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Title: Quantifying the geographical distribution effect on decreasing aggregated nitrogen intensity in the Chinese electrical generation system

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Keywords: aggregated NOx generation intensity; electricity generation; LMDI; geographical distribution effect; China

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Response to reviewers' comments

Dear Editors and Reviewers:

Thank you very much for your careful review and constructive suggestions about our manuscript, titled "Quantifying geographical distribution effect on decreasing aggregated nitrogen intensity in the Chinese electrical generation system" (JCLEPRO-D-18-05802). According to your comments, we made careful and appropriate revisions in our manuscript. The revised portions are marked in blue. The responses to the reviewer comments have been prepared and included herewith. We thank you for your thoughtful suggestions and insights, which have enriched the manuscript and produced a more balanced and better account of the research. We hope that the revised manuscript is now suitable for publication in your journal.

Responses to the reviewer's comments:

Reviewer #1:

1. Comment: Abstract: Besides the Identification of a knowledge gap in the abstract, the knowledge gap and the value of this research need to be point out in this part.

Response: Thank you for your suggestions. Based on your comments, we added a sentence to the Abstract that concisely shows the knowledge gap and the value of this study. Please see details on Page 2 Line 12-15.

2. Comment: Introduction: This section still needs revision. I suggest that that the author organize the reference by 1) the calculation and measurement of the NO_x emissions, 2) the influencing factors and mechanisms of the NO_x emission. and 3) the forecast of the future trend.

Response: Thank you for your suggestions. Based on your comments, we have reorganized the references in the introduction. Please see details on Pages 3-5.

3. Comment: Overview of China's electricity generation and ANI: Figure 2& 3 shows the special distribution of the energy generation and consumption in China of the 4 periods, however, there are no further explanation in this part. Please consider whether you want to keep it in this paper, and how this relevant to the main research findings of the paper.

Response: Thank you for your suggestions. Based on your comments, we removed Figures 2 and 3 and the related description. Instead, we quoted the conclusion of

Wang et al. (2018a) to confirm this spatial characteristic of China's power system. Please see details in Pages 10-11.

4. Comment: Conclusion. This part could point out the significance of the findings as well as summaries and bring together the main areas covered in the writing. However, the elaborations could be more plain and simple to meet the journal's standard.

Response: Thank you for your suggestions. Based on your comments, we have summarized the main areas involved and clearly pointed out the significance and implications of each finding. In addition, we have modified the elaborations of the Conclusion to meet the journal’s standard. See details in Pages 23-24.

5. Comment: The English of the manuscript must be improved before submission. I strongly suggest the author obtain assistance from a colleague who is well-versed in English or whose native language is English.

Response: Thank you for your comments. According to your comments, we asked the help of Elsevier Webshop language service to polish the English of this manuscript.

Reviewer #2:

6. Comment: The author has addressed all the reviewer comments.

Response: Thank you very much for your comments. We hope that this revised manuscript meets the requirements of the journal.

Title:

Quantifying the geographical distribution effect on decreasing aggregated nitrogen intensity in the Chinese electrical generation system

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Highlights

- The ANI of electrical generation has decreased by 33.18% over the past 20 years.

- Electrical generation efficiency inhibited ANI strongly but gradually weakened over time.
- The geographical distribution effect reduced the ANI but transferred environmental costs.
- The electrical generation structure will hopefully affect ANI reduction in future.

Abstract

Over the past 20 years, the spatial distribution of electrical generation and its relationship to cross-regional power transmission has impacted China’s power generation system and significantly affected the total amount of NO_x and the aggregated nitrogen intensity (ANI) of the system. An investigation of the driving mechanisms of ANI that considers the unevenness of regional electricity generation will be crucial to future improvements in the NO_x efficiency of the electrical generation system in China. In this study, we built a decomposition model for ANI by incorporating the spatial distribution of electrical generation and found that the spatial distribution of electricity generation together with energy-related factors gradually caused decreases in ANI. The efficiency of electricity generation presented the dominant inhibitory effect on ANI, but its effect size has weakened since 2010. In contrast, the fossil fuel structure of thermal power shows an increasingly positive effect on changes in ANI. The primary energy composition only slightly affected changes in ANI. Moreover, the changed geographical distribution of electricity generation is non-negligible and has a positive effect on reduction of the ANI of the Chinese electrical generation system. The transferred amount of local NO_x emissions by cross-provincial electricity transmission, however, could cause lead to additional environmental costs for generators. This issue should receive more attention in the future.

Keywords: aggregated NO_x generation intensity, electricity generation, LMDI, geographical distribution effect, China

1. Introduction

Urbanization and economic growth in China has resulted in a sharp increase in electrical generation and consumption (Pu et al., 2018), leading to increasing pressure to manage atmospheric pollutants, such as nitrogen oxides (NO_x). The NO_x generated by the Chinese electrical generation system are important pollutants related to urbanization and industrialization (Wang et al., 2018b) and have an influential effect on urban air quality challenges (He et al., 2014). In China, the total amount of NO_x emissions from the Chinese electrical generation system has been increasing yearly and accounted for approximately 33% of total NO_x generation in 2012 (Huang et al., 2016); however, the aggregated nitrogen intensity (ANI) of the system, an important indicator of NO_x emissions efficiency in power generation, has been decreasing over the past 20 years. Investigation of the drivers of ANI reduction is crucial for policymakers in order to maintain the ongoing trend and further reduce NO_x emissions from electrical generation in China.

Previous studies have explored NO_x emissions from electricity generation using the three following approaches. The first approach calculated and measured NO_x emissions from electricity generation. Huang et al. (2016) accounted for NO_x emissions of China's power plants from 2004 to 2010. Tian et al. (2013) established a NO_x emissions inventory for Chinese electricity plants in 2010. Zhao et al. (2008) estimated NO_x emissions for coal-fired electricity generation in China between 2000 and 2005. All of these findings indicated a notable change in the spatial distribution of NO_x emissions related to electricity generation.

A second approach explored the impact factors and mechanisms of NO_x emissions. Some of these studies considered the impacts of technological solutions for NO_x reduction in electrical generation, such as Selective Catalytic Reduction (Ma et al., 2016), hydrogen enrichment (Kornbluth et al., 2012), the optimal overfire air ratio (Ti et al., 2014), or steam-treated pellets (McKechnie et al., 2016). Other studies explored the impact of factors related to energy utilization on NO_x emissions, including biomass power generation (Monroy et al., 2018), biogas with a stoichiometric air-fuel ratio (Kim et al., 2016), or natural gas power generation (Gür, T. M., 2016). Other studies considered the impacts of energy policy on NO_x emissions. Asane-Otoo (2016) showed that regulations, such as privatization and unbundling vertically integrated activities in the electricity market, decrease sectoral NO_x emission intensity in OECD countries, and Huang et al. (2017) simulated the impacts of different environmental regulations on NO_x emissions across eastern China (Anhui, Fujian, Shanghai, and Zhejiang).

There is increasing concern about the effects of geographical distribution and regional differences in electrical generation on GHG emissions. Chen et al. (2018a) studied driving factors of electrical carbon productivity (ECP) changes in China from a regional and departmental perspective (including the power industry). Chen et al. (2018b) analyzed the driving factors of electrical carbon productivity (ECP) changes in China's power industry from a regional perspective, where the influence of power transfers among provinces, imports and exports, and transmission losses are considered. Liu et al. (2017) explored the driving force of the aggregate carbon intensity (ACI) of electrical generation in China in 30 provinces. These studies only compared provincial differences, and there has been a lack of quantification of the contribution of geographical distribution. Contextually, some studies have attempted to introduce geographical distribution as a substantial effect on the model to explore emissions from the power industry. Ang and Su (2016) explained the impact of the global geographic transformation on aggregated CO_2 intensity generated by electricity generation. Zhou et al. (2014) explored the drivers of regional CO_2 emissions from thermal power generation activities, considering changes in the spatial distribution of electricity generation.

A third approach predicted and explored future trends of NO_x emissions from electrical generation. Wang et al. (2018c) predicted future air pollution (including NO_2) in Beijing based on a series of thermal power emission control policies for the Beijing-Tianjin-Hebei region. Hu et al. (2016) assumed different scenarios for future power development and simulated their effects on China's air quality (including NO_x) in 2030. Wang et al. (2015) used the Canadian Applied Mathematics Quarterly model to simulate and evaluate the environmental impact of NO_2 from Emission Standards for Air Pollutants from Thermal Power Plants. Shim and Hong (2016) predicted NO_x emissions in 2027 based on the changes in South Korean power plants. Cofala et al. (2007) developed two scenarios to estimate future anthropogenic emissions of the air pollution precursors (including NO_x) using a global version of the Regional Air Pollution Information and Simulation (RAINS).

Existing studies reveal a two-fold research gap to fill: on one hand, when comparing the increasing amount of electrical generation and its NO_x emissions, it is important to find the drivers that affect ANI change and improve the NO_x efficiency of the Chinese electrical generation system. On the other hand, the decomposition method in previous studies was largely a comparison among different regions instead of quantifying the effect of geographical distribution into the decomposition model and should be improved.

In this study, we proposed three main advances to bridge the knowledge gap in previous studies. First, we estimated ANI and displayed the temporal change and spatial distribution of the NO_x emissions efficiency of the Chinese electrical generation system over the past 20 years in China. Second, we explored how energy-related drivers, including electricity generation structure, the efficiency of electrical generation, and primary energy composition affected the deceasing ANI of the Chinese electrical generation system. Third, we elaborated in detail how geographical electricity distribution affected decreasing ANI by incorporating the geographical distribution of electrical generation into the decomposition model.

The following sections are organized as follows: Section 2 describes the method of accounting for NO_x generation, the LMDI model, and data acquisition. Section 3 describes the traits of electricity generation, electricity consumption, and ANI. Section 4 illustrates the results of the LMDI model. Section 5 presents the study's conclusions and provides suggestions.

2. Method and data

2.1 Estimation of NO_x generation from electrical generation

In this study, the total amount of NO_x generation from the Chinese electrical generation system in China was estimated by the bottom-up approach, which is suitable for large-scale data accounting.

$$E_{(t)} = \sum_{j,i} EF_{j,i} \times Q_{j,i(t)} \quad (1)$$

where $E(t)$ is the amount of NO_x generation from electricity generation at year t; j and i are respectively the mean province and fuel type; EF is the NO_x generation factor, which means the quality (kg) of NO_x generated by the combustion of 1 ton of a particular energy source; Q characterizes the quality of fuel consumption.

In this paper, ANI is used to characterize the level of NO_x generation in China's electrical generation. The specific formula was as follows:

$$\mathrm{V} = \frac{E}{G} \quad (2)$$

where V means the ANI and G denotes the gross electrical generation.

2.2 Decomposition method

Generally, NO_x produced by electrical generation is influenced by electrical generation technology and by the energy composition, energy efficiency and the provincial distribution of electrical generation (Shrestha et al., 1998; Huang et al., 2017). Based on the LMDI model created by Ang (2001, 2005), we decomposed the changes in ANI into the following factors:

$$\mathrm{V} = \frac{E}{G} = \sum_{i,j} \frac{G_j}{G} \cdot \frac{Q_j}{G_j} \cdot \frac{F_j}{Q_j} \cdot \frac{F_{i,j}}{F_j} \cdot \frac{C_{i,j}}{F_{i,j}} = \sum_{i,j} s_j \cdot p_j \cdot u_j \cdot m_{i,j} \cdot e_{i,j} \qquad (3)$$

where G_j, Q_j, and F_j represent electricity generation, thermal power generation, and fossil fuel consumption in *j* province. F_{ij} and E_{ij} respectively mean the consumed fossil fuel and NO_x generation connected with electrical generation from using fossil fuel *i* in province *j*.

This study assumed the following: the geographical distribution effect is reflected by $s_j = \frac{G_j}{G}$, the electrical generation in province *j* as a percentage of the domestic total electricity generation. The electrical generation structure effect is represented by $p_j = \frac{Q_j}{G_j}$, which is the ratio of thermal power generation to national electrical generation. The electrical generation efficiency effect is expressed by $u_j = \frac{F_j}{Q_j}$, which shows the ratio of energy input and electrical generation. The primary energy composition effect is characterized by $m_{ij} = \frac{F_{ij}}{F_j}$, which expresses the proportion of various types of fossil fuel in thermal power generation. $e_{ij} = \frac{C_{ij}}{F_{ij}}$ is the NO_x emissions factor for certain fuels, which are known constants.

Based on the LMDI model, Eq. (4) can be used to account for changes in ANI between year *t* and 0. In addition, Eq. (5)–(11) can be applied to each effect.

$$\Delta V_{tot} = V^T - V^0 = \Delta V_s + \Delta V_p + \Delta V_u + \Delta V_m + \Delta V_e \qquad (4)$$

$$\Delta V_s = \sum_{i,j} L(w_{ij}^T, w_{ij}^0) \ln \left(\frac{s_j^T}{s_j^0}\right) \qquad (5)$$

$$\Delta V_p = \sum_{i,j} L(w_{ij}^T, w_{ij}^0) \ln\left(\frac{p_j^T}{p_j^0}\right) \quad (6)$$

$$\Delta V_u = \sum_{i,j} L(w_{ij}^T, w_{ij}^0) \ln\left(\frac{u_j^T}{u_j^0}\right) \quad (7)$$

$$\Delta V_m = \sum_{i,j} L(w_{ij}^T, w_{ij}^0) \ln\left(\frac{m_j^T}{m_j^0}\right) \quad (8)$$

$$\Delta V_e = \sum_{i,j} L(w_{ij}^T, w_{ij}^0) \ln\left(\frac{e_j^T}{e_j^0}\right) \quad (9)$$

$$w_{ij}^T = \frac{C_{ij}^T}{G^T}, w_{ij}^0 = \frac{C_{ij}^0}{G^0} \quad (10)$$

$$\mathrm{L(x, y)} = \frac{x-y}{lnx-lny}, \text{ for } \mathrm{x} \neq \mathrm{y}, \text{and } \mathrm{L(x, y)} = \mathrm{x} \text{ for } \mathrm{x} = \mathrm{y} \quad (11)$$

Usually, the consumption of a specific fossil fuel will have a positive or zero value, which would cause decomposition failure; therefore, the method introduced by Ang and Liu (2001) was used in order to deal with zero-values.

2.3 Data

This study estimated the NO_x generation from electrical generation in 29 provinces of China, which is a prerequisite for estimating the ANI of electrical generation. Some provinces, including Ningxia, Xizang, Hong Kong, Taiwan, and Macau are not studied due to data deficiencies.

Fuel types considered in this study were coal, diesel oil, coke, gasoline, fuel oil, crude oil, coke oven gas, kerosene, natural gas, liquefied petroleum gas, other gas, and refinery gas. The factors of NO_x generation for each fuel were obtained from Kato and Akimoto (1992) and Hao et al. (2002), which are widely accepted in China (Tian et al., 2001; Gao et al., 2006; Lang et al., 2008; Jiang et al., 2016). Standard coal coefficients for every kind of fuel were derived from the China Energy Statistical Yearbook (CESY). This study estimated the provincial and national consumption of every type of fuel by using the energy balance sheet in the CESY from 1994 to 2016.

This paper divides 20 years into four phases: 1995-2000 (Stage 1), 2000-2005 (Stage 2), 2005-2010 (Stage 3), and 2010-2015 (Stage 4). Every stage matches the starting and ending times of “The Five-Year Plan” in China, which fully reflects China's economic development, social changes, and energy consumption.

3. Overview of China’s electrical generation and ANI

3.1 Characteristics of China’s electrical generation and demand

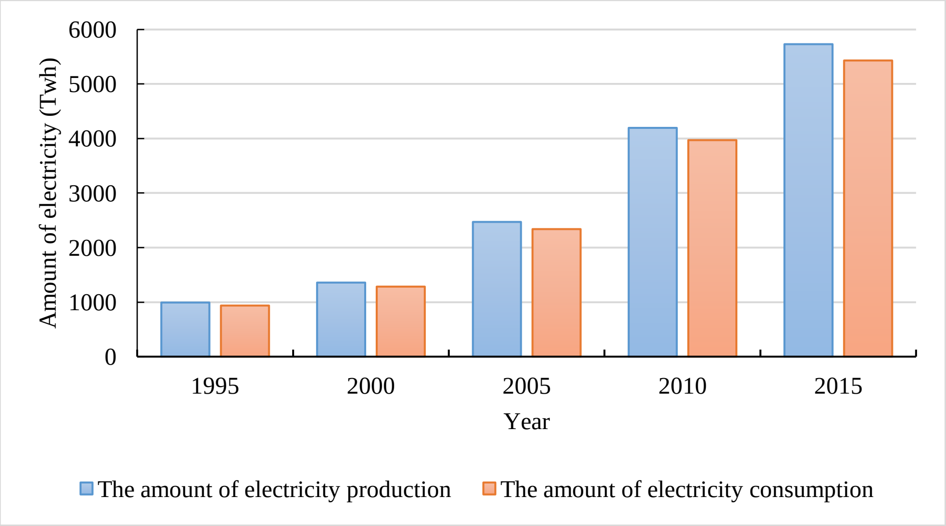


Figure 1. Electrical generation and consumption in China from 1995 to 2015

As shown in Figure 1, China’s electrical generation and consumption have rapidly grown from 991.86 to 5728.58 TWh and from 936.69 to 5429.68 TWh, respectively. Electrical consumption showed a higher rate of increase than electrical generation. The average annual rates of electrical generation changed synchronously with consumption during each of the four stages. Both electrical generation and consumption showed the fastest growth in stage 2, which might be related to the many investments into the economy during that stage. The spatial distribution of electrical generation did not match that of electrical consumption, a characteristic feature of the electrical generation system of China (Wang et al., 2018a). This did not simply change the provincial distribution of NO_x emissions from electrical generation, but might consequently affect the national ANI.

3.2 Characteristics of NO_x generation from electrical generation in China

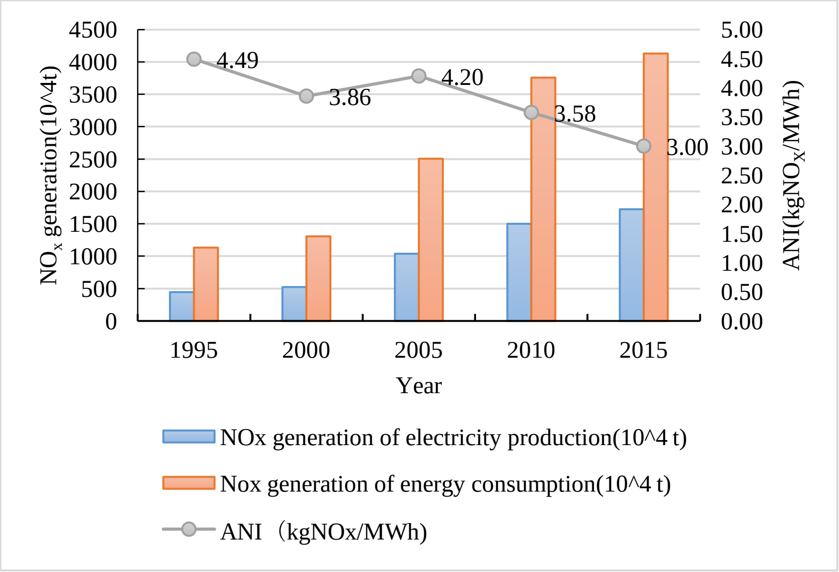


Figure 2. Changes in ANI and the total amount of NO_x **generation in China**

In Figure 2 we observe that NO_x emissions from the Chinese electrical generation system played an important role in the total amount of NO_x generation related to energy consumption, which made 39.33, 40.10, 41.43, 39.93, and 41.77% contributions during each of the five-year periods, respectively. The total amount of NO_x generation from electrical generation grew rapidly from 4.6 million tons to 16.9 million tons from 1995 to 2015, representing an increase of 280.04%. The average growth rate in NO_x generation during the four stages were 17.58, 98.19, 44.54, and 12.84%, respectively, and the maximum rate occurred in the second stage. Although the total amount of NO_x generation related to energy consumption increased, we found that ANI showed a downward trend from 1995 to 2015 with a decline rate of 33.18%. The annual rates of ANI were -2.82, 1.79, -2.98, and -4.04% per stage, respectively.

We found that NO_x emissions from electrical generation showed spatial heterogeneity in China (Figure 3 and 4). The hot spots (high ANI accumulation areas) were mainly concentrated in the north of China. The cold spots (low ANI accumulation areas) were mainly concentrated in the south of China, which included Chongqing, Fujian, Gansu, Guangdong, Guangxi, Guizhou, Hainan, Hubei, Hunan, Qinghai, Sichuan, Yunnan, and Zhejiang. Hot spots with higher electrical generation and ANI included Hebei, Henan, Inner Mongolia, Jiangsu, Liaoning, Shandong, and Shanxi. In contrast, Beijing, Chongqing, Gansu, Guangxi, Hainan, and Qinghai were cold spots with lower electricity generation and ANI. Heilongjiang, Jilin, Jiangxi, and Xinjiang had high ANI but produced less electricity, while Guangdong and Sichuan had low ANI but produced more electricity.

Considering that the spatial distribution of China’s electricity generation has undergone significant changes over the past 20 years, we explored how the spatial distribution of provincial electrical generation has influenced decreasing ANI and whether this interaction is beneficial for the reduction of NO_x generation from electricity generation. The following sections introduce a decomposition model that considers the spatial distribution of electrical generation to quantify the driving forces affecting the ANI of the Chinese electrical generation system.

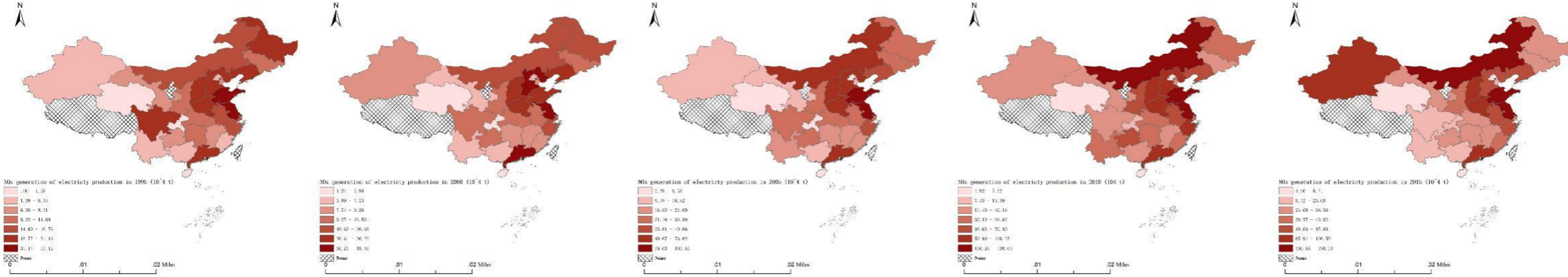


Figure 3. NO$_x$ generation by electrical generation in China from 1995 to 2015

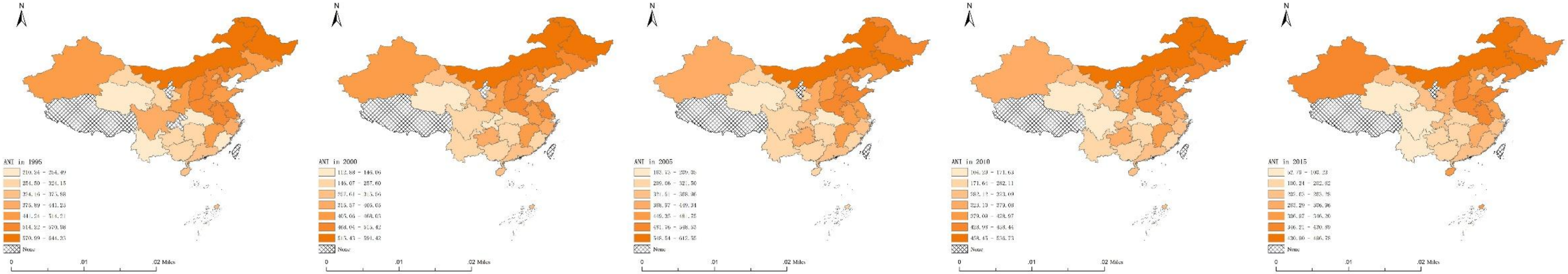


Figure 4. Geographical shift of aggregated nitrogen intensity (ANI) in China from 1995 to 2015

4. Results and discussion

4.1 Overview of LMDI results for ANI

As shown in Figure 5, ANI showed a declining trend except during stage 2. Overall, over the past 20 years, the four effects all caused ANI to decrease. The effect of efficiency of electrical generation played the leading role in ANI reduction ,while the geographical distribution of electrical generation together with electrical generation structure and primary energy composition effects made important contributions. In detail, the driving forces of ANI reduction differed during the four time periods. In stage 1, the efficiency of electrical generation was the most powerful effect in reducing ANI, and geographical distribution effect ranked second, while the other two effects increased ANI. In stage 2, all effects except for primary energy composition increased ANI. In stage 3, the efficiency of electrical generation, electrical generation structure, and primary energy composition effects played roles in reducing ANI. In stage 4, all four effects contributed to ANI reduction in China’s electrical generation system.

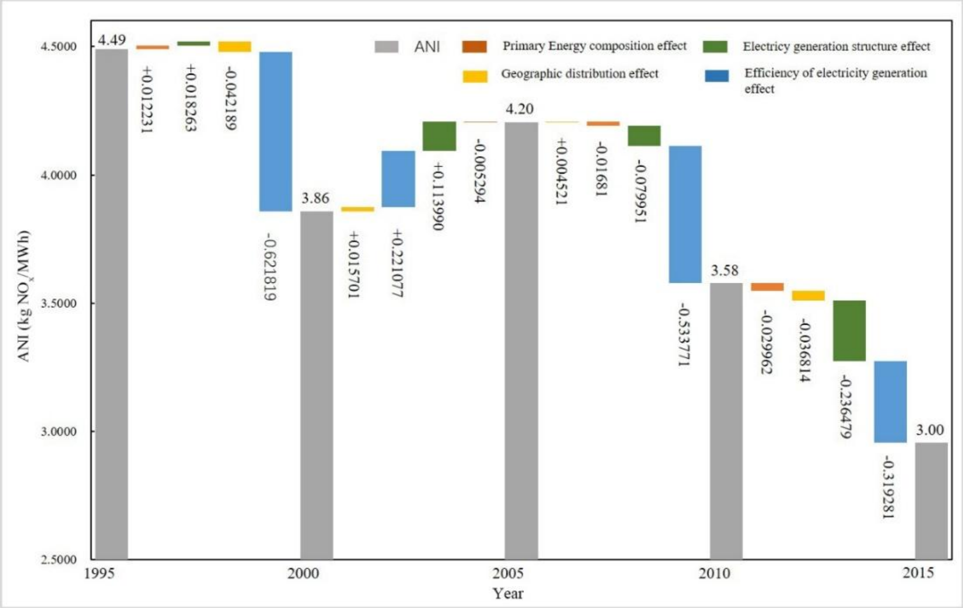


Figure 5. **Decomposition results of ANI from electrical generation in China**

4.2 Discussion of drivers decreasing ANI

4.2.1 Geographical distribution effect

The geographical distribution effect reflected the change in spatial distribution of electrical generation on the temporal decreasing trends of ANI. We found that over the four stages, the geographical distribution effect totally contributed to ANI of -0.05815 kg NO_x/MW and ranked the third among all factors on ANI reduction. This indicated that the changed spatial heterogeneity of electrical generation in China did influence the decreasing ANI of the Chinese electrical generation system, similar to the conclusion of Wang et al. (2018b). On the one hand, the national ANI of electrical generation decreased when provinces with higher ANI produced less electricity and provinces with lower ANI produced more electricity. On the other hand, national ANI was increased by provinces with higher ANI producing more electricity.

Over the past 20 years, the cross-regional transmission of electricity has become a feature of China’s electrical generation and consumption. The implementation of the

West-East Power Transmission project took surplus electricity in the western provinces to the eastern and southern provinces (Zeng et al., 2016). The transmission of power across provinces led to increasing electrical generation in lower ANI provinces and contributed to China’s continuous ANI decline. A similar effect was noted in a previous study about power transmission between Laos and Thailand (Watcharejyothin et al., 2009), but they did not model this effect and quantify its size.

We classified provinces in China into three types by comparing changes in electrical generation and consumption from 1995 to 2015 (Figure 6). The first type grouped provinces in which historical electrical generation has been less than electrical consumption, including Beijing, Chongqing, Liaoning, and Shandong. These provinces need electricity transmitted from other provinces. Another type grouped provinces where electrical generation and consumption were variable. Over four stages, this group featured more electrical consumption than electrical generation, was expanding, and currently covers ten provinces including Guangdong, Hebei, Henan, Hunan, Jiangsu, Jiangxi, Qinghai, Shanghai, Tianjin, and Zhejiang. The final group has had historically higher electrical generation than electrical consumption, including Anhui, Fujian, Guizhou, Hainan, Hubei, Inner Mongolia, Jilin, Shaanxi, Shanxi, Sichuan, Xinjiang, and Yunnan. We found that most of the provinces in this group had lower ANI and transferred more electricity than others with higher ANI. This indicated that electricity transported from regions of low ANI to those of high ANI decreased the ANI of the Chinese electrical generation system overall.

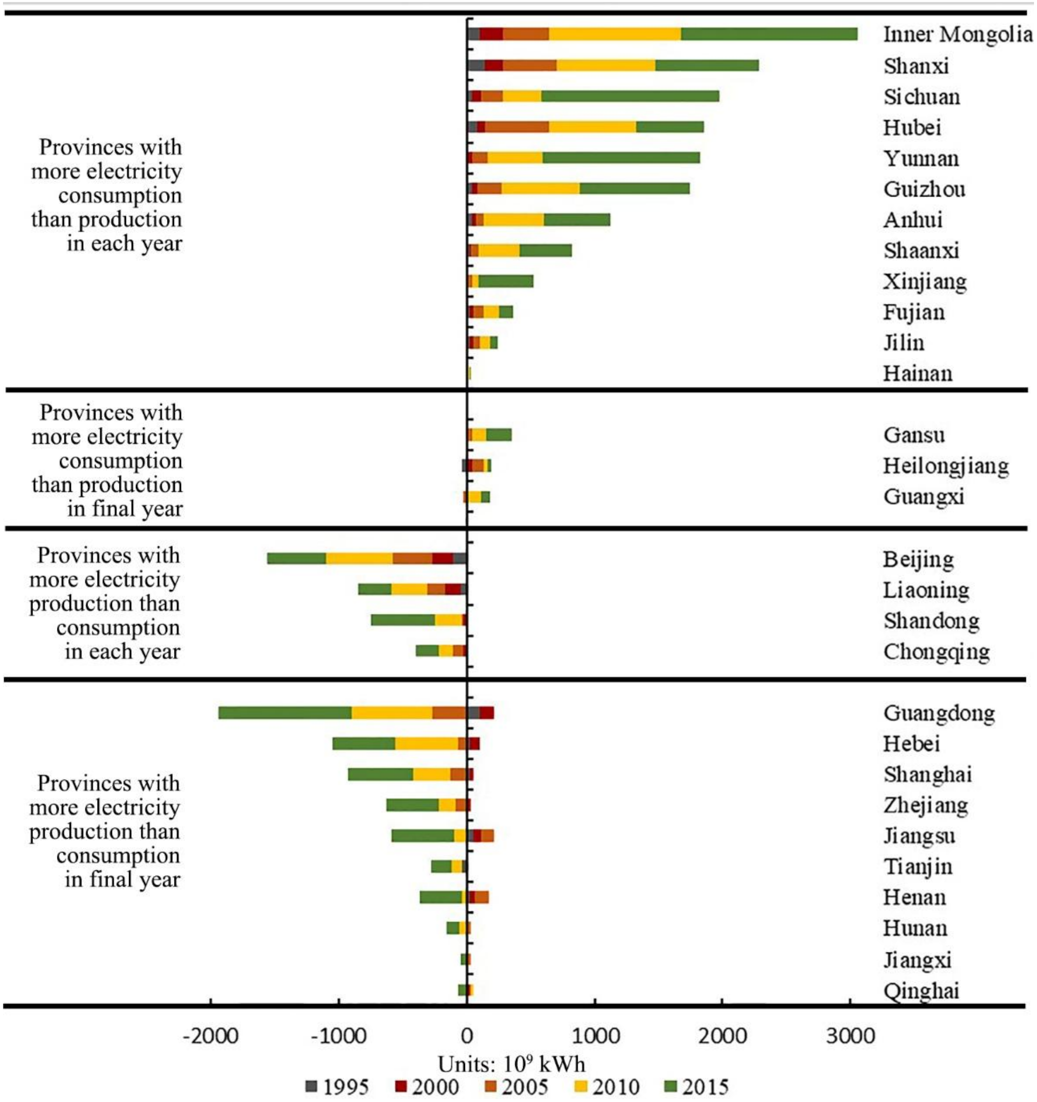


Figure 6. Differences between electrical generation and electrical demand in Chinese provinces

When we compared the geographical distribution effect in different stages, we further found that this effect showed a little change from slightly negative effects in stages 2 and 3 to the positive effect of reducing ANI in stage 4. We quantified the contributions of this driver in four stages, which were -0.042189, 0.015701, 0.004521, and -0.03618 kg NO_x/MW, respectively. According to these results, we observed that the geographical distribution effect was not significant in the rapid growth stage of electrical generation regardless of whether the provincial ANI of the electrical generation system was high or low. When all provinces are in a rapid economic growth phase, electrical generation will increase dramatically and would render the effect of the cross-regional transmission of electricity on ANI insignificant.

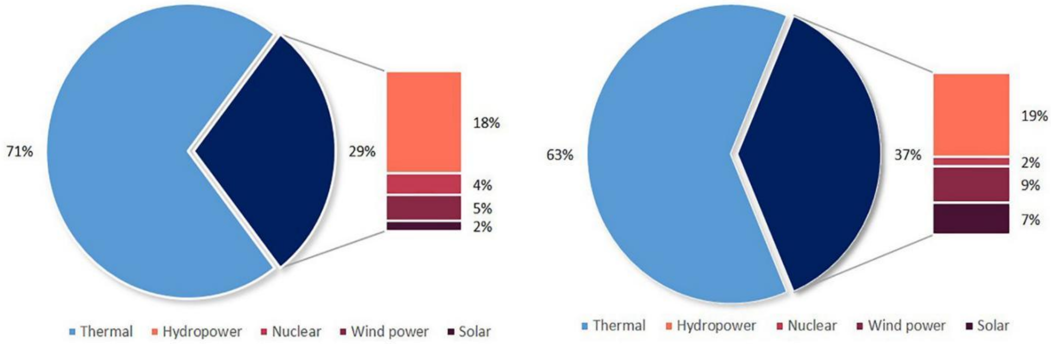
Something about this effect should be mentioned and cannot not be deemed negligible. We know that the increasing effect of the geographic distribution of electrical generation contributes to decreases in the ANI of the electrical generation system, but transferred amounts of NO_x emissions related to this effect could still impose additional reduction costs and even environmental health risks for generators. Consequently we should give additional attention to the negative impacts caused by future cross-province electrical transmission.

4.2.2 Electrical generation structure effect

The electrical generation structure usually includes thermal and renewable-energy (Hasanuzzaman et al., 2017, Huang et al., 2017). Thermal power has a higher NO_x generation than other primary energy, whereas hydro, wind and nuclear power are considered to be "close-to-zero NO_x generation" (Liu., 2017). In China, thermal power always plays a dominant role in the electrical generation structure (Xie et al., 2019; Yan et al., 2017) and has a significant influence on the NO_x emissions of the electrical generation system. We quantified electrical generation structure effects by using the thermal power proportion and found that this effect decreased the ANI by 0.18418 kg NO_x/MWh from 1995 to 2015 and was relatively significant in reducing ANI.

We found that this effect has changed from a positive to an inhibiting influence on ANI over the four stages. According to the contributions of the electrical generation structure effect to ANI reduction, which were 0.018263, 0.113990, -0.079951, and -0.23648 kg NO_x/MW in four stages, respectively, we observed that the thermal power proportion started to reduce ANI after 2010. In China, thermal power continued to play a dominant role in the electrical generation structure, accounting for 74.37% of the total amount of electrical generation in 2016 (China Electric Power Yearbook, 2017); however, we observed that the proportion of thermal power began to show a downward trend over the peak proportion in stage 2. In contrast, the proportion of renewable energy electrical generation increased from 17.76% in 2005 to 26.6% in 2015. The increasing installed capacity of renewable energy in China provides a potential for cross-regional transmission of renewable energy power (Xie et al., 2019). According to Figure 7, the installed capacity of China's renewable energy electrical generation reached 650 million kW in 2017, whereas generated electricity only reached 170 million kW. All of the above factors affect the electrical generation structure in China.

We found that the changing effect size of thermal power became the fastest growing contributor to the reduction of ANI after 2010, although the proportion of thermal power did not drastically decrease. The reason for this is the massive scale of thermal power in China. A minor decrease in the proportion of the total amount of power generation using thermal power can cause a significant effect on the ANI of the electrical generation system.



(a) Power installation (b) Power generation

Figure 7. Structure of power installation and generation in 2017

4.2.3 Efficiency of the electrical generation effect

The effect of electrical generation efficiency related to thermal power utilization reflected the influence of thermal power generation technology innovation and could play a significant effect in decreasing the ANI of the power generation system. We quantified the effect size of the efficiency of electrical generation and found that it reduced ANI by 1.25379 kg NO_x/MWh in total over four stages. Compared with the other effects, we found that the efficiency of electrical generation effect was the most important driving force in reducing ANI (Figure 1). This finding indicated that the innovation of thermal power technology was the most efficient way to reduce China's ANI over the past 20 years (Ma et al., 2017).

We quantified the effect size in different stages, which are -0.621819, 0.221077, -0.533771, and -0.31928 kg NO_x/MWh, respectively. We found that the efficiency of electrical generation effect shows an inhibiting influence on ANI in all stages other than stage 2, which relates to the rapid growth of energy-intensive industries since 2001 and did not influence the innovation of thermal power generation technology. This phenomenon was not observed after 2005 because China made many improvements in emissions reduction (Ding et al., 2017), which increased its reducing effect on ANI.

We have observed that the inhibiting influence of the efficiency of electrical generation effect on ANI started to show a downward trend after 2010. This phenomenon is mainly caused by the technological improvement of power generation (Peng et al., 2018) in order to gradually narrow the gap of the electrical generation efficiency between China and developed countries such as Japan (Wang et al., 2018a), listed in Table 1. Initiatives including the closure of old inefficient plants and encouraging more energy-conservation technologies (Zhang et al., 2013) continuously improve utilization efficiency in China's thermal power sector.

Table 1. Gross coal consumption rate for fossil-energy power plants (gce/kW·h) in China and Japan

Country	1990	1995	2000	2005	2010	2011	2012	2013	2014	2015
China	392	379	363	343	312	308	305	305	300	297
Japan	317	315	303	301	294	295	394	291	287	—

Data source: China Energy Statistical Yearbook (2016)

4.2.4 Primary energy composition effect

Thermal power is generated mainly from three primary energy types including coal products, oil products, and natural gas (Hasanuzzaman et al., 2017). Compared with coal and oil, natural gas has greater benefits for improving the efficiency of electrical generation and generating less NO_x overall (Liu et al., 2017). We quantified the effect size of the changed composition of primary energy into thermal power and found that it reduced ANI by 0.03984 kg NO_x/MWh from 1995 to 2015. This result indicated that the changes in fuel structure affected reduction of ANI, though its effect size was much smaller than other effects. After we further decomposed the effect size of the primary energy composition of thermal power on ANI in the four stages, which are 0.012231, -0.005294, -0.016814, and -0.02996 kg NO_x/MWh, respectively, we found that the inhibiting effect size has shown a gradually increasing trend since 2000.

The increasingly positive role played by the primary energy composition effect was related to the optimization of the fuel structure of thermal power. Comparing the changed proportions of different primary energy types (Figure 8), we observed that China's coal-fired power generation proportion increased from 94.64 to 96.79% from 1995 to 2015, and natural gas power generation increased gradually from 0.32 to 3.07%, while power generation from oil products decreased from 5.04 to 0.14%.

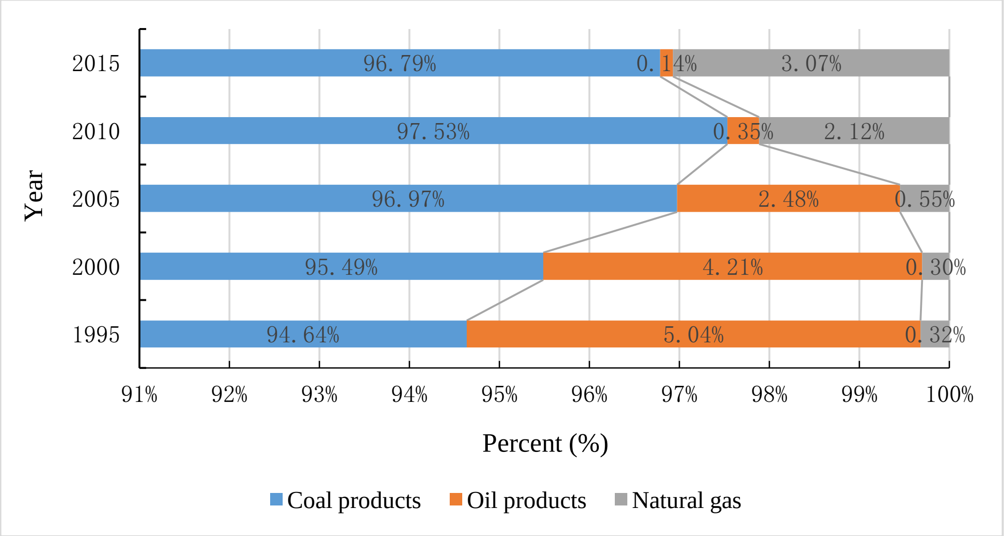


Figure 8. Primary energy composition of thermal power from 1995 to 2015

In future, expanding natural gas power and natural gas's total installed capacity (NDRC, 2016) in China will further increase the proportion of natural gas in electrical generation and have a much increased effect on inhibition of NO_x emissions (Man et al., 2018) and ANI in China.

5. Conclusions

China has the largest electrical generation system in the world and plays an important role in reducing NO_x emissions related to energy consumption. To explore the NO_x emissions efficiency of the Chinese electrical generation system, we first estimated ANI and characterized its temporal trends and spatial changes from 1995 to 2015. We found that with China's growing scale and changing spatial distribution of electricity generation and consumption, the total amount of NO_x generation from the power industry has increased. In contrast, the ANI of the Chinese electrical generation system steadily decreased from 4.49 kg/MWh in 1995 to 3.00 kg/MWh in 2015.

Furthermore, this study quantified the driving forces of ANI reduction in the Chinese electrical generation system and found that of all factors, the efficiency of electrical generation, related to the influence of technological innovations on low NO_x emissions from thermal power, had the most significant impact on the reduction of ANI in China; however, this effect has shown a decreasing trend since 2010. In contrast, the effect of electricity generation structure has been ranked second in importance among overall reduction factors and showed a gradually increasing trend. Significantly, the above-findings could bring researchers important insights into the changing driving mechanism of ANI reduction in China, and provides China with crucial guidance on how to reduce NO_x emissions by balancing the future roles of driving factors.

We found that the primary energy composition of the electrical generation system only slightly affected changes in ANI but that this effect on ANI showed a gradual increasing trend and was the only inhibitory effect on ANI in stage 2. This finding indicates that China still faces the important challenge of adjusting the primary energy input structure for thermal power system. This finding provides another significant indication that China should move faster than ever and give full attention to the long-term plan to transition to a cleaner primary energy structure. This approach will be a fundamental means of keeping this positive effect on ANI reduction and expanding this emerging trend in the future.

Moreover, we observe that increasing numbers of provinces in China have changed from electricity provider into electricity consumer over the past 20 years, which results in a new geographical distribution of electricity generation. We found that this changed geographical distribution was a non-negligible factor in reducing the ANI of the Chinese electrical generation system; its effect is even more significant than that of the primary energy composition. These interesting results have not been mentioned in previous studies and are meaningful for understanding the NO_x emission impact of electricity transmission across provinces in China, which closely links with the changing geographical distribution of electricity generation. This finding supports the position that it will be helpful to continuously decrease ANI by increasing the share of electrical generation in low-ANI provinces. However, we should not leave off negative effects, including increased regional NO_x emissions and abatement costs in provinces generating more electricity for transmitting to other provinces.

We suggest that China should give priority to continual future improvements in the ANI of the electrical generation system. China might incorporate the indicator of ANI into policies related to NO_x emissions and manage ANI as an essential indicator to improve the efficiency of NO_x emissions from the electricity generation. Moreover, the energy efficiency factor should continue to be of concern because of its currently dominating influences on NO_x reduction in China. At the same time, considering the narrowing gap in energy efficiency compared with other developed countries, China should move forward on increasing the share of clean energy and renewable energy in the current electrical generation system because it will play a more decisive role in the suppression of ANI in future. Policymakers should focus additional attention on economic compensation to reduce generators' cost to abate NO_x emissions.

Acknowledgements

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Conflicts of Interest: None.

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Jan 2nd, 2019

Dear Editor:

Thank you for your letter and response to our previous manuscript submission. The paper was co-authored by Ye Qiu, Yupei Ma, Shutong He, Nan Liu, Yinchang Feng, Zhanfeng Dong, Lingxuan Liu. After reading your letter, we carefully revised the manuscript, including title, abstract, introduction, method and data, and conclusion. Also, the manuscript has been reviewed by an English editing service. We believe this letter will change your and the reviewer's minds.

Firstly, this study found, over the past 20 years, the aggregated nitrogen intensity (ANI) of electricity generation systems declines while the NOx emissions scale increases. Especially, cross-regional power transmission related to spatial distribution differences between electricity generation and consumption has become a significant trend in China's power system. Secondly, to investigate the driving forces for decreasing ANI from the electricity generation system in China, this study built a logarithmic mean divisia index model incorporating geographical distribution effect and quantifying the drivers. This study found that the efficiency of electricity generation effect played the most significant role in this reduction, followed by the electricity generation structure, geographical distribution, and primary energy composition effects. The increasing inter-provincial differentiation in China's electricity production and consumption will contribute to reducing the national ANI of power generation systems, but this will increase regional NOx emissions, which will have the adverse effect of increasing abatement costs. Finally, we believe that our study makes a significant contribution to the literature of NOx emissions reduction policy on electricity generation systems.

Further, we believe that this paper will be of interest to the general readership of Journal of Cleaner Production because it aims to help electricity generation industry become more sustainable and prevent the production of NOx, while increasing efficiencies in the uses of energy.

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Thank you for your consideration. I look forward to hearing from you.

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Highlights

- The ANI of electrical generation has decreased by 33.18% over the past 20 years.
- Electrical generation efficiency inhibited ANI strongly but gradually weakened over time.
- The geographical distribution effect reduced the ANI but transferred environmental costs.
- The electrical generation structure will hopefully affect ANI reduction in future.

Figure

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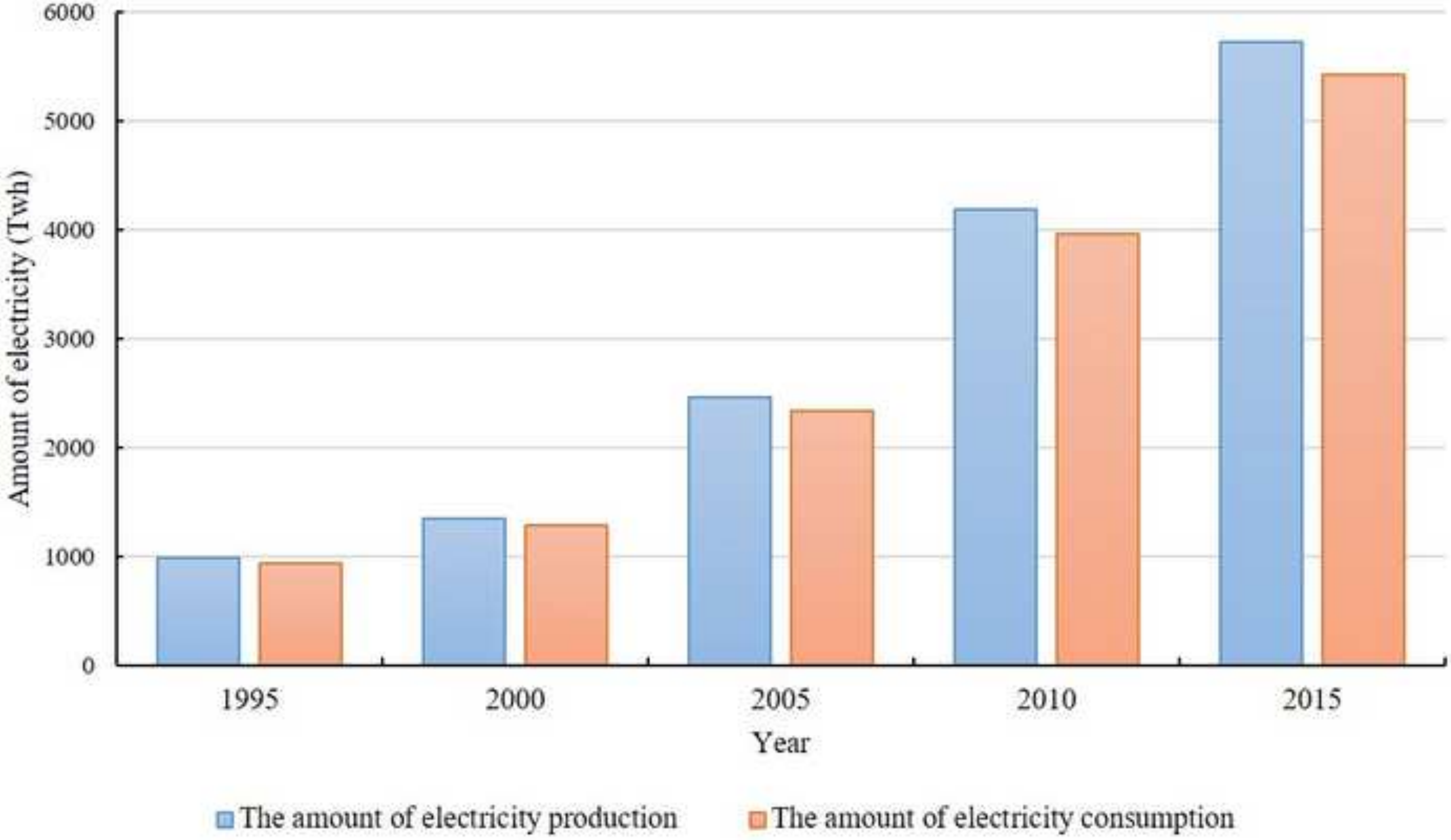

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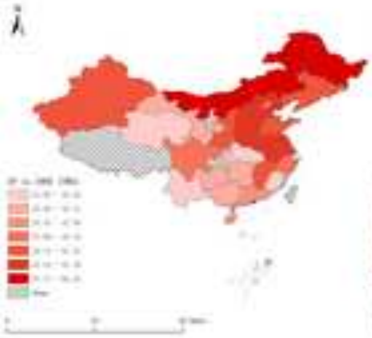

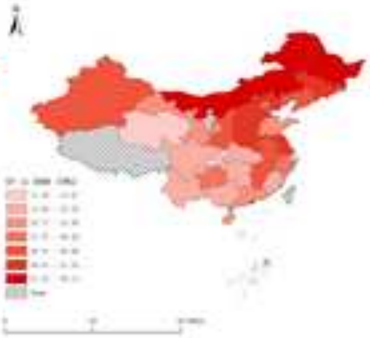

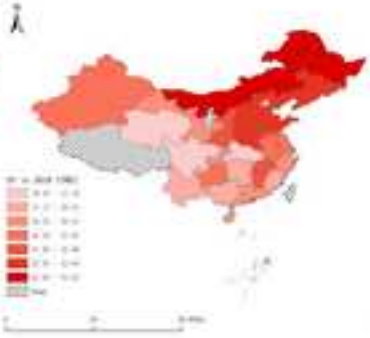

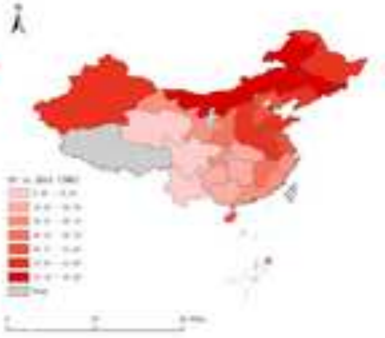

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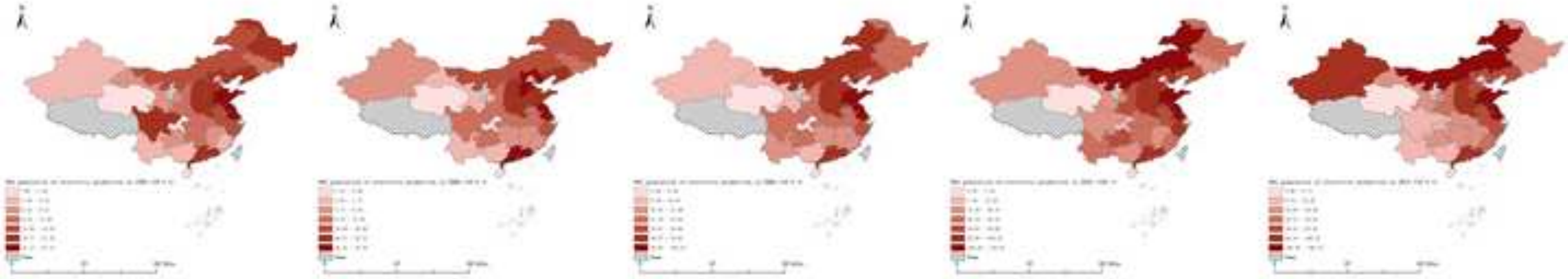

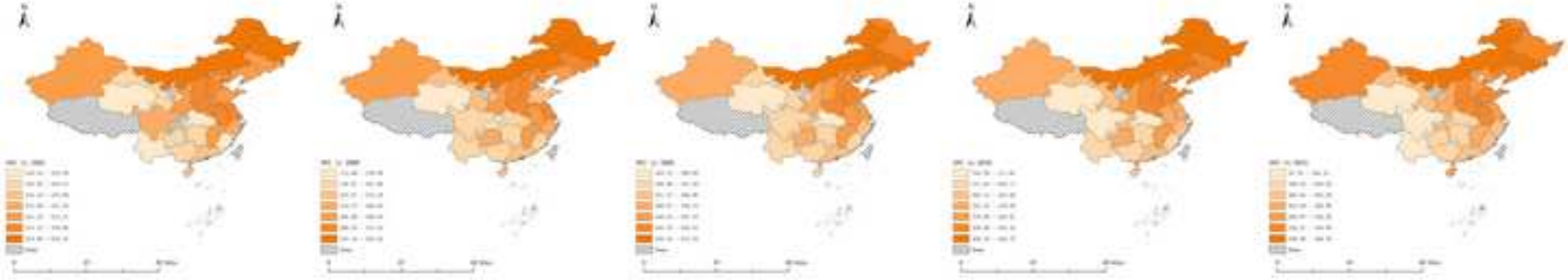

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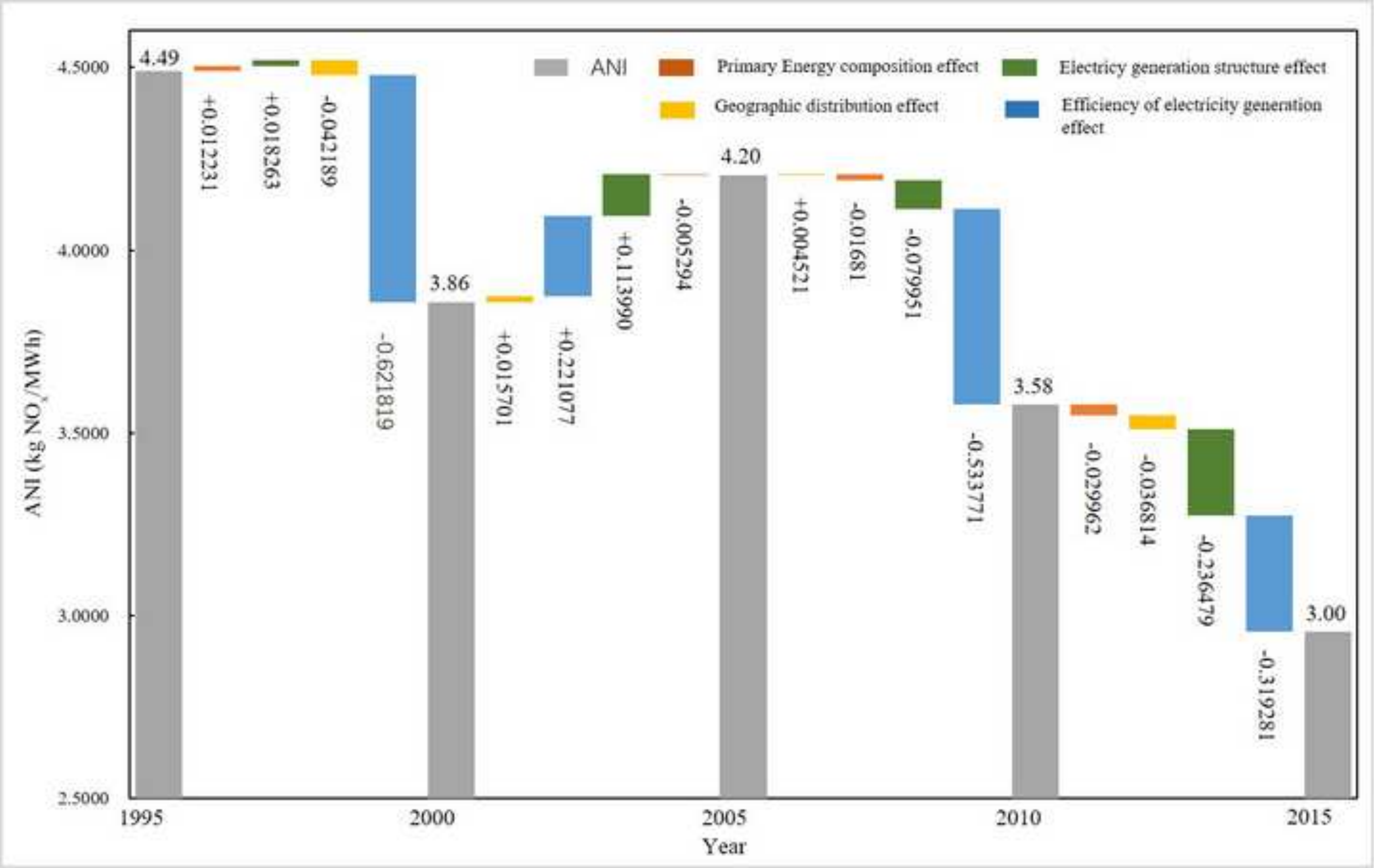
ANI
Primary Energy composition effect
Electricy generation structure effect
Geographic distribution effect
Efficiency of electricity generation effect
4.49
+0.012231
+0.018263
-0.042189
-0.621819
3.86
+0.015701
+0.221077
+0.113990
-0.005294
4.20
+0.004521
-0.01681
-0.079951
-0.533771
3.58
-0.029962
-0.036814
-0.236479
-0.319281
3.00
4.5000
4.0000
3.5000
3.0000
2.5000
ANI (kg NO_x/MWh)
1995
2000
2005
2010
2015
Year

Figure

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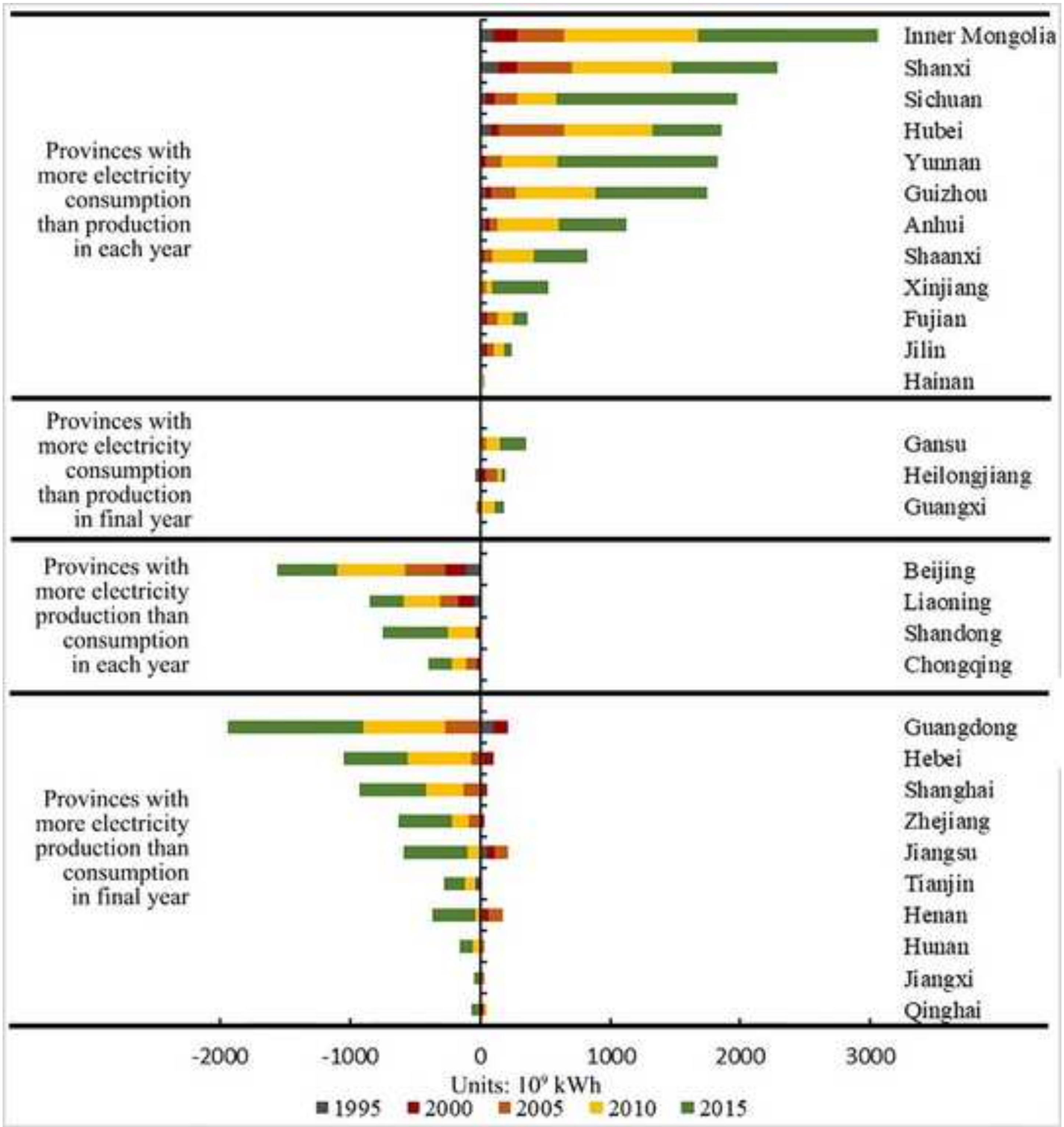
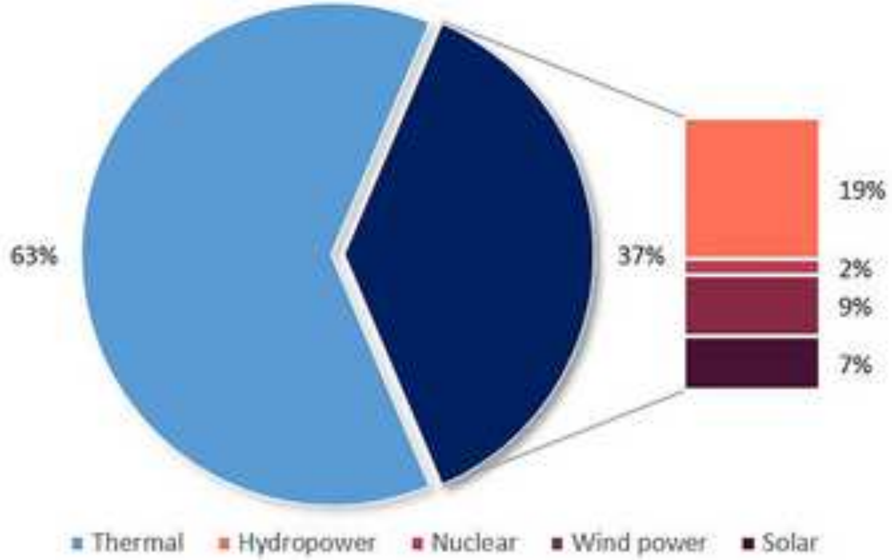
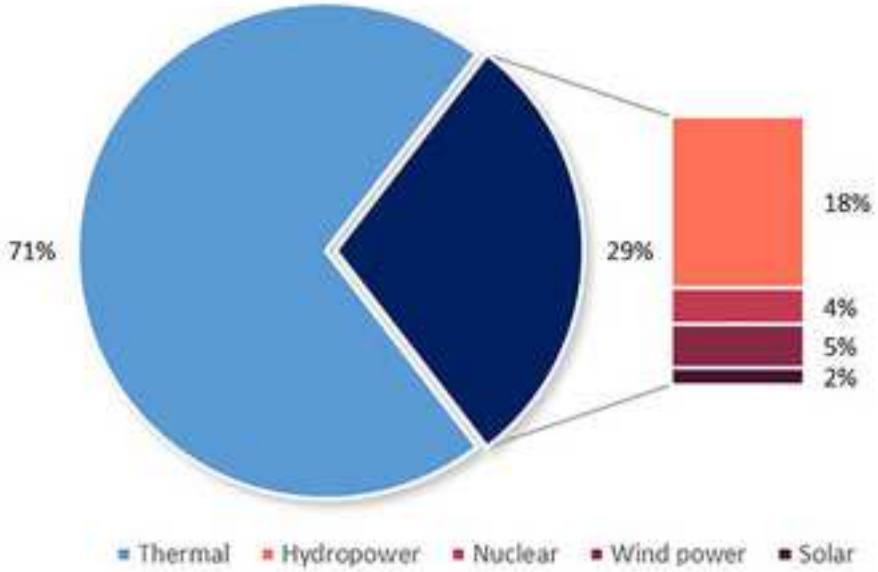


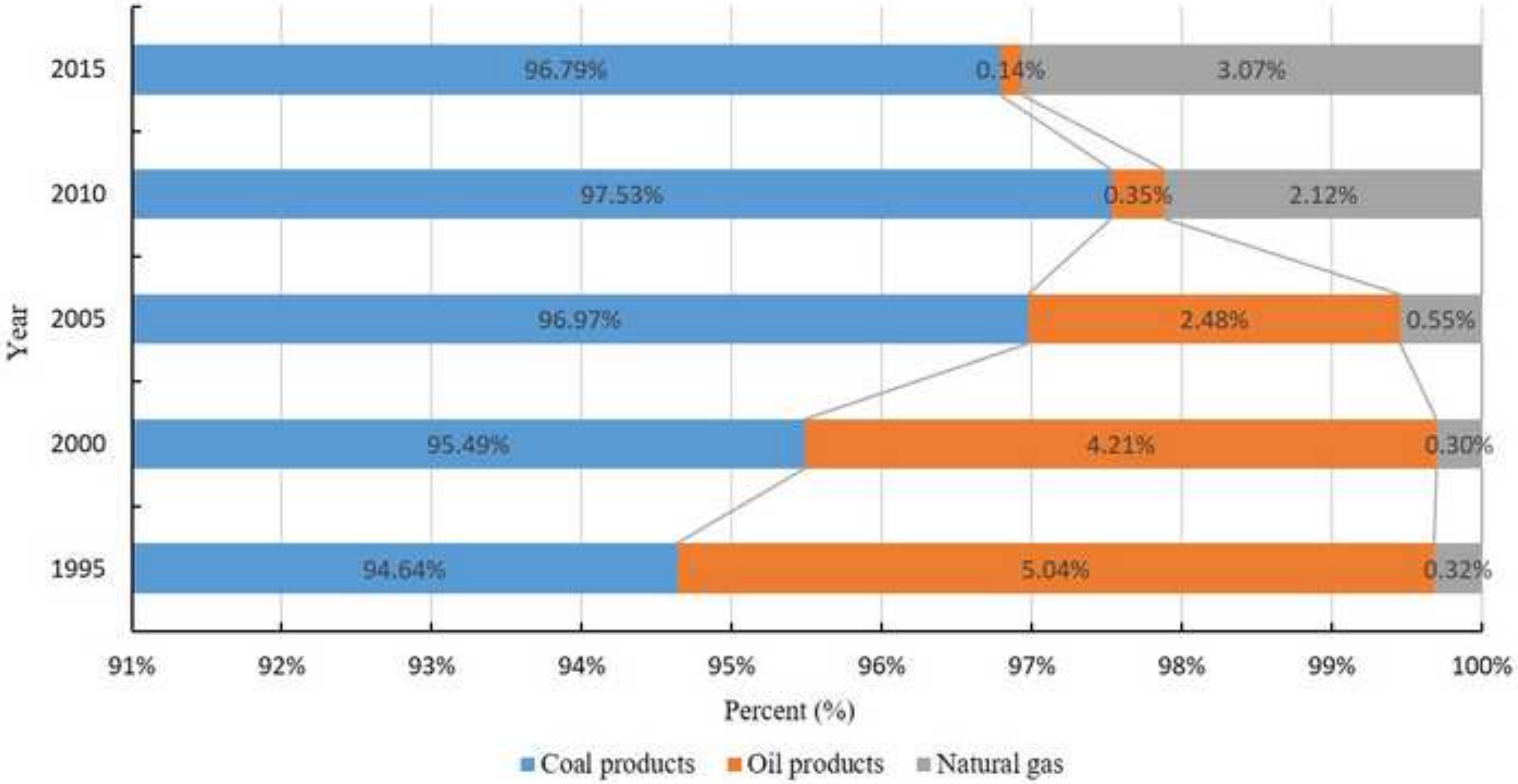


(a) Power installation



(b) Power generation

Figure


2015
96.79%
0.14%
3.07%
2010
97.53%
0.35%
2.12%
2005
96.97%
2.48%
0.55%
2000
95.49%
4.21%
0.30%
1995
94.64%
5.04%
0.32%
Year
91%
92%
93%
94%
95%
96%
97%
98%
99%
100%
Percent (%)
Coal products
Oil products
Natural gas

Table

Table 1. Gross coal consumption rate for fossil fuel–fired power plants (gce/kW·h) in China and Japan

Country	1990	1995	2000	2005	2010	2011	2012	2013	2014	2015
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Data source: China Energy Statistical Yearbook (2016)