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Original Research

CO_2 Emissions from the Power Industry in the China's Beijing-Tianjin-Hebei Region: Decomposition and Policy Analysis

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Abstract

Based on the energy consumption data of power industry in the Beijing-Tianjin-Hebei region from 1995 to 2014, our paper first estimated CO_2 emissions using the IPCC carbon accounting methods. Then, starting from the perspective of the power industry chain – including power generation, transmission, and final consumption – we established the hierarchical LMDI decomposition model; decomposed driving factors of CO_2 emissions into effects of fuel mix; the coal consumption rate; power generation structure; the ratio of power generation to consumption, transmission, and distribution losses; production sectors' electricity intensity; industrial structure; household electricity intensity; economic scale; and population size. Results show that:

1. During 1995-2014, CO_2 emissions of power industry in the Beijing-Tianjin-Hebei region developed in fluctuation and showed a rising trend in general, with annual average growth rate of 5.93%.
2. The factors that drive the growth of CO_2 emissions from the power industry in the Beijing-Tianjin-Hebei region are, in order, economic scale, population size, transmission and distribution losses, and industrial structure, with a contribution rate of 150.70%, 20.80%, 8.86%, and 8.83%. The factors that drive CO_2 emissions reduction are production sectors' electricity intensity, the coal consumption rate, the ratio of electricity generation and consumption, household electricity intensity, power generation structure, and fuel mix, with a contribution rate of -45.97%, -22.38%, -19.41%, -0.62%, -0.49%, and -0.32%, respectively.

Keywords: Beijing-Tianjin-Hebei region, power industry, CO_2 emissions, hierarchical LMDI decomposition model, driving factors

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Introduction

Climate change is of growing concern worldwide due to its contribution to environmental pollution and obstacles to sustainable socio-economic development [1]. The ongoing emission of greenhouse gas (GHG), which gives priority to carbon dioxide (CO_2), is responsible for climate change. Slightly more than 40% of the global energy-related CO_2 emissions are attributable to emissions from electricity and heat production [2]. The power industry, which is the basic industry related to lifelines of China's national economy, faces problems such as high energy consumption and large-scale of carbon emissions. Based on resource endowment conditions and energy consumption structures in china, the power industry mainly adopts coal-fired power generation and is the primary source of CO_2 emissions across China.

According to Enhanced Actions on Climate Change: China's Intended Nationally Determined Contributions (INDC) on June 30, 2015, the action targets of greenhouse gas (GHG) emission control in China by 2030 are as follows:

- CO_2 emissions will reach the peak in 2030 or as soon as possible.
- Carbon dioxide emissions per unit of GDP will be reduced by 60% to 65% from the 2005 level.
- The share of non-fossil fuels in primary energy consumption will be increased to about 20%.

Thus, to develop low-carbon economy, achieve the goals on climate change ahead of schedule, and reach the peak of CO_2 emissions, China's power industry should take the major responsibility of cutting consumption and emissions.

The Beijing-Tianjin-Hebei region is the center of China's political, cultural, and international exchanges, and its scientific and technological innovation center. It is also the most developed town and industrial base with the highest level of modernization in northern China. With the economy booming, it faces many regional environmental problems, including severe haze pollution, increasing energy consumption, and CO_2 emissions. The CO_2 emissions of the Beijing-Tianjin-Hebei region account for about 12% of all emissions. The region has become one of the metropolis circles with relatively large CO_2 emissions in China and even all over the world. It is also the key area for reducing emissions. Based on its resource endowment conditions, the power industry in this region relies mainly on thermal power. In 2014, thermal power generation accounted for 94.17% of all power generation, and CO_2 emissions from the power industry account for 34.85% of all CO_2 emissions from the region. Therefore, our paper, which studies CO_2 emissions of the power industry in the Beijing-Tianjin-Hebei region, has great practical significance in conserving energy and reducing power industry emissions.

Literature Review

Climate change [3], CO_2 concentrations [4], and CO_2 emissions [5-6] have been thoroughly studied. And most of all, intensive studies on national [7-8], regional [9-10], and industrial [11-13] CO_2 emissions that account for influencing factors have been conducted. Comprehensive literature, the main measuring and calculating methods of CO_2 emissions are the material balance method, the actual measurement method, and the model estimation method [14-16]. The main analyzing methods of driving factors for CO_2 emissions are decomposition analysis (DA), environmental Kuznets curve (EKC), and the metrological method [17-19]. These methods have different characteristics and applicabilities. Among the methods for studying CO_2 emissions in the fields of energy and the environment, the DA is the most widely applied method to uncover the driving forces of CO_2 emissions.

Numerous studies have adopted DA to analyze the changes in energy use and emissions [20]. DA aims to decompose the aggregate energy use and emissions into quantifiable explanatory variables under ceteris paribus assumption [21]. The two popular decomposition techniques are structural decomposition analysis (SDA) and index decomposition analysis (IDA) [22]. The studies on SDA in energy and energy-related CO_2 emission applications can be found in Su and Ang [23] and Cansino et al. [24], while the studies on IDA can be found in Ang [25] and González [26]. SDA requires detailed input-output (I-O) data to account for the indirect requirement in an economic system, which is dependent on the availability of I-O tables [27]. IDA is less data intensive and more diverse in decomposition forms than SDA, thereby allowing the decomposition of continuous annual data at both economy-wide and industrial levels [28]. To make better research and analysis, Ang, Liu, and Choi proposed using the logarithmic mean divisia index (LMDI) technique, which is favored in the current study of CO_2 emissions due to its advantages, such as complete decomposition, path independence, no residual term, and consistency in aggregation [29-31].

In literature, the LMDI method was widely used to identify the driving factors of energy-related CO_2 emissions in the manufacturing industry [32], the nonmetallic mineral products industry [33], the industrial sector [34], and others. Similarly, many studies are involved in CO_2 emissions of the power industry. Ang applied LMDI to study the influence of changes in power generation level, CO_2 emission factors for fuel, power generation structure, and fuel intensity on CO_2 emissions of the power industry in Korea [35]. Malla used this approach to decompose the driving effects of CO_2 emissions in seven Asian and North American power industries into power generation level, power generation structure, and energy consumption of power generation. They also found that energy consumption of power generation was the only negative driving factor affecting CO_2 emissions and that changes of power generation structures would help to reduce CO_2 emissions in the future [36]. Karmellos adopted the LMDI-I decomposition approach and conducted research on CO_2 emissions from the power industry of 28 EU countries from 2000 to 2012. They considered the influence of economic activities, electricity intensity, power trade, productive efficiency, and fuel mix of power industry on CO_2 emissions [37].

Chinese scholars Huo and Molin took the CO_2 emission intensity of China's power industry from 1991 to 2010 as a research object and studied the effects of power consumption rate, power generation structure, coal consumption in power generation, and line loss on it with LMDI. They discovered that the cumulative declines in CO_2 emissions were mainly influenced by the positive effect of coal consumption reduction in power generation, and that the short-term variations of CO_2 emission intensity were mainly decided by the power generation structure [38]. Zhang and Ming applied LMDI to research the major factors influencing CO_2 emissions of China's power industry from 1991 to 2009. They discovered that the most important factor of CO_2 emission increases in China's power industry was economic growth effect, and that the main factor curbing CO_2 emissions was productive efficiency of the power industry, with secondary factors being reduction in electricity intensity and changes in power fuel mix [39]. Yang Lisha and Lin Boqiang concluded that six factors affect the carbon emissions in China's power industry, primarily among them electricity intensity and economic activity, with energy efficiency also playing a key role in future emissions abatement [40].

The comprehensive research findings indicate that present literature mainly concentrates on the level of countries or regions around the world, while there are not enough studies of CO_2 emissions from the power industry at the level of China's provinces. China is a large country with regionally diversified economic development, resource endowment, and power generation and power demands, therefore, research results based on different spacial scales are inevitably distinct. Furthermore, some research has concentrated on driving factors of CO_2 emissions of the power industry from the perspective of power generation, such as fuel mix, generation structure, and coal consumption rate. However, there are rare studies about the the factors of CO_2 emissions from the power industry concerning comprehensive power generation, transmission and distribution, final consumption, and other stages. So these integrated factors remain to be further studied.

Therefore, our paper treats the power industry in the Beijing-Tianjin-Hebei region as a research subject. We estimated the CO_2 emissions of the power industry in this region from 1995 to 2014 and established the hierarchical LMDI decomposition model, starting from the perspective of the power industry chain, including power generation, transmission, and final consumption. Our paper aims to find the change features and driving factors of CO_2 emissions of the power industry in the Beijing-Tianjin-Hebei region, and identify the interactions between the factors. Then, combined with empirical analyses, the paper will propose related policy suggestions to reduce energy consumption and CO_2 emissions of the power industry and promote realization of the goal of energy conservation and emission reduction in the region as soon as possible.

Material and Methods

Estimating Energy-Related CO_2 Emissions

For the lack of actual monitoring data of CO_2 emissions from China's power industrial sectors and the difficulty in constructing an estimation model based on industry and region, the paper will apply the material balance method – especially the estimate method with classification of detailed fuels to estimate CO_2 emissions.

According to the international conventions of accounting CO_2 emissions from the power industry, renewable energy sources like wind power, nuclear power, and hydropower can be set to zero. Besides, in China's coal-burning electricity-generating enterprises, CO_2 emissions in the process of desulfuration are too few to count. Therefore, CO_2 emission of the power industry only involve that of fossil fuel combustion in the process of thermal power generation. The specific calculation formula is as follows:

$$C = \sum_i E_i \times NCV_i \times CEF_i \times COF_i \times \frac{44}{12} \quad (1)$$

...where C represents total energy-related CO_2 emissions of the power industry, E_i is energy consumption based on fuel type i, NCV_i represents average lower calorific value of the i th fuel, CEF_i is the i th fuel's carbon content of the unit heat value, COF_i is the i th fuel's carbon oxidation rate, and $^{44}/_{12}$ represents the molecular weight ratio of carbon dioxide to carbon.

Hierarchical LMDI Decomposition Model

This chapter attempts to construct a hierarchical LMDI decomposition model, beginning with the six factors (CO_2 emission factors for fuel and fuel mix, the coal consumption rate, power generation structure, the ratio of power generation to consumption, and power consumption scale) that influence CO_2 emissions of the power industry in the Beijing-Tianjin-Hebei Region. Then the driving factor of the power consumption scale is further analyzed, and finally the complete decomposition model can be constructed. That is to say, our paper takes into account the whole power industry chain, including power generation, transmission, and final consumption, and comprehensively analyzes the driving factors of CO_2 emissions of the power industry in this region.

Primary Decomposition

The decomposition study of CO_2 emissions in the power industry from 28 EU countries made by Karmellos provides a new idea for our paper [33]. Improving upon this basis, the paper constructs the following model:

$$\mathrm{C}=\sum_{\mathrm{i=1}}^{3}\mathrm{C_i}=\sum_{\mathrm{i=1}}^{3}\frac{\mathrm{C_i}}{\mathrm{E_i}}\bullet\frac{\mathrm{E_i}}{\mathrm{E}}\bullet\frac{\mathrm{E}}{\mathrm{TP}}\bullet\frac{\mathrm{TP}}{\mathrm{G}}\bullet\frac{\mathrm{G}}{\mathrm{EC}}\bullet \mathrm{E}C= \\ =\sum_{\mathrm{i=1}}^{3}\mathrm{CE_i}\bullet ES_i\bullet CR\bullet S\bullet R\bullet \mathrm{EC} \tag{2}$$

…where C is total CO_2 emissions from power generation in the Beijing-Tianjin-Hebei Region; C_i is the CO_2 emissions from from power generation by fuel type i; $i = 1, 2, 3$, which respectively represents the consumed "coal and its products," "oil and its products," and "gas and its products" in power generation; E represents total fossil energy consumption of power industry in the region; E_i is energy consumption based on fuel type i; and G represents total power generation, including thermal power production (TP) and clean energy power production. Symbols and meanings of factors are shown in Table 1.

Ang takes time factors into consideration when solving the problem of boundary value in CO_2 emissions decomposition [26]. Based on this study, CO_2 emission changes of power industry in the Beijing-Tianjin-Hebei region take time into account and can be expressed as:

$$\dot{\mathrm{C}}=\sum_{\mathrm{i=1}}^{3}\dot{\mathrm{CE}}_{\mathrm{i}}\bullet ES_i\bullet CR\bullet S\bullet R\bullet EC+\sum_{\mathrm{i=1}}^{3}\mathrm{CE_i}\bullet \\ \bullet \dot{ES}_i\bullet CR\bullet S\bullet R\bullet EC+\sum_{\mathrm{i=1}}^{3}\mathrm{CE_i}\bullet ES_i\bullet \dot{CR}\bullet \\ \bullet S\bullet R\bullet EC+\sum_{\mathrm{i=1}}^{3}\mathrm{CE_i}\bullet ES_i\bullet CR\bullet \dot{S}\bullet R\bullet EC+ \\ +\sum_{\mathrm{i=1}}^{3}\mathrm{CE_i}\bullet ES_i\bullet CR\bullet S\bullet \dot{R}\bullet EC+\sum_{\mathrm{i=1}}^{3}\mathrm{CE_i}\bullet ES_i \\ \bullet CR\bullet S\bullet R\bullet \dot{EC} \tag{3}$$

Transform the right side of Eq. (3) into the form of growth rates:

$$\dot{\mathrm{C}}=\sum_{\mathrm{i=1}}^{3}g_{CE}\bullet C_i+\sum_{i=1}^{3}g_{ES}\bullet C_i+\sum_{i=1}^{3}g_{CR}\bullet C_i+ \\ +\sum_{i=1}^{3}g_{S}\bullet C_i+\sum_{i=1}^{3}g_{\mathrm{R}}\bullet C_i+\sum_{i=1}^{3}g_{\mathrm{EC}}\bullet C_i \tag{4}$$

…where, g_{CE}, g_{ES}, g_{CR}, g_S, g_R, and g_{EC} respectively represent the growth rates of CO_2 emission factors of fuel and fuel mix, the coal consumption rate, power generation structure, the ratio of power generation to consumption, and the power consumption scale.

Suppose t is base year, T is target year, then C_{t} and C_{T} represent CO_2 emissions of power industry in the Beijing-Tianjin-Hebei region in the base year and target year, respectively. ΔC is the variation from base year to target year (that is $\Delta C = C_T - C_t$). Over the time interval of $[t, T]$, Eq. (4) can be converted into:

$$\Delta\mathrm{C}=\int_{\mathrm{t}}^{\mathrm{T}}\sum_{\mathrm{i=1}}^{3}\mathrm{g_{CE}}\bullet C_i d_t+\int_{\mathrm{t}}^{\mathrm{T}}\sum_{\mathrm{i=1}}^{3}\mathrm{g_{ES}}\bullet C_i d_t+\int_{\mathrm{t}}^{\mathrm{T}}\sum_{\mathrm{i=1}}^{3}\mathrm{g_{CR}}\bullet C_i d_t \\ +\int_{\mathrm{t}}^{\mathrm{T}}\sum_{\mathrm{i=1}}^{3}\mathrm{g_{S}}\bullet C_i d_t+\int_{\mathrm{t}}^{\mathrm{T}}\sum_{\mathrm{i=1}}^{3}\mathrm{g_{R}}\bullet C_i d_t+\int_{\mathrm{t}}^{\mathrm{T}}\sum_{\mathrm{i=1}}^{3}\mathrm{g_{EC}}\bullet C_i d_t \tag{5}$$

With LMDI, variation of CO_2 emissions from base year t to target year T can be decomposed completely as follows:

$$\Delta\mathrm{C}=\Delta C_{CE}+\Delta\mathrm{C_{ES}}+\Delta\mathrm{C_{CR}}+\Delta\mathrm{C_S}+\Delta\mathrm{C_T}+\Delta\mathrm{C_{EC}} \tag{6}$$

…where ΔC_{CE} is the change in CO_2 emissions factor effect, which can be shown as:

$$\Delta\mathrm{C_{CE}}=\sum_{\mathrm{i=1}}^{3}\mathrm{L}\left(\mathrm{C}_{i,t},C_{i,T}\right)\ln\left(\mathrm{CE_{i.T}}/\mathrm{CE}_{i,t}\right) \tag{7}$$

ΔC_{ES} is the change in fuel mix effect, which can be shown as:

$$\Delta\mathrm{C_{ES}}=\sum_{\mathrm{i=1}}^{3}\mathrm{L}\left(\mathrm{C_{i,t}},C_{i,T}\right)\ln(ES_{i,T}/ES_{i,t}) \tag{8}$$

ΔC_{CR} is the change in the coal consumption rate effect, which can be shown as:

$$\Delta C_{\mathrm{CR}}=\sum_{\mathrm{i=1}}^{3}\mathrm{L}\left(\mathrm{C_{i,t}},C_{i,T}\right)\ln\left(CR_{\mathrm{T}}/CR_{\mathrm{t}}\right) \tag{9}$$

ΔC_S is the change in power generation structure effect, which can be shown as:

$$\Delta\mathrm{C_S}=\sum_{\mathrm{i=1}}^{3}\mathrm{L}\left(\mathrm{C_{i,t}},C_{i,T}\right)\ln\left(S_{\mathrm{T}}/S_{\mathrm{t}}\right) \tag{10}$$

ΔC_R is the change in ratio of power generation to consumption effect, which can be shown as:

$$\Delta\mathrm{C_R}=\sum_{\mathrm{i=1}}^{3}L\left(C_{i,t},C_{i,T}\right)\ln\left(\mathrm{R_T}/R_{\mathrm{t}}\right) \tag{11}$$

ΔC_{EC} is the change in power consumption scale effect, which can be shown as:

$$\Delta\mathrm{C_{EC}}=\sum_{\mathrm{i=1}}^{3}L\left(C_{i,t},C_{i,T}\right)\ln(EC_T/EC_t) \tag{12}$$

The function $L(C_{i,t}, C_{i,T})$ in the above formulas is the logarithmic mean function, and the specific expression is:

$$L(C_{i,t}, C_{i,T}) = \begin{cases} (\mathrm{C}_{i,t} - C_{i,T}) / (\ln C_{i,t} - \ln \mathrm{C}_{\mathrm{i,T}}), C_{i,t} \neq C_{i,T} \\ \mathrm{C}_{i,t}, C_{i,t} = C_{i,\mathrm{T}} \\ 0, C_{i,t} = C_{i,T} = 0 \end{cases} \tag{13}$$

Decomposition in the Phase of Power Consumption

The electrical system is a unified whole that requires instant supply-demand balance. On the one hand, the delivery, transmission, distribution, and consumption of power are finished at the same time, and problems at any stages will lead to a breakdown of the system. On the other hand, within the operation there is almost no electrical energy storage device as a buffer. Electric energy is doomed to be consumed once it is produced. Therefore, the balance equation of total power consumption can be established, and changes of power consumption at the stage of power consumption can be decomposed according to its different forms.

Decomposition of the Changes in Power Consumption Scale

Total power consumption is composed of two parts: transmission and distribution losses (*L*) and final power consumption (*F*), which is $EC = \mathrm{L} + F$. In the time interval [t, T], ΔEC can be expressed with the following formula:

$$\Delta EC = EC_T - EC_t = L_T - L_t + F_T - F_t = \Delta \mathrm{L} + \Delta F \tag{14}$$

…where ΔL and ΔF are the changes of power consumption caused by changes of transmission and distribution and that of final power consumption, respectively.

Final power consumption (*F*) can be decomposed according to different industrial sectors and household consumption, which can be expressed as:

$$\mathrm{F} = \sum_{\mathrm{j}=1}^{7} F_i = \sum_{\mathrm{j}=1}^{6} \frac{F_j}{Y_j} \bullet \frac{\mathrm{Y}_j}{Y} \bullet \frac{Y}{P} \bullet P + \frac{F_7}{Y} \bullet \frac{Y}{P} \bullet P = \\ = \sum_{j=1}^{6} EI_j \bullet IS_j \bullet AR \bullet P + EIC \bullet AR \bullet P \tag{15}$$

…where $j = 1, 2, ..., 7$ represent, respectively, the sectors of agriculture, forestry, animal husbandry, fishery and water conservancy, industry, construction, transportation, warehousing and postal, wholesale, retail, lodging, carting, other industries and household departments; F_j is the final power consumption of different industrial sectors or household departments; Y_j is the gross domestic product of the *j* sector; *Y* is regional gross domestic product; and *P* is population size. Symbols and meanings of factors are shown in Table 2.

When time factor is considered, changes of final power consumption of the power industry in the Beijing-Tianjin-Hebei region can be expressed as:

$$\dot{F} = \sum_{j=1}^{6} E\dot{I}_j \bullet IS_j \bullet AR \bullet P + \sum_{j=1}^{6} EI_j \bullet I\dot{S}_j \bullet AR \bullet \\ \bullet P + \sum_{j=1}^{6} EI_j \bullet IS_j \bullet A\dot{R} \bullet P + \sum_{j=1}^{6} EI_j \bullet IS_j \bullet AR \bullet \\ \bullet \dot{P} + EI\dot{C} \bullet AR \bullet P + EIC \bullet A\dot{R} \bullet P + EIC \bullet AR \bullet \dot{P} \tag{16}$$

Transform the right side of Eq. (16) into the form of growth rates:

$$\dot{\mathrm{F}} = \sum_{j=1}^{6} g_{EI} \bullet F_j + \sum_{j=1}^{6} g_{IS} \bullet F_j + \sum_{j=1}^{6} g_{AR} \bullet F_j + \\ + \sum_{j=1}^{6} g_P \bullet F_j + g_{EIC} \bullet F_7 \tag{17}$$

…where g_{EI}, g_{IS}, g_{AR}, g_{P}, and g_{EIC} represent growth rate of production sectors' electricity intensity, industrial structures, per capita GDP, population size, and household electricity intensity, respectively.

Suppose *t* is base year, *T* is target year, then F_t and F_T represent, respectively, final power consumption of power industry in the Beijing-Tianjin-Hebei region in the base year and target year. ΔF is the variation of final power consumption, that is $\Delta \mathrm{F} = \mathrm{F}_{\mathrm{T}} - \mathrm{F}_{\mathrm{t}}$. Over the time interval of [*t, T*], Eq. (17) can be converted into:

$$\Delta \mathrm{F} = \int_{\mathrm{t}}^{\mathrm{T}} \sum_{j=1}^{6} g_{EI} \bullet F_j d_t + \int_{\mathrm{t}}^{\mathrm{T}} \sum_{j=1}^{6} g_{IS} \bullet F_j d_t + \\ + \int_{\mathrm{t}}^{\mathrm{T}} \sum_{j=1}^{7} g_{AR} \bullet F_j d_t + \int_{\mathrm{t}}^{\mathrm{T}} \sum_{j=1}^{7} g_P \bullet F_j d_t + \int_t^T g_{EIC} \bullet F_7 d_t \tag{18}$$

With LMDI, variations of final power consumption from base year *t* to target year *T* can be decomposed completely as follows:

$$\Delta \mathrm{F} = \Delta F_{EI} + \Delta F_{\mathrm{IS}} + \Delta F_{\mathrm{AR}} + \Delta \mathrm{F}_{\mathrm{P}} + \Delta F_{EIC} \tag{19}$$

ΔF_{EI} is variation of final power consumption caused by changes of industrial electricity intensity.

$$\Delta \mathrm{F}_{\mathrm{EI}} = \sum_{j=1}^{6} L(F_{j,t}, F_{j,T}) \ln(EI_{j,T} / EI_{j,t}) \tag{20}$$

ΔF_{IS} is a variation of final power consumption caused by changes to industrial structures.

$$\Delta \mathrm{F}_{\mathrm{IS}} = \sum_{j=1}^{6} L(F_{j,t}, F_{j,T}) \ln(\mathrm{IS}_{\mathrm{i,T}} / \mathrm{IS}_{\mathrm{i,t}}) \tag{21}$$

ΔF_{AR} is a variation of final power consumption caused by changes of economic scale.

$$\Delta \mathrm{F}_{\mathrm{AR}} = \sum_{j=1}^{7} \mathrm{L}\left(\mathrm{F}_{j,t}, F_{j,T}\right) \ln\left(AR_{j,T} / AR_{j,t}\right) \tag{22}$$

ΔF_{P} is a variation of final power consumption caused by changes of population size.

$$\Delta \mathrm{F}_{\mathrm{P}} = \sum_{j=1}^{7} L\left(F_{j,t}, F_{j,T}\right) \ln\left(P_{j,T} / P_{j,t}\right) \tag{23}$$

ΔF_{EIC} is a variation of final power consumption caused by changes of household electricity intensity.

$$\Delta \mathrm{F}_{\mathrm{EIC}} = L\left(F_{7,t}, F_{7,T}\right) \ln\left(EIC_{T} / EIC_{t}\right) \tag{24}$$

The function L($\mathrm{F}_{\mathrm{i,\,t}}$, $F_{i,\,T}$) in the above formulas is the logarithmic mean function, and its specific expression is:

$$L(F_{i,t}, F_{i,T}) = \begin{cases} \left(\mathrm{F}_{i,t} - F_{i,T}\right) / \left(\ln F_{i,t} - \ln F_{i,T}\right), F_{i,t} \neq F_{i,T} \\ F_{i,t}, F_{i,t} = F_{i,T} \\ 0, F_{i,t} = F_{i,T} = 0 \end{cases} \tag{25}$$

Decomposition of Consumption-Related CO$_2$ Emissions

According to the above decomposition of power consumption, changes of CO$_2$ emissions at the stage of power consumption can be expressed as follows:

$$\begin{aligned} \Delta C_{EC} &= \Delta C_{L} + \Delta C_{F} = \Delta C_{L} + \Delta C_{EI} + \\ &+ \Delta C_{IS} + \Delta C_{AR} + \Delta C_{P} + \Delta C_{EIC} \end{aligned} \tag{26}$$

…where $\Delta \mathrm{C}_{\mathrm{L}}$ is the change in transmission and distribution losses effect, which can be shown as:

$$\Delta \mathrm{C}_{\mathrm{L}} = \Delta \mathrm{C}_{\mathrm{EC}} \frac{\mathrm{L}_{\mathrm{T}} - \mathrm{L}_{\mathrm{t}}}{\mathrm{EC}_{\mathrm{T}} - \mathrm{EC}_{\mathrm{t}}} \tag{27}$$

ΔC_{EI} is the change in production sectors' electricity intensity effect, which can be shown as:

$$\Delta \mathrm{C}_{\mathrm{EI}} = \Delta \mathrm{C}_{\mathrm{EC}} \frac{\sum_{j=1}^{6}\left(F_{j,T} - F_{j,t}\right)}{EC_{T} - EC_{t}} \sum_{j=1}^{6} L\left(F_{j,t}, F_{j,T}\right) \ln\left(EI_{j,T} / EI_{j,t}\right) \tag{28}$$

ΔC_{IS} is the change in industrial structure effect, which can be shown as:

$$\Delta \mathrm{C}_{IS} = \Delta C_{EC} \frac{\sum_{j=1}^{6}\left(F_{j,T} - F_{j,t}\right)}{EC_{T} - EC_{t}} \sum_{j=1}^{6} L\left(F_{j,t}, F_{j,T}\right) \ln\left(IS_{j,T} / IS_{j,t}\right) \tag{29}$$

ΔC_{AR} is the change in economic scale effect, which can be shown as:

$$\Delta \mathrm{C}_{\mathrm{AR}} = \Delta \mathrm{C}_{\mathrm{EC}} \frac{\sum_{j=1}^{7}\left(F_{j,T} - F_{j,t}\right)}{EC_{T} - EC_{t}} \sum_{j=1}^{7} L\left(F_{j,t}, F_{j,T}\right) \ln\left(AR_{j,T} / AR_{j,t}\right) \tag{30}$$

ΔC_{P} is the change in population size effect, which can be shown as:

$$\Delta \mathrm{C}_{\mathrm{P}} = \Delta \mathrm{C}_{\mathrm{EC}} \frac{\sum_{j=1}^{7}\left(F_{j,T} - F_{j,t}\right)}{EC_{T} - EC_{t}} \sum_{j=1}^{7} L\left(F_{j,t}, F_{j,T}\right) \ln\left(\mathrm{P}_{j,T} / \mathrm{P}_{j,t}\right) \tag{31}$$

ΔC_{EIC} is the change in household electricity intensity effect, which can be shown as:

$$\Delta \mathrm{C}_{\mathrm{EIC}} = \Delta C_{EC} \frac{F_{7,T} - F_{7,t}}{EC_{T} - EC_{t}} L\left(F_{7,T} - F_{7,t}\right) \ln\left(EIC_{T} / EIC_{t}\right) \tag{32}$$

Total Decomposition of CO$_2$ Emissions from the Power Industry

Combined with the above primary decomposition of CO$_2$ emissions in the power industry and the decomposition of CO$_2$ emissions at the stage of power consumption, variations of CO$_2$ emissions in the power industry from base year to target year in the Beijing-Tianjin-Hebei region can be expressed as:

$$\begin{aligned} \Delta \mathrm{C} &= \Delta C_{CE} + \Delta C_{ES} + \Delta C_{CR} + \Delta C_{S} + \Delta C_{R} + \Delta C_{L} + \\ &+ \Delta C_{EI} + \Delta C_{IS} + \Delta C_{AR} + \Delta C_{P} + \Delta C_{EIC} \end{aligned} \tag{33}$$

In the decomposition model, the CO$_2$ emissions factor of energy is supposed to be invariable because of the short-term stability of CO$_2$ emissions' coefficient of various energies, the short-term study of the paper, and the subtle changes of the CO$_2$ emissions factor of energy. Therefore, in decomposition, the effect associated with it can be ignored. Eq. (33) can be simplified as follows:

$$\begin{aligned} \Delta C &= \Delta C_{ES} + \Delta C_{CR} + \Delta C_{S} + \Delta C_{R} + \Delta C_{L} + \Delta C_{EI} + \\ &+ \Delta C_{IS} + \Delta C_{AR} + \Delta C_{P} + \Delta C_{EIC} \end{aligned} \tag{34}$$

Data Sources

Annual data are used in the paper, and the sample interval is from 1995 to 2014. The data of energy consumption of various types in power generation, power production, and power consumption come from the China Energy Statistical Yearbook (1996-2015). Data of average lower calorific value are from China Energy Statistical Yearbook 2015 and Energy Consumption Statistical System of Public Institutions. Data of carbon content of the unit heat value and data of the carbon oxidation ratio come from the Provincial Greenhouse Gas Listing Guidelines. Data of standard coal coefficient come from China Energy Statistical Yearbook 2015. A few data are from Energy Consumption Statistical System of Public Institutions, Reports on the State of Energy Utilization of Major Energy-consuming Units, IPCC Guidelines for National Greenhouse Gas Inventories 2006, and GHG Protocol Tool for Energy Consumption in China. Moreover, data of population size, gross regional production, and gross industrial production are from the Beijing Statistical Yearbook (1996-2015), the Tianjin Statistical Yearbook (1996-2015) and the Hebei Economic Yearbook (1996-2015). To eliminate the effect of price factor, the GDP and gross production values of various industries will be converted at a constant price using 1995 as the base period.

Results and Discussion

Evolution of Energy Consumption and CO_2 Emissions

The total energy consumption and composition in thermal power generation of the power industry in the Beijing-Tianjin-Hebei region are shown in Fig. 1. This indicates that from 1995 to 2014, total energy consumption in this region rose from 32 695.93 ktce to 99 439.72 ktce, and the pace of yearly growth is 6.03%. The structure of energy consumption shows that coal and other products are absolutely superior all the time at the basic rate over 95% and that consumption of natural gas has begun to increase since 2005.

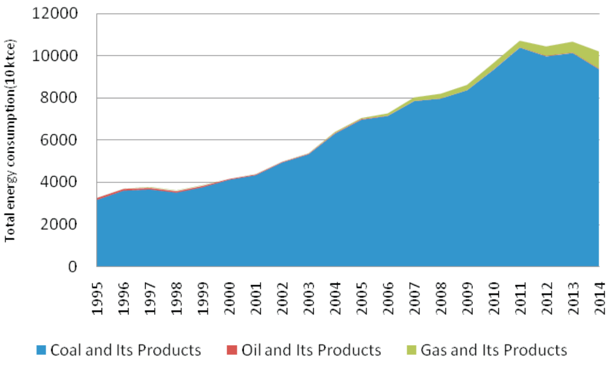

Fig. 1. Total energy consumption of the power industry in the Beijing-Tianjin-Hebei region from 1995 to 2014.

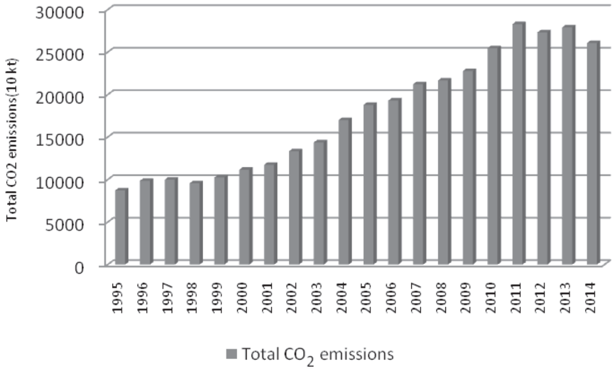

Fig. 2. CO_2 emissions from the power industry in the Beijing-Tianjin-Hebei region from 1995 to 2014.

Total CO_2 emissions and the development tendency of the power industry in the Beijing-Tianjin-Hebei region are shown in Fig. 2, which shows that from 1995 to 2014, total CO_2 emissions rose from 87,221.87 kt to 260,694.17 kt, with a yearly growth of 5.93%. However, the stage fluctuation of development tendency is obvious, and the stages of fastest growth are: from 1999 to 2005, 2007, and from 2009 to 2011; in contrast, CO_2 emissions dropped markedly in 1998, 2006, and 2008 because of downturns in the economy and decreases in power generation. From 2012 to 2014 growth slowed down gradually due to a series of measures, including adjusting energy structure, adopting advanced power generation technology, strengthening unit technology promotion, implementing energy conservation and emission reduction, and promoting industrial transformation.

Decomposition Results

To make a deep analysis of key factors that affect changes of CO_2 emissions from power industry in the Beijing-Tianjin-Hebei region, the paper takes 1995 as a base year, and makes interval decomposition and yearly decomposition through the hierarchical LMDI model. Then it considers interval and yearly decomposition results and analyzes every driving factor in detail. Results of interval decomposition during 1995 to 2014 can be shown in Table 3 and Fig. 3, and results of yearly decomposition are shown in Tables 4 and 5.

The range as a whole shows that between 1995 and 2014, the differences in effects of each driving factor on changes of CO_2 emissions from the power industry in the Beijing-Tianjin-Hebei region are obvious. Positive driving factors of CO_2 emissions are, in order, economic scale, population size, transmission and distribution losses, and industrial structure, with respective contribution rates of 150.70%, 20.80%, 8.86%, and 8.83%. Negative driving factors are production sectors' electricity intensity, the coal consumption rate, the ratio of electricity generation to consumption, household electricity intensity, power generation structure and fuel mix, with contribution rates

Table 1. Symbols and meanings of factors.

Driving Factors	Symbols	Meaning
CO_2 emissions factor of fuel	CE_i	$CE_i = C_i/E_i$, CO_2 emissions of the ith kind of fossil energy per unit
Fuel mix	ES_i	$ES_i = E_i/E$, proportion of the ith kind of fossil energy consumption in total energy consumption
The coal consumption rate	CR	CR = E/TP, energy consumption in generating per unit power in the process of thermal power production
Power generation structure	S	S = TP/G, proportion of thermal power production in total power production
The ratio of power generation to consumption	R	R = G/C, ratio of total power generation to total power consumption
Power consumption scale	EC	EC, total power consumption

Table 2. Symbols and meanings of factors.

Driving Factors	Symbols	Meaning
Production sectors' electricity intensity	EI_j	$EI_j = F_j / Y_j$, power consumed for per unit GDP of the j industrial sector
Industrial structure	IS_j	$IS_j = Y_j / Y$, proportion of the production from the j industrial sector in the regional GDP
Household electricity intensity	EIC	EIC = F_7 / Y , ratio of the household power consumption and regional GDP
Economic scale	AR	$AR = Y/P$, per capita GDP
Population size	P	P, population size

of -45.97%, -22.38%, -19.41%, -0.62%, -0.49% and -0.32%, respectively.

Positive Driving Factors of CO_2 Emissions

1) Economic scale effect. The results of interval decomposition reveal that among the 10 factors influencing CO_2 emissions of power industry in the Beijing-Tianjin-Hebei region, economic scale effect contributes 150.70%, which is much larger than other factors and devotes the greatest contribution to CO_2 emissions growth. The results of yearly decomposition show that economic scale effect has always had a positive driving effect on CO_2 emissions from the power industry, with a great contribution in this region. The reasons can be concluded from the following data: from 1994 to 2015, per capita GDP in this region rises from 6,128.77 yuan to 60,147.76 yuan and increases by 9.81 times with an average growth rate of 12.77% per annum. The data indicate rapid economic development in the Beijing-Tianjin-Hebei region. On the one hand, economic development depends on the drive of all industries and the support of power energy; on the other hand, with prosperity of economy and increase of residents' wealth, there are more consumer electronics like air conditioning and refrigerators, which lead to great increases in power consumption. All these factors have promoted an increase of CO_2 emissions from the power industry. It is also worth noting that between 1997 and 2000, the contribution of economic scale on CO_2 emissions of the power industry in the Beijing-Tianjin-Hebei region presents short-term fluctuations. This may result from the Asian financial crisis and macro-control of China, which have caused a downturn in economic growth and a decline of power consumption in this region. Laws and regulations in 1996 from the State Council of China, such as industrial projects of shutting or idling "Fifteen small" and "New Five" enterprises, which have high energy consumption, high pollution, and low efficiency, also play an important role. In addition, from 2007 to 2010 and 2012, the decline of contribution can be attributed to a slowdown in economic growth caused by the international financial crisis and the new normal of the

Table 3. Decomposition analysis results of changes in CO_2 emissions from power industry in the Beijing-Tianjin-Hebei region from 1995 to 2014 (contributory value). Unit:10kt

Time Interval	ΔC	ΔC_{ES}	ΔC_{CR}	ΔC_S	ΔC_R	ΔC_L	ΔC_{EI}	ΔC_{IS}	ΔC_{EIC}	ΔC_{AR}	ΔC_P
1995-2014	17,347.23	-55.10	-3,883.02	-85.01	-3,367.03	1,537.04	-7,974.63	1,532.60	-107.58	26,141.62	3,608.36

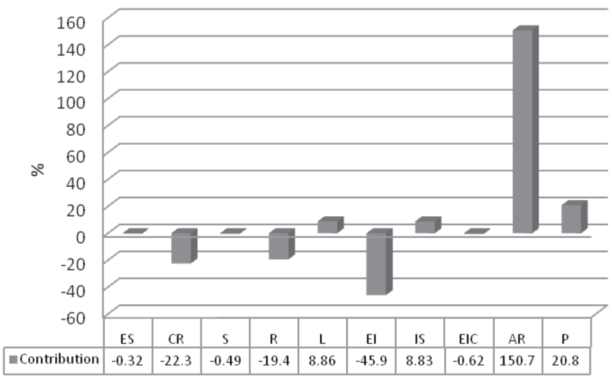

Fig. 3. Decomposition analysis results of changes in CO_2 emissions from the power industry in the Beijing-Tianjin-Hebei region from 1995 to 2014 (contribution degree).

Chinese economy. It can also be attributed to strategic development goals of "energy conservation and emission reduction" in the "Eleventh Five Year Plan," and efforts for energy conservation and environmental protection in the "Twelfth Five Year Plan."

2) Population size effect. According to results of interval decomposition, population size effect is a significant factor of growth in CO_2 emissions from the power industry in the Beijing-Tianjin-Hebei region, with a contribution rate of 20.80%. The changes of generation capacity of power industrial sectors are affected by per capita power consumption and social demands for electricity, because of variations of population scale and living standards. According to yearly decomposition of contribution variation tendency, population size effect is slowly being enhanced. This is because population size is growing slowly in the Beijing-Tianjin-Hebei region. The contribution of population size effect on CO_2 emissions will not drop too much in the short term for the gradual opening of the "two-child policy," improved urbanization, and a continuing influx of outsiders.
3) Transmission and distribution losses effect. The results of interval decomposition reveal that transmission and distribution losses effect has a positive effect on CO_2 emissions of power industry in the Beijing-Tianjin-Hebei region. It promotes the growth of CO_2 emissions with a contribution rate of 8.86%. From 1995 to 2014, transmission and distribution losses in the region were kept to 5% to 7% of whole power consumption constantly. They are the losses in the process of power transmission and distribution, which cannot create any value. In recent years, investments of building and reconstructing grids are reinforced, new technologies

Table 4. Annual decomposition analysis results of changes in CO_2 emissions from power industry in the Beijing-Tianjin-Hebei region (contribution value). Unit:10kt

Time Interval	ΔC	ΔC_{ES}	ΔC_{CR}	ΔC_{S}	ΔC_{R}	ΔC_{L}	ΔC_{EI}	ΔC_{IS}	ΔC_{EIC}	ΔC_{AR}	ΔC_{P}
1995-96	1,142.68	17.14	361.69	282.55	31.72	-1.13	-646.01	48.51	32.25	977.34	38.61
1996-97	129.09	7.29	-778.74	44.47	219.09	91.02	-553.93	39.27	28.21	979.45	52.96
1997-98	-421.83	4.31	-451.72	24.81	-130.19	5.57	-747.13	-3.10	-8.62	828.03	56.21
1998-99	686.15	3.92	-417.38	10.98	150.25	96.29	-127.70	60.97	44.54	802.53	61.76
1999-2000	905.56	16.29	-216.01	51.70	39.37	96.93	-161.89	51.94	44.48	749.88	232.86
2000-01	574.67	-6.79	-184.18	88.89	-6.04	10.09	-336.81	-9.36	-10.72	971.27	58.31
2001-02	1,598.34	11.13	319.08	4.58	-18.83	97.73	-43.72	3.73	33.07	1,092.78	98.79
2002-03	1,038.16	3.99	-166.95	8.38	-297.89	-11.23	-43.84	108.63	-40.14	1,376.78	100.45
2003-04	2,632.81	4.81	799.14	-5.64	-340.84	332.70	-130.30	205.57	-34.98	1,668.11	134.25
2004-05	1,778.08	-0.26	604.16	-19.00	-1,233.21	86.57	121.35	100.59	35.17	1,893.99	188.71
2005-06	517.70	-42.23	-94.65	13.20	-1,777.77	-67.67	176.06	45.53	-4.44	2,040.03	229.64
2006-07	1,923.42	-16.34	-706.44	6.15	-63.69	318.78	-99.61	72.60	-51.64	2,192.40	271.20
2007-08	437.59	-86.37	761.28	7.91	-1,156.81	32.01	-1 176.09	-40.25	-21.24	1,770.13	347.02
2008-09	1,105.76	-24.87	-184.23	4.54	-853.13	169.65	-334.08	-18.22	95.19	1,920.72	330.15
2009-10	2,695.19	-23.59	-1,283.47	-481.82	1,312.28	156.86	158.15	222.49	-94.13	1,774.85	953.64
2010-11	2,833.51	33.65	698.49	-281.17	129.83	-395.05	-314.17	277.29	-113.98	2,400.93	397.75
2011-12	-982.38	-102.40	-1,767.58	-422.80	166.18	559.69	-2,105.93	217.44	-67.36	2,155.31	385.00
2012-13	595.43	-116.25	-567.46	-207.48	363.60	132.03	-1,126.92	107.42	-254.28	1,907.81	356.99
2013-14	-1,842.70	-197.94	-1,574.36	-121.81	-578.62	5.60	-1,043.65	-81.19	-101.09	1,544.69	305.70

Table 5. Annual decomposition analysis results of changes in CO_2 emissions from power industry in the Beijing-Tianjin-Hebei region (contribution degree).

Time Interval	ΔC	ΔC_{ES}	ΔC_{CR}	ΔC_{S}	ΔC_{R}	ΔC_{L}	ΔC_{EI}	ΔC_{IS}	ΔC_{EIC}	ΔC_{AR}
1995-96	1.50%	31.65%	24.73%	2.78%	-0.10%	-56.53%	4.25%	2.82%	85.53%	3.38%
1996-97	5.64%	-603.24%	34.45%	169.72%	70.51%	-429.10%	30.42%	21.86%	758.72%	41.03%
1997-98	-1.02%	107.09%	-5.88%	30.86%	-1.32%	177.12%	0.73%	2.04%	-196.29%	-13.33%
1998-99	0.57%	-60.83%	1.60%	21.90%	14.03%	-18.61%	8.89%	6.49%	116.96%	9.00%
1999-2000	1.80%	-23.85%	5.71%	4.35%	10.70%	-17.88%	5.74%	4.91%	82.81%	25.71%
2000-01	-1.18%	-32.05%	15.47%	-1.05%	1.76%	-58.61%	-1.63%	-1.86%	169.01%	10.15%
2001-02	0.70%	19.96%	0.29%	-1.18%	6.11%	-2.74%	0.23%	2.07%	68.37%	6.18%
2002-03	0.38%	-16.08%	0.81%	-28.69%	-1.08%	-4.22%	10.46%	-3.87%	132.62%	9.68%
2003-04	0.18%	30.35%	-0.21%	-12.95%	12.64%	-4.95%	7.81%	-1.33%	63.36%	5.10%
2004-05	-0.01%	33.98%	-1.07%	-69.36%	4.87%	6.83%	5.66%	1.98%	106.52%	10.61%
2005-06	-8.16%	-18.28%	2.55%	-343.40%	-13.07%	34.01%	8.80%	-0.86%	394.05%	44.36%
2006-07	-0.85%	-36.73%	0.32%	-3.31%	16.57%	-5.18%	3.77%	-2.68%	113.98%	14.10%
2007-08	-19.74%	173.97%	1.81%	-264.36%	7.31%	-268.76%	-9.20%	-4.85%	404.52%	79.30%
2008-09	-2.25%	-16.66%	0.41%	-77.15%	15.34%	-30.21%	-1.65%	8.61%	173.70%	29.86%
2009-10	-0.88%	-47.62%	-17.88%	48.69%	5.82%	5.87%	8.26%	-3.49%	65.85%	35.38%
2010-11	1.19%	24.65%	-9.92%	4.58%	-13.94%	-11.09%	9.79%	-4.02%	84.73%	14.04%
2011-12	10.42%	179.93%	43.04%	-16.92%	-56.97%	214.37%	-22.13%	6.86%	-219.40%	-39.19%
2012-13	-19.52%	-95.30%	-34.85%	61.07%	22.17%	-189.26%	18.04%	-42.70%	320.41%	59.96%
2013-14	10.74%	85.44%	6.61%	31.40%	-0.30%	56.64%	4.41%	5.49%	-83.83%	-16.59%

are adopted, power transmission and distribution are improved, and losses are reduced in this region. But problems of frequency in power dispatch, the aging of power transmission lines, and outdated equipment make the losses inevitable. Therefore, transmission and distribution losses effect is a non-negligible driving factor of CO_2 emissions from power industry in the Beijing-Tianjin-Hebei region.

4) Industrial structure effect. Results of interval decomposition show that industrial structure effect plays a positive role in CO_2 emissions growth in the Beijing-Tianjin-Hebei region, but it has a lesser effect and its contribution rate is only 8.83%. Industrial internal structure in the region is still not reasonable. With the continuous optimization of regional industrial structure, proportion of primary industry represented by agriculture, forestry, animal husbandry, fishery and water conservancy in the region between 1995 and 2014 declines significantly (from 14.5% to 4.41%), and proportion of tertiary industry keeps about 40% constantly. Secondary industry, such as industry and construction is upgrading and transforming, but it maintains a strong momentum of development (its proportion rises from 47.02% to 55.31%). The leading role of secondary industry is unshakable in the short term. Accordingly, power consumption of the secondary industry in the Beijing-Tianjin-Hebei region is the main part of final power consumption, with a proportion of 63.2% to 72.13%. Therefore, proportion growth of secondary industry, especially high energy-consuming industry will result in increase of final power consumption. With harmonious and coordinated development of the Beijing-Tianjin-Hebei region in recent years, the region is accelerating industrial structure adjustment and optimization, and emphasizing development of non-energy-intensive industry. Energy-intensive industry is being relocated gradually, service-leading economic characteristics are appearing progressively and regional power consumption growth is slowing down. It can be predicted that industrial structure effect will have a lesser influence on CO_2 emission growth in the Beijing-Tianjin-Hebei region and it may be converted into negative driving effect.

Negative Driving Factors of CO_2 Emissions

1) Production sectors' electricity intensity effect. According to interval decomposition results, production sectors' electricity intensity effect is the

most important factor restricting CO_2 emissions from power industry in the Beijing-Tianjin-Hebei region, with a contribution rate of -45.97%. According to yearly decomposition results, contribution of production sectors' electricity intensity effect to CO_2 emissions from power industry in each year between 1995 to 2014 is negative. Production sectors' electricity intensity reflects dependency of industry development on power consumption. From 1995 to 2014, electricity intensity of each production sector declines, and regional electricity intensity of GDP decreases from 1972.72kW·h/10000 yuan to 1246.97kW·h/10000 yuan. It shows that extensive development of industries is transferred in the region, and that utilization efficiency of electric power is improving. It also manifests the positive effect of technological progress and industrial structure adjustment. At the same time, with the continuous progress of energy-saving technology, reform of power prices, improvement of power demand side management, and deepening of "efficient energy-saving" projects and energy conservation based macro-control, the awareness of energy saving and consumption reducing for power consumers of all industries is enhancing. It is estimated that efficiency of energy use in the Beijing-Tianjin-Hebei region will continue to rise, production sectors' electricity intensity will descend and inhibitory function of electricity intensity effect on CO_2 emissions from power industry will be strengthened constantly.

2) The coal consumption rate effect. Results of decomposition show that the coal consumption rate effect is the second major negative driving factor of CO_2 emissions from power industry in the Beijing-Tianjin-Hebei region. Its contribution in each year is negative, except 1995 to 1996, 2001 to 2002, 2003 to 2005, and 2010 to 2011. The reason can be attributed to the following measures: the first is continuously implementing the policy "encouraging large projects and discouraging small energy-inefficient power plants", which means adopting large-capacity and high-parameter of the units and closing down backward production facilities; the second is emphasizing on energy conservation transformation of coal units; the third is increasing proportion of cogeneration units yearly. The above measures make the rate of coal consumption decrease significantly and restrict the growth of CO_2 emissions. Meanwhile, in the long term, thermal power dominates in power generation structure in the Beijing-Tianjin-Hebei region, or even in China, and the situation will not change in the short term. The improvement of coal utilization efficiency for power generation enterprises will have a profound meaning in reducing CO_2 emissions from power industry in the region.

3) The ratio of power generation to consumption effect. Interval decomposition results indicate that the change in the ratio of power generation to consumption effect is the third largest negative driving factor of CO_2 emissions from power industry in the Beijing-Tianjin-Hebei region, with a contribution rate of -22.38%. It effectively suppresses the growth of CO_2 emissions. The Beijing-Tianjin-Hebei region, which accepts large proportion of external power, often presents a relatively tight situation in power supply in the long term. Therefore, for this region, the ratio of electricity generation to consumption, on the one hand, reflects auxiliary power ratio of power plant and transmission and distribution losses of power grid. More importantly, it reflects the situation of power diversion. Large scale of diverted power is the main reason for maintaining electricity generation and consumption ratio under 1.0 for a long time. According to "producer responsibility system" of current carbon emission assessment standard, the large scale of diverted power in the Beijing-Tianjin-Hebei region not only relieves the pressure of power generation, but transfers CO_2 emissions to the places diverting electricity to inhibit CO_2 emissions in the Beijing-Tianjin-Hebei region. Yearly decomposition results indicate that during 1995 to 1997,1998 to 2000 and 2009 to 2013 , the contribution of this effect on changes of CO_2 emissions in the Beijing-Tianjin-Hebei region is positive. The reason is that during these periods, diverted power slightly falls year-on-year, which leads to recovery of CO_2 emissions. Nowadays, at the request of integration in prevention and control of atmospheric pollution in the Beijing-Tianjin-Hebei region, proportion of diverted electricity in the region will continue to increase. It can be predicted that the change in the ratio of power generation to consumption effect will devote greater contribution on reducing CO_2 emissions from power industry in the Beijing-Tianjin-Hebei region in the future.

4) Household electricity intensity effect. Between 1995 and 2014, the contribution of household electricity intensity effect on CO_2 emissions of power industry is changing from positive to negative, which is to say that its function on CO_2 emission growth changes from promotion to inhibition. According to interval results, the contribution of household electricity intensity to the growth of CO_2 emissions from the power industry in the Beijing-Tianjin-Hebei region is -0.62%, which restrains CO_2 emission growth in the region, but its influence is relatively weak. The reasons are as follows: during 1995 to 2002, household electricity intensity rises with fluctuation for the promotion of people's living standards, electrification levels, and other factors. However, since 2003 projects of energy conservation, emission reduction, and low-carbon development have been implemented in the field of life, including publication of the national Medium- and Long-Term Energy Saving Special Planning, the National Energy Saving and Emission Reduction Action plan of Beijing, and the Ecological City Construction Action Plan of Tianjin. Besides, energy-saving technology and standards are improved for all types of electrical products. These slow the growth of final power consumption by residents' and decrease

consumption intensity. And these measures will have a stronger inhibition of CO_2 emissions from the power industry.

5) Power generation structure effect. The interval decomposition results reveal that the power generation structure effect has a negative influence on changes in CO_2 emissions from the power industry in the Beijing-Tianjin-Hebei region, and its contribution is -0.49%. The yearly decomposition results show that between 1995 and 2014, the contribution of the power generation structure effect on CO_2 emissions varies from positive to negative. Before 2009, the influence of the power generation structure effect is positive, but the value is small, which indicates that its promoting effect on CO_2 emissions growth is not obvious; while after 2009, the power generation structure effect is continuously negative with a large absolute value, which shows that its inhibition of CO_2 emissions from the power industry has become stronger in recent years. The reasons are as follows: thermal power generation dominates in the Beijing-Tianjin-Hebei region for resource endowment. Therefore, during 1995 to 2009, the proportion of thermal power generation to the regional power generation rises from 94.69% to 99.77% slowly, which leads to a slight growth in CO_2 emissions every year. Since 2009, with the promotion of clean energy technology, the enforcement of the country's "Renewable Energy Law" and the orderly development of wind power and photovoltaic power generation in Zhang Jiakou, Chengde, and other regions, the power generation structure of the Beijing-Tianjin-Hebei region is upgraded and adjusted. The proportion of the primary source in power generation rises from 0.23% in 2009 to 5.83% in 2014, and average annual contribution on changes of CO_2 emissions reaches -3,030.24kt. The measures have an excellent effect on emission reduction. As a consequence, it is an indispensable factor of improving the proportion of primary energy in energy generation to realize the goal of CO_2 emissions for the power industry.
6) Fuel mix effect. According to yearly decomposition results, between 1995 and 2014 there was a greater fluctuation of fuel mix effect between positive and negative in the Beijing-Tianjin-Hebei region. The fluctuation can be divided into two stages: from 1995 to 2004 the contribution was positive, that is, fuel mix effect promotes CO_2 emissions growth. However, from 2004 to 2014 the contribution was almost always negative and the absolute value was on the rise, which means the fuel mix effect restrains the growth of CO_2 emissions. The results are consistent with consumption proportion of coal and its products, oil and its products, and natural gas and its products. Between 1995 and 2004, the proportion of consumption of coal and its products in overall fuel consumption in the Beijing-Tianjin-Hebei region rises from 96.97% to 99.13%. From 2005, the number of gas generator units increased, but the proportion of coal-fire and oil-fired units slightly declined, which indicates that improvement of fuel mix for power generation promotes CO_2 emissions growth in the power industry. In recent years, under the stress of air pollution control, the State Council in China has proposed forbidding the support of construction of coal-fired power stations in favor of new projects in the Beijing-Tianjin-Hebei region. Furthermore, except for cogeneration, new projects of coal-fired generation are prohibited in order to help realize the negative growth of coal consumption. It is estimated that the fuel mix effect will have a stronger inhibiting influence on CO_2 emission changes over the next few years.

Conclusions

Major Conclusions

Our paper calculates CO_2 emissions from the power industry in the Beijing-Tianjin-Hebei region based on energy consumption data of power industry in the region through the material balance method, especially the estimate method with classification of detailed fuel. Then it establishes the hierarchical LMDI decomposition model, decomposes driving factors of CO_2 emissions into effects of fuel mix, coal consumption rate, power generation structure, the ratio of power generation to consumption, transmission and distribution losses, the production sectors' electricity intensity, industrial structure, household electricity intensity, economic scale and population size, and analyzes their influences on CO_2 emissions from power industry in the Beijing-Tianjin-Hebei region. The major conclusions are:

- During 1995-2014, CO_2 emissions by the power industry in the Beijing-Tianjin-Hebei region developed in fluctuation and show a rising trend in general, and the annual average growth rate is 5.93%. Since 2012 the growth of CO_2 emissions has dropped significantly, because economic development has entered a new normal in the Beijing-Tianjin-Hebei region, and national and regional action goals of air pollution control have been positively implemented, and measures like energy conservation, emission reduction, and energy structure upgrade and adjustment have been taken.
- From 1995 to 2014, among the 10 driving factors, the factors that drive the growth of CO_2 emissions from the power industry in the Beijing-Tianjin-Hebei region are economic scale, population size, transmission and distribution losses, and industrial structure, and the respective contributions are 150.70%, 20.80%, 8.86%, and 8.83%. The factors that drive CO_2 emissions reduction are production sectors' electricity intensity, the coal consumption rate, the ratio of electricity generation and consumption, household electricity intensity, and power generation structure and fuel mix, and the respective contributions are -45.97%, -22.38%, -19.41%, -0.62%, -0.49%, and -0.32%.

Policy Implications

The purpose of analyzing CO_2 emissions from the power industry in the Beijing-Tianjin-Hebei region is discovering driving factors of CO_2 emissions, their effects and underlying reasons to reduce energy consumption and CO_2 emissions of the power industry, and to realize the goal of regional energy consumption and emission reduction as soon as possible. According to the above conclusions, to realize CO_2 emissions reduction of the power industry, efforts should be paid in the following aspects:

1) Scientific planning: on the basis of economic growth, develop scientific and reasonable low-carbon development planning and emission reduction performance evaluation mechanisms that are low-carbon economy oriented, with integration and coordinated development of the Beijing-Tianjin-Hebei region as the strategic basis, and with government, research institutes, industry association, grid company, and large power generation groups in the region as support.
2) Changing the mode: extensive mode of economic growth of high energy consumption and high pollution in the Beijing-Tianjin-Hebei region should be transferred. Regional industrial structure, especially that in Hebei, should be upgraded by emphasizing high value-added, low-energy (-power) high-tech industries, and industrial undertaking and coordination of Beijing, Tianjin, and Hebei should be actively promoted and energy disposition should be optimized. Moreover, power demand side management should be strengthened and power demands should be effectively guided.
3) Adjusting structure: on the one hand, continuously adjusting the internal industrial structure of thermal power generation, accelerating the steps of shutting down regional small thermal power plants, increasing the proportion of large capacity and high-parameter coal-fired units, reducing coal consumption in power generation, and raising the proportion of gas power generation to replace coal-fired power generation under conditions of regional resource capacity; on the other hand, continuing to optimize power supply structure, speed up the exploitation of regional new and renewable energy resources in power generation, and concentrate on utilizing wind and solar resources in Zhang Jiakou, Chengde, and other regions, accelerating new energy planning projects such as wind power generation, solar power generation, biomass power generation, and waste power generation, and limit the expansion of thermal power units. Furthermore, strengthen energy-saving power generation dispatching, motivate units with high efficiency and energy conservation to generate more electricity, and increase the proportion of power generation into electrical grids using clean energy.
4) Developing technology: in the aspect of links of power generation, clean coal technology like ultra supercritical units, integrated gasification combined cycles power generation, and circulating fluidized beds should be reinforced. The transformation and integration management of environmental protection and energy conservation technologies of current power units should be strengthened; in the aspect of links of power grid, upgrading of transmission and distribution networks construction should be emphasized, exploiting UHV transmission technology and large power system operation technology should be intensified, construction and development of a strong smart grid should be advanced, power transmission, transformation, and interconnection projects should be accelerated, transmission ability of power grid should be strengthened, and losses of transmission and distribution should be minimized. Besides, technologies of carbon capture, use, and storage should be developed moderately.
5) Guaranteeing diversion: according to the planning of "Capital power supply security relies on Beijing-Tianjin-North Hebei Grid, and power supply security of Beijing-Tianjin-North Hebei Grid relies on North China Power Grid," continue to speed up constructing a power channel, power transmission facilities, and a high pressure ring in the Beijing-Tianjin-Hebei region, enhance the ability to ensure diverted power supply, and relieve the stress of production and CO_2 emissions of the power industry in the region, with diverted power from Inner Mongolia, Shanxi, and northeastern China as compensation for the power deficit.
6) Innovating system: make the most of the carbon emission permits trade mechanism of China, develop regional CDM, CCERm and other projects, implement energy management contract, and promote energy saving management of power industry. At the same time, guide power consumers to be concerned with CO_2 emissions, perfect energy saving regulations and standards, strengthen energy conservation management of key energy consumption units, promote energy-saving technologies and projects of "high efficiency and energy conservation," push power consumers to form the awareness and habit of energy conservation and environmental protection, and, finally, decrease industrial and household electricity intensity continuously.

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