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Research Article

Identifying the Determinants of CO_2 Emission Change in China's Power Sector

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Power sector is significantly important for China to achieve the CO_2 emission reduction targets. In this study, we analyze the features of CO_2 emissions and environment effect in China's power sector, investigate the driving factors of CO_2 emission change based on the logarithmic mean Divisia index (LMDI) method, and evaluate the mitigation potential of CO_2 emissions in China's power sector. Results show that CO_2 emissions in China's power sector increased rapidly from 492.00 Mt in 1990 to 3049.88 Mt in 2014 while CO_2 emission intensity experienced an unsteady downward trend during the study period. Industrial scale effect is the key contributor to CO_2 emission growth in China's power sector, and its contribution degree reaches 123.97%. Energy intensity effect contributes most to the decrease in CO_2 emissions, with a contribution degree of −20.01%. Capital productivity effect is another important factor leading to CO_2 emissions increase. The aggregate CO_2 emission reduction would reach 17973.86 million tons (Mt) during 2015–2030 in the ideal emission reduction scenario. Finally, policy recommendations are made for future energy-saving and CO_2 emission reduction in China's power sector.

1. Introduction

Climate change has aroused growing concern worldwide due to its contribution to environmental pollution and being an obstacle to sustainable socioeconomic development [1]. The ongoing emission of greenhouse gas (GHG) which gives priority to carbon dioxide is responsible for the climate change. In the context of limited energy resources availability and increasingly serious environmental problems, the development of low-carbon economy with lower power consumption and CO_2 emissions is becoming a common choice for the world economic development to mitigate climate change and achieve sustainable development. As world's largest emitter of CO_2 emissions [2], China has attached great importance to transition to a low-carbon economy and taken effective measures to support it through industrial restructuring, renewable energy consumption promotion, and carbon market establishment [3].

China's power sector plays a leading role in CO_2 emissions of China. In 2013, CO_2 emissions of China's power sector accounted for 48.86% of the total CO_2 emissions. The low-carbon development of China's power sector drives the low-carbon development of energy-economic-society in China. Therefore, the CO_2 emission reduction in China's power sector becomes the key factor to achieve the low-carbon development of China. In addition, power sector belongs to the fundamentals of industrial production and residents' living which are being conquered by electricity. It is particularly important to balance the relationship between adequate supply of electricity and CO_2 mitigation when developing strategies for mitigating the increasing CO_2 emissions and global climate change. Therefore, the analysis of the CO_2 emissions in China's power sector is very important.

Against this background, many studies on CO_2 emissions in China's power sector have been conducted. The work in [4] presented the results of a life cycle analysis of GHG emissions from power generation systems to understand the characteristics of these systems from the perspective of global warming. The work in [5] quantified the CO_2 emissions of the power sector from both production and consumption perspectives and explained the environmental impact of the regional supply and demand mismatch of electricity in China. The work in [6] proposed a consumer responsibility method to calculate the CO_2 emissions of the power sector at the provincial level in China based on the detailed origins of each province's electricity consumption. The work in [7] conducted a cointegration analysis to explore the significant factors affecting CO_2 emissions in China's power sector including standard coal consumption rate for generating power, average thermal power equipment utilization hours, and industrial value added. The work in [8] conducted a comparative study of dynamic changes in CO_2 emission performance of fossil fuel power plants in China and Korea through developing a new index called the nonradial metafrontier Malmquist CO_2 emissions performance index (NMMCPI). The NMMCPI was decomposed into an efficiency change index, a best-practice gap change index, and a technology gap change index. The proceeding literatures mainly analyzed the evolution trends and the influencing factors of CO_2 emissions in the power sector.

The LMDI method is a preferred index decomposition analysis approach not only because of being less data intensive and more diverse in decomposition forms but also because of the advantages of path independence, being residue free, ability to handle zero values, and consistency in aggregation [9, 10]. In recent studies, the LMDI method is widely used to identify the major influencing factors of CO_2 emission change. The energy-related CO_2 emissions were decomposed into carbon intensity effect, energy structure effect (or substitution effect), energy intensity effect, and industrial activity effect and industrial scale effect in the textile industry [11], nonmetallic mineral products industry [12], and cement industry [13] and chemical industry [14]. CO_2 emissions change in the Chinese manufacturing industry was decomposed into the emission coefficient effect, energy structure effect, energy intensity effect, economic structure effect, and economic scale effect [15]. The work in [16] decomposed the CO_2 emissions of China's cement industry into kiln efficiency effect, clinker share effect, structural shift effect and activity effect, which reflected the production features of cement industry. As a popular method, LMDI is used to explore the affecting factors of CO_2 emission change at sector level.

Less literature is involved in the study on the driving factors of CO_2 emission in China's power sector. Research on the reduction potential of CO_2 emissions in China's power sector is limited. Therefore, this study decomposes the CO_2 emission change of China's power sector into five parts using the improved Kaya identity and LMDI method, predicts the CO_2 emissions, and assesses the emission reduction potential based on scenarios analysis. More importantly, this study proposes the comprehensive CO_2 emission reduction policy recommendations for policymakers.

The remainder of this study is organized as follows. Section 2 presents the methodology and data sources. Section 3 provides the LMDI decomposition results by time series and time intervals and conducts the scenario analysis. Section 4 draws the research conclusions and proposes policy recommendations.

2. Methodology and Data

2.1. Estimation of Environment Effect. The *IPAT* identity is often used as a basis for investigating the effect of economic activities on emissions.

$$I = P \cdot A \cdot T, \tag{1}$$

where I represents environmental impact, typically measured in terms of the emission level of a pollutant, P denotes population size, A represents the wealth of a society, measured by per capita GDP, and T is a technology index, which is generally measured by the effect on the environment per unit of GDP. *IPAT* identity is used to analyze the environment condition at economy-wide level and indexes such as employee, productivity, and energy efficiency are suitable for the analysis of environment issue at industry level. In order to fully examine the environmental effect at industry level, this study use installed capacity, average power generation capacity per unit installed capacity, and energy intensity to substitute for population or employee, per capita GDP, and technology index. Because the power sector is capital-intensive sector, it is reasonable to use the indexes of capital input and capital productivity to analyze the effect of power sector development. However, the purpose of the index rate of I is to provide an absolute effect of power sector development and reveal the influencing trend and thus help to identity the whole effect on environmental condition of power sector.

2.2. Estimation of Energy-Related CO_2 Emissions. According to the method proposed by Intergovernmental Panel on Climate Change (IPCC), the total energy-related CO_2 emissions in China's power sector can be calculated based on energy consumption, CO_2 emission factor, and the fraction of oxidized carbon, followed by

$$C^t = \sum_i E_i^t \cdot f_i \cdot O_i, \tag{2}$$

where C^t denotes total energy-related CO_2 emissions of China's power sector in year t; i denotes ith energy type; E_i^t denotes the ith fossil energy consumption in year t; f_i denotes CO_2 emission factor of the ith fossil energy; and O_i denotes the fraction of carbon dioxide of the ith fossil energy.

2.3. Decomposition Analysis

2.3.1. Method Construction. Based on the improved Kaya identity, CO_2 emissions in China's power sector can be decomposed into the following variables:

$$C^t = \frac{C^t}{E_f^t} \cdot \frac{E_f^t}{E^t} \cdot \frac{E^t}{Y^t} \cdot \frac{Y^t}{K^t} \cdot K^t, \tag{3}$$

where E_f^t denotes fossil energy consumption of China's power sector in year t; E^t denotes the total energy consumption in year t; Y^t denotes the total output in year t, referring to the total power generation capacity in this study; and K^t denotes the installed capacity of China's power sector. In this study, we use installed capacity to represent the industrial scale in this study; $\mathrm{CI} = C^t/E_f^t$ is the CO_2 emissions factor; $\mathrm{ES} = E_f^t/E^t$ denotes the energy structure; $\mathrm{EI} = E^t/Y^t$ denotes the energy intensity; and $\mathrm{IA} = Y^t/K^t$ denotes the capital utilization efficiency, namely, the average power generation capacity per unit installed capacity.

2.3.2. LMDI Decomposition Method. In this paper, LMDI method is adopted to uncover the key influencing factors to CO_2 emissions growth in China's power sector. We decompose the CO_2 emissions change (ΔC) in China's power sector into five driving factors, that is, carbon intensity effect ($\mathrm{CI_{eff}}$), energy structure effect ($\mathrm{ES_{eff}}$), energy intensity effect ($\mathrm{EI_{eff}}$), capital efficiency effect ($\mathrm{IA_{eff}}$), and industrial scale effect ($\mathrm{IS_{eff}}$).

The additive form of decomposition is usually used to identify the absolute change of aggregate indicator while the multiplicative decomposition is applied to a relative change of the aggregate variables. Therefore, based on the additive form of decomposition, CO_2 emissions change of China's power sector between t year and $t+1$ year is expressed as

$$\begin{aligned}\Delta C &= C^{t+1} - C^t \\ &= \mathrm{CI}_{\mathrm{eff}}^{t,t+1} + \mathrm{ES}_{\mathrm{eff}}^{t,t+1} + \mathrm{EI}_{\mathrm{eff}}^{t,t+1} + \mathrm{IA}_{\mathrm{eff}}^{t,t+1} + \mathrm{IS}_{\mathrm{eff}}^{t,t+1}.\end{aligned} \tag{4}$$

The effects of driving factors of CO_2 emissions in China's power sector between t year and $t+1$ year are calculated by the following equations:

$$\begin{aligned}\mathrm{CI}_{\mathrm{eff}}^{t,t+1} &= \frac{C^{t+1} - C^t}{\ln C^{t+1} - \ln C^t} \ln\left(\frac{\mathrm{CI}^{t+1}}{\mathrm{CI}^t}\right), \\ \mathrm{ES}_{\mathrm{eff}}^{t,t+1} &= \frac{C^{t+1} - C^t}{\ln C^{t+1} - \ln C^t} \ln\left(\frac{\mathrm{ES}^{t+1}}{\mathrm{ES}^t}\right), \\ \mathrm{EI}_{\mathrm{eff}}^{t,t+1} &= \frac{C^{t+1} - C^t}{\ln C^{t+1} - \ln C^t} \ln\left(\frac{\mathrm{EI}^{t+1}}{\mathrm{EI}^t}\right), \\ \mathrm{IA}_{\mathrm{eff}}^{t,t+1} &= \frac{C^{t+1} - C^t}{\ln C^{t+1} - \ln C^t} \ln\left(\frac{\mathrm{IA}^{t+1}}{\mathrm{IA}^t}\right), \\ \mathrm{IS}_{\mathrm{eff}}^{t,t+1} &= \frac{C^{t+1} - C^t}{\ln C^{t+1} - \ln C^t} \ln\left(\frac{\mathrm{IS}^{t+1}}{\mathrm{IS}^t}\right).\end{aligned} \tag{5}$$

CO_2 emissions change of China's power sector between 0 year and T year is expressed as

$$\Delta C = C^T - C^0 = \mathrm{CI}_{\mathrm{eff}}^{0,T} + \mathrm{ES}_{\mathrm{eff}}^{0,T} + \mathrm{EI}_{\mathrm{eff}}^{0,T} + \mathrm{IA}_{\mathrm{eff}}^{0,T} + \mathrm{IS}_{\mathrm{eff}}^{0,T}. \tag{6}$$

And, the effects of various driving factors of CO_2 emissions in China's power sector between 0 year and T year are calculated by the following equations:

$$\begin{aligned}\mathrm{CI}_{\mathrm{eff}}^{0,T} &= \frac{C^T - C^0}{\ln C^T - \ln C^0} \ln\left(\frac{\mathrm{CI}^T}{\mathrm{CI}^0}\right), \\ \mathrm{ES}_{\mathrm{eff}}^{0,T} &= \frac{C^T - C^0}{\ln C^T - \ln C^0} \ln\left(\frac{\mathrm{ES}^T}{\mathrm{ES}^0}\right), \\ \mathrm{EI}_{\mathrm{eff}}^{0,T} &= \frac{C^T - C^0}{\ln C^T - \ln C^0} \ln\left(\frac{\mathrm{EI}^T}{\mathrm{EI}^0}\right), \\ \mathrm{IA}_{\mathrm{eff}}^{0,T} &= \frac{C^T - C^0}{\ln C^T - \ln C^0} \ln\left(\frac{\mathrm{IA}^T}{\mathrm{IA}^0}\right), \\ \mathrm{IS}_{\mathrm{eff}}^{0,T} &= \frac{C^T - C^0}{\ln C^T - \ln C^0} \ln\left(\frac{\mathrm{IS}^T}{\mathrm{IS}^0}\right).\end{aligned} \tag{7}$$

2.4. Prediction. Considering the huge CO_2 emissions of China's power sector, the prediction of CO_2 emissions in China's power sector becomes extremely important. A good understanding of the CO_2 emissions of China's power sector in the future contributes to not only production management but policy development and implementation of CO_2 emissions reduction in the power sector.

The prediction of CO_2 emissions in China's power sector is constructed through (6). CO_2 emission of China's power sector in target year T is calculated by

$$C^T = C^0 + \left(\mathrm{CI}_{\mathrm{eff}}^T + \mathrm{ES}_{\mathrm{eff}}^T + \mathrm{EI}_{\mathrm{eff}}^T + \mathrm{IA}_{\mathrm{eff}}^T + \mathrm{IS}_{\mathrm{eff}}^T\right). \tag{8}$$

The effects of various driving factors are calculated by the following equations:

$$\mathrm{CI}_{\mathrm{eff}}^T = W \cdot \ln(1+\alpha), \tag{9}$$

$$\mathrm{ES}_{\mathrm{eff}}^T = W \cdot \ln(1+\beta), \tag{10}$$

$$\mathrm{EI}_{\mathrm{eff}}^T = W \cdot \ln(1+\gamma), \tag{11}$$

$$\mathrm{IA}_{\mathrm{eff}}^T = W \cdot \ln(1+\delta), \tag{12}$$

$$\mathrm{IS}_{\mathrm{eff}}^T = W \cdot \ln(1+\rho), \tag{13}$$

where

$$\begin{aligned}W &= \frac{C^0 \cdot \left[(1+\alpha)\cdot(1+\beta)\cdot(1+\gamma)\cdot(1+\delta)\cdot(1+\rho) - 1\right]}{\ln\left[(1+\alpha)\cdot(1+\beta)\cdot(1+\gamma)\cdot(1+\delta)\cdot(1+\rho)\right]}.\end{aligned} \tag{14}$$

And the symbols α, β, γ, δ, and ρ represent the growth rate of various variables between the base year 0 and the target year T.

2.5. Data Sources and Process. The data from 1990 to 2014 used in this paper mainly include fossil energy consumption by energy type, power generation, and installed capacity. The data on energy consumption by energy type are drawn from China Statistical Yearbook (CSY) (1990–2014). In order to understand CO_2 emissions in power sector and other sectors, this study provides a comparison analysis of CO_2 emissions among sectors. According to energy consumption and CO_2 emissions of various sectors, we aggregate 49 sectors in CSY into 14 sectors; see Table 1. The energy resources considered in this study consist of nine kinds of energy: raw coal, Coke, crude oil, gasoline, kerosene, diesel oil, fuel oil, natural gas,

Table 1: Sector classification and abbreviations.

Sectors numbers	Sectors	Short for sectors	Abbreviation
1	Agriculture, hunting, forestry, and fishing	Agriculture sector	AGR
2	Mining and quarrying	Mining sector	MIN
3	Coke, Refined Petroleum, and Nuclear Fuel	Coke sector	COK
4	Chemicals fuels and chemical products	Chemicals sector	CHE
5	Nonmetallic mineral products	Nonmetallic sector	NMT
6	Ferrous metal smelting and processing industry	Ferrous metal sector	FMT
7	Nonferrous metal smelting and rolling processing industry	Nonferrous metal sector	NFM
8	Other manufacturing industry	Other manufacturing sectors	OMF
9	Electricity, gas, and water supply	Electricity, gas, and water supply sector	EGW
10	Construction	Construction sector	CON
11	Transportation, warehousing, and postal service industry	Transportation sector	TWP
12	Wholesale, retail, and accommodation, catering	Wholesales sector	WHO
13	Other sectors	Other sectors sector	OST
14	Households	Household sector	HSH

and electricity. Energy consumption is in the unit of million tons of standard coal equivalents (Mtce) and the conversion coefficients from physical to standard coal coefficient are derived from NDRC [17]. The data of power generation and installed capacity are obtained from National Power Sector Statistics Bulletin (NPISB) (1990–2014). Power generation is measured by million kWh and the installed capacity is in the unit of million kW. In addition, CO_2 emission factor and fraction of carbon dioxide by energy type are collected from IPCC (2006).

3. Results and Discussions

3.1. Emissions in China's Power Sector

3.1.1. Environment Effect of China's Power Sector. Using (1), we calculate the total emissions of power sector represented by *IPAT* index, which denotes the total environment effects of power sector development. The total impact of power sector increased continually from 220.49 to 1473.90, and the *IPAT* index increased steadily during 1990–2001 while it accelerated its growth from 2002. The *IPAT* index increased by 5.70 times during 1990–2014, denoting that power sector development leads to significant change of environmental condition due to energy consumption and CO_2 emissions. Especially after 2001, power market reform promoted the development of power sector and corresponding energy consumption and pollutant emissions including SO_2 and N_xO_y rocketed during 2002–2014. However, the relevant supervision measures and energy efficiency standards are imperfect during 2002–2010. Therefore, high-pollution, lower energy efficiency, and small power plants entered into power market. This explosive growth of power sector resulted in the significant increase in environmental effect.

3.1.2. CO_2 Emissions in China's Power Sector. In this study, CO_2 emissions consist of two parts: CO_2 emission scale and CO_2 emission intensity. CO_2 emissions scale means the total CO_2 emissions in China's power sector, while CO_2 emission intensity means the CO_2 emissions per unit of power generation. Figure 1 displays that, during 1990–2014, total CO_2 emissions in China's power sector showed an upward trend while the CO_2 emission intensity experienced a downward trend. CO_2 emissions in China's power sector increased continuously from 492.00 Mt in 1990 to 3049.88 Mt in 2014, with an aggregate growth of 519.89%. This increase in CO_2 emissions of China's power sector was largely due to the increasing power generation capacity. In the past two decades, the urbanization and industrialization in China improved continuously, and power generation increased rapidly to meet growing power demand. During 1990–2014, thermal power generation capacity even accounted for about 80%. Thus, increasing power generation led to large amount of fossil energy consumption and CO_2 emissions. Specifically speaking, CO_2 emissions of China's power sector during 2002–2011 increased significantly, and the average annual growth rate reached 11.10% which was higher than the average level during the whole study period (7.80%). The rapid increase in CO_2 emissions of China's power sector during

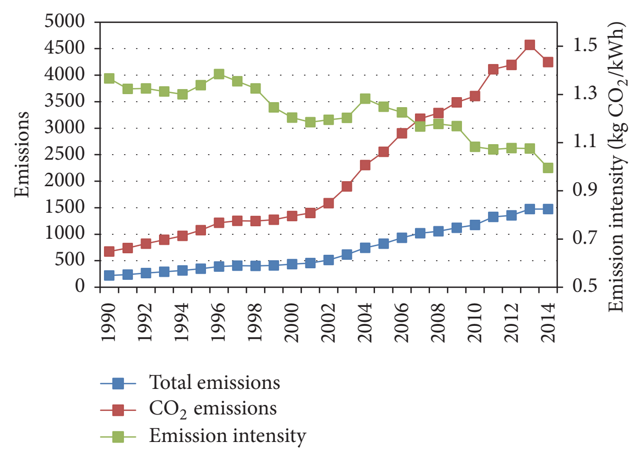


Figure 1: CO_2 emission trends in China's power sector during 1990–2014.

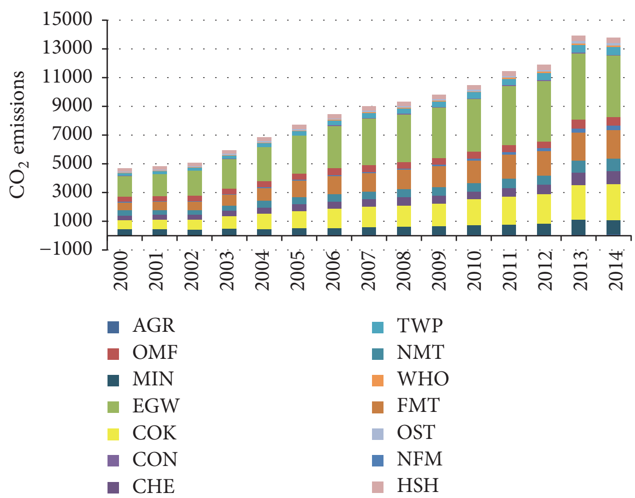


Figure 2: CO_2 emissions of various sectors in China during 2000–2014.

2002–2011 was closely related to the electricity market reform since 2002 which contributed to the rapid development of power sector.

In general, CO_2 emission intensity in China's power sector declined during the study period, which was attributed to the improvement of energy efficiency. CO_2 emission intensity reduced from 0.99 kg CO_2/kWh in 1990 to 0.71 kg CO_2/kWh in 2014, with a decline rate of 28.19%. It should be noted that CO_2 emission intensity in China's power sector did not show a continuous decline trend and fluctuated during 1990–2014. Even during 1995–1997 and 2004-2005, CO_2 emission intensity rose instead, and energy efficiency was certain to be depressed. The significant decline in CO_2 emission intensity of China's power sector occurred from 2004 and corresponding average annual change rate was 2.55% during 2004–2014, which indicated that energy efficiency improved distinctively.

3.1.3. Comparison of CO_2 Emissions with Other Sectors. Power sector accounted for the largest share of CO_2 emissions in China. Figure 2 shows that during 2000–2014 CO_2 emissions of China's power sector accounted for above 30%, and the share in national CO_2 emissions reached the maximum of 36.17% in 2007. During 2011–2014, the share of CO_2 emissions of China's power sector in total decreased continually. The sector with second largest CO_2 emissions is Coke, Refined Petroleum, and Nuclear Fuel sector (COK). CO_2 emissions of COK increased from 652.24 Mt in 2000 to 2484.90 Mt in 2014, and corresponding share in total CO_2 emissions increased steadily from 13.91% in 2000 to 18.01% in 2014. The third sector with large CO_2 emissions is ferrous metal sector (FMT) and the share in total CO_2 emissions remained between 11.57% and 14.53%. Following sectors with large CO_2 emissions are mining sector (MIN), chemicals sector (CHE), nonmetallic sector (NMT), other manufacturing industries (OMF), and transportation sector (TWP). Other sectors accounted for a small part of national CO_2 emissions. The share of household sector (HSH) in national CO_2 emissions decreased to 2.64% in 2014. As to agriculture sector (AGR), its CO_2 emissions accounted for a very small part in national CO_2 emissions and corresponding share is below 1%.

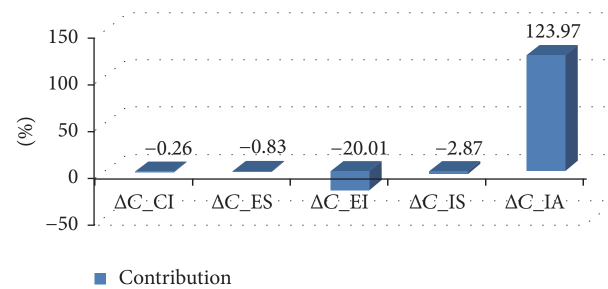


Figure 3: Contribution of each driving factor to CO_2 emission change in China's power sector.

3.2. Contribution of Each Factor. Figure 3 shows the contribution degree of each factor to CO_2 emission change in China's power sector during 1990–2014. In this study, CO_2 emission change in China's power sector is decomposed into five parts: carbon intensity effect (CI_{eff}), energy structure effect (ES_{eff}), energy intensity effect (EI_{eff}), capital efficiency effect (IA_{eff}), and industrial scale effect (IS_{eff}).

During 1990–2014, CO_2 emissions in China's power sector increased 2735.70 Mt. The contribution of carbon intensity effect, energy structure effect, energy intensity effect, capital efficiency effect, and industrial scale effect is −6.99 Mt −22.65 Mt, −547.51 Mt, −78.55 Mt, and 3391.40 Mt, respectively, and corresponding share is −0.26%, −0.83%, −20.01%, −2.87%, and 123.97%. Obviously, industrial scale effect is the dominant driving factor to CO_2 emission increase, which reveals that the industrial production expansion leads to the increase in fossil energy consumption and CO_2 emissions. In contrast, energy intensity effect is the key factor restraining the CO_2 emission increase, indicating that significant energy efficiency improvement in China's power sector reduces fossil energy consumption and CO_2 emissions. In addition, capital efficiency effect is another important factor leading CO_2 emission decrease. Therefore, we put emphasis on the above three driving factors, that is, industrial scale effect, energy intensity effect, and capital efficiency effect. Both carbon intensity effect and energy structure effect are negative, indicating that they also promote the decrease in CO_2 emissions. Considering relatively small contribution, carbon intensity effect and energy structure effect are analyzed briefly in this study.

3.3. Decomposition of Time Series. Figure 4 shows the effects of each driving factor to CO_2 emission change by time series during 1990–2014. Generally, during 1990–2002, the effect of each influencing factor is relatively little fluctuation, which is attributed to the small CO_2 emission change in China's power sector during the corresponding study period, while during 2002–2014 the effects of various driving factors increase and fluctuate significantly, in particular to the industrial scale effect and energy intensity effect.

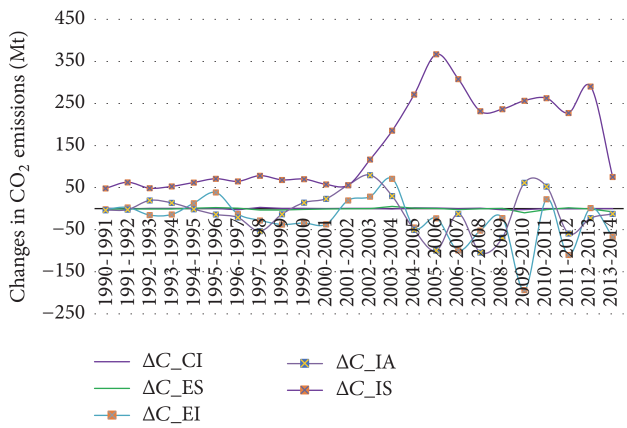


Figure 4: Driving factors to CO_2 emission change by time series in China's power sector.

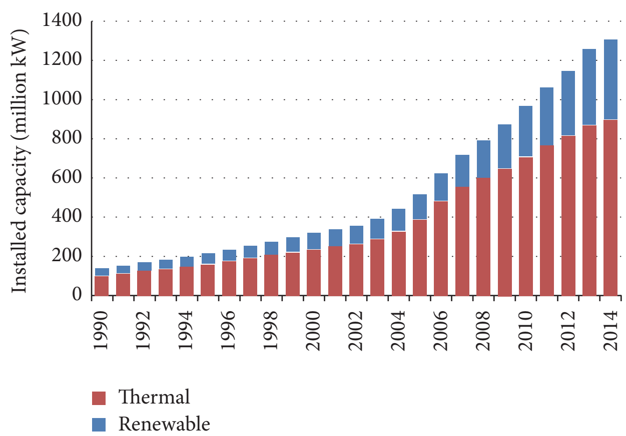


Figure 5: Installed capacity in China's power sector during 1990–2014.

3.3.1. *Industrial Scale Effect.*

The effect of industrial scale has been positive and higher than that of other influencing factors during 1990–2014. The positive effect of industrial scale denotes the expansion of industrial production scale, which means that the installed capacity in China's power sector increases continuously during the whole study period. The effect of industrial scale keeps relatively stable during 1990–2002 and during 2009–2014, while it increases rapidly from 55.95 Mt in 2002 to 366.97 Mt in 2006. In addition, the effects of industrial scale during 2006–2008 and 2013-2014 fall sharply. Change of industrial scale effect is attributed to the change of installed capacity growth rate. After 2002, electricity market reform leads to the significant increase in installed capacity and power generations, which generates large amount of fossil energy consumption and CO_2 emissions. The growth of thermal power generation slows down along with the development and utilization of renewable energy sources generation and surplus power supply, which leads to the decrease in the effect of industrial scale.

Figure 5 shows the evolution trends of power generation installed capacity in China's power sector during 1990–2014. There is a significant and sustained increase in installed

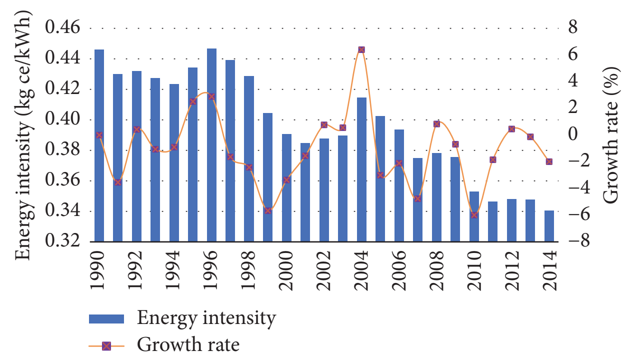


Figure 6: Energy intensity in China's power sector during 1990–2014.

capacity of China's power sector during the study period. Installed capacity of thermal power increased slowly during 1990–2002 while it increased rapidly during 2002–2009. The growth rate of thermal power declined during 2009–2014. In addition, the share of thermal power generation decreased constantly during 1990–2014, indicating the low carbonization development of power generation structure. The proceeding analysis indicates that the change of power structure is roughly consistent with the change of industrial scale effect.

3.3.2. *Energy Intensity Effect.*

As shown in Figure 4, the effect of energy intensity presents the positive and negative evolution trend as the energy efficiency change of China's power sector. The improvement of energy efficiency decreases the energy consumption and CO_2 emissions per unit of power generation. Therefore, the effect of energy intensity depends on the change of energy efficiency. Except for some specific years, energy intensity effect showed a negative trend which is attributed to the improvement of energy efficiency. Energy intensity reached its positive maximum of 74.91 Mt in 2004 and the negative maximum of 203.35 Mt in 2010.

Figure 6 shows the energy intensity change in China's power sector during 1990–2014. The change of growth rate of energy intensity is almost consistent with the change of energy intensity effect. Energy intensity in China's power sector continued to decline during 2004–2014 and fluctuated during 1990–2004. The introduction of new power generation technology and energy-saving technology improved the energy efficiency of China's power sector. In addition, improvement of energy efficiency standards, the elimination of backward production capacity, and the shutdowns of small power enterprises also contributed to the improvement of energy efficiency. Unusually, energy intensity increased during 2002–2004. The early electricity market reform promoted the disordered development of the power sector because of the insufficient market and supervision system.

3.3.3. *Capital Efficiency Effect.*

Capital efficiency effect indicates the effect of capital utilization efficiency on CO_2 emissions. The improvement of capital efficiency reduces the waste of energy recourses and thus decreases the energy consumption and CO_2 emissions of generating one unit of electricity. Figure 4 shows that during 2000–2004 and during 2010-2011 the effect of capital efficiency increased the CO_2 emissions in China's power sector. Surplus power supply was the key reason for the decline of capital efficiency. Power sector experienced a rapid development during 2002–2014 while the development of China's economy slowed down during the corresponding study periods. The growth rate of power generation capacity exceeded the power demand of economic development, which led to the decrease of capital efficiency. After the Asian financial crisis, the growth rate of capital efficiency improvement in China's power sector declined constantly, and the effect of capital efficiency on CO_2 emissions turned to the positive during 2000–2004. The decline of the growth rate of China's economic development was affected by the US Subprime Mortgage Crisis and economic structure adjustment; therefore, the power supply became surplus and the effect of capital efficiency was positive during 2010-2011. However, development of intelligent power system also promoted the improvement of power resources and power units and improved the capital efficiency.

3.3.4. Energy Structure Effect. The effect of energy structure shows a varying trend and is relatively small. Energy structure effect is almost negative during the whole study period, which indicates the continuous low carbonization of energy structure. Large scale of development and utilization of renewable energy resources promotes the optimization of energy structure. The effect of energy structure was roughly negative during 1990–2002, which revealed the increasing share of renewable power generation. However, after power market reform in 2002, the small and thermal power developed significantly during 2002–2006, leading to rapid increase in the fossil energy consumption.

Carbon intensity effect fluctuates around coordinate axe. Carbon intensity effect denotes the effect of the substitute among fossil energy. The increase of carbon intensity effect means the energy substitute from low-carbon content (such as oil and natural gas) to high-carbon content (such as coal). Carbon intensity effect did not show a clear change trend during 1990–2014. The effect of carbon intensity is very small.

3.4. Decomposition of Time Intervals

3.4.1. Definition of Time Intervals. The purpose of decomposition analysis of time intervals is to better understand the CO_2 emissions change during time intervals. Based on the features of CO_2 emissions evolution of China's power sector, the study period is divided into four stages (see Figure 6): steady growth stage (1990–1997), remaining steady (1997–2002), high-speed growth stage (2002–2009), and transition stage (2009–2014). Division of time intervals of CO_2 emission helps to better understand the CO_2 emissions evolution trajectory and explore the major driving factors of CO_2 emissions. In the first stage, CO_2 emissions increased steadily from 492.00 Mt in 1990 to 907.32 Mt, which was defined as the steady growth stage. During 1997–2002, CO_2 emissions in China's power sector showed a less significant increase in CO_2 emissions and we defined this time period as remaining steady stage. In the third stage, China's power sector experienced a rapid increase in CO_2 emissions and CO_2 emission increased significantly from 1143.70 Mt to 2501.21 Mt during 2002–2009; therefore, we defined the third stage as high-speed growth stage. In the fourth stage, the growth rate of CO_2 emissions decreased, and CO_2 emissions appeared to be a downward trend which was affected by the transformation of national economic development strategy.

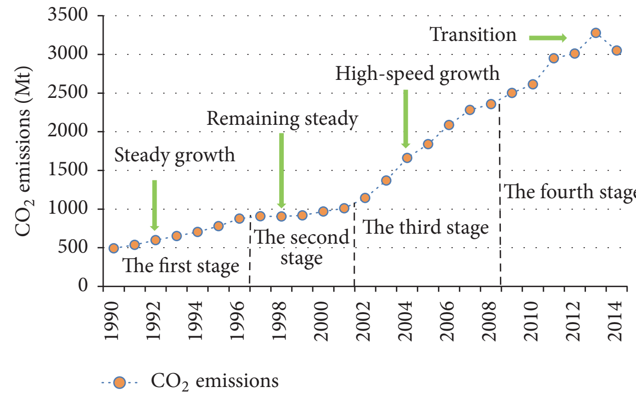
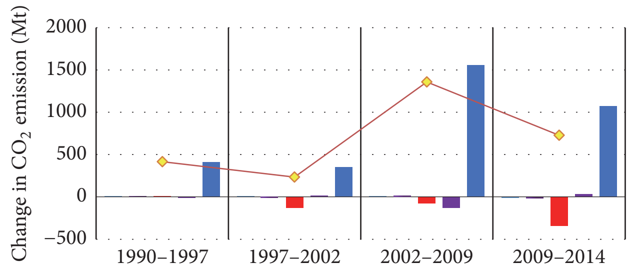


FIGURE 7: Division of time intervals of CO_2 emission growth in China's power sector.

3.4.2. Decomposition Analysis of CO_2 Emission Change by Time Interval. Decomposition analysis by time interval quantifies the impact of each driving factor to CO_2 emission change. The results of LMDI decomposition of CO_2 emission change by time interval in China's power sector are shown in Figure 8. In general, there has been a significant increase in CO_2 emissions of China's power sector during 1990–2014. CO_2 emissions in China's power sector increased by 2557.88 Mt, which is appropriately 519.10% of the level in 1990. CO_2 emission change varies among the four time intervals. The CO_2 emission growth during the last two intervals is higher than that during the first two time intervals. In particular, CO_2 emission growth was 415.65 Mt during 1990–1997 and 235.10 Mt during 1997–2002, respectively, while it reached 1356.17 Mt during 2002–2009 and 728.78 Mt during 2009–2014, respectively. Figure 7 illustrates that industrial scale effect contributes to most of CO_2 emissions during each time interval. Industrial scale expansion and consequent power generation lead to the significant increase in both energy consumption and CO_2 emissions, mainly driven by the constant and high-speed development of national economy. Industrial scale expansion leads to the increase in the CO_2 emissions with varying degrees among the time intervals. Energy intensity effect plays a crucial role in curbing CO_2 emission increase in China's power sector. The improvement in energy efficiency is the key reason to curb the CO_2 emission increase. Capital productivity effect is another main factor that results in the decrease in CO_2 emissions. Capital productivity improvement lowers the waste of energy



	1990–1997	1997–2002	2002–2009	2009–2014
ΔC_CI	1.28	3.81	0.56	−12.64
ΔC_ES	0.21	−10.77	6.29	−18.38
ΔC_EI	5.24	−129.88	−76.40	−346.48
ΔC_IA	−0.64	18.15	−129.85	33.78
ΔC_IS	409.56	353.78	1555.57	1072.49
ΔC	415.65	235.10	1356.17	728.78

Figure 8: Driving factors to CO_2 emission change by time series in China's power sector.

resources, and thus increases energy efficiency and decreases CO_2 emissions.

(1) 1990–1997. As shown in Figure 8, during 1990–1997, the CO_2 emissions increased by 415.65 Mt. Industrial scale effect increases CO_2 emissions by 409.56 Mt, which accounts for appropriately 98.53% of the total CO_2 emissions change during 1990–1997. Compared with other stages, CO_2 emission increase in this stage is lower than that in the third and fourth stage, which roots in the moderate expansion of industrial scale and corresponding power generation. During 1990–1997, the levels of industrialization and urbanization were both relatively low in China, and thus power demand was limited.

Energy intensity effect is 5.24 Mt, indicating that energy efficiency decreased during 1990–1997. The key reason for the decrease in energy efficiency is the rapid development of small thermal power enterprises, energy efficiency standards, and loose market mechanism. During 1990–1997, more attention was paid to the increasing power demand and power generation capacity due to rapid economic development, industrialization, and urbanization. Sustainable and low-carbon development of China's power sector was ignored, which led to the decrease in energy efficiency.

Capital productivity effect reduces CO_2 emissions by 0.64 Mt on the first stage, indicating that capital productivity improved lightly. During 1990–1997, in the context of rapid economic development, low-level industrialization and insufficient construction of power infrastructure result in insufficient power supply, and power generation units are always in high-load operation. Therefore, capital productivity effect is relatively small.

Both energy structure effect and carbon intensity effect are very small on the first stage, which reveals that the coal-dominant energy structure in China's power sector is unchanged.

(2) 1997–2002. In this stage, industrial scale effect is depressed sharply while other effects go up significantly. CO_2 emissions increased by 235.10 Mt during 1997–2002, which is lower than that in the other stages. Effect of industrial scale expansion during 1997–2002 drops to 353.78 Mt which is the lowest level in the four stages, while contribution of industrial scale effect reaches the highest level (150.48%). The reason lies in the Asian financial crisis in 1997. When the Asian financial crisis struck China, the economic growth rate of China fell sharply. Affected by declining power demand, power generation dropped during 1997–2002. Accordingly, effect of industrial scale decreased.

Meanwhile, backward production capacity with lower energy efficiency was eliminated. The overall energy efficiency in China's power sector improved substantially. Effect of energy intensity improvement reduces CO_2 emissions by 129.88 Mt during 1997–2002, accounting for 55.24% of the total CO_2 emissions on this stage.

Economic depression cut down power demand, leading to power generation units standing idle. Therefore, during 1997–2002, capital productivity declined. Effect of capital productivity increases CO_2 emissions by 18.15 Mt, which is appropriately 7.72% of the CO_2 emissions change.

Energy structure effect is −10.77 Mt during 1997–2002, which suggests the optimization of energy structure in China's power sector. In addition, carbon intensity effect during 1997–2002 is 3.81 Mt, indicating the energy consumption shift from high-carbon content to high-carbon content.

(3) 2002–2009. The CO_2 emission growth because of the expansion of power industrial scale amounts to 1555.57 Mt during 2002–2009. The key reason for the rapid expansion of the power sector during 2002–2009 was the mounting power demand during the rapid industrialization and urbanization process. The output increase of energy-intensive industries promoted the power demand and power generation. The production of major home appliances also underwent a rapid increase. Since 2002, power market reform has promoted the increase of installed capacity and power generation. In the loose market access mechanism, high profit drove the fixed assets investment in the power sector due to the lower production costs of thermal power generation than that of renewable power generation. Consequently, fossil energy consumption and CO_2 emissions increased rapidly in China's power sector during 2002–2007.

The energy intensity effect during the study period plays a significant role in reducing the CO_2 emissions of China's power sector during 2002–2007. Energy intensity effect reduces CO_2 emissions by 76.40 Mt. The decrease of energy intensity of China's power sector basically depends on the improvement of energy efficiency standards, the introduction of advanced energy-saving technology, and the elimination of backward production capacity (i.e., shutting down the small thermal units).

The effect of capital productivity is −129.85 Mt during 2002–2009, which demonstrated that utilization efficiency of power units improved. The reasons for capital efficiency improvement are the increasing power demand from national economic development and the insufficient supply of power generation, leading to the high-load and long-time operation of power units.

In addition, energy structure effect is 6.29 Mt during 2002–2009. The positive effect of energy structure denotes the increasing share of fossil energy consumption.

(4) 2009–2014. During 2009–2014, CO_2 emissions of China's power sector increased by 728.78 Mt. Industrial scale effect leads to CO_2 emissions increase by 1072.49 Mt, accounting for 147.16% of the total CO_2 emissions change. In contrast, the growth rate of CO_2 emissions lowered during 2009–2014 compared with the level during 2002–2009. Affected by American subprime mortgage crisis in 2008, the economic development was sputtering and power demand was also deficient. In the context of the "new normal" economy development stage, adjustment of economic development structure restrained the energy consumption because the development of high energy consuming industries was limited. Therefore, inadequate power demand and decreasing power consumption reduced the CO_2 emission in China's power sector.

The effect of energy intensity reached the maximum during 2009–2014, revealing that energy efficiency in China's power sector largely improved. Energy intensity effect accounted for 47.54% of the total CO_2 emission change during the fourth stage.

Energy efficiency in China's power sector improved remarkably during 2009–2014.

Introduction of new energy-saving technology and higher energy efficiency standards all contributed to energy efficiency improvement of China's power sector. After 2009, increasing surplus power supply drove more power units with higher energy efficiency and lower production costs to participate in power generation, which improved the overall energy efficiency in China's power sector.

By contrast, the effect of capital productivity is positive during 2002–2009. The large-scale use of air conditioning systems contributes to the increase of the maximum load and peak valley, which drive the increase of installed capacity and the decrease of load rate and unit utilization efficiency. In addition, the transformation of economic growth mode pulled by investment leads to the decline of power consumption growth and the power units and generation capacity becomes surplus, which sharpens the fall of power unit production efficiency.

Energy structure and carbon intensity effects reach their maximum of −12.64 Mt and −18.38 Mt, respectively. Due to promotion of renewable energy power generation and development of new energy resources after 2007, the share of renewable energy power generation increased; therefore, energy structure effect rose during 2009–2014.

3.5. CO_2 Emission Reduction Potential

3.5.1. Scenario Setting. Scenario analysis is one of the effective measures to estimate the CO_2 emission reduction potential. In this study, we also predict the CO_2 emissions of China's power sector during 2015–2030 based on equations (8)–(13). Power sector is the crucial sector for China to achieve its emission reduction targets. Therefore, it is necessary to understand the CO_2 emission reduction potential and then provide appropriate policy implications. In this study, two forecast scenarios are set to assess the CO_2 emissions and the ideal emission reduction scenario is developed to estimate the CO_2 emission reduction potential by setting the change rate of each variable at the target year. We take 2014 as the base year and 2030 as the target year.

We developed two forecast scenarios as follows.

(1) Business as Usual (BAU) Scenario. BAU scenario is established based on the historical development of each factor. All parameters chosen for BAU scenario are the average annual growth rate during 1990–2014. BAU scenario reflects the possible evolution trends of CO_2 emissions in China's power sector. The BAU scenario is the benchmark for setting other scenarios.

(2) Ideal Scenario. In the ideal scenario, CO_2 emissions in China's power sector are predicted to reach the possible minimum level by maximizing the negative driving factors and minimizing the positive driving factors. The energy intensity of China's power sector during 2005–2014 dropped significantly and is assumed to be the ideal decline rate. Growth rate of energy intensity during 2015–2030 is consistent with the average level during 2005–2014. In this scenario, according to the "12th Five-Year Plan" and "13th Five-Year Plan" of the power sector, power structure is in continuous optimization assuming that the installed capacity of hydro, nuclear, wind, and solar power reaches 330, 90, 180, and 100 million kW in 2020, respectively [18]. The thermal power installed capacity is assumed to remain unchanged during 2010–2030 and other types of power are assumed to increase during 2020–2030 at the same growth rate during 2015–2020. We assume that the capital productivity improves constantly during 2015–2030 and reaches the highest level of 4838.06 (the level in 2005) by 2030. Consequently, the annual growth rate of capital productivity in ideal scenario is calculated according to the preceding assumption. The share of fossil energy consumption is assumed to reach 90% in the total energy consumption of China's power sector. CO_2 emission factor follows the level in BAU scenario.

The corresponding growth rates of various variables under BAU scenario and ideal scenario are shown in Table 2.

3.5.2. CO_2 Emission Forecast. Based on the hypothesis shown in Table 2, we calculate the effects of the driving factors BAU scenario and ideal scenario using (8)–(12) and assess the CO_2 emissions of China's power sector during 2015–2030 using (13). Figure 9 shows the CO_2 emissions in China's power sector under BAU scenario and ideal scenario. In the BAU scenario, the CO_2 emissions are predicted to be 4132.75 Mt in 2020 and 7294.08 Mt in 2030, respectively. The aggregate CO_2 emissions during 2015–2030 reach 78746.59 Mt which is nearly 30.13 times of the 2010 level and 25.82 times of the 2014 level.

The CO_2 emissions in the ideal scenario are considerably lower than those in the BAU scenario. CO_2 emissions in the ideal scenario are 3541.38 Mt in 2020 and 4560.10 Mt in 2030 under the ideal scenario, respectively. The aggregate CO_2 emissions in China's power sector during 2015–2030 are

Table 2: Hypothesis of variables (unit: %).

Variables	BAU scenario	Ideal scenario
CI	0.0049	0.0049
ES	−0.0473	−0.2950
EI	−1.0260	−2.3749
IA	−0.1634	0.6697
IS	8.3070	6.5257

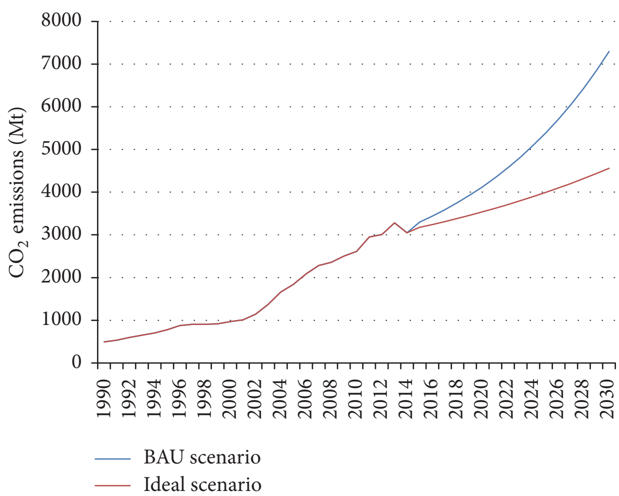


Figure 9: CO_2 emissions in China's power sector under BAU scenario and ideal scenario.

60772.73 Mt in the ideal scenario, which are equivalent to approximately 23.25 times of CO_2 emissions in 2010 and 19.63 times of CO_2 emissions in 2010, respectively.

3.5.3. CO_2 Emission Reduction Potential. In order to estimate the future CO_2 emissions reduction potential of China's power sector, the ideal emission reduction scenario is set. The ideal emission reduction scenario means that CO_2 emissions of China's power sector transform from BAU scenario to the ideal scenario, which is the gap of CO_2 emissions between BAU scenario and ideal scenario. Figure 10 displays the CO_2 emission reduction potential in China's power sector during 2015–2030. There has been a significant CO_2 emission reduction potential in China's power sector. Under the ideal emission reduction scenario, CO_2 emissions reduced by 591.36 Mt in 2020 which accounts for 14.30% of the total CO_2 emissions of China's power sector in 2020 and by 2733.98 Mt in 2030 which accounts for 37.48% of the total CO_2 emissions in 2030, respectively. The accumulated CO_2 emission reduction during 2015–2030 in the ideal emission reduction scenario reaches 17973.86 Mt, which is approximately equal to 6.88 times of the total emissions in 2010 and 5.89 times of the total emissions in 2014.

4. Conclusions and Policy Implications

4.1. Conclusions. This study aims to identify the major driving factors of CO_2 emission change and evaluate the

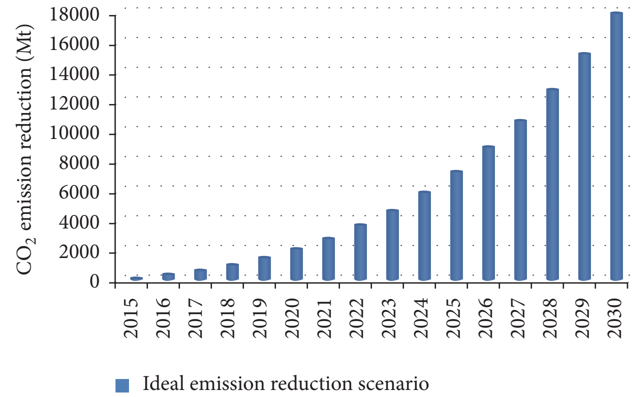


Figure 10: CO_2 emission reduction potential in China's power sector.

mitigation potential in China's power sector according to the LMDI method.

During 1990–2014, CO_2 emissions from China's power sector showed a growing upward trend, increasing from 492.00 Mt to 3049.88 Mt. However, the growth course is shaky. By contrast, the CO_2 emission intensity experienced a downward trend, and the performance during 2005–2014 was remarkable, with a decline rate of 22.75%. Thus, power sector plays a dominant role in strengthening the national CO_2 emission increase.

Industrial scale effect (contribution degree: 123.97%) is the major contributor to CO_2 emission growth in China's power sector, whereas energy intensity effect (contribution degree: −20.01%) is the main factor leading to CO_2 emission decline. Capital productivity effect is another important factor that results in the decrease in CO_2 emissions (contribution degree: 2.87%). Both energy structure effect and emission factor effect are small and they display a varying trend among the time intervals.

There has been a significant reduction potential in CO_2 emission of China's power sector. The aggregate reduction potential of CO_2 emissions during 2015–2030 is 17973.86 Mt. which is approximately equal to 6.88 times of the total emissions in 2010 and 5.89 times of the total emissions in 2014.

4.2. Policy Implications

(1) Technology-Oriented Mitigation Policies. (a) Significant attention should be paid to the promotion of renewable energy in power generation in China's power sector. In China, abundant renewable energy resource endowment and decreasing costs offer great potentials for developing renewable energy resources. Policymakers should not only increase R&D of renewable energy power generation, but also promote the use of renewable generation technology. Thus, large-scale renewable energy generation contributes to the adjustment of the power generation structure.

(b) Energy-saving is one of the most important ways to realize the low-carbon-oriented development of the power sector. The power sector should promote the development and utilization of energy-saving equipments, like high-efficiency power generator, energy-saving transformer, and wires with low resistivity, and so forth.

(c) Other technologies that can directly reduce CO_2 emissions to atmosphere are also encouraged to be used in thermal power plants. CO_2 capture and storage technology is a preferred technology that allows conventional fuels for electricity generation to be used while achieving deep reductions in GHG (greenhouse gas) emissions. In addition, accelerating the development and use of innovative recycling CO_2 technology is helpful to reduce CO_2 emissions in power sector.

(d) Intelligent monitor, dispatching, and load prediction systems are also useful to optimize energy resource allocation and avoid energy waste and thus reduce CO_2 emissions. Based on the accurate real-time data and predicted data on power generation and consumption provided by the intelligent power system, power supplier can arrange power units to generate and guide power consumption reasonably.

(e) The energy efficiency in China's power sector can also be improved in several ways, including improving boiler efficiency, residual heat for preheating, blending coal combustion, and usage of high-quality coal.

(2) Power Demand Side Management. Power demand side management (DSM) is to adjust power load by means of technology, economy, energy-saving, energy institution, and so forth. DSM helps to release the tension between electricity supply and demand and reduces energy consumption and CO_2 emissions. In order to further exert the role of DSM, several suggestions provided are as follows. First, policymakers and power enterprises should further improve power price and incentive mechanism. More flexible power mechanisms including peak-valley price, tiered power price, and two-part tariff are needed to guide power consumer to achieve efficient, economical, and orderly power use. Government should take efficient actions to establish incentive mechanism and reasonably guide power consumption. Implementing the incentive mechanism such as tax and loan preferential policies helps to encourage power consumer to start energy-saving renovation project. For residents, government can expand the scope of energy-saving home appliances subsidies and promote the use of energy-saving electric meter. Finally, the TV and newspaper ads plump the virtues and technology of energy-saving, which contributes to the energy-saving awareness improvement.

(3) Industrial Structure Adjustment. Government departments should take resolute measures to optimize industrial structure by closing or merging energy-intensive, high-pollution and small steel mill, oil refineries, and chemical plants. Energy-intensive and high-pollution industries tend to be low value-added and have high energy and carbon intensity. Most small plants have no environmental protection measures and thus induce large amount of CO_2 emissions. Therefore, the government should strictly manage industrial sector production and firmly close high polluting small plants. Government should take effective measures to promote high-tech industry development in order to improve the power utilization efficiency and reduce CO_2 emissions generated by industrial production.

(4) Population Policy. Government should call on the people to control population growth and population birth policy should be adjusted to optimize the age structure. In addition, more attention should be paid to the western region and different population policies should be formulated in different regions to narrow the population gap because the western region has abundant resource endowment, such as renewable energy and natural gas, and would support more people. Urban consumptive expenditure per capita has an obvious positive impact on CO_2 due to urban residents' high consumptive level that is more energy-intensive. Therefore, strict energy efficiency standards should be promoted in urban settings.

Competing Interests

The authors declare that there are no competing interests regarding the publication of this paper.

Acknowledgments

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