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CO_2 Emission and Energy Consumption from Automobile Industry in China: Decomposition and Analyses of Driving Forces

Shaohua Hu [1], Jie Yang [2,3,*], Zhigang Jiang [3], Minda Ma [4] and Wei Cai [2,5,*]

1 School of Intelligent Manufacturing and Transportation, Chongqing Vocational Institute of Engineering, Chongqing 402260, China; hshua424@yahoo.com.cn
2 College of Engineering and Technology, Southwest University, Chongqing 400715, China
3 Hubei Key Laboratory of Mechanical Transmission and Manufacturing Engineering, Wuhan University of Science & Technology, Wuhan 430081, China; jzg100@163.com
4 Department of Earth System Science, Tsinghua University, Beijing 100084, China; maminda@tsinghua.edu.cn
5 Department of Logistics and Maritime Studies, Faculty of Business, The Hong Kong Polytechnic University, Hung Hum, Kowloon 999077, Hong Kong
* Correspondence: yjzuipiaoliang@163.com (J.Y.); weicai@swu.edu.cn (W.C.)

Abstract: Despite the increasing contribution of the automotive industry to China's national economy, CO_2 emissions have become a challenge. However, the research about its energy consumption and carbon emissions is lacking. The significance of this study is to fill the research gap and provide suggestions for China's automotive industry to reduce its carbon emissions. In this paper, the extended logarithmic Division index (LMDI) method is adopted to decompose the factors affecting carbon emissions and determine the key driving forces. According to provincial statistical data in China in 2017, the annual emissions of six provinces exceeded five million tons, accounting for 55.44% of the total emissions in China. The largest source of emissions in China is in Jilin Province, followed by Jiangsu, Shandong, Shanghai, Hubei and Henan. The decomposition results show that investment intensity effect is the greatest factor for CO_2 emissions, while R&D intensity and energy intensity are the two principal factors for emission reduction. After the identification of driving factors, mitigation measures are proposed considering the current state of affairs and real situation, including improving energy structure, accelerating product structure transformation, stimulating sound R&D investment activities, promoting energy conservation and new energy automobile industry development and boosting industrial cluster development.

Keywords: energy consumption; CO_2 emissions; LMDI; driving forces; China's automotive industry

Citation: Hu, S.; Yang, J.; Jiang, Z.; Ma, M.; Cai, W. CO_2 Emission and Energy Consumption from Automobile Industry in China: Decomposition and Analyses of Driving Forces. *Processes* **2021**, *9*, 810. https://doi.org/10.3390/pr9050810

Academic Editor: Ambra Giovannelli

Received: 6 April 2021
Accepted: 27 April 2021
Published: 6 May 2021

1. Introduction

China has become the world's superpower for automobile manufacturing and consumption. The automotive industry is a vital pillar industry in China's national economy; since the reform and opening-up, the development and growth of China's automobile industry has strongly promoted the rapid improvement of the national economy and has had a far-reaching impact on the gross industrial output value, social taxation, labor employment, industrial collaboration, technology upgrading and urban construction. Its competitiveness directly reflects the level of industrial manufacturing in an economy. From 2012 to 2017, the automotive industry in China experienced a rapid development. Its added value increased 1.7 times, and its contribution to GDP has been rising steadily [1] (see Figure 1). Compared with that in western developed countries, the automotive industry in China developed much later, but it is developing rapidly and has accounted for the largest number of new car production and sales for eleven consecutive years since 2009. After more than half a century of development, with the process of urbanization and the rising middle class, the demand for automobiles continues to rise and the automotive industry has played a vital role in the development of national economy. Figure 2 shows that the total value of output in the automotive industry grew from 5039 billion RMB (2015 constant price) in 2012 to 8404 billion RMB (1 USD = 6.8 RMB) in 2017, with an average annual growth rate of more than 10% [2,3]. Along with the further significant upside of the automobile consumption market, the automotive industry is facing many challenges, such as energy consumption and environmental damage [4–8]. With the increase in output value, there is also an increase in energy and resource consumption and the CO_2 emissions (see Figure 3) [3]. Besides the enlargement of market demand, the increase of enterprises and the expansion of the industry are constantly putting pressure on the control of CO_2 emissions and pollution treatment [9].

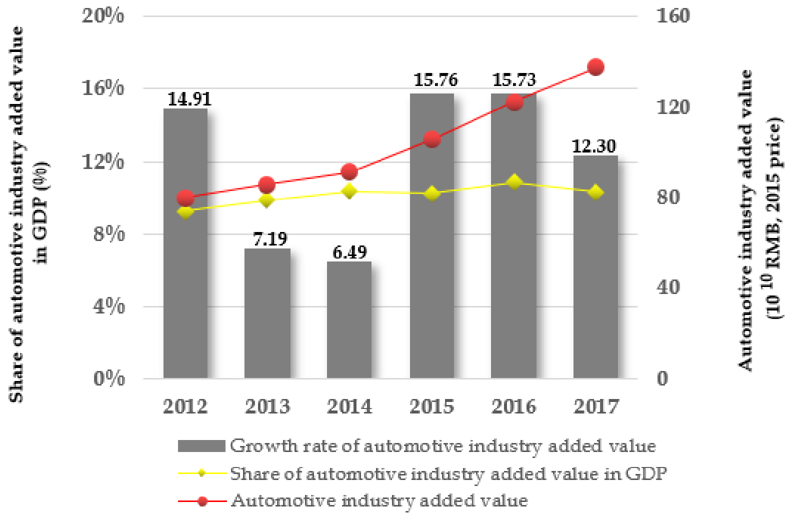


Figure 1. The automotive industry added value and its share in the total GDP. Source: China Statistical Yearbook on Auto Industry.

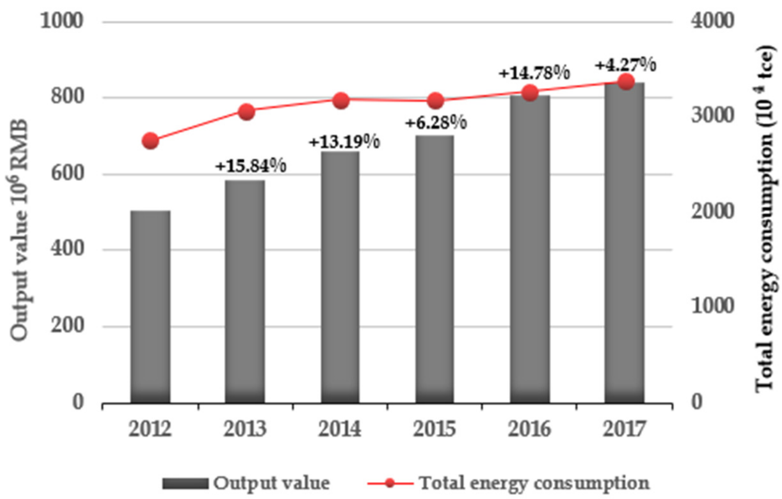


Figure 2. The value of output and total energy consumption of China' automotive industry.

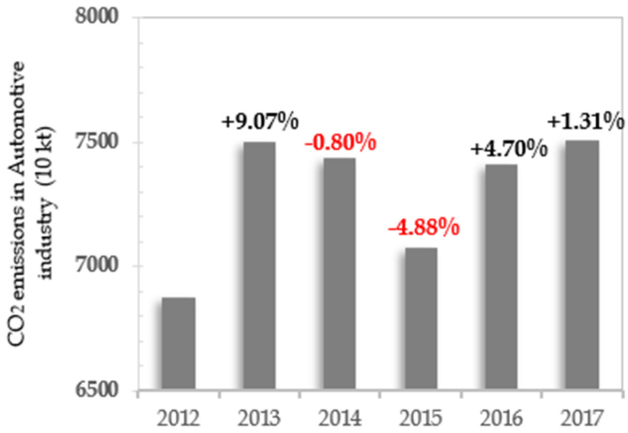


Figure 3. CO_2 emissions based on energy consumption in the automotive industry.

For the automotive industry, traditional vehicles consume a lot of fuel, which generate massive pollution and are likely subject to fuel supply shortage. Therefore, the industry has witnessed a rapid development of new energy automotive, which is considered as a key measure to solve the energy and environmental problems in the automotive industry [8,9]. However, from the view of the life cycle of new energy vehicles, emissions from the use and production processes of new energy vehicles also need to be strictly controlled [9]. Meanwhile, the focus should be confined not only to the electric vehicle itself but also the energy structure of electric power. If traditional primary energy continues to be used to generate electricity, the carbon emissions of this process far exceed the carbon emissions of fuel vehicles in the short-distance driving power conversion process. Moreover, research shows that, when the level of carbon subsidies for electric vehicles is high enough, the carbon emission control scheme for China's automotive industry will be effective [10].

The automobile itself is very complex, which requires a lot of energy for manufacturing. Thus, the development of automobile manufacturing needs to move towards low-carbon technology. Several studies are concerned with the automotive industry, discussing how to achieve higher ecological benefits. Manojit et al. [11] explained that, to overcome the economic and environmental impact, scientists are studying renewable and sustainable materials in the automotive industry, such as bio-composite materials. Natural Fiber Reinforced Composites (NFRC) have become the most popular alternative materials in research [12,13] and the wide use of kenaf fiber-reinforced materials, which have good recyclability, renewability and ecological efficiency, has further reduced the weight and cost of automobiles [14,15]. Morgadinho et al. [16] studied the contribution factors to European automotive industry to identify means to reduce greenhouse gas emissions, arguing that technology and behavioral aspects could help reduce fossil fuel consumption and thus CO_2 emissions. In addition, many big automobile manufacturing countries have studied approaches to save energy consumption and improve energy efficiency. Giampieri et al. [17] investigated the status of the implementation of ISO energy, environment and quality management standards by British automobile manufacturers as well as the improvement of energy efficiency through the superheat recovery manufacturing process. José et al. [18] identified three environmental protection organizations in Spain's automotive industry and argued that the behavior of automobile enterprises corresponding to eco-balanced, eco-marketer and eco-blind groups can promote ecological innovation. For China, a major challenge for sustainable development is how to deal with the growing problem of scrap vehicles and their recycling. Therefore, Automotive Components Remanufacturing (ACR) is an important developing direction of energy saving and emission reduction in China [19]. Yee et al. [20] put forward an interesting concept to establish a partnership between automobile and construction industry, i.e., using End-of-Life Vehicle (ELV) waste as building material to improve ELV recyclability. Although there is no direct effect on reducing carbon emissions in the automotive industry, the carbon emissions based on energy consumption in the construction industry decline, so emission reduction is feasible from the perspective of the whole economy.

Tan et al. proposed a whole-life cycle carbon emissions methodology, namely GREET and MOBILE model, to account for CO_2 emission in the Chinese automotive manufacturing industry and verified the feasibility through application in the automotive industry in Chongqing, China [21]. Javadi et al. used the Radial Basis Function (RBF) network model to predict CO_2 emission in Iran and considered that the application of renewable energy sources could decrease the carbon intensity by 12.6% [22]. Zhao et al., from the micro-enterprise level, analyzed the relationship between the capital allocation efficiency of new energy vehicle enterprises and vehicle carbon emissions with technological innovation as the threshold variable [23]. Although the above studies use different methods to analyze the impact of carbon emissions on automobile manufacturing, there is no detailed description of the factors that cause carbon emissions. Thus, due to the absence of domestic research on energy-related carbon emissions in the automotive industry, to fill this gap, this paper takes the extended method of LMDI to decompose and analyze the relevant emission factors and provides a preliminary understanding of the situation in the various provinces. The novelty of this paper lies in the approach adapted for the comparative analysis of indirect and direct CO_2 emissions in the field of automobile manufacturing and the analysis of energy consumption and carbon emission in 31 provinces of China.

The paper is structured as followed. The methods and data collection are detailed in Section 2. Section 3 covers the discussion, presents the analysis and results. Section 4 describes the conclusions and policy suggestion. The data referred to in this paper can be seen in the Appendix A.

2. Methods and Data

In this paper, the factor decomposition method, which is commonly divided into two methods, namely Structure Decomposition Analysis (SDA) and Index Decomposition Analysis (IDA), is used to analyze the problems discussed in this paper [24]. IDA is used in this paper as it is widely adapted in energy systems studies, for instance, energy balances and energy flows in an economy. It needs fewer data and is easier to use and obtain results. Compared with SDA, IDA is easier to compare time series, simple and flexible [25]. Moreover, IDA has two main types of methods: Laspeyres index and Divisia index. After analyzing the advantages and disadvantages of the two methods [26,27], the additive Logarithmic Divisia Index (LMDI) method is chosen. The LMDI method leaves no unexplainable residual in the analysis and copes well with negative and zero values. This paper employs Kaya identity and LMDI method to analyze the driving forces that affects CO_2 emissions in China's automotive industry. Particularly, the emissions from fossil fuel combustion are discussed in this study. The Kaya identity was originally put forward by Yoichi Kaya, and, in 1989, at a seminar organized by the UN's IPCC (The Intergovernmental Panel on Climate Change), Kaya combined carbon emissions with energy, economic scale and population level to quantify the relative roles of key drivers of production and CO_2 emissions. There are several benefits of this method such as simple structure, residual-free and easy-to-understand analysis. Accordingly, it is the mainstream analysis measure to analyze the driving factors of CO_2 emissions.

This paper involves data from various sources, including energy consumption data from "China Statistic Yearbooks (National Bureau of Statistics (NBS), 2013–2019)" [1]; the data of output value and investment in fixed assets and R&D expenditure from "China Statistical Yearbook on Auto Industry" [2]; and thermal energy consumption from "China Energy Statistics Yearbook" [3]. Considering the impact of inflation, all current prices have been justified to the prices in 2015. Constant price can eliminate the influence of price changes in different periods and ensure the comparability of data. Moreover, the output value is adjusted by PPI deflator index. R&D expenditure and fixed assets investment are converted by investment price index. All price indices come from "China Energy Statistic Yearbook (2018)". It is worth putting out that the energy consumption data of the automobile manufacturing industry was not counted separately until 2012; thus, to ensure the reliability and availability of the data, the data are collected from 2012.

The boundary of the study should be established first before the calculation. In light of "The Greenhouse Gas Protocol-A Corporate Accounting and Reporting Standard" [28], the boundary definition is shown in Table 1. This paper mainly considers the direct emissions (i.e., the consumption of various primary energy sources) and certain indirect emissions (i.e., mainly the power consumption and thermal energy consumption), as the data are easy to obtain.

Table 1. Research boundary divisions and examples based on energy-related CO_2 emissions.

Emission Type	Scope	Definition	Example	Whether Covered in This Study
Direct Emissions	1	Direct CO_2 emissions that exist in sources that are owned or controlled by China's automotive industries	Emissions from combustion in owned or controlled boilers, furnaces, vehicles, etc.; emissions from chemical production in owned or controlled process equipment	Yes
Indirect Emissions	2	CO_2 emissions from the generation of purchased electricity, heat, steam, etc., which are consumed by automotive industries	Emissions occurring at the facility where purchased electricity, heat and steam are generated	Yes
	3	Emissions in consequence of the activities of the automotive industry rather than occurring from sources owned or controlled by automotive industries	Emissions from the extraction and production of purchased materials; transportation of purchased fuels; and use of sold products and services	No

This paper assumes that the CO_2 directly emitted is generated by the combustion of fossil fuels. Equation (1) (the definitions of the letters in the equation is shown in Table 2) is used to calculate the CO_2 emissions based on the effective emission factors and the lower calorific value in various energy types. Indirect emissions of CO_2 are mainly generated by thermal energy and power consumption, which is measured by Equation (2), based on generation and thermal emission factors (the nationwide average CO_2 emission factors for heat and electricity generation are computed by applying the China's energy balance sheet (physical quantity) in China Energy Statistic Yearbooks (2013–2018)).

$$C_1 = \sum_j E_j \times a_j \times b_j \times \frac{44}{12} \tag{1}$$

$$C_2 = EP \times G_{ele} + EH \times G_{heat} \tag{2}$$

2.1. Decomposition Analysis 1 (DA1)—Time Series Analysis

For the sake of disclosing the macroeconomic influences of traditional factors and the micro-economic influences of R&D and investment activities about energy-related carbon emissions from the automobile manufacturing industry, both LMDI decomposition and the Kaya identity method are employed to divide the energy-related CO_2 emission into eight factors using the following equation (the definitions of the letters in the equation is shown in Table 3):

$$C = \sum_j C_j = \sum_j \frac{C_j}{E_j} \times \frac{E_j}{E} \times \frac{E}{P} \times \frac{P}{R} \times \frac{R}{I} \times \frac{I}{P} \times \frac{P}{S} \times S$$
$$= \sum_j EC_j \times ES_j \times EI \times RE \times RI \times II \times G \times S \quad (3)$$

Table 2. Variable definitions of Equations (1) and (2).

Symbol	Implication
C_1	The total direct emission, unit: 10,000 t
E_j	Final energy consumption of energy *j*, unit: 10,000 t
a_j	The lower calorific value of energy type *j*, unit: kJ/kg
b_j	The effective emission factor of energy type *j*
C_2	The total national indirect emission, unit: 10,000 t
EP	The electricity consumption, unit: 10^8 kW
EH	The consumption of heat, unit: 10^{10} kJ
G_{ele}	The average CO_2 emission factor for electricity generation
G_{heat}	The average CO_2 emission factor for heating supply
$\frac{44}{12}$	For calculating CO_2 from carbon combustion based on molecular weight

Note: The values of a_j and b_j refer to IPCC 2006.

Table 3. Variable definitions of DA1.

Symbol	Implication
C	CO_2 emissions in the automotive industry
j	Fuel type (divided into eight categories: raw coal, coke, crude oil, gasoline, kerosene, diesel oil, fuel oil, natural gas, electricity and heat)
E	Energy consumption
E_j	Consumption from energy *j*
P	The automotive industry output value measuring production scale effect
S	Population
R	R&D expenditure of the automotive industry
I	Fixed asset investment of the automotive industry
EC_j	CO_2 emission coefficient for energy source *j* (emission coefficient effect)
ES_j	The share of energy source *j* in total energy consumption measuring energy structure effect
EI	Comprehensive energy consumption per unit of output representing energy intensity effect (tce/RMB)
RE	The output per unit of R&D expenditure representing R&D efficiency effect
RI	The share of R&D expenditure in fixed asset investment representing R&D intensity effect
II	Fixed asset investment per unit of output value measuring investment intensity effect
G	Economic activity in output value per capita

For EC_j, due to data availability, the emission factors of various energy sources are supposed to be unchanged except that of electricity and heat sources.

Adopting the addition operation of LMDI model, Y and 0, respectively, represent year Y and base year:

$$
\begin{aligned}
\Delta C = C_{(Y)} - C_{(0)} &= \Delta EC_j + \Delta ES_j + \Delta EI + \Delta RE + \Delta RI + \Delta II + \Delta G + \Delta S \\
\Delta EC_j &= L(W^Y, W^0) \times \ln\left(\frac{EC_j^Y}{EC_j^0}\right) \\
\Delta ES_j &= L(W^Y, W^0) \times \ln\left(\frac{ES_j^Y}{ES_j^0}\right) \\
\Delta EI &= L(W^Y, W^0) \times \ln\left(\frac{EI^Y}{EI^0}\right) \\
\Delta RE &= L(W^Y, W^0) \times \ln\left(\frac{RE^Y}{RE^0}\right) \\
\Delta RI &= L(W^Y, W^0) \times \ln\left(\frac{RI^Y}{RI^0}\right) \\
\Delta II &= L(W^Y, W^0) \times \ln\left(\frac{II^Y}{II^0}\right) \\
\Delta G &= L(W^Y, W^0) \times \ln\left(\frac{G^Y}{G^0}\right) \\
\Delta S &= L(W^Y, W^0) \times \ln\left(\frac{S^Y}{S^0}\right) \\
W = EC_j \times ES_j \times EI \times RE \times RI \times II \times G \times S,&\ L(W^Y, W^0) = \sum_j \frac{(W^Y - W^0)}{(\ln W^Y - lnW^0)}
\end{aligned} \tag{4}
$$

2.2. DA2—Regional and Spatial Differences

The previous section is based on time series analysis and calculation. This section focuses on the regional and spatial differences and analyses the changes of carbon emissions in 31 provinces during 2012–2017. There are 34 provinces and cities in China, including 23 provinces, 4 municipalities directly under the central government, 5 autonomous regions and 2 special administrative regions. This paper collects statistics on 31 provinces, excluding Taiwan, Hong Kong Special Administrative Region and Macao Special Administrative Region. Thirty-one provinces account for 97% of the total area of China, so they can represent the overall situation of China.

Among these 31 provinces, 21 have energy consumption data, but the fuel types in the yearbooks of each province are not the same, nor are they as comprehensive as the national statistical yearbooks. However, for consistency, only the reported data from national statistical yearbooks are analyzed in this paper. Except for the use of data in energy consumption, the computing procedures of direct emissions are the same as those for national level accounting. Specific power emission factors are decided by the regional power network and might vary greatly in different times [29]. Therefore, the equivalent emission factors for provincial accounting are defined in light of the regional power grid, and the data are from NDRC (2014 B) [30].

Due to insufficient energy consumption data in 10 provinces (i.e., Hebei, Guangxi, Shanghai, Hainan, Shandong, Jiangsu, Tibet, Sichuan, Guizhou and Zhejiang), their CO_2 emissions are collectively accounted through the carbon intensity and output values in the automotive industry [30]. The estimate equation is as below (the definitions of the letters in the equation is shown in Table 4):

$$
E_{Pro,n} = \frac{E_{nat} - \sum_{m=1}^{21} E_{pro,m}}{\sum_{k=1}^{10} P_k} \times P_n \tag{5}
$$

Table 4. Variable definitions of Equation (5).

Symbol	Implication
$E_{Pro,n}$	The CO_2 emission of the automotive industry in province n
E_{nat}	The total national CO_2 emission of the automotive industry
$E_{pro,m}$	The CO_2 emission of the automotive industry in province m where energy consumption data are available
P_k	The output value of the automotive industry in province k where energy consumption data are lacking
P_n	The output value of the automotive industry in province n

3. Results and Discussions

3.1. CO_2 Emissions

Figure 4 shows the CO_2 emissions trail and annual emissions per unit of production for the automotive industry in China from 2012 to 2017. It can be clearly seen that coal makes a major contribution to direct emissions, while electricity is the main source of indirect emissions, and electricity is greater than coal, accounting for 76.57% of all energy-related carbon emissions in 2017. The proportion of coal consumption is gradually decreasing, while electricity consumption is increasing. Moreover, CO_2 emissions from indirect sources (electricity and heat) have always been higher than those from direct sources, and the gap is gradually widening. Figure 4 shows that CO_2 emission fluctuates, but, on the whole, it shows a slow upward trend. This change is related to the policy of that year. Starting in 2011, under the background of weak international economic growth, falling domestic economic growth and the gradual withdrawal of policies to stimulate automobile consumption, China's automotive industry has been growing slowly and China's automobile market has gradually transited from a rapid growth stage to a stable growth stage. From 2012 to 2017, the average increment of carbon emissions in the automobile manufacturing industry is about 8%. In addition, the emission per unit output is decreasing year by year, from 3.57 t/per vehicle in 2012 to 2.59 t/per vehicle in 2017. In particular, between 2013 and 2015, carbon emissions fell, while production was still growing, resulting in emissions per unit of production still falling. This is related to the implementation of energy-saving and emission reduction planning and vigorous development of energy-saving and new energy automotive industry in China. This progress shows that China's emission regulations continue to be stricter, and efforts are made to vigorously promote green manufacturing, energy saving and consumption reduction technologies.

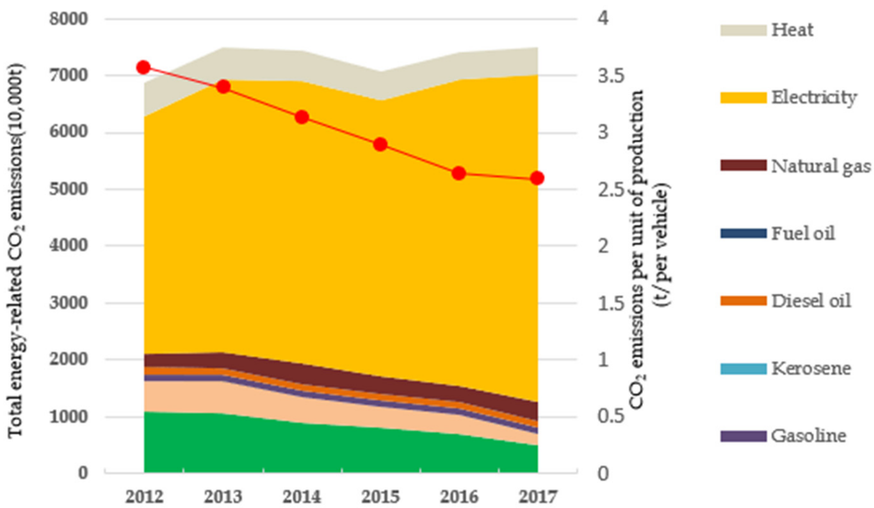
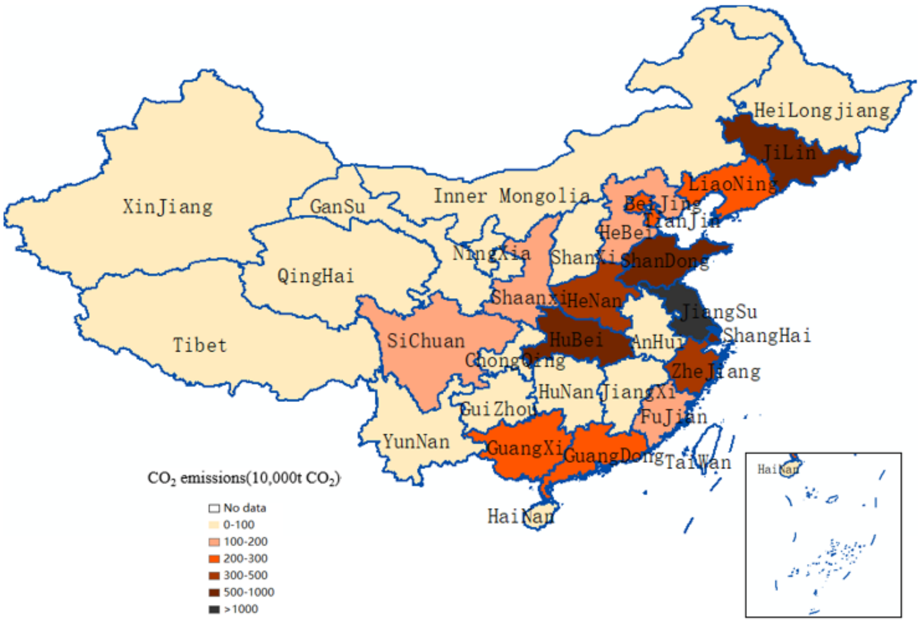


Figure 4. Various energy-related CO_2 emissions and emissions per unit of production.

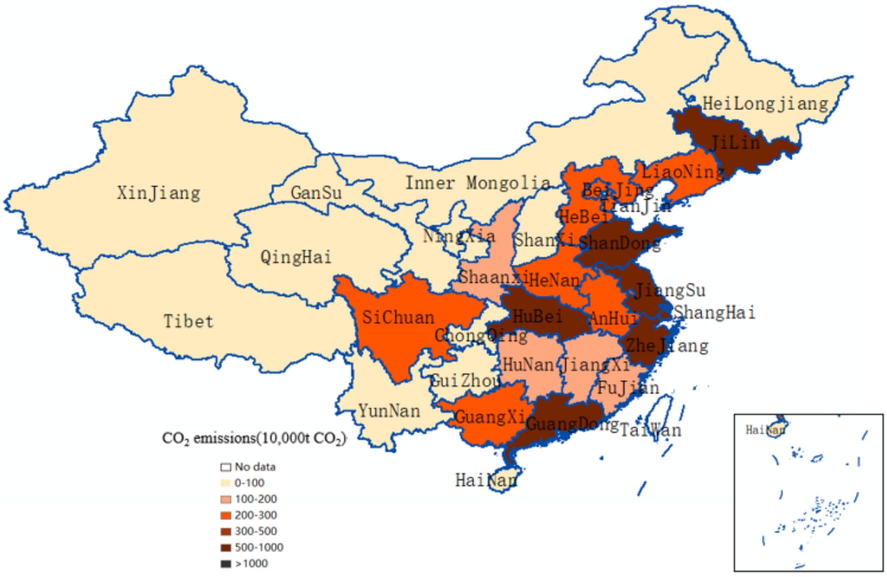
3.2. Spatial Differences of Carbon Emissions from China's Automotive Industry

Figure 5 shows the CO_2 emissions of 31 provinces in China at two time points, 2012 and 2017. All emission data containing all 31 provinces for the years of 2012–2017 are displayed in Appendix A (Table 2). Obviously, from 2012 to 2017, CO_2 emissions mainly concentrated in the eastern and some central regions, especially in Jilin, Beijing, Tianjin, Shanghai, Henan, Shandong, Hubei, Jiangsu, Zhejiang and Guangdong. These regions are relatively developed in economy and industry in China, so they contribute a lot to the carbon emissions of the automobile manufacturing industry. Jiangsu, Hubei, Jilin, shanghai and Shandong, which have always been on the first gradient, accounted for 54.82% of the total emissions in 2012 and 48.7% in 2017. The regional change of carbon emission can be seen in the figure. The areas with high emissions are obviously inclined from the northeast to the central and western regions. This change is related to the gradual transfer of the automotive industry cluster to the central and western regions, where the development in the automotive industry used to be weak but has great potential. Interestingly, Jiangsu's automobile output in 2012 was 0.887 million vehicles, ranked only tenth, while its emission ranked first. In 2017, Guangdong was ranked fourth in output, but only seventh in emissions, while Jiangsu was ranked first in emissions, while ranked fourth in output with 1.8537 million vehicles. The inconsistency between the spatial emission pattern and the spatial output pattern is widespread in these provinces. The main reason is that the energy structure is different in provinces. What is more obvious is that both Shanxi and Inner Mongolia are China's major coal reserves and more than 92% of their energy comes from coal. This might be the reason that, in 2017, the carbon emissions from Shanxi and Inner Mongolia accounted for 0.46% and 0.31% of the country, respectively, while the output accounted for only 0.41% and 0.08%, respectively.



(**a**) Provincial CO_2 emissions (10^4 t) in China's automotive industry in 2012.

Figure 5. *Cont.*



(**b**) Provincial CO_2 emissions (10^4 t) in China's automotive industry in 2017

Figure 5. Provincial CO_2 emissions in China's automotive industry in: 2012 (**a**); and 2017 (**b**).

3.3. *Driving Forces of CO_2 Emissions Changes of the Automotive Industry in China*

Figures 6 and 7 show the overall and annual influences of various driving forces from 2012 to 2017, respectively. From the viewpoint of cumulative effect, the energy structure effect, investment intensity effect, economic activity effect and the population effect are the only four driving forces of emission growth, increasing by 7.04, 116.16, 35.40 and 1.93 Mt, respectively, during the period. On the contrary, emission coefficient effect, energy intensity effect, R&D efficiency effect and R&D intensity effect contribute to emission reduction. These factors contributed 5.06, 33.01, 4.58 and 111.59 Mt, respectively. According to Figure 7, the magnitude and direction of the driving forces vary greatly in different periods, and the expansion analysis of each factor is as follows.

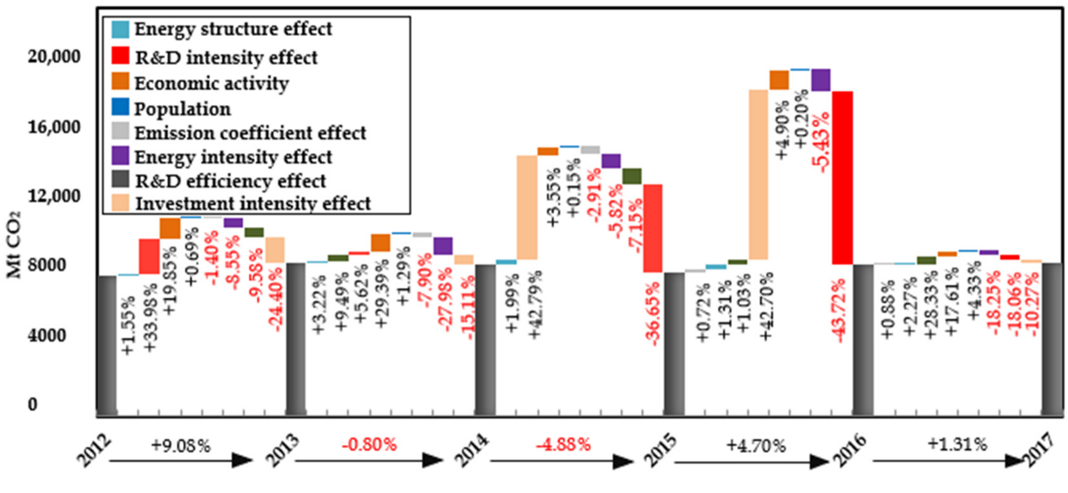


Figure 6. Annual impacts on various driving forces during 2012–2017.

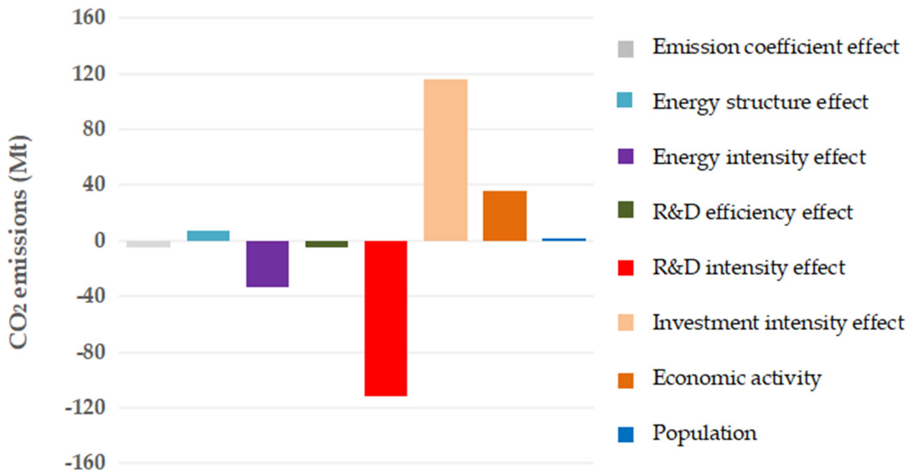


Figure 7. The cumulative impact of various driving forces during 2012–2017.

Investment intensity effect: This investment intensity effect is the ratio of fixed investment to the output value of the automotive industry, promoting the carbon emissions of the automotive industry and representing the ability of extended reproduction for the automotive industry [31]. Similarly, this factor on CO_2 emission rests with the comparative magnitudes of these influences on emission reduction and expansion of production scale, which means that the higher the investment intensity of the automotive industry is, the stronger the reproductive capacity is and the more the corresponding CO_2 emissions are [32,33]. Specifically, combining Figures 6 and 7, during 2012–2014, the effect value of investment intensity showed a downward trend, which correspondingly led to emission reduction. Therefore, reducing investment intensity can effectively promote the emission reduction of the automotive industry. With the expansion in the automotive industry chain, the problem of unwise investment, i.e., zombie enterprises and ineffective production capacity occupy many key resources, has arisen, leading to the problem of unequal expenditure and income. Especially in recent years, the technology level in the new energy automobile industry has been improved, the market scale has been gradually expanded and the seemingly unwise development has appeared, which is not only conducive to the healthy development of the industry but also brings unnecessary carbon emissions.

Economic activity: Figures 6 and 7 shows that this is the main factor for carbon emissions in the automotive industry. Figure 8 shows that the growth rate of economic activity value is not very large during 2012–2017, probably due to the huge impact of the international financial crisis in 2009. Under this case, the development of global trade has entered a downturn period. Significantly, the economic expansion of China having moderated to a "new normal" pace. The reduction in automobile import and export trade and the gradual withdrawal of relevant policies to stimulate domestic demand have resulted in a decline in domestic consumption. Since China's entry into World Trade Organization (WTO), remarkable achievements have been made by China's automotive industry and frequent economic activities have been occurring. There are two main factors contributing to the development in the automotive industry: (1) the introduction of a series of policies to give impetus to the development in the automotive industry; and (2) market competition lowers costs and prices, enlarges market consumption and promotes the economies in scale of production, thus accelerating the production and consumption in the automotive industry in China. In fact, the balance between economic growth and CO_2 emissions is no single shape: various shapes, e.g., inverted U-shaped, inverted N-shaped, U-shaped and M-shaped exist. That is to say, there are different relationships in different countries at different times [34–36]. China currently is in the process of rapid urbanization and industrialization, so its economic growth corresponds to the growth of environmental pressures.

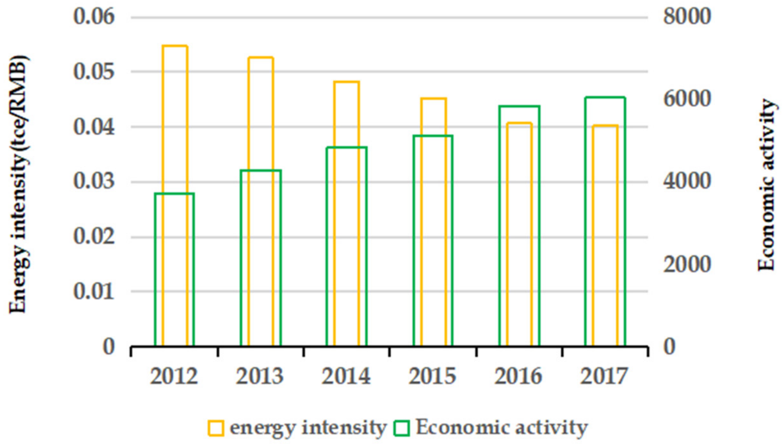


Figure 8. Energy intensity and Economic activity of China's automotive industry in 2012–2017.

Energy structure effect: Figures 6 and 7 show that this effect makes a positive contribution to CO_2 emissions. As shown in Figure 4, the main emissions come from coal, coke, electricity and heat. Figure 9 shows that the consumption of energy from these four sources is relatively large. Coal consumption totally shows a downward trend and so does coke, while electricity shows the opposite. Heat is in a steady consumption trend. Comparing Figures 6 and 8, it can be seen that natural gas consumption has exceeded coke since 2012, but emissions are always lower than coke, because the effective emission factor of coke is higher than the effective emission factor of natural gas. Therefore, the energy structure is closely linked with emissions [37–39]. For instance, the reduction of energy consumption with high emission factors such as coal and coke and the increase of energy consumption with low emission factors such as oil and gas will reduce emissions. Because of the serious imbalance of energy structure in China, considering the cost, coal is the most convenient and direct fuel to use, but it is not conducive to sustainable development, damages the environment and offsets the ecological benefits.

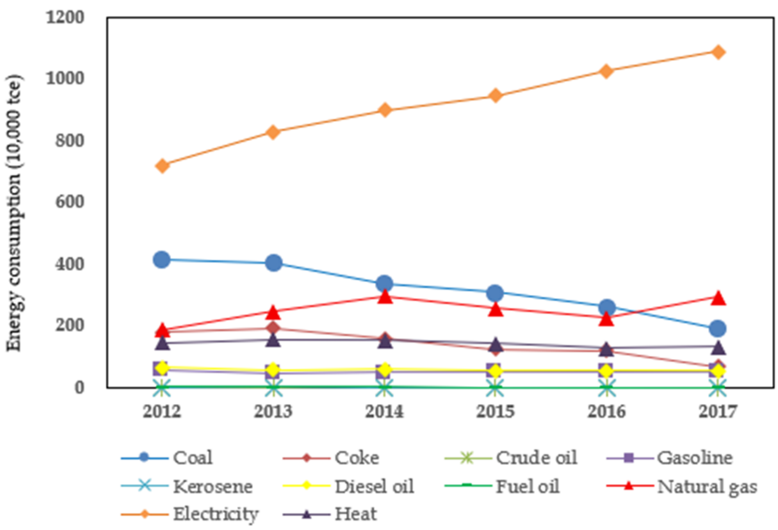


Figure 9. Various energy consumption of China's automotive industry in 2012–2017.

Energy intensity effect: Energy intensity is the representative of energy efficiency. The lower the energy intensity is, the higher the utilization efficiency is and the better the economic benefit is [40]. Not only that, similar studies [41] have also shown that high energy intensity and low energy efficiency will lead to a large amount of energy consumption and CO_2 emission per output value, which is also reflected in this paper. Figure 6 shows that energy intensity is the second largest factor to carbon emissions reduction, which indicates that the reduction of energy intensity can effectively reduce carbon emissions. Figure 8 shows that the overall energy intensity of China's automotive industry is declining rapidly, from 0.055 tce/RMB in 2012 to 0.040 tce/RMB in 2017, a decrease of 26.63%. Comparing Figures 6 and 9, the steeper is the downward trend, the more obvious is the role of emission reduction.

R&D intensity effect: The R&D intensity effect is the ratio of R&D expenditure to investment, reflecting technological content and innovation intensity [41,42]. Overall, as shown in Figure 7, R&D intensity inhibits the carbon emissions of the automotive industry during the period. Combining Figures 6 and 7, the R&D intensity effect value was on the rise from 2012 to 2014, which contributes to emission reduction. That is to say, the emission reduction effect of improvements in energy efficiency brought by research and development activities can be offset by extra energy consumption and relevant emissions caused by the new round of output growth brought about by technical advancement and efficiency increase in the automotive industry [42,43]. Therefore, reducing R&D intensity can help the automotive industry reduce emissions, e.g., by promoting the proportion of R&D investment. However, it is a high-level strategic suggestion to increase R&D investment, while, at the operation level, the suggestion is to strengthen the absorption and application of technology.

Population: Population has always positively correlated with carbon emissions in the automotive industry. With the increase of population and economic development, people's demand for cars is increasing, which promotes emissions. However, according to Figures 6 and 7, compared with the other factors, the impact is relatively weak.

4. Conclusions

The automotive industry is a technology- and capital-intensive industry, which has the largest output value, the longest industrial chain and the largest number of related industries, impacting technology and the economy greatly. However, the rapid development of the automobile industry has adverse impacts on emissions. Therefore, understanding the factors contributing to carbon emission in the automotive industry is paramount due to huge energy consumption of the industry. Investment intensity effect is the biggest driver of the automotive industry; thus, its associated emissions and impact are expected to remain unchanged in the foreseeable future. R&D intensity and energy intensity, as two main contributors to emission reduction, may provide solutions for the optimal development of the automotive industry. Meanwhile, improving energy efficiency and increasing investment in research and development of cleaner production technologies can effectively reduce carbon emissions.

With the introduction of supportive policies such as "the adjustment and revitalization plan of automobile industry (2009)", the automotive industry in China has entered a steady development stage. The focus of development has begun to shift from speed based to quality based considering the overall sustainability of the industry covering economy, environmental protection and energy conservation as the long-term direction. To push forward the sustainable and high-quality development of China's automotive industry, the following policy recommendations are put forward:

1. Optimizing energy structure and promote energy consumption with low emission factors. This includes reducing coal consumption, increasing oil and gas consumption and improving energy efficiency as conducive to reducing carbon emissions. The trend of global energy development is moving from the current diversified structure to the renewable energy dominated structure, gradually realizing the substitution of fossil fuels. This is a long and necessary process, which is conducive to alleviating energy demand and maintaining national energy security.

2. Accelerate the adjustment of product structure and optimize the management structure of the automotive industry. Based on data published by the China Automobile Industry Association, China sold 330,000 new energy vehicles in 2015, surpassing the

US as the world's largest new energy vehicle market. In addition, while the production and sales of traditional internal combustion automobiles have declined, the new energy vehicles maintain a high-speed growth trend. Not surprisingly, this is the inevitable development trend of the automotive industry. In addition, improvement on product structure, from heavy load and high fuel consumption to lightweight, small displacement, intelligent development will further promote the fuel efficiency and reduction in emissions. Furthermore, optimizing the management structure of the industry system is a key to the over capacity of the industry. This includes avoidance of unwise investment, improvement of the industry exit system, enhancing the technical strength of the automotive industry and strengthening scientific and technological research and development.

3. Speed up the development of energy-saving and new energy automobile industry and improve technological research and innovation capability of enterprises. Under the guidance and support of the National "863" Plan (National High-tech Research and Development Plan) and several five-year plans, dramatic advances have been made in the research and development of new energy automotive technology in China and the level of technology research and development has shown a trend of rapid improvement. However, a major problem is a lack of key technologies. Considering the "sailboat effect" of the automotive industry's innovative behavior on new and old technologies, incremental adjustment of old technologies has a greater overall impact on emissions growth [44,45]. Thus, increasing R&D investment is a principled suggestion. However, considering the issues of cost and innovative talents, a more operable suggestion is to strengthen the absorption and application of existing technology and on this basis to enhance technological innovation capability.

4. Promote the automotive industry cluster and realize the integration of production supply chain. Based on the results in Figure 5, at present, China has formed a centralized regional distribution mainly in Shanghai, Jilin, Hubei, Shandong and Guangdong Provinces, among others. However, compared with the major automobile producing countries, the agglomeration degree in China's automotive industry is relatively low. In terms of the spatial layout in the automotive industry and the coordination and cooperation for the supply chain of the automotive industry, it still needs to be further improved according to the local conditions of different regions [46]. In other words, the improvement should be conducted based on the consideration of resources, factor endowments and reasonable spatial distribution, as well as industrial clusters making full use of resources to reduce energy consumption and improve economic efficiency.

Author Contributions: For research articles with several authors, conceptualization, S.H., and W.C.; formal analysis, S.H., and M.M.; writing—original draft preparation, S.H.; project administration, S.H., and W.C.; methodology, J.Y.; validation, J.Y.; data curation, J.Y.; writing—review and editing, J.Y.; visualization, M.M., Z.J., and W.C.; investigation, Z.J.; supervision, W.C.; funding acquisition, W.C. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by the Science and Technology Research Program of Chongqing Municipal Education Commission (Grant No. KJZD-K201903401), Hong Kong Scholars Program (XJ2019059) and the Chongqing Research Program of Basic Research and Frontier Technology (Grant No. cstc2020jcyj-bsh0029).

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Not applicable.

Acknowledgments: This work was supported in part by the Science and Technology Research Program of Chongqing Municipal Education Commission (Grant No. KJZD-K201903401), Hong Kong Scholars Program (XJ2019059) and the Chongqing Research Program of Basic Research and Frontier Technology (Grant No. cstc2020jcyj-bsh0029).

Conflicts of Interest: The authors declare no conflict of interest.

Appendix A

See Tables 2–4 and A1 here.

Table A1. Energy consumption of various energy in China's automotive industry. Unit: 10,000 t.

Energy	2012	2013	2014	2015	2016	2017
Coal	583	562.71	469.7	431	365.72	269.2
Coke	185.01	198.93	162.38	129	123.4	69.2
Crude oil	0.07	0.16	0.02	0.02	0.02	0.06
Gasoline	37.63	32.08	32.92	35.33	36.07	34.65
Kerosene	0.96	0.92	0.65	0.61	0.5	0.43
Diesel oil	45.01	39.05	41	37.97	37	37.8
Fuel oil	1.58	1.26	0.9	0.79	0.53	0.57
Natural gas (10^8 m^3)	14.01	18.46	22.28	19.26	16.96	22.16
Electricity (10^8 kJ)	586.63	673.68	731.32	769.06	834.7	885.42
Heat (10^{10} kJ)	4267.81	4588.2	4543.26	4187.25	3779.05	3901.86

Table 2. Provincial CO_2 emissions of China's automotive industry, 2012–2017. Unit: 10,000 t Coal equivalent.

Province	2012	2013	2014	2015	2016	2017
Shandong	630.2432	785.9357	877.6231	767.1542	702.8319	685.9814
Jiangsu	3.7275	4.4464	2.8590	2.1468	3.4396	0.7957
Jilin	958.8643	1016.3361	716.8166	713.7615	739.0613	770.7695
Inner Mongolia	9.0055	19.4489	24.0729	11.8905	23.7374	23.1426
Ningxia	0.2951	0.3832	0.1008	0.0754	0.0587	0.9494
Sichuan	181.0612	273.1373	308.4789	291.7467	272.6500	295.0512
Zhejiang	390.3511	329.3396	405.9221	438.5492	452.4759	505.3014
Henan	320.3642	341.1315	299.7106	303.0743	292.5888	275.9187
Hubei	579.9682	670.5360	674.1281	694.8552	709.8402	670.9139
Shanxi	64.0545	37.7298	36.4662	27.8137	29.0773	34.4262
Hebei	197.0387	254.7141	269.8103	262.9944	256.1251	256.0007
Heilongjiang	37.3662	121.6389	73.6140	55.2871	113.6138	52.5103
Xinjiang	1.2705	1.9642	3.1056	3.3187	3.2586	3.1561
Shanghai	578.6617	692.3165	734.7439	622.2142	576.8863	689.4864
Hunan	90.8416	96.2960	95.5972	96.7122	109.2542	115.4717
Anhui	171.9065	179.4955	176.4605	190.4403	218.0684	218.4912
Guangxi	214.1003	270.7841	295.1612	292.3949	265.1534	285.6195
Liaoning	229.1775	321.9058	226.4321	263.0390	267.2980	252.6896
Guizhou	12.0626	20.6628	23.6257	27.2646	25.5254	26.9797
Jiangxi	0.459	0.538	0.517	0.530	0.666	0.639
Guangdong	280.2330	306.9948	319.8475	323.0917	415.3030	459.6767
Beijing	244.6330	249.1329	262.7014	279.6929	307.9053	298.5189
Tianjin	236.9560	268.0446	263.4341	10.7135	311.7734	303.2824
Fujian	104.6115	112.4638	116.0030	108.5183	106.7801	113.0429
Chongqing	84.2533	80.0941	83.1771	72.3129	80.5734	68.6135
Yunnan	34.7981	34.0271	37.0046	12.6691	12.7908	14.2041
Shaanxi	107.4960	110.0329	140.6076	118.6492	109.4302	139.8458
Gansu	3.7275	4.4464	2.8590	2.1468	3.4396	0.7957
Hainan	16.0860	13.3868	12.6699	8.1860	6.5383	5.0915
Qinghai	0.1334	0.5802	0.2668	0.3341	0.0863	0.2961
Tibet	0.0690	0	0	0	0	0

Note: The CO_2 emission of Tibet's automobile manufacturing industry is too small, so the value of 0 is used instead.

Table 3. The factor of CO_2 power generation and heating emission.

	Power Generation Factor (10^4 $CO_2/10^7$ kWh)	Heating Emission Factor (10^4 $CO_2/10^{10}$ kJ)
2012	0.713	0.136
2013	0.710	0.124
2014	0.678	0.121
2015	0.631	0.122
2016	0.648	0.123
2017	0.649	0.124

Table 4. Emission factors and geographical boundaries of different power grids (National Development and Reform Commission (NDRC), 2014).

Region.	CO_2 Emission Factor		Geographical Boundaries of Covered Areas
	2011	2012	
Northeastern China	0.8189	0.7769	Liaoning, Jilin, Heilongjiang,
Northwestern China	0.6860	0.6671	Shaanxi, Gansu, Qinghai, Ningxia, Xinjiang
Central China	0.5955	0.5257	Henan, Hubei, Hunan, Jiangxi, Sichuan, Chongqing
Northern China	0.8967	0.8843	Beijing, Tianjin, Hebei, Shanxi, Shandong, Inner Mongolia
Eastern China	0.7129	0.7035	Shanghai, Jiangsu, Zhejiang, Anhui, Fujian
Southern China	0.5748	0.5271	Guangdong, Guangxi, Yunnan, Guizhou, Hainan

Note: The latest data are updated to 2012 so that emissions after 2012 were calculated based on CO_2 emission factors of 2012.

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