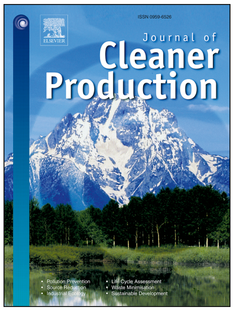

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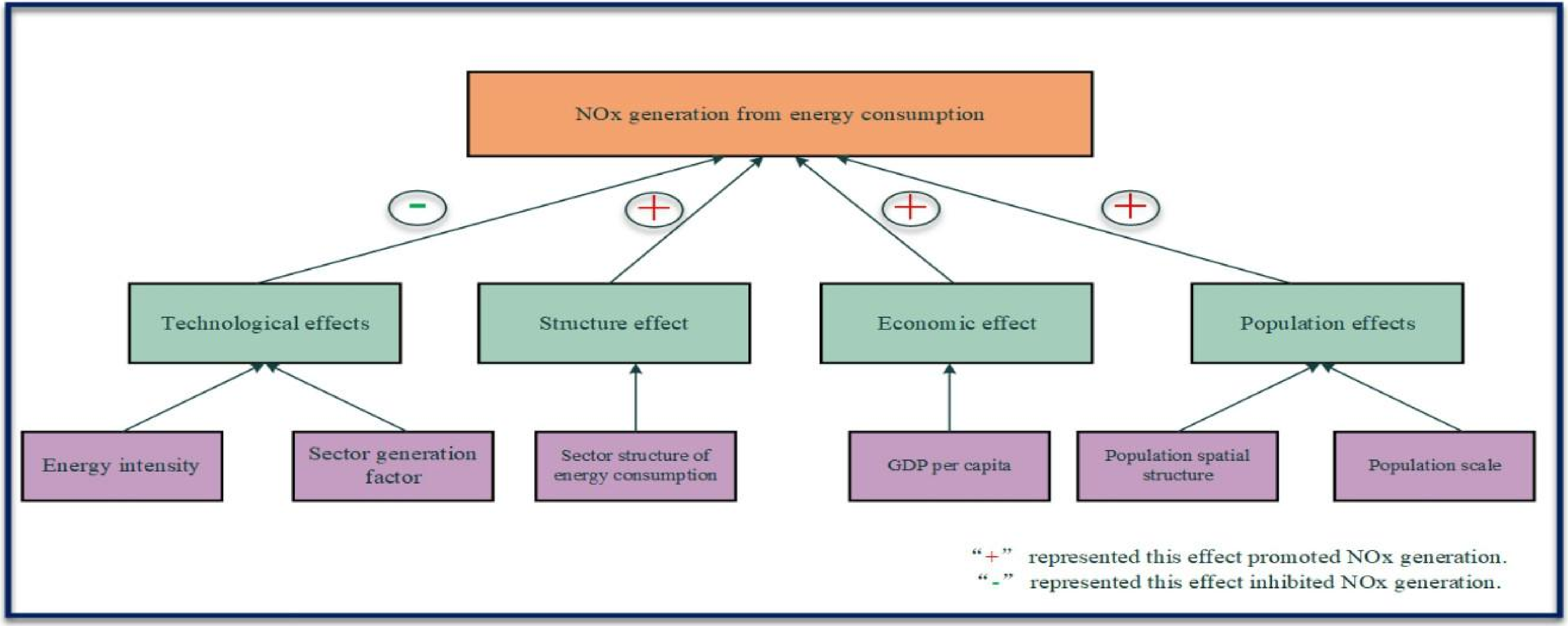
NOx generation from energy consumption
-
+
+
+
Technological effects
Structure effect
Economic effect
Population effects
Energy intensity
Sector generation factor
Sector structure of energy consumption
GDP per capita
Population spatial structure
Population scale
"+" represented this effect promoted NOx generation.
"-" represented this effect inhibited NOx generation.

Investigating the driving forces of NOx generation from energy consumption in China

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Highlights

- Temporal, spatial, and structural features on NOx generation in China are shown
- Driving forces of NOx generation from energy consumption were studied using LMDI
- Energy intensity is the primary factor affecting the reduction of NOx generation
- GDP per capita is the primary factor affecting the increase in NOx generation
- Population spatial structure has a minor but clear role in increasing NOx generation

Abstract

In China, nitrogen oxide (NOx) emissions have been declining in recent years, whereas NOx generation continues to increase. This has prompted a growing focus of policy design to inspect the driving mechanisms of NOx generation. In this study, a decomposition model of NOx generation in China from 1995 to 2014 was built using the Logarithmic Mean Divisia Index (LMDI) method. According to the decomposition results, technological effects (e.g., energy intensity and the sector generation factor) inhibited NOx generation in China, while gross domestic product (GDP) per capita was found to have the most positive effect on increasing NOx generation, accounting for 151.00% of the total change and showing an increasing trend in recent years. The sector structure of energy consumption always increased NOx generation, which contradicts the results of previous studies. All population effects considered in this study contributed to the growth in NOx generation. The population scale effect was increasingly impactful on the growth of NOx generation; the population spatial structure was active but less impactful. In general, technological impact cannot offset the increases caused by economic, structural, and population effects. Considering NOx reduction policy in China, more attention should be given to emission reduction policies, energy consumption, and socio-economic effects; together, these approaches will improve initiatives to reduce NOx.

Keywords: China, NOx generation, LMDI, driving forces, population effects

1 Introduction

Haze and smog have been frequently observed in China over the past several years. NOx is an important precursor of haze particles (i.e., PM2.5); therefore, it has attracted attention from both researchers and government. Over the past 20 years, the Chinese government has implemented a number of air quality policies, including the Ambient Air Quality Standard (GB3095-1996), the Emission Standards for Air Pollutants in Thermal Power Plants (GB132-1996), and the Technical Policy of Nitrogen Oxides Prevention and Control in Thermal Power Plants. These policies focused on total NOx emissions, an indicator that was listed as high importance in the Twelfth Five-year Plan and was thus integrated into the Target Responsibility

System of all provincial governments. Owing to ambitious planning and strict regulations, NOx emissions have fallen from 2.40×10^7 t in 2011 to 1.85×10^7 t in 2015.

Despite the positive effects on air pollutant reduction, NOx generation continued to rise from 1995 to 2014. Human activity is the most important source of NOx generation (e.g., energy consumption, industrial processes, and agricultural activity). Approximately 90% of anthropogenic NOx generation is from energy consumption.

There are a number of key differences between NOx generation and NOx emissions (Table 1). Firstly, NOx generation is greater than NOx emissions; NOx generation equals the amount of NOx emissions from energy consumption plus the NOx reducing amount through denitrification measures[1], such as Selective Catalytic Reduction (SCR) and Selective Non-Catalytic Reduction (SNCR). Secondly, NOx generation is driven by socio-economic factors, while NOx emissions reflect the mixed effect of socio-economic factors and pollution control measures (Table 1). Finally, each is related to different reducing policies; in particular, NOx generation is affected by the policies of energy consumption structure and energy utilization.

Table 1. Comparisons between NOx emissions and NOx generation

	NOx generation	NOx emissions
Estimation method[2]	● E_T	● $N_T = E_T - E_T P_T$
Unit	● t	● t
Impact factors	● Socio-economic factors	● Socio-economic factors ● NOx denitrification measures
Related policies	● Policies about energy consumption structure and energy utilization	● Policies about NOx denitrification ● Policies about energy consumption `structure and energy utilization

Previous studies about China have focused on NOx emissions. Some have considered NOx emission inventories; for example, Lei et al. (2011) analyzed historical emissions of NOx and other air pollutants from 1990 to 2008 in China, and future emissions were projected up to 2020

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[1] Since 2010, China has established strict requirements for NOx emissions. Most sectors, including power plants and cement industries, use denitrification measures such as low NOx combustion technology, SCR, and SNCR, with the aim of reducing NOx emissions by approximately 40% to 80%.

[2] E_T is the amount of NOx generated from energy consumption at year T, which is calculated from the energy consumption and generation factors. N_T is the amount of NOx emissions from energy consumption at year T; P_T represents the denitrification rate at year T.

based on current energy-related and emission control policies. Zhang et al. (2011) analyzed uncertainty in calculation methods for NOx emission inventories. Zhao et al. (2012) established a NOx emission inventory for the Huabei region. Tian et al. (2013) studied the NOx emission inventory and trends of electricity production of China in 2010. Deng et al. (2017) studied NOx emissions from goods consumption and import-export trade in China from 1995 to 2009. Wang et al. (2017) identify key sectors that contribute to the transfer of embodied NOx emissions in the Beijing-Tianjin-Hebei region. A number of studies have also focused on vehicle NOx emissions. Huo et al. (2012) measured NOx emissions and other air pollutions from 175 diesel trucks in five Chinese cities. Wang et al. (2016) studied NOx emission trends with the unit-based annual activity and specific dynamic emission factors for the period 1978–2011. Sun et al. (2016) studied the spatial distribution of vehicle NOx emissions in Shandong province. Liu et al. (2017) estimated multi-year inventories of vehicle NOx emissions from 1994 to 2014 in China. Other studies have considered the effectiveness of NOx reduction technologies. Yu et al. (2010) chose six typical NOX control technologies, including low NOx combustion technology, over fire air reburning, SCR, SNCR, and joint SCR-SNCR, and selected the best combination for different power plants. Van Caneghem et al. (2016) compared direct and indirect effects between SCR and SNCR. Ma et al. (2016) analyzed the effects of coal type, unit size, and denitrification technology on NOx reduction. Chen et al. (2017) studied the effectiveness of the over fire air (OFA) method for NOx reduction in China.

With regard to the driving forces of NOx emissions, Shi et al. (2014) showed that economic scale and industrial structural effects increased NOx emissions, but that technological effects reduced NOx emissions from 1990 to 2010 in China. Wang (2016) found that economic scale factors could increase NOx emissions, whereas an energy intensity factor inhibited NOx emissions from 2010 to 2015; furthermore, economic structure optimization and energy structure adjustment have the potential to reduce NOx emissions in China in the future. Ding et al. (2017) and Diao et al. (2016) both showed that economic growth was the dominant driving force, whereas both technological and energy efficiency factors were the main reasons for NOx emission reductions from 2006 to 2013 in China. Lyu et al. (2016) identified economic growth as a primary factor influencing the increase in NOx emissions in China from 1997 to 2012. Energy intensity was found to be the key factor affecting NOx reduction, and structural change in the economy began to reduce NOx emissions in 2010. This study also emphasized that population scale plays a significant role in increasing NOx emissions. Wang et al. (2017) studied the impact of sector structure on NOx emissions and other air pollutants, and found that the transfer process was the most significant sector for NOx emissions.

In summary, previous studies have focused on three types of driving forces for controlling NOx emissions from energy consumption in China: technological effects, structural effects, and economic effects. Only Lyu et al. (2016) pointed to the importance of population effects on NOx emissions, rather than NOx generation from energy consumption. Population effect has mainly been considered through the lens of CO_2 emissions. Zhu et al. (2015) found that both population scale and the migration of rural populations into cities played important roles in increasing CO_2 emissions in China. Meng and Han (2016) emphasized that an increase in population density (number of people/km^2) would reduce the per capita level of CO_2 emissions in Shanghai. Miao et al. (2017) found that population scale and population compactness had positive roles in CO_2 reduction in China. These results all indicate that population effects are critical. Considering that both NOx and CO_2 are generated from energy consumption, it follows that the population effects of NOx generation require further study.

This study is different from previous studies in that the socio-economic driving mechanisms of NOx generation from energy consumption have been explored using the LMDI method. The results make three main contributions to advancing NOx reduction policies in China. Firstly, this study estimated NOx generation data to investigate the impact of socio-economic factors on NOx generation from 1995 to 2014 in China. Secondly, this study investigated technological effects, including energy intensity, sector generation factor, economic effects, and the sector structure of energy consumption effect, on changes in NOx generated from energy consumption. Finally, this study systematically introduced and explored the impacts of population scale and population spatial distribution structure.

This study is organized as follows. Section 2 presents the method for calculating NOx generation, the LMDI approach for decomposing the change in NOx generation, and the data source. Section 3 analyzes the temporal, spatial, and structural characteristics of NOx generation. Section 4 presents and discusses the results of the LMDI method, and Section 5 presents our conclusions and suggestions for future work.

2 Methods and data

2.1 Estimation of NOx generation

Total NOx generation from energy consumption was estimated using a bottom-up approach:

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

where $E_{(T)}$ is the amount of NOx generation at year T; subscripts i, j, and f represent the province, sector, and fuel type of energy consumption, respectively; EF is the NOx generation factor; and Q represents the quality of fuel consumption from each sector.

2.2. Decomposition of NOx generation

Considering recent studies mentioned above, NOx generated from energy consumption is mainly impacted by economic effects, technological effects, and structural effects. Furthermore, population factors are closely related to energy consumption and pollutant reduction. To comprehensively investigate the driving mechanisms of NOx generation, this study decomposed NOx generation into energy intensity, a sector generation factor, the sector structure of energy consumption, GDP per capita, population scale, and population spatial structure, based on the LMDI method (Ang, 2005):

$$N = \sum_{i,j} \frac{N_{i,j}}{E_{i,j}} \times \frac{E_{i,j}}{E_i} \times \frac{E_i}{G_i} \times \frac{G_i}{P_i} \times \frac{P_i}{P} \times P = \sum_{i,j} F_{i,j} \cdot S_{i,j} \cdot EI_i \cdot A_i \cdot R_i \cdot P \quad (2)$$

where N is NOx generation from energy consumption; subscripts i and j represent the province and sector, respectively; E represents energy consumption; G represents gross regional domestic product; and P is the resident population.

As shown in Eq. (2), the total change in NOx generation is driven by six effects: the sector generation factor (F), the sector structure of energy consumption (S), energy intensity (EI), GDP per capita (A), the population spatial structure (R), and population scale (P).

According to the LMDI method, the change in NOx generation between year *T* and year 0 is given as:

$$\Delta N_F = \sum_{i,j} L(N_{ij}^T, N_{ij}^0)\ln(\frac{F_j^T}{F_j^0}) \qquad \Delta N_S = \sum_{i,j} L(N_{ij}^T, N_{ij}^0)\ln(\frac{S_j^T}{S_j^0})$$

$$\Delta N_{EI} = \sum_{i,j} L(N_{ij}^T, N_{ij}^0)\ln(\frac{EI_j^T}{EI_j^0}) \qquad \Delta N_A = \sum_{i,j} L(N_{ij}^T, N_{ij}^0)\ln(\frac{A_j^T}{A_j^0})$$

$$\Delta N_R = \sum_{i,j} L(N_{ij}^T, N_{ij}^0)ln(\frac{R_j^T}{R_j^0}) \qquad \Delta N_p = \sum_{i,j} L(N_{ij}^T, N_{ij}^0)ln(\frac{p_j^T}{p_j^0})$$

where $\mathrm{L(x,y)} = \frac{x-y}{lnx-lny}$ for $\mathrm{x} \neq \mathrm{y}$ and $\mathrm{L(x,y)} = \mathrm{x}$ for $\mathrm{x} = \mathrm{y}$.

The LMDI of driving forces for each year were computed as:

$$(\frac{\Delta N_F}{\Delta N} + \frac{\Delta N_S}{\Delta N} + \frac{\Delta N_{EI}}{\Delta N} + \frac{\Delta N_A}{\Delta N} + \frac{\Delta N_R}{\Delta N} + \frac{\Delta N_p}{\Delta N})\times 100\% = 100\%$$

In practical applications, the consumption of a fossil fuel produces both positive values and zero values, which leads to failure of the decomposition. To deal with the zero-value problem, the method introduced by Ang and Liu (2007) was adopted.

2.3 Data sources

The study period was from 1995 to 2014, and was further divided into four stages (stage 1, 1995–2000; stage 2, 2000–2005; stage 3, 2005–2010; and stage 4, 2010–2014), reflecting five-year plans that guide the national economy, energy utilization, and other national issues in China. Since official data for 2015 was not published until after this study, the final stage was shorter than the others.

This study analyzed NOx generated from energy consumption in 29 of China's 34 provinces (Anhui, Beijing, Chongqing, Fujian, Gansu, Guangdong, Guangxi, Guizhou, Hainan, Hebei, Heilongjiang, Henan, Hubei, Hunan, Inner Mongolia, Jiangsu, Jiangxi, Jilin, Liaoning, Qinghai, Sichuan, Shaanxi, Shandong, Shanghai, Shanxi, Tianjin, Xinjiang, Yunnan, and Zhejiang). Hong Kong, Macau, Ningxia, Taiwan, and Xizang were not studied because of data deficiencies.

The sectors involved in this study included thermal power, heating supply, agriculture, industry, construction, transport, wholesale, residential consumption, and others. The fuel types included coal, diesel oil, coke, gasoline, fuel oil, coke oven gas, kerosene, natural gas, other gas, crude oil, LPG, and refinery gas.

The NOx generation factor reflected NOx generation from a unit of energy consumption, while the NOx emission factor reflected NOx emissions from a unit of energy consumption considering denitrification rates. The NOx generation factor is closely related to both economic sectors and fossil fuel types. Although some studies have explored the generation factors of some combustion equipment and vehicles, there is currently no systematic set of NOx generation factors in China; therefore, this study consulted all related studies and summarized a table of NOx generation factors that could correspond to the energy consumption of different sectors and fossil fuel types (Table 2). Data on thermal power, industry, construction, transport, wholesale, residential consumption, and others were obtained from Lang et al. (2008), who sourced most of their data from Kato and Akimoto (1992), and Tian et al. (2001). To better reflect NOx generation, this study introduced the heating supply sector and agriculture sector. According to the characteristics of energy consumption activities, the NOx generation factor of heating supply and agriculture refers to heating supply and wholesale, respectively.

Table 2. NOx generation factors for each fossil fuel type in nine sectors

Sector/fuel type	Coal (kg/t)	Coke (kg/t)	Crude oil (kg/t)	Gasoline (kg/t)	Kerosene (kg/t)	Diesel oil (kg/t)	Fuel oil (kg/t)	LPG (kg/t)	Refinery gas (kg/t)	Coke oven gas (g/m^3)	Other gas (g/m^3)	Natural gas (g/m^3)
Thermal power	9.95	/	7.24	16.70	21.20	27.40	10.06	3.74	0.75	1.39	1.35	4.10
Heating supply	7.25	9.00	5.09	16.70	7.46	7.40	5.84	2.63	0.53	0.97	0.95	2.09
Industry	7.25	9.00	5.09	16.70	7.46	9.62	5.84	2.63	0.53	0.97	0.95	2.09
Construction	7.25	9.00	/	16.70	7.46	9.62	5.84	2.63	0.53	/	/	2.09
Transport	7.50	9.00	5.09	16.70	27.40	54.10	54.10	/	/	/	/	2.09
Wholesale	3.75	4.50	3.05	16.70	4.48	5.77	3.50	1.58	0.32	0.68	0.74	1.46
Agriculture	3.75	4.50	3.05	16.70	4.48	5.77	3.50	1.58	0.32	0.68	0.74	1.46
Residential consumption	1.88	2.25	1.70	16.70	2.49	3.21	1.95	0.88	0.18	0.68	0.74	1.46
Others	3.75	4.50	3.05	16.70	4.48	5.77	3.50	1.58	0.32	0.68	0.74	1.46

"/" denotes a data deficiency

Provincial and nationwide sector energy consumption and standard coal coefficients for each fuel type were obtained from the China Energy Statistical Yearbook. Other indicators of driving forces, such as population and GDP, were obtained from the China Statistical Yearbook.

3 Characteristics of NOx generation from energy consumption in China

3.1 Temporal evolution of NOx generation

NOx generation from energy consumption in China increased over the study period, as shown in Fig. 1. The accumulated NOx generation increased from 1.17×10^7 t in 1995 to 4.15×10^7 t in 2014, with an annual growth rate of 13.39%. The annual growth rates for NOx generation during the four stages were 4.34%, 13.95%, 7.15%, and 6.60%.

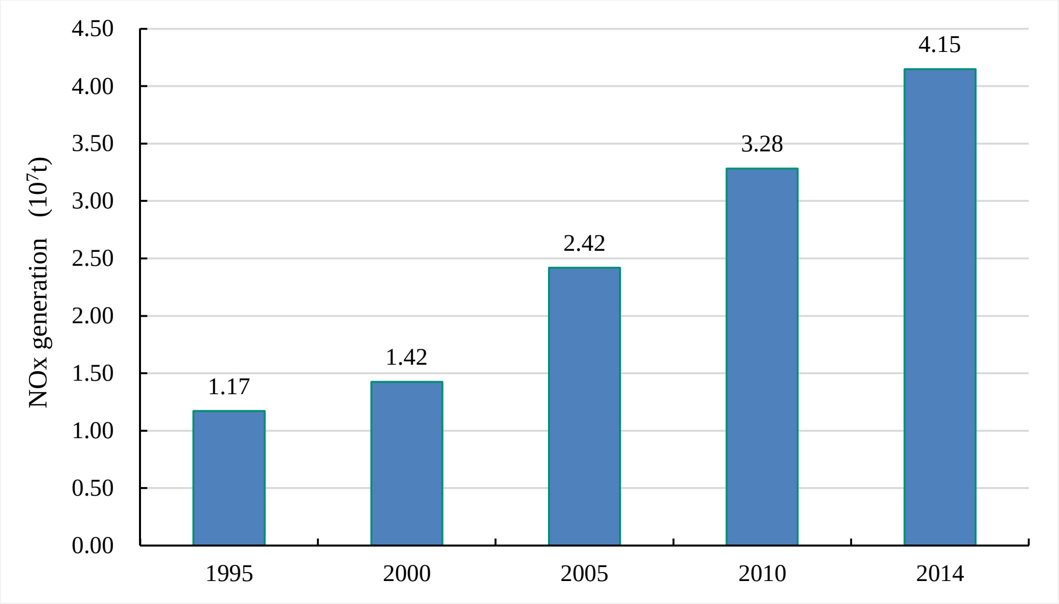

Fig. 1. NOx generation from energy consumption in China

During the first stage, the growth rate of NOx generation was slow, reflecting the low growth rates of China’s GDP and energy demand. However, the growth rate of NOx generation increased rapidly and reached its peak during the second stage. Compared to stage 1, the growth rate of NOx generation decreased during the third and fourth stages, even though China's energy consumption continued to increase. This can be explained by enhanced NOx reduction efficiency due to improvements in energy utilization technology, possibly resulting from energy conservation and emission reduction policies (such as The Renewable Energy Law of the People’s Republic of

China, the Medium and Long Term Renewable Energy Development Plan, and improved energy efficiency due to strict supervision and industrial structural optimization).

3.2 Spatial distribution of NOx generation

There is clear spatial heterogeneity in NOx generation from energy consumption in China; provinces with high GDP and population have tended to be hot spots of NOx generation. According to the distribution (Fig. 2), ‘hot spots’ (i.e., high-volume accumulation areas) of NOx generation are mainly distributed in Inner Mongolia, Hebei, Shandong, Jiangsu, Zhejiang, Anhui, and Guangdong; ‘cold spots’ (i.e., low-volume accumulation areas) are mainly distributed in Qinghai, Gansu, southern Yunnan, Guangxi, Jiangxi, and Hainan.

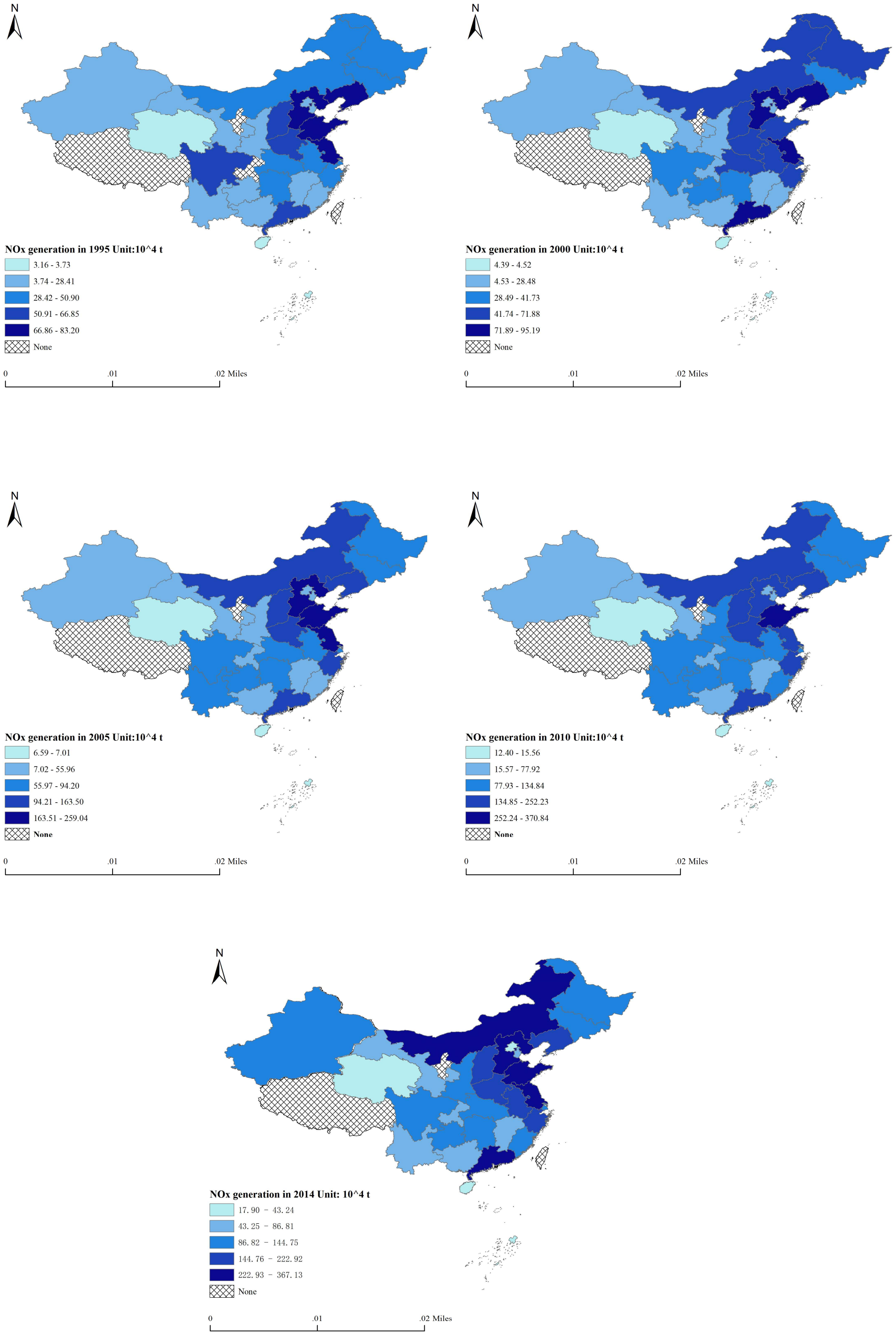

Fig. 2. Spatial distribution of NOx generation in China from 1995 to 2014

The spatial heterogeneity of NOx generation in China became increasingly obvious from 1995 to 2014. Provinces with high NOx generation in 1995 included Guangdong, Sichuan, Shanxi, Shandong, Henan, Hebei, Jiangsu, and Liaoning. Of these provinces, all but Sichuan continued to have high NOx generation in 2014; Inner Mongolia, Zhejiang, and Anhui also showed high NOx generation by 2014. These provinces are mainly concentrated in the Bohai Sea economic zone and the Yangtze River triangle economic zone.

3.3 Structural features of NOx generation

The NOx generation of all sectors increased throughout the study period (Fig. 3). Thermal power involved the greatest accumulated NOx generation, followed by industry, transport, heating supply, residential, others, agriculture, construction, and wholesale. More importantly, increasing rates of NOx generation in thermal power generation, industry, and transportation were larger than those in other sectors. NOx generation due to residential energy consumption has shown a non-negligible increasing trend since 2000. Residential energy consumption has consistently increased with improved living standards and rapid expansion of the GDP.

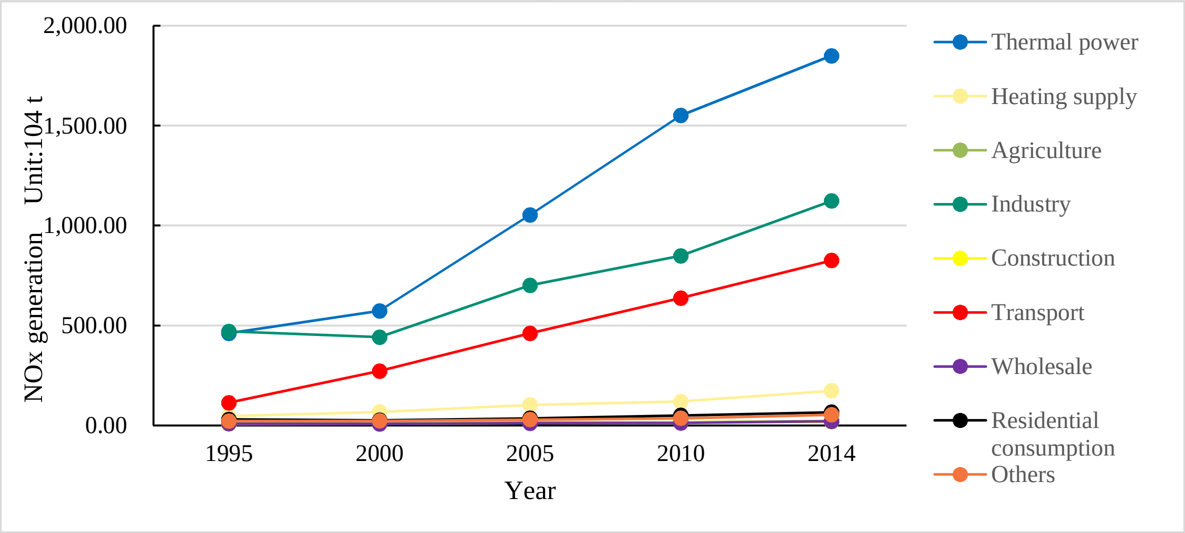

Fig. 3. NOx generation from the energy consumption sector in China

The amount of NOx generated by coal consumption accounted for more than 64.00% of the total amount of NOx generated from all fossil fuels from 1995 to 2014, followed by diesel oil, coke, gasoline, fuel oil, coke oven gas, kerosene, natural gas, other gas, crude oil, LPG, and refinery gas. Simultaneously, the proportion of NOx generated from natural gas was found to increase over the study period (Fig. 4). Although NOx generation from coal burning declined over the study period, this reduction was negligible compared to the total amount of NOx generation.

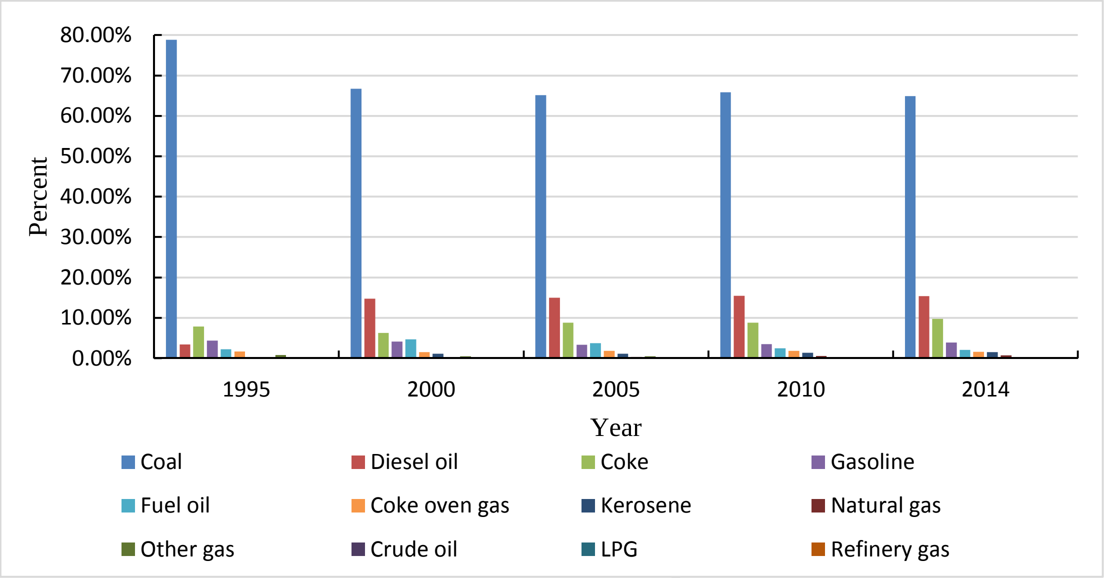

Fig. 4. NOx generated from different fossil fuels in China

4 Results and discussion

4.1 Overview of LMDI results

Results obtained from decomposition analysis using the LMDI method are shown in Table 3. During the study period, the energy intensity effect showed the most important role in reducing NOx generation, followed by the sector generation factor effect; these represented the only two inhibiting effects on NOx generation found in this study. The GDP per capita effect and the sector structure of energy consumption effect played positive roles in increasing NOx generation, and both showed increasing trends after 2005; the GDP per capita effect made the biggest contribution to increasing NOx generation in all stages. Importantly, population effects, including population scale and population spatial structure, which have not been analyzed in the published literature, played roles in increasing NOx generation.

Table 3. Decomposition of changes in NOx generation

	Sector generation factor	Energy intensity	Sector structure of energy consumption	GDP per capita	Population spatial structure	Population scale
Stage 1	−17.37%	−407.35%	49.40%	426.39%	1.76%	47.18%
Stage 2	0.06%	19.44%	8.95%	67.07%	2.13%	2.35%
Stage 3	6.02%	−60.21%	3.78%	138.24%	2.74%	9.43%
Stage 4	−20.54%	−262.85%	8.12%	354.30%	0.46%	20.51%
1995–2014	−0.95%	−70.18%	8.32%	151.00%	2.15%	9.66%

In stage 1 and stage 4, the primary inhibiting factor for NOx generation was energy intensity, followed by the sector generation factor; in contrast, GDP per capita, the sector structure of energy consumption, population spatial distribution, and population scale contributed to increase NOx generation. In stage 2, all effects contributed to increasing NOx generation. In stage 3, all factors, other than energy intensity, promoted NOx generation, reflecting improvements in the efficiency of energy utilization.

4.2 Discussion for the energy intensity effect on NOx generation

Energy intensity represents the efficiency of energy utilization, which is closely related to the influence of technological innovation. The energy intensity factor had the strongest effect on reducing NOx generation over the whole study period, with a contribution rate of −70.18%. This indicates that improving the efficiency of energy utilization was the most effective way for controlling NOx generation in China.

Based on the decomposition results, the energy intensity effect on NOx generation during the four stages was −407.35%, 19.44%, −60.21%, and −262.85%. The energy intensity effect inhibited NOx generation in all stages other than stage 2, perhaps reflecting China's accelerating industrialization and inefficient technical processes during this stage, which strongly increased energy intensity and promoted an increase in energy consumption.

As shown in Table 3, the ability of energy intensity to reduce NOx generation has increased since 2005. This could be related to the effect of energy policies, such as the Energy Development "Twelfth Five Year Plan" and the Medium and Long-Term Development of Energy (2004–2020), which required improvements to the efficiency and technology of energy utilization. Additionally, the increase in the effect of energy intensity reflects the gap in energy use efficiency between China and other developed countries.

4.3 Discussion for the sector generation factor on NOx generation

The sector generation factor represents generation efficiency, which is the level of NOx generated from a unit of energy consumption among different sectors. This effect is not only related to energy combustion technology, but also has a direct bearing on the structure of economic sectors, with the latter neglected by the studies of Ding et al. (2017) and Diao et al. (2016). According to the results of this study, the contribution of the sector generation factor to NOx generation was −0.95% over the study period. Although it was much smaller than the contribution of energy intensity, it was one of only two inhibiting effects on NOx generation found in this study. Contributions of the sector generation factor to NOx generation showed no significant fluctuations between the four stages (−17.37%, 0.06%, 6.02%, and −20.54%).

In stage 1, the sector generation factor was one of only two effects inhibiting NOx generation. This result was likely because the sector generation factors of heating supply, transport, residential consumption, and others were smaller in 1995 and 2000 than they were in 2005 and 2010; additionally, the proportion of energy consumption for transport between 1995 and 2000 was smaller than in other years (Fig. 6). Considering that the sector generation factor for the transport sector was the largest among all the sectors (Table 4), a change of energy consumption in this sector could cause a relatively significant influence

Table 4. Sector generation factors for nine sectors from 1995 to 2014 in China[b]

	1995	2000	2005	2010	2014	Average
Thermal power	136.41	136.12	134.87	134.55	133.77	135.15
Heating supply	83.74	89.41	90.91	93.27	93.84	90.23
Industry	87.53	81.38	81.46	82.02	76.29	81.73
Construction	91.20	88.81	85.54	81.44	81.78	85.75
Transport	218.74	231.60	249.07	271.50	264.99	247.18
Wholesale	63.66	59.37	53.48	50.52	47.23	54.85
Agriculture	52.94	53.37	50.67	52.12	54.00	52.62
Residential consumption	25.35	23.35	31.81	39.82	45.25	33.11
Others	67.01	73.09	68.99	65.78	64.79	67.93

b. The sector generation factor of some sectors was calculated from the NOx generation scale by energy consumption of the sector.

In stage 2, the sector generation factor contributed 0.06% to NOx generation, peaking at 6.02% in stage 3. According to the results shown in Table 4 and Figure 5, although the sector generation factors of thermal power, construction, and wholesale declined over time, this did not offset the increases in industry, transportation, and residential consumption. As shown in Figure 6, the proportion of transport also continued to increase; therefore, in these two stages, the sector generation factor played roles in increasing NOx generation.

In stage 4, the sector generation factor significantly inhibited NOx generation. As shown in Figure 5, rates of annual increase in the sector generation factors of heating supply and residential consumption were much weaker than in the previous two stages. Secondly, rates of annual decline in the sector generation factors of thermal power and wholesale continued to strengthen. Finally, the sector generation factors of industry and transport showed declining trends for the first time.

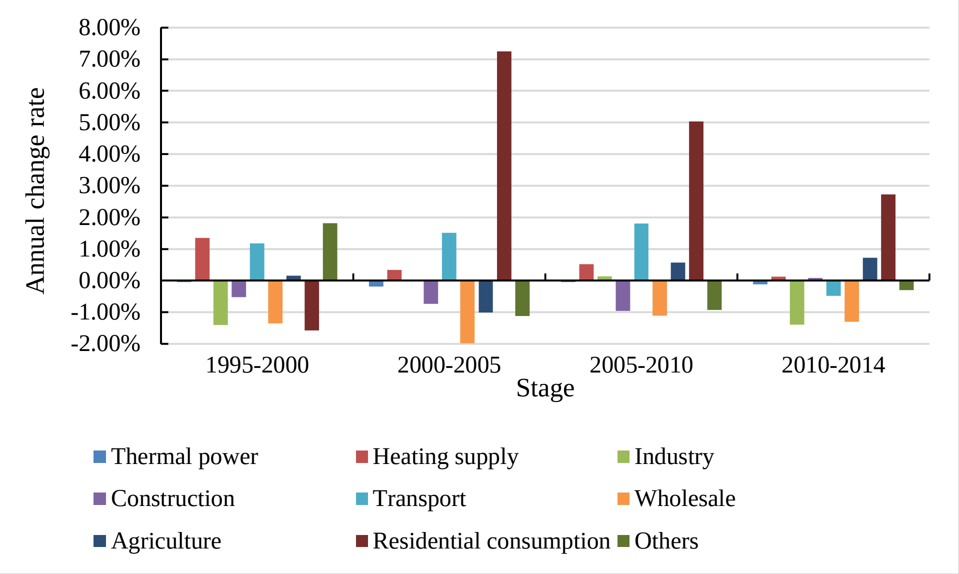

Fig.5. Annual change rates for each sector generation factor during the four stages

From the perspective of the sector generation factor, improving energy combustion technologies for transport is more challenging than for other sectors (e.g., industry and thermal power). The NOx generation factor of residential consumption showed an obviously increasing impact on NOx generation. This study suggests that the Chinese government should consider the residential consumption sector (e.g., by encouraging green travel and green consumption).

4.4 Discussion for the sector structure of energy consumption on NOx generation

Numerous studies have considered the effects of different structures on NOx generation. Wang (2016) explored the structure effects of fossil fuel consumption on NOx emissions; Lyu et al. (2016) analyzed the effect of economic structure in different sectors on NOx emissions. However, few studies have considered the sector structure of energy consumption. Optimizing energy consumption could be an effective way to reduce NOx; in particular, by disincentivizing sectors with high energy consumption and high pollutant emissions, while incentivizing sectors with low energy consumption and low pollutant emissions.

According to our results, the sector structure of energy consumption contributed 49.40%, 8.95%, 3.78%, and 8.12% to NOx generation in the four stages, and it accounted for 8.32% of the total change in NOx generation over the study period. Generally, the sector structure of energy consumption had an important role in increasing NOx generation during the first stage, along with population scale and GDP per capita. In addition, the contributions of the sector structure of energy consumption to NOx generation in the following three stages became gradually weaker, and indicated increasing difficulties in optimizing the sector structure of energy consumption.

According to the decomposition results, the sector structure of energy consumption effect always played a negative role in NOx reduction; this result differs from those in previous studies, where structural effects have shown inhibiting roles in recent years. As shown in Figure 6, the proportion of energy consumption from industry and thermal power has been consistently dominant over the past 20 years; however, sectors including construction, wholesale, and transport have consumed more energy and produced more NOx in the most recent years. Based on these results, the government should not only focus on traditional high-energy consumption and high pollutant production sectors, but also pay more attention to burgeoning sectors.

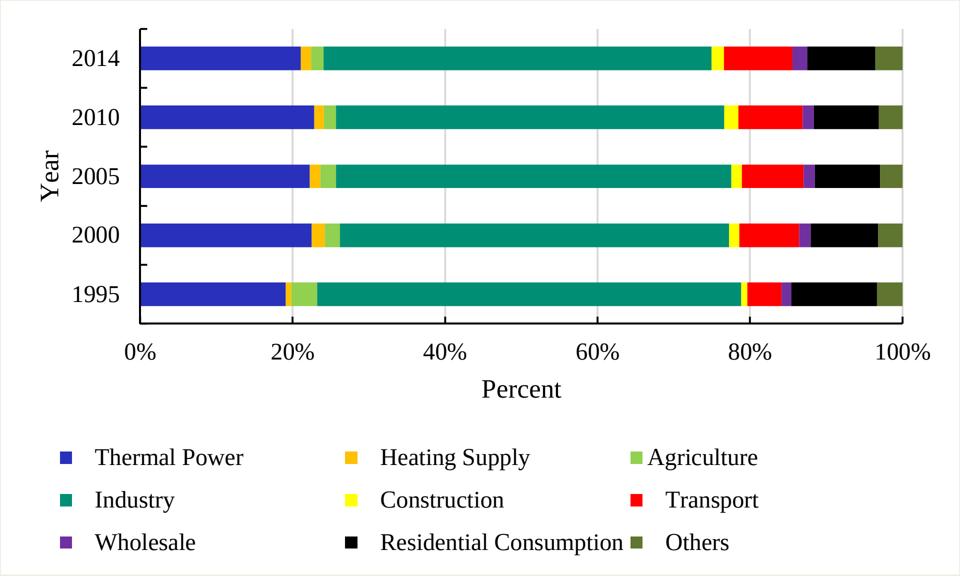

Fig. 6. Energy consumption of different sectors in China

4.5 Discussion for the GDP per capita effect on NOx generation

The decomposition results indicate that GDP per capita accounted for 151.00% of the total NOx generation change from 1995 to 2014; it was the primary driving force for NOx generation in China, which is consistent with the results of previous studies. The contributions of GDP per capita to NOx generation were 426.39%, 67.07%, 138.24%, and 354.30% in the four stages, which closely correlates with China's annual growth rates of GDP per capita. Constant economic growth increased energy consumption and led to increasingly high NOx generation.

The increasing contributions of GDP per capita to NOx generation after 2005 contradict the results of Ding et al. (2017), Diao et al. (2016), Lyu et al. (2016), and Wang (2016). The economic effect may have correlated with reducing NOx emissions because the application of denitrification technology expanded as the economy developed. However, from the perspective of NOx generation, the economic effect failed to improve the technology of energy utilization and adjust the economic sector structure.

Additionally, for all stages, the increase in NOx generation induced by GDP per capita was not offset by the reduction in NOx generation following technological advancements. Finding a balance between economic development and environmental protection will remain a challenge for sustainable development in China.

4.6 Discussion for the population scale effect on NOx generation

The population scale effect increased NOx generation throughout the study period. From 1995 to 2014, the population scale effect accounted for 9.66% of the increase in NOx generation, making it the second most important factor.

The contributions of the population scale effect to NOx generation were 1.76%, 2.35%, 9.43%, and 20.51% during the four respective stages. This relationship may reflect the synchronous growth of direct energy demand and indirect energy consumption from energy-intensive sectors, such as automobiles and real estate. Thus, the results in this study confirm the population results of Lyu et al. (2016) and suggest that the population scale effect should become a focus of policy designers in China.

4.7 Discussion for population spatial structure effect on NOx generation

The population spatial structure effect is an important population indicator that was introduced to explain the driving force of NOx generation in the decomposed model. The results show that where the population proportion decreased in regions with high NOx generation per capita, and where the population proportion of regions with low NOx level increased at the same time, NOx was reduced on a national scale.

As shown in Table 3, the contributions of the population spatial structure to NOx generation for the four stages were 1.76%, 2.13%, 2.74%, and 0.46%. The mean contribution of the population spatial structure effect over the study period was 2.15%, which is smaller than the effects of GDP per capita, population scale, and the sector structure of energy consumption.

According to the results shown in Figure 7 and Figure 8, the population proportion of regions with low NOx generation per capita increased significantly, including Beijing, Zhejiang, Fujian, Guangdong, Yunnan, and Qinghai; the population proportion of regions with high NOx generation per capita declined, including Inner Mongolia, Shandong, and Jiangsu. However, some regions with high NOx generation per capita had increasing population proportions, including Hebei, Tianjin, Shanxi, and Xinjiang, which played a negative role in NOx reduction. Overall, the population spatial effect had a slight positive impact on NOx generation. The spatial distributions of NOx generation per capita in China were broadly similar during the different stages; therefore, Figure 8 shows only the results from 2014 as a representative example.

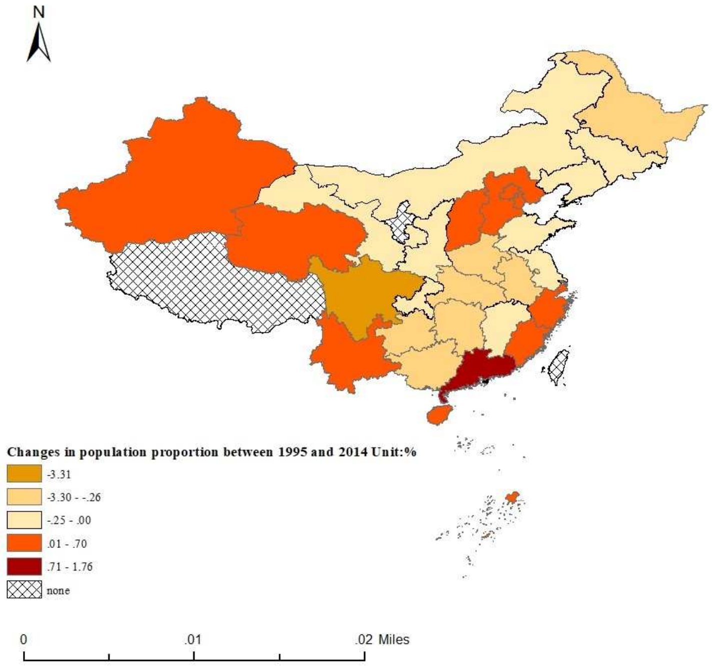

Fig.7. Changes of population proportion between 1995 and 2014 in China

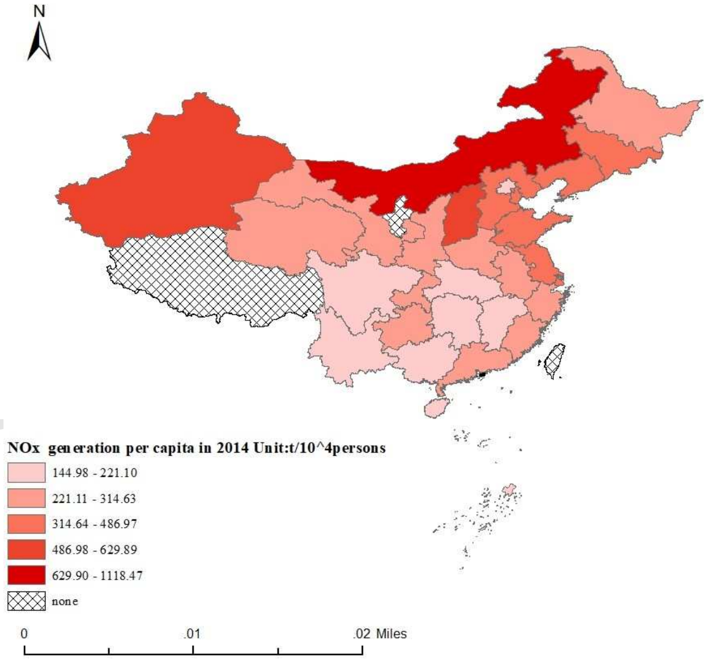

Fig.8. Spatial distribution of China's NOx generation per capita in 2014

5 Conclusions and policy implications

To explore the driving forces of NOx generation in China, this study estimated NOx generation from energy consumption and built a decomposition model. Based on the results, the following conclusions were drawn:

(1) Accumulated NOx generation from energy consumption showed a gradually increasing trend from 1.17 ×10^7 t in 1995 to 4.15 ×10^7 t in 2014, while the annual growth rates for NOx generation declined. Provinces with high GDP and population scale tended to be hot spots of NOx generation. The key sector and fuel type for NOx generation were thermal power and coal, respectively; since 2000, NOx generation from residential consumption has also increased substantially.

(2) This study found that the driving mechanisms of NOx generation showed some differences with those from previous studies of NOx emissions. Overall, energy intensity had the most positive effect on the reduction of NOx generation, followed by the sector generation effect, which was ignored by previous studies. GDP per capita has played the most important role in increasing NOx generation, with a contribution of 151.00% for the study period; it also showed an increasing contribution after 2005, which differs from the results of previous studies. This study introduced the sector structure of energy consumption, which has not been explored in previous studies, and found that it was positively correlated with increasing NOx generation from 1995 to 2014. However, this study also found that NOx reductions induced by all inhibiting factors did not balance the NOx increases induced by GDP per capita during the four study stages, reflecting the difficulty of synchronous economic development and environmental protection.

(3) This study also quantified the influence of population effects, including population scale and population spatial structure, which have not been considered in previous studies. In contrast to the energy intensity and sector generation factors, which had non-negligible effects on NOx reduction, all population effects were positively correlated with NOx generation. Notably, population scale had a significant effect on NOx generation and has shown an increasing trend since 2005. In contrast, the population spatial structure exerted a minor, increasing effect on NOx generation. The increasing proportions of population in regions with low NOx generation per

capita generally played a positive role in NOx reduction. In the future, population mobility will likely increase; therefore, the effect of population spatial structure on NOx reduction should be a focus of future studies.

(4) Based on the results of this study, it is essential for NOx reduction policies to consider socio-economic driving forces. Firstly, future reduction policies should give sufficient weight to the transportation and residential consumption sectors, as well as to the thermal power and industry sectors. Secondly, NOx generation control areas should be considered to establish high-volume accumulation areas of NOx generation. Thirdly, technological and economic effects are still essential for NOx reduction in both end treatment and source control. The Chinese government should set an appropriate growth rate for GDP per capita. Fourthly, the sector structure of high NOx generation should be systematically adjusted to reduce its effect on increasing NOx generation. Finally, policy designers should integrate population factors into the reduction policy system, including reducing energy consumption induced by population scale and reducing its promotional effect on NOx generation. It is important to monitor and control the influence of population spatial distribution on NOx generation, a factor that is greatly impacted by urbanization and will inhibit long-term NOx reductions in China.

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