set in the wind power market, accounting for more than half of the total installed capacity.\textsuperscript{30} After comprehensive consideration, an onshore wind farm with thirty-three 1.5 MW wind turbines in Inner Mongolia is selected as the representative case. The LCI data are mainly collected from Li et al.,\textsuperscript{24} which have been listed in Table SA1.

Wind farm is mainly composed of several parts of wind turbine, foundations, station, and cables. Steel, aluminum, concrete, copper, and other materials are mainly used for the production of building materials. The construction stage mainly consumes electricity and diesel fuel. Fuel input is not required during the power generation stage of wind power, and the consumption of water and lubricating oil is considered in this study. The system lifetime is assumed to be 20 years, and the GHG intensity is evenly distributed to each year, and then distributed to per kWh electricity generation according to the average annual utilization hours of wind power. Due to the different annual utilization hours in different regions, the data share allocated to unit electricity generation in LCI is also different.
3.2.2 Solar PV power

The solar PV industry in China is mainly concentrated in Qinghai, Gansu, Inner Mongolia, Xinjiang, and other northwest regions. The power generation capacity of the solar PV system is greatly affected by solar radiation, which is basically positively correlated with the regional solar radiation.\(^{31}\) Different factors such as longitude and latitude, altitude, and climate conditions in different regions lead to great differences in solar PV power generation capacity. LCI data of solar PV power generation are mainly collected from Xu et al.,\(^{32}\) and have been listed in Table SA1. Xu et al.\(^{32}\) studied the environmental impacts of China’s solar PV power generation from 2011 to 2016. The defined system boundary is consistent with this study, and the time period of the data is close to 2017. Therefore, the data are used as LCI input for this study.

There are mainly three types of solar PV products in the existing market, including polycrystalline silicon, monocrystalline silicon, and thin-film. Crystalline silicon technology basically dominates the market, and it has been found that the difference in GHG intensity between polycrystalline silicon system and monocrystalline silicon system is very small.\(^{33}\) Therefore, a polycrystalline silicon system is selected as the representative to calculate the environmental impacts of solar PV power generation. The input data of the system construction is standardized into a 1 kW h solar PV system, which is composed of five 200 W modules and 54 polycrystalline silicon cells, and the conversion efficiency is 16%.\(^{31}\) The production of solar PV panels is the core part of the solar PV system, which is mainly composed of silicon ore mining, wafer slicing, cell processing, and modules assembly stages. Then the panels will be combined with the balance of system. There is no energy input in the power generation stage, and the water required is considered in the study. The system lifetime is assumed to be 30 years, and the LCI data are also adjusted according to the system life and average annual utilization hours in the same way as wind power.

3.2.3 Nuclear power

Almost all nuclear power plants in China are located in coastal areas because a large amount of energy is dissipated in the form of heat during the operation of nuclear power plants, which requires great quantities of cooling water to cool the units.\(^{29}\) LCI data of nuclear power generation are collected from the Chinese LCI in the Ecoinvent database,\(^{28}\) and have been listed in Table SA1. For there are only several provinces that have a nuclear power supply, regional differences are not considered. The study assumes that nuclear power is generated in a 1000 MW nuclear power plant, using uranium as fuel. Apart from the infrastructure construction and fuel supply stage, the LCI data also includes chemicals, diesel requirements as well as other raw materials requirements. Water use for cooling is included, but the cooling tower infrastructure is not considered. In addition, the treatment of radioactive waste and non-radioactive waste is considered in the power generation stage. The lifetime of the nuclear power plant is assumed to be 40 years.

3.2.4 Biomass power

The scale of biomass power in China is still relatively small. LCI data of biomass power generation are collected from the Chinese LCI in the Ecoinvent database,\(^{28}\) and have been listed in Table SA1. Regional differences are not considered due to the lack of data. The research assumes that biomass power is generated in a 6667 kW biomass power plant which is powered by wood chips.\(^{28}\) The fuel is burned at a temperature of 800–1300°C under excess air conditions and converted into carbon dioxide and water. Burning takes place with the following steps: drying, degradation of the wood into carbon and gases, degradation of the carbon into gases, oxidation of the gases. After that the heat generated is used to generate electricity with an organic rankine cycle steam generator. The chemicals, water, and lubricating oil are included in the power generation stage. Besides, the emissions to air and the disposal of the ashes are considered. The lifetime of the biomass power plant is assumed to be 20 years.

3.2.5 Hydropower

Most of China’s hydropower stations are located in the Yangtze river and Yellow River basins, which can be divided into the conventional station and pumped storage station, of which conventional hydropower station accounts for a larger share of power generation and is the more common type.\(^{29}\) Therefore, in this study the conventional power station is selected as the representative type of hydropower generation. LCI data of hydropower generation are collected from Wang et al.,\(^{29}\) and have been listed in Table SA1. And regional differences are not considered for there is no linear relationship between power generation and water resource characteristics. The LCI input of hydropower mainly comes from the infrastructure construction stage, in which the production of steel and cement accounts for the vast majority, and the
consumption of diesel oil is considered. While there is no other energy input in the process of power generation, only the lubricating oil is considered. The lifetime of the power station is assumed to be 50 years.

3.2.6 | Thermal power

The GHG intensity of thermal power generation mainly includes direct and indirect parts. Direct part refers to the GHG emissions generated by fuel combustion, and indirect part refers to those caused by fossil fuel supply and transportation, and so forth. In addition, due to the insignificant amount of GHG brought by the construction of power plant over its lifetime, it is not considered in this study. Most domestic research focus on quantifying the direct part of thermal power generation but do not consider the impact of indirect part.

Thermal power includes coal-fired power, gas-fired power, oil-fired power, and some other power types. In this study, different types of thermal power are not calculated separately, but as a whole. We collected and counted the fossil fuel consumption of the thermal power industry in 2017, and made an overall calculation with reference to the method provided by the Ministry of ecological environment. The GHG intensity of direct part is calculated according to the data of fossil fuel consumption and GHG emission factors of three major GHG: CO₂, CH₄, and N₂O. And the lower limit of 95% confidence interval of Intergovernmental Panel on Climate Change default value of these gases are selected according to the conservative principle. The impacts of other gases are small, so that are ignored in the study.

For the indirect part, the GHG intensity is calculated with the help of the upstream energy data in the Ecoinvent database. The input data of thermal power generation have been listed in Table SA1.

3.3 | Life cycle impact assessment method

Life cycle impact assessment (LCIA) is a part of the LCA methodology aimed at evaluating and understanding the magnitude and significance of the potential environmental impacts for a product system throughout the life cycle. The ReCiPe Midpoint method is used for LCIA calculations to assess the GHG intensities of six types of power. The GWP 100 indicator is chosen, which quantifies the integrated infrared radiative forcing increase of a GHG and means the global warming potential with a time span of 100 years. The unit of that is gCO₂eq, namely the equivalent value of CO₂ emission.

3.4 | Method for obtaining GHG intensities of regional power grids

This study calculates the average power GHG intensities in six grid regions. Firstly, we calculate the average power generation GHG intensities of the province based on the grid mix of each province, and then further weight the average GHG intensity of the regional power grid.

\[
e_a = \sum_{x=1}^{n} p_x \mu_x, \quad (1)
\]

where \(e_a\) is the GHG intensity of power generation in province \(a\); \(p_x\) is the production GHG intensity of power type \(x\); \(\mu_x\) is the proportion of the output of power type \(x\); \(n\) is the number of power types.

\[
e_t = \sum_{a=1}^{m} e_a \mu_a, \quad (2)
\]

where \(e_t\) is the average power generation GHG intensity of the regional power grid; \(\mu_a\) is the proportion of power generation in province \(a\); \(m\) is the number of provinces.

3.5 | Method for predicting GHG emissions from electricity system in 2035

To explore the trend of total GHG emissions of China’s electricity system and the practical impact of renewable power, this study predicts the GHG emissions from China’s electricity system in 2035, which is a key milestone of sustainable development of electricity system in China. In the past few years, the GHG intensity of thermal power has shown a downward trend year by year. In addition, referring to Wang et al.’s research, we consider that the future GHG intensity of thermal power could be predicted by curve fitting. Firstly, the average GHG intensities of China’s thermal power from 2005 to 2020 are calculated. Then the existing data points are fitted by using drawing software “Origin” and the fitting curve used is exponential. In the process of fitting, we find that the conventional linear curve and polynomial curve could not fit the data well, and the exponential curve has better accuracy, so the exponential curve is used in this study. Moreover, considering the uncertainty in the fitting process, the 95% confidence interval is calculated. As for other types of power, the GHG intensities of that use the previous results without considering the changes in emissions brought about by the passage of time.

The national renewable energy center of China has predicted China’s power mix in 2035, and the predicted...
Two scenarios are mainly analyzed. The SPs scenario is expected to fully achieve the relevant energy targets in the 13th Five-Year Plan and the report of the 19th National Congress of the Communist Party of China (CPC), showing the energy development forecast if the existing policies are resolutely implemented. The below 2°C (B2) scenario goes one step further, with meeting the carbon constraints of the Paris Agreement as the blueprint vision and backtracking on the energy development path required.

In the SP scenario, China’s total power generation will increase to nearly twice of that in 2017 by 2035. Wind power and solar PV power generation will increase sharply, reaching 10 times and 15 times more that of 2017. Nuclear power will also expand rapidly, accounting for about 6.2% by 2035 while the proportion of thermal power generation will decrease from 71.0% to 36.2%. In B2 scenario, the total power generation is about 12.7% higher than that in SP scenario, in which wind power and solar PV power will get more rapid development while the thermal power will decrease to about 24.5% of the total power generation.

4 | RESULTS AND DISCUSSION

4.1 | GHG intensities of power generation

Figure 4 shows the GHG intensities of six types of power generation and Figure 5 shows the contributions of GHG intensities. The results of renewable power are listed in Table SA2, and the GHG intensity of thermal power is listed in Table SA3.

The average GHG intensity of thermal power generation is about 1079.3 gCO₂-eq/kWh, much higher than that of other types of renewable power. The GHG intensity of thermal power generation is calculated according to the power mix and GHG intensities of power generation.

**TABLE 2** Forecast of China’s grid mix in 2035 under two scenarios

| Power types | Stated policies (×10⁸ kWh) | Proportion (%) | Below 2°C (×10⁸ kWh) | Proportion (%) |
|-------------|-----------------------------|----------------|----------------------|----------------|
| Hydro       | 1622                        | 13.7           | 1622                 | 12.2           |
| Thermal     | 4274                        | 36.1           | 3265                 | 24.5           |
| Nuclear     | 735                         | 6.2            | 735                  | 5.5            |
| Wind        | 3271                        | 27.7           | 5159                 | 38.7           |
| Solar PV    | 1836                        | 15.5           | 2380                 | 17.9           |
| Others      | 86                          | 0.7            | 163                  | 1.2            |
| Total       | 11,824                      | 100            | 13,324               | 100            |

*Note: The greenhouse gas (GHG) intensities and total GHG emissions from the electricity system in 2035 are calculated according to the power mix and GHG intensities of power generation. Abbreviation: PV, photovoltaic.*
intensity of power generation stage is about 847.3 gCO₂-  
eq/kWh, accounting for 78.5%. As a result, pollutant  
control and efficiency enhancement are keys to reduce  
the GHG intensity of thermal power. As a renewable  
power source, biomass still makes up a relatively small  
proportion in the thermal power generation at the pre-  
sent stage, accounting for only about 1.7%. However,  
compared with thermal power, biomass power shows  
great advantage in GHG intensity, which is only about  
57.4 gCO₂-eq/kWh. GHG intensity from the infra-  
structure construction stage account for about 2.7%, and  
that from the power generation stage account for about  
19.8%. It is worth mentioning that the supply of raw  
materials is the main source of GHG intensity, account-  
ing for about 71.9%. This suggests that the key GHG in-  
tensities reduction potential is to effectively reduce the  
collection and transportation of biomass, such as locating  
the power plant in areas with abundant biomass supply.  

Wind power and solar PV power have great ad-  
vantages over thermal power, with GHG intensities of  
30.5 and 36.2 gCO₂-eq/kWh, respectively, about 34 times  
and 29 times lower than that of thermal. GHG missions  
from infrastructure materials such as aluminum, steel,  
and concrete are main contributors. Therefore, for  
these types of power, reducing the use of these raw  
materials can effectively reduce the GHG intensities.  
Besides, the GHG intensities of wind power and solar PV  
power are greatly affected by regions. In coastal areas and  
some regions with high effective wind energy density, the  
GHG intensity of wind power has advantages compared  
with regions with low wind energy density such as He-  
nan and Shaanxi. In terms of solar PV power, high-  
radiation regions in Northwest China, such as Inner  
Mongolia, Qinghai, and Xinjiang have advantages over  
low-radiation regions.  

China's nuclear power plants are located along the  
coast because they require large amounts of cooling  
water to operate. The GHG intensity of nuclear power is  
only about 7.5 gCO₂-eq/kWh, and that of fuel supply  
stage accounts for about 48.3%. This means that in  
addition to reducing the materials consumption in the  
construction stage, the improvement of generation effi-  
ciency may also bring significant GHG emissions re-  
duction. The GHG intensity of hydropower is only  
4.0 gCO₂-eq/kWh, which can be considered as the lowest  
power generation mode of GHG intensity. Almost all of  
its GHG emissions come from the construction of the  
power station itself, and only a very small quantity of  
GHG emissions are generated in the operation stage.  

There are some uncertain data in the power genera-  
tion process, such as the difference caused by the dif-  
fERENCE IN THE SCALE OF THE POWER GENERATION SYSTEM,  
raw material production and transportation, resource  
utilization efficiency, and so forth, which will directly or  
indirectly affect the GHG intensities results. In this study,  
the GHG intensities of six types of power generation in  
existing studies are investigated and are compared. Most  
of the findings come from China, and some from other  
regions. As can be seen from the data in Table 3, results  
obtained in this study are all within ranges and are  
considered available.  

4.2 | GHG intensities of power  
generation of regional power grids  

The average GHG intensities of the six regional power  
grids in 2017 is shown in Figure 6. According to the  
calculation, the electricity system as a whole contributes  
about 4.9 × 10⁹ tCO₂-eq emissions in 2017, and the GHG  
intensity is about 769.4 gCO₂-eq/kWh. Among them,  

| Power types | Results of the study (gCO₂-eq/kWh) | Results of the literature (gCO₂-eq/kWh) |
|-------------|------------------------------------|---------------------------------------|
| Thermal     | 1079.3                             | 1045.7, 931.6–1189.9                   |
| Hydro       | 4.0                                | 3.84, 15.7–20                         |
| Nuclear     | 7.5                                | 12.4, 6.4–35                          |
| Solar PV    | 36.2                               | 53.4, 13–190                          |
| Wind        | 30.5                               | 28.3, 15.7–41                         |
| Biomass     | 57.4                               | 42–85, 8.5–130                        |

Abbreviation: PV, photovoltaic.
North China Grid contributes $1.7 \times 10^9$ tCO$_2$-eq absolute GHG emissions, accounting for 33.7% of the total electricity system GHG emissions. Due to its small power generation, Northeast China Grid accounts for the smallest proportion among all power grids, about 7.5%. Comparing with the thermal power generation, the absolute GHG emissions of other renewable power is very small, about $6.8 \times 10^7$ tCO$_2$-eq, accounting for only about 1.4%. However, the renewable power generation reaches 29% of the total, showing great environmental advantages.

GHG intensities of the Central China grid and China Southern Grid are significantly lower than those of other regional power grids because their proportion of hydropower is relatively high. The proportion of renewable power in the Northeast China Grid is around 20%, higher than that in North China Grid and East China Grid. But the GHG intensity is higher, reaching 1076.7 gCO$_2$-eq/kWh. This is mainly due to the relatively low efficiency of thermal power generation in this region and the relatively high proportion of coal power generation. The GHG intensity of Northwest China Grid is in the middle level, and the contribution of renewable energy power generation to the GHG intensity is only about 1.3%.

The regions with a high proportion of renewable power have significant advantages over that with high proportion of thermal power. However, the development of renewable power largely depends on the availability of regional resources, and the environment and resources of six regions in China present great differences. Under the guidance of the 14th Five-Year Plan as well as carbon emission peak and neutrality policy, different regions should continue to promote the emission reduction of power generation according to their own characteristics.

For regions with a high proportion of thermal power generation, such as regional power grids in North China and Northeast China, it is necessary to continuously optimize thermal power generation. This could be done by terminating low-capacity and high-pollution thermal power units, and enhancing the construction of biomass power plants, especially in resource-rich regions like Northeast China Grid area.

China’s wind energy resources are widely distributed. The overall developable capacity of wind energy resources is about $6.3 \times 10^9$ kW, and the total potential of wind power reaches 21.2 TW h. Solar PV power also has great development potential, and the potential development capacity of that can reach about $2.7 \times 10^9$ kW. In 2017, the installed capacity of wind power in China was only $1.6 \times 10^9$ kW, while that of solar PV power was $1.3 \times 10^9$ kW, showing great development potential. China’s wind energy resources are mainly distributed in Northwest, Northeast, and North China, accounting for more than 85% of the potential development. Provinces in these areas could vigorously promote the development of large-capacity wind power units. The GHG intensity of wind power in the eastern coastal areas is low, but the total potential development is relatively small, it is suitable for developing appropriately according to local conditions. The deserts that are capable of building large-scale centralized solar PV power plants are mainly distributed in Northwest China, provinces such as Gansu, Qinghai, and Xinjiang, have excellent solar energy resources reservation and relatively low GHG intensities. Moreover, the regions with great potential for solar PV power are concentrated in North China, including Shandong (4.9 TW h), Hebei (3.1 TW h), and Shanxi (2.1 TW h). Their local governments could promote the development of solar PV power via both centralized and distributed installation through incentives policies for example.

Central China Grid and China Southern Grid areas have a relatively high proportion of hydropower, which is attributed to concentrated water resources. However, these areas still have great potential for hydropower development. Among them, Sichuan, Yunnan, Hubei, and Guangdong have the largest potential (over 5.3 TW h). The total amount of hydropower generation in China in 2017 was about 1193.1 TW h, and there is still nearly 1253.9 TW h to be developed. As a traditional renewable power, hydropower is relatively mature technically and the future development is mainly affected by geographical resources and environmental policies. According to the guidelines of the Action Plan for Carbon Emission Peak and Neutrality, hydropower should be further developed, especially in Southwest China where water resources is underused. However, risks to the local ecological environment shall be assessed carefully and controlled before the construction of hydropower sites.

In addition, nuclear power is a high-energy-density and low-carbon power that has received great attention from the government. However, there are certain risks in the development process, and nuclear safety must be fully guaranteed.

### 4.3 GHG emissions forecast of the electricity system in 2035

#### 4.3.1 Prediction results of GHG emissions

The fitting curve is shown in Figure 7. The equations for the fitting curve and the 95% confidence interval are as follows:
\[ y = 956.9 + 331.2e^{(-0.11(x-2005))}, \quad (3) \]

\[ y = (956.9 \pm 19.4) + (331.2 \pm 17.1)e^{(-0.11\pm0.01)(x-2005)}. \quad (4) \]

The GHG intensity of thermal power generation will gradually decline because (1) the efficiency of thermal power generation gradually increases, which directly leads to the reduction of its GHG intensity; (2) the proportions of biomass power and gas power increase, which reduce the overall GHG emissions of thermal power.

According to the power mix and GHG intensities of power generation, the GHG intensities per kWh power generation and the total GHG emissions from the electricity system in 2035 are predicted and shown in Figure 8. Under the SP scenario, China’s average GHG intensity will be 376.9 gCO\textsubscript{2}-eq/kWh in 2035, a decrease of 51.0% compared with 2017. By that time, the total GHG emissions from the electricity system will reach about 4.5 × 10\textsuperscript{9} tCO\textsubscript{2}-eq. The GHG intensity of power generation in the B2 scenario is further reduced, about 264.7 gCO\textsubscript{2}-eq/kWh, which is 65.6% of that in the SP scenario. Although the total power generation is higher than that in SP scenario, the total GHG emissions will decrease to 3.6 × 10\textsuperscript{9} tCO\textsubscript{2}-eq.

Assuming that the GHG intensity per unit of thermal power generation will not decrease from 2017, and considering the change of grid mix, the total GHG emissions from the electricity system will reach about 4.8 × 10\textsuperscript{9} and 3.8 × 10\textsuperscript{9} tCO\textsubscript{2}-eq, respectively under the two scenarios in 2035, which means that the efficiency improvement and emission reduction of thermal power can achieve the absolute GHG emission reduction of 0.3 × 10\textsuperscript{9} and 0.2 × 10\textsuperscript{9} tCO\textsubscript{2}-eq. Considering only the decline in GHG intensity per unit of thermal power generation, the total GHG emissions will reach 8.4 × 10\textsuperscript{9} and 9.5 × 10\textsuperscript{9} tCO\textsubscript{2}-eq, respectively. It can be seen that the substitution of renewable power for thermal power in the grid mix could bring about 3.9 × 10\textsuperscript{9} and 6.0 × 10\textsuperscript{9} tCO\textsubscript{2}-eq absolute emission reduction respectively under the two scenarios.

### 4.3.2 | Suggestions on electricity system development

To promote the low-carbon development of the electricity system, the Chinese government has formulated
and implemented positive policies. During the period of 12th Five-Year Plan, remarkable achievements have been made in adjusting the power generation structure and improving energy efficiency. The installed capacity of nonfossil energy increased from 27.2% in 2010 to 34.8% in 2015.49 The 13th Five-Year Plan clearly proposed to effectively control the carbon emissions of the electricity system and the coal consumption of coal power supply should be lower than 310 g/kW h by 2020. The target was reached days ahead of schedule in 2017.39 Accelerating the development of renewable energy generation and the GHG emissions reduction of thermal power is the main theme of the development of China’s electricity system. The 14th Five-Year Plan period (2021–2025) will be a turning point in the history of China’s energy transformation. In the 14th Five-Year Plan and Vision 2035 reports, the Chinese government focuses on promoting the low-carbon transformation of the electricity system.40

From our findings, a more ambitious low-carbon development policy would lead to a more significant reduction in GHG emissions. And the increase of renewable power generation, combined with the optimization of grid mix and the improvement of thermal power efficiency, could greatly promote the reduction of total GHG emissions from the electricity system. And the growth of renewable power will be the dominant factor.

1. The overall development strategy. The government could set more proactive long-term development goals for the electricity system, and set installed capacity targets for different types of power based on available data. In addition, it is also necessary to promote the continuous optimization of the grid mix and continue to promote the development of renewable power.

2. Thermal power development. In recent years, the rapid growth of thermal power has caused the significant negative effect, and the annual operation hours of thermal power plants in many areas do not meet the design standards. The continuous growth of thermal power undoubtedly brings great pressure to electricity system decarbonization. Due to the ever-increasing power demand, thermal power still has room for further development, but it cannot be developed blindly for the short-term demand. The government could make full use of market means to effectively control the scale of thermal power and improve the efficiency of thermal power plants.40 In addition, the application of (carbon capture, utilization and storage (CCUS) technology can effectively reduce GHG emissions of thermal power. The State Grid Energy Research Institute predicted that in the scenario of deep decarbonization pathway, the gradual large-scale promotion of CCUS will help the total GHG emissions from the electricity system to achieve a rapid decline after 2035 and zero emissions by 2060.38 However, CCUS currently is only in the small-scale demonstration stage, which is still far from large-scale commercial use. Not only is it expensive, but it also brings some potential safety problems.39 The government should strengthen scientific and technological support, attach importance to CCUS technology, speed up the development and promotion of related technologies.

3. Renewable power development. The total GHG emissions from the electricity system is sensitive to the share of renewable power. Among them, the development of wind power and solar PV power is a crucial link, occupying the main position to replace thermal power generation in the future. The government could provide favorable conditions for the development of renewable energy, improve the economic support policies and retain a reasonable level of subsidies. Besides, it is also necessary to further promote technology research and innovation, reduce the cost of renewable power generation, and improve the safety of nuclear power. The abundant water resources in Southwest China could also be further developed and some coastal areas with increasing power demand should continue to promote the construction of nuclear power plants, but the risks should be effectively avoided. Areas rich in renewable energy should focus on promoting the development of renewable power. Besides, they should cooperate with the construction of power grid to achieve cross-regional power substitution.

5 CONCLUSION

The utilization of renewable energy plays an important role in the development of the electricity system, and the low-carbon development of the industry also profoundly affects the achievement of the national carbon-neutral goal. This study uses LCA to calculate the GHG intensities of six types of power generation and analyzes the contributions of various life cycle stages of thermal, wind, solar PV, nuclear, biomass, and hydropower generation. The results show that renewable power has a great advantage over thermal power, among which traditional hydropower has the lowest GHG intensity. Solar PV power generation has a lower GHG intensity in high-radiation areas such as Inner Mongolia, Ningxia, and Qinghai, while wind power generation has more advantages in coastal areas and some areas with rich wind resources. In addition, the average GHG intensities of six power grids are calculated, and the results show that
different power ratios and production efficiencies exhibit great differences among these regions.

In recent years, the Chinese government has issued some powerful policies to promote the development of renewable energy, which has promoted the rapid development of renewable energy such as solar PV power and wind power. In addition, the continuous technological innovation of thermal power generation and the elimination of inefficient units have effectively reduced the GHG intensity of power generation. This study predicts GHG emissions of China's electricity system in 2035, and the GHG intensity of China's electricity system will drop to about 376.9 gCO2eq/kWh in 2035 in “stated policies” scenario, a decline of about 51.0% compared to that in 2017. And the total GHG emissions from the electricity system are predicted to reach 4.5 × 109 tCO2eq in 2035, while in “below 2°C” scenario this value will decrease to 3.6 × 109 tCO2eq. According to the national planning and policy, renewable power will gradually occupy the dominant position in the future, and different regional power grids should grasp their own characteristics of grid mix to achieve sustainable development. The reduction of total GHG emissions of China’s electricity system in the future will mainly come from the GHG emission reduction of thermal power generation and the increase of the proportion of renewable power. And a more ambitious target could help accelerate the low-carbon development of China’s electricity system.

CONFLICTS OF INTEREST
The authors declare no conflicts of interest.

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SUPPORTING INFORMATION

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