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Carbon Productivity: Findings from Industry Case Studies in Beijing

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Abstract: Simultaneously protecting the environment and promoting the economy are two critical dimensions for sustainable development. Carbon productivity is popularly used in assessing the environmental and economic efficiency over time, and is deemed as the appropriate indicator of sustainable development. Given the prominent contribution of energy consumption to sustainable development, this study incorporates energy consumption into the Log Mean Divisia Index (LMDI) decomposition model to explore the main factors influencing carbon productivity change. Based on the data from 19 industries in Beijing from 2013 to 2016, this study then reports the carbon productivities and their changes. Energy productivity change is the main cause of carbon productivity changes, and its correlation with carbon productivity change is significantly positive, whereas there is a weak correlation and no significant difference in energy consumption per unit of carbon emissions. Although the average carbon productivities in all 19 industries increased year over year in Beijing, the average level could be further promoted by improving energy productivity. The carbon productivities of the primary and secondary industries are less than the average, and far below the tertiary industry level. For the primary industry, increasing economic levels is conducive to improving carbon productivity; for secondary industry, reducing energy consumption and enhancing energy efficiency are most effective; and for tertiary industry, maintaining an outstanding performance will guarantee sustainable development in Beijing. This study has defined carbon productivity change from the energy consumption perspective and for the first time, comprehensively measured it for all industries in Beijing. The results are expected to assist these industries to essentially improve productivity performance and thus improve development sustainability.

Keywords: negative externalities; carbon productivity; industrial structure; energy productivity; Logarithmic Mean Divisia Index (LMDI)

1. Introduction

Extreme climate change calls for worldwide efforts to cut down carbon dioxide (CO_2) emissions and globally realize sustainable development. Regional and national actions to solve the environmental problems caused by climate change have continued to progress. In the Paris Agreement, the goal of maintaining the global average temperature increase at well below 2 °C and to hold the increase to 1.5 °C, was recognized by the participants [1]. In 2017, during the United Nations Climate Change Conference held in Bonn, Germany, details of the Paris Agreement execution after implementation in 2020 were discussed, and other plans for combating climate change were also implemented [2]. Governments are striving to balance CO_2 reduction and economic development, and they are strictly regulating the principles of a circular economy to promote the transition to more sustainable development [3–6]. The relationship between carbon emissions and economic growth is connected by the relationship between energy consumption and economic growth [7,8]. Energy consumption is usually linked to a high level of emissions and pollution [9]. Data from the International Energy Agency (IEA) reported that global energy-related CO_2 emissions grew by 1.4% in 2017, reaching a historical high of 32.5 gigatonnes (Gt) [10]. Energy consumption is of great importance for sustainable development.

In parallel to international attempts, the Chinese government pledged to reduce the CO_2 per unit of its gross domestic product (GDP) by 40–45% before the Copenhagen Conference. In the latest "Thirteenth Five-Year Plan" issued by the National Development and Reform Commission (NDRC), China declared its goal to further reduce its unit GDP CO_2 emissions by 18% by the end of 2020, with 2015 as the base year [11]. However, China's energy consumption rose by 3.1% in 2017, ranking China as the largest growth market for energy for the 17th consecutive year [12], and its carbon emissions increased by 1.7% in 2017, which is 1% higher than the 2014 level [10]. Along with sustainable medium-to-high economic growth under a new normal, total energy consumption has increased gradually from 2000 to 2016 in China, as shown in Figure 1. Energy-related carbon emissions will inevitably increase in the following years, which is a serious challenge for Chinese sustainable development. Therefore, this is a critical point in the Chinese government plan to manage carbon emissions without negatively influencing productivity improvement.

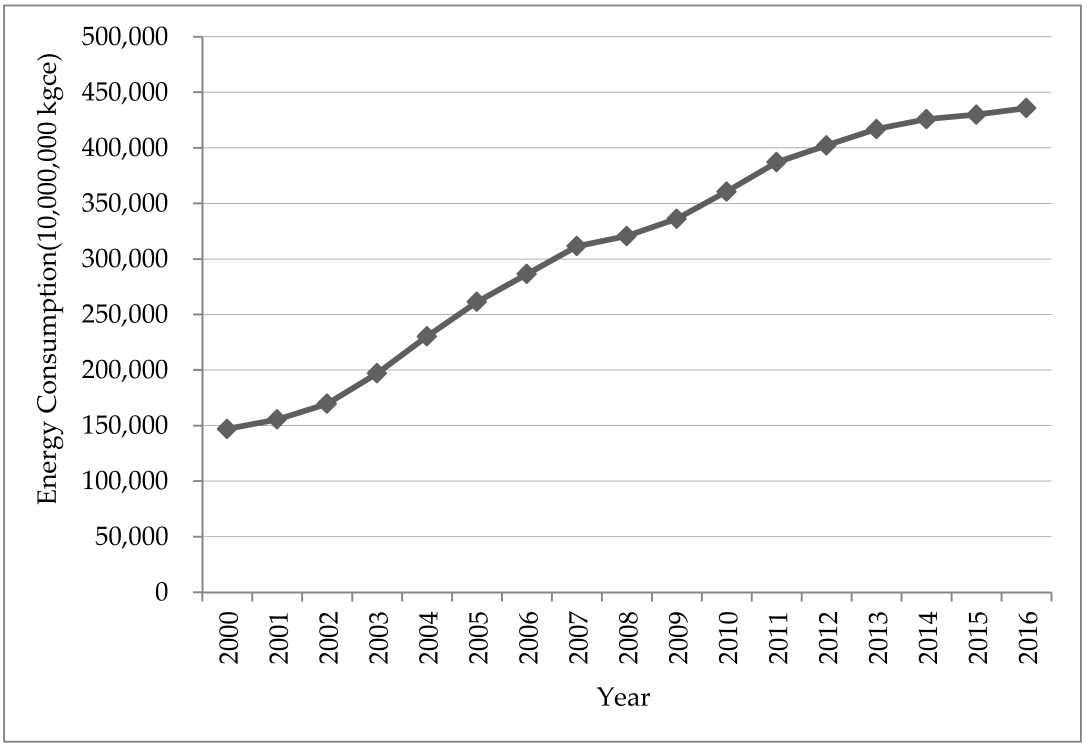

Figure 1. Total energy consumption in Beijing. Source: China Statistics Yearbook (2017).

The usual concept of productivity is defined as the ratio of the outputs produced to the inputs consumed [13,14]. Outputs are mainly economic results, such as services, goods, and added values, while input resources usually consist of labors and capitals. Productivity is an important indicator of how the inputs are effectively transformed into outputs, and thus becomes a hot topic in academia (for example, Park et al. [15], Li and Liu [16], and Gopinath et al. [17]). Furthermore, with the increasing emphasis on sustainable development, more attention has been paid to evaluating productivity in conjunction with carbon emissions. Under this circumstance, pollutants such as carbon emissions have been treated as inputs [18,19].

However, to the best of our knowledge, no existing study investigates a comprehensive understanding of productivity improvement with carbon emissions reduction in all industries of one city. Consequently, this study attempts to assess productivity in relation to carbon emissions for all industries in Beijing from 2013 to 2016. Productivity related to carbon emissions is carbon productivity, which is an effective combination index of environmental protection and economic development. Thus, based on the concept of productivity, this study has defined carbon productivity change from the energy consumption perspective, and explored carbon productivities and their changes of all industries in Beijing during 2013–2016.

We chose Beijing as the case study for our analysis on account of the following reasons. First, Beijing, the capital of China, suffers from serious pollution in the process of development [20]. Like most of the capitals in the world, Beijing was also confronted with huge energy consumption and carbon emissions under the rapid development of urbanization and industrialization. Although Beijing has fulfilled its pollution reduction target outlined in the national "Thirteenth Five-Year Plan" ahead of schedule, Beijing's air quality fails to meet national standards in particulate matter under 2.5 μm and under 10 μm in diameter ($PM_{2.5}$ and PM_{10}, respectively) [21]. The research results in Beijing could be a valuable reference for cities in other countries.

Second, the approach of productivity improvement related to carbon emissions in Beijing could offer some implications available for other cities in China. Since Chairman Xi introduced the new orientation of Beijing in 2014, Beijing has accumulated lots of experience in weakening non-capital function, optimizing the economic structure, upgrading and transferring its industrial structure, scientifically allocating resources, and realizing sustainable development. As seen from Figure 2, Beijing's gross domestic product (GDP) proportion in China changed less from 2000 to 2016, whereas energy consumption proportion decreased more. Thus, compared with other cities in China, Beijing managed the energy consumption without discouraging economic growth. Research on Beijing is of great significance to the whole country.

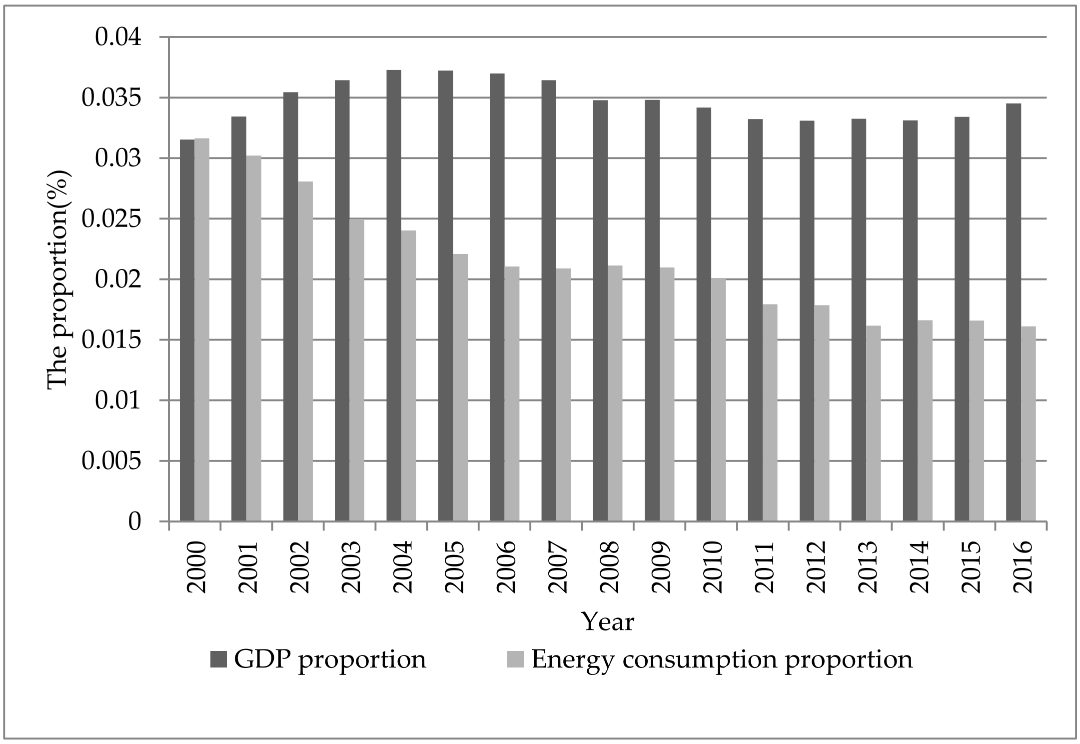

Figure 2. Beijing GDP and energy consumption proportion in China. Source: Elaboration on China Statistics Yearbook (2017).

Third, Beijing is planning to curb environmental pollution problems. Given the available energy saving and coping strategies for climate change in Beijing's "Thirteenth Five-Year Plan", Beijing intends to control energy consumption, as well as the quantity and intensity of carbon dioxide emissions, and aims for the per unit GDP of carbon dioxide emissions to fall by 20.5% from the base of 2015 by 2020 [22]. A specific reduction target has already been distributed to different industries. Moreover, Beijing's carbon emissions trading system started a pilot study in 2013, aiming to adopt a market mechanism to solve pollution problems. It is anticipated that these measures to deal with environmental problems are valuable to China and even the world.

Therefore, understanding carbon emissions and the development of different industries in Beijing are crucial to improving environmental protection and promoting economic development. Research results from this study present approaches of simultaneously slowing down greenhouse gas emissions and promoting the development of the economy for cities in China and worldwide.

This paper is organized as follows: Section 2 provides a literature review; Section 3 presents the methodology and data, and introduces a carbon emissions estimation, a carbon productivity decomposition method, and a decomposition of carbon productivity change; the empirical results are discussed in Section 4; and Section 5 concludes the paper.

2. Literature Review

Carbon productivity is defined as the corresponding economic outputs of per unit carbon dioxide emissions [23], and it assesses the impact of the negative environmental externalities of a region, sector, or industry on economic development. Compared with the per unit economic outputs of carbon dioxide (or the carbon emission intensity), carbon productivity represents the efficiency of carbon emissions, and it places more emphasis on environmental and economic efficiency [24,25]. Therefore, the improvement in carbon productivity could be defined as "doing the right thing" and "doing things right". Doing the right thing means increasing the economic output, and doing things right means reducing carbon emissions [19].

After the concept of carbon productivity was introduced, a range of studies applied the concept to China's carbon emissions and economic development. These studies basically analyzed the carbon productivity of the main industries in China. Industrial production, especially energy-intensive industries, produced most of the CO_2 in China [26]; thus, carbon productivity research originates from industry. Considerable differences were observed in the industrial carbon productivity in 30 provinces in China, and industrial productivity was significantly and positively correlated with industrial energy efficiency, openness, technological progress, and industrial-scale structure [27]. Technological progress has played a vital role in the improvement of carbon productivity in the industrial sectors [28]. For capital- and technology-intensive industrial sectors, optimization of the industrial structure can improve carbon productivity; for resource intensive sectors, foreign direct investment (FDI) and energy consumption structure may work; and for labor intensive sectors, the approach could focus on the industrialization levels [29]. Li et al. [30] furthered the concept of carbon productivity in industry to total factor carbon productivity, and proposed that the difference among the sectors is significant, and that technology innovation plays a dominant role in the growth of industry. In energy-intensive industries, at least one-quarter of China's carbon emissions are produced by the power industry, which mostly directly relies on fossil fuels, and its energy consumption has been rising [31]. The carbon productivity in the power industry of the 30 provinces in China could be improved by power transfers among provinces, imports and exports, the emission intensity of power consumption, and regional electrical carbon productivity [32]. Specifically, the carbon productivity of coal-fired power plants increased during 1999–2008 for state- and non-state-owned power plants [33]. The carbon productivity of the transport industry increased by 4% from 2000 to 2012, and pure efficiency changes led to the growth in carbon productivity in Eastern China, whereas in Central China, the driving factor was transport innovation in low-carbon technology [34]. Carbon productivity in the service industry showed an increasing trend in China, with technological progress as the main driving factor [35]. Some studies have focused on the carbon productivity of several industries. For example, Lu et al. [36] reported the carbon productivity of six major industries in China. However, there are few studies that have related the carbon productivity of all the industries in a single city.

Due to its desirable properties, such as ease of application, perfect theoretical foundation, and adaptability [24,37], the Logarithmic Mean Divisia Index (LMDI) method is widely employed to perform decomposition in energy consumption [38,39] and carbon emissions [40–43]. Some carbon productivity studies are grounded in the LMDI factor decomposition method. We envisage the primary factors in carbon productivity decomposition to be as follows: regional structure [13,32,36,44,45], energy intensity [31,32,36], and technological innovation [13,44,45]. Against this background, to examine carbon productivity and its change in Beijing, we incorporate a novel decomposition factor with LMDI to address the factors influencing carbon productivity for all industries.

This study provides three primary contributions to the carbon productivity literature. Firstly, this study extends the research on carbon productivity to 19 industries at the province level. We thoroughly investigated the carbon productivities of 19 industries in Beijing, and revealed the trends, the main influencing factors, and the differences. Secondly, we opt to employ energy productivity to decompose carbon productivity. The regional change effect is small at the province level among industries. Due to the inherent economic cycle, the gross domestic product cannot change much over a short time, so the carbon productivity is mainly determined by the carbon emissions, which entirely depend on energy consumption. Thus, different from the aforementioned literature, energy productivity is introduced as a key factor in carbon productivity decomposition. Thirdly, we extend the data to examine Beijing's 19 industries from 2013 to 2016, in order to estimate the direct and indirect carbon emissions, and to precisely reflect the characteristics of carbon productivity.

In doing so, the trends of carbon productivity in different industries in Beijing are illuminated based on carbon emissions estimation, and the Logarithmic Mean Divisia Index method is adopted to decompose the factors in carbon productivity, explore the factors affecting carbon productivity, and argue the potential reasons for those changes. After finding the main factor influencing Beijing carbon productivity change, the empirical results are reported for the 19 industries. Figure 3 shows the research process of this study.

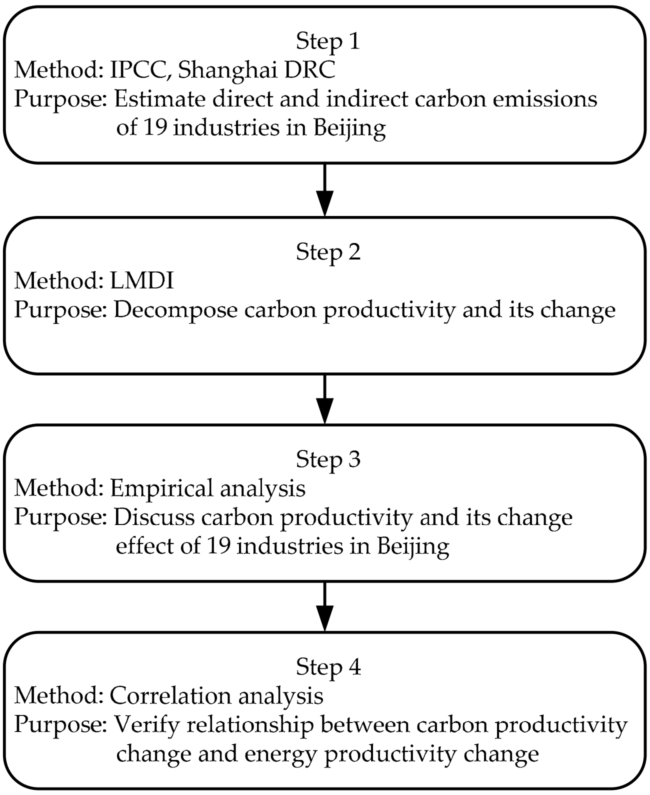

Figure 3. Overview of this study. IPCC: Intergovernmental Panel on Climate Change; DRC: Development and Reform Commission; LMDI: Log Mean Divisia Index.

3. Methodology and Data

3.1. Direct Carbon Emissions Estimation

The method we use to estimate direct carbon dioxide emissions (DCO_2) is provided in the National Greenhouse Gas Inventory Guidelines (2006), prepared by the United Nations Intergovernmental Panel on Climate Change (IPCC) [46], which is written as follows:

$$DCO_2 = \sum_i CO_{2,i} = \sum_i E_i \times NCV_i \times CEF_i \times COF_i \times (44/12) \quad (1)$$

where $CO_{2,i}$ is the carbon emission of consumption of the energy source i; E_i is the amount of energy consumed; NCV_i and CEF_i are the average low calorific value and carbon emission coefficient, respectively; COF_i is the carbon oxidation factor; and 44 and 12 are the molecular weights of carbon dioxide and carbon, respectively.

When calculating carbon emissions using the IPCC approach in Equation (1), the carbon emissions are likely overestimated in China [47]. Therefore, we appropriately change the calculation of carbon dioxide emissions directly caused by the consumption of seven fossil energy types in 19 industries. We only keep the carbon emission coefficient provided by the 2006 IPCC Guidelines, and we change all other variables in Equation (1). Though the IPCC does not have a coefficient for coal, we observed that the proportion of different types of coal in China's coal production is fixed in the long term, and the proportion of bituminous coal is always around 75–80%. Thus, prompted by Chen S. [48], we substitute the weighted average of bituminous coal and anthracite with the ratio of 80% and 20% for the coal coefficient, respectively.

3.2. Indirect Carbon Emissions Estimation

For the accurate estimation of indirect carbon dioxide emissions ($IDCO_2$) from the consumption of heat and electricity in various industries, we use the method in the Shanghai Greenhouse Gas Emission Accounting and Reporting Guidelines (2012) issued by the Shanghai Development and Reform Commission (DRC) [49], which is:

$$IDCO_2 = IC \times CF \quad (2)$$

where IC is the consumption of heat and electricity by different industries, and CF is the carbon emission factor of heat and electricity.

3.3. Carbon Productivity Decomposition Using LMDI

Carbon productivity is defined as the corresponding amount of GDP produced per unit carbon dioxide emissions [23,50], which is considered as:

$$CP_i^t = \frac{Y_i^t}{C_i^t} \quad (3)$$

where i $(i = 1, \cdots, 19)$ is the number of industries in Beijing; t is time; CP_i^t is the carbon productivity; and Y_i^t and C_i^t are the gross added value and carbon emissions, respectively, of industry i in year t.

We introduce the most important factor (energy) into the decomposition of carbon productivity to conduct our analysis. We define energy productivity (or energy efficiency) as the amount of GDP produced per unit energy consumption, $EP_i^t = \frac{Y_i^t}{E_i^t}$, where E_i^t is the amount of energy consumption of industry i in year t. $CE_i^t = \frac{E_i^t}{C_i^t}$ is the corresponding amount of energy consumption per unit carbon emissions.

After introducing the energy factor, the carbon productivity can be written as:

$$CP_i^t = \frac{Y_i^t}{C_i^t} = \frac{Y_i^t}{E_i^t}\frac{E_i^t}{C_i^t} \tag{4}$$

Equation (4) is also expressed by $CP_i^t = EP_i^t \cdot CE_i^t$, with the carbon productivity being equal to the product of the energy productivity and the energy consumption per unit of carbon emissions.

Solving the derivative of Equation (4) to explore the change in CP_i^t along with time t, we obtain Equation (5):

$$\frac{dCP_i^t}{dt} = \frac{d\frac{Y_i^t}{E_i^t}}{dt}\frac{E_i^t}{C_i^t} + \frac{Y_i^t}{E_i^t}\frac{d\frac{E_i^t}{C_i^t}}{dt} \tag{5}$$

where $\frac{dCP_i^t}{dt}$, $\frac{d\frac{Y_i^t}{E_i^t}}{dt}$ and $\frac{d\frac{E_i^t}{C_i^t}}{dt}$ denote the change in carbon productivity, energy productivity, and energy consumption per unit of emissions over time, respectively. Consequently, Equation (5) indicates that the change in CP_i^t over time could be decomposed into the change in energy productivity and energy consumption per unit of carbon emissions over time. The economic meaning of each factor is summarized in Table 1.

Table 1. Definition of each factor used in our analysis.

Factor	Meaning	Abbreviation
$\frac{Y_i^t}{C_i^t}$	Carbon productivity	CP_i^t
$\frac{Y_i^t}{E_i^t}$	Energy productivity	EP_i^t
$\frac{E_i^t}{C_i^t}$	Energy consumption per unit carbon emissions	CE_i^t
$CP_i^n - CP_i^m$	Effect of carbon productivity change	$\Delta CP_i^{(m,n)}$
$\omega_{i1}(EP_i^n - EP_i^m)$	Effect of energy productivity change	$\Delta EP_i^{(m,n)}$
$\omega_{i2}(CE_i^n - CE_i^m)$	Effect of energy consumption per unit carbon emissions	$\Delta CE_i^{(m,n)}$

3.4. Decomposition Factors of Carbon Productivity Change

In order to study the change in carbon productivity in the different industries, we analyze the absolute change in the carbon productivity from period m to n and the factors incurring these changes.

The absolute change in carbon productivity can be demonstrated as follows:

$$\begin{aligned}\Delta CP_i^{(m,n)} = CP_i^n - CP_i^m &= \int_m^n \frac{dCP_i^t}{dt}dt = \int_m^n \left(\frac{d\frac{Y_i^t}{E_i^t}}{dt}\frac{E_i^t}{C_i^t} + \frac{Y_i^t}{E_i^t}\frac{d\frac{E_i^t}{C_i^t}}{dt}\right)dt \\ &= \int_m^n \frac{E_i^t}{C_i^t}\frac{d\frac{Y_i^t}{E_i^t}}{dt}dt + \int_m^n \frac{Y_i^t}{E_i^t}\frac{d\frac{E_i^t}{C_i^t}}{dt}dt\end{aligned} \tag{6}$$

The change in CP_i^t from period m to n is decomposed into two parts, both expressed as integrals. However, on the right of Equation (6), the integrand in the two integrals is a function of time, and the time data are discrete in this paper. Therefore, we adopt the LMDI algorithm transformation [51] to calculate the two parts of the change on the right-hand side.

Let $L(x,y) = \begin{cases} \frac{x-y}{lnx-lny}, & x \neq y \\ x, & x = y \end{cases}$, substitute $\omega_{i1} = \frac{L(\frac{Y_i^m}{C_i^m}, \frac{Y_i^n}{C_i^n})}{L(\frac{Y_i^m}{E_i^m}, \frac{Y_i^n}{E_i^n})}$, $\omega_{i2} = \frac{L(\frac{Y_i^m}{C_i^m}, \frac{Y_i^n}{C_i^n})}{L(\frac{E_i^m}{C_i^m}, \frac{E_i^n}{C_i^n})}$ for $\frac{E_i^t}{C_i^t}$, $\frac{Y_i^t}{E_i^t}$, and then Equation (6) is simplified as:

$$\Delta CP_i^{(m,n)} = CP_i^n - CP_i^m = \omega_{i1}\left(\frac{Y_i^n}{E_i^n} - \frac{Y_i^m}{E_i^m}\right) + \omega_{i2}\left(\frac{E_i^n}{C_i^n} - \frac{E_i^m}{C_i^m}\right) = \omega_{i1}(EP_i^n - EP_i^m) + \omega_{i2}(CE_i^n - CE_i^m)$$

Let $\Delta EP_i^{(m,n)} = \omega_{i1}(EP_i^n - EP_i^m)$ and $\Delta CE_i^{(m,n)} = \omega_{i2}(CE_i^n - CE_i^m)$ be the change in energy productivity and energy consumption per unit of carbon emissions, respectively, from the year m to n in industry i. Then, the equation can be written as:

$$\Delta CP_i^{(m,n)} = \Delta EP_i^{(m,n)} + \Delta CE_i^{(m,n)} \quad (7)$$

which means that the change in CP_i^t from period m to n is decomposed into two influencing factors: change in energy productivity and energy consumption per unit of carbon emissions. Accordingly, $\frac{\Delta EP_i^{(m,n)}}{\Delta CP_i^{(m,n)}}$ and $\frac{\Delta CE_i^{(m,n)}}{\Delta CP_i^{(m,n)}}$ are the contribution ratios of the parts to the overall change. Equation (7) is used for an empirical analysis in the following sections. The economic meaning of each factor is summarized in Table 1. Table 2 outlines the purpose of each equation.

Table 2. The purpose of each equation.

Equation Number	Motivation
(1)	Direct carbon emissions estimation
(2)	Indirect carbon emissions estimation
(3)	Carbon productivity definition
(4)	Rewritten form of definition
(5)	Derivative of definition
(6)	Carbon productivity change in integral
(7)	Absolute change in carbon productivity

3.5. Data Sources

Given the Chinese national standard for national economy industry classification in 2017 [52], we select 19 industries of Beijing and divide them into primary industry (industry 1), secondary industry (industries 2–5), and tertiary industry (industries 7–19).

For estimating the direct carbon emissions, we choose seven energy sources: coal, petrol, kerosene, diesel oil, fuel oil, liquefied petroleum gas (LPG), and natural gas. As the data for coke and liquefied natural gas were incomplete in some years, and their consumption was zero in most industries, we delete these two sources of energy for ease of comparability. The rate of consumption of the seven energy sources was obtained from Beijing Statistical Yearbook (2014–2017) [53]. The average low calorific values were directly sourced from the China Energy Statistics Yearbook (2017) [54]. The carbon emission coefficient was provided by the 2006 IPCC Guidelines, except for the coal coefficient. The carbon oxidation factors were sourced from the Handbook of Provincial Greenhouse Gas Inventories (2011) issued by the NDRC [55]. The above seven types of energy-related parameters are shown in Table 3. Then, based on Equation (1), the direct carbon emissions of the 19 industries during 2013–2016 are calculated.

Table 3. Energy-related parameters. LPG: Liquefied Petroleum Gas.

Energy Source	Average Low Calorific Value (KJ/kg, KJ/m^3)	Carbon Emission Coefficient (kgC/GJ)	Carbon Oxidation Factor
Coal	20,908.00	26.36	0.93
Petrol	43,070.00	18.90	0.98
Kerosene	43,070.00	19.60	0.98
Diesel	42,652.00	20.20	0.98
Fuel Oil	41,816.00	21.10	0.98
LPG	50,179.00	17.20	0.98
Natural Gas	38,931.00	15.30	0.99

Source: Own elaboration.

For calculating indirect carbon emissions, the consumption of heat and electricity in the different industries was obtained from the Beijing Statistical Yearbook (2014–2017), and the carbon emission factors for heat and electricity were provided by the Shanghai Greenhouse Gas Emission Accounting and Reporting Guidelines (2012) (Table 4). Using Equation (2), we obtain the indirect carbon emissions of the 19 industries in Beijing.

Table 4. Carbon emission factors for heat and electricity

Category	Carbon Emission Factor
Heat Emission Factor	0.11 t CO_2/GJ
Electricity Emission Factor	7.88 t CO_2/ 10^4 kWh

Source: Own elaboration.

Table 5 displays the total carbon emissions of the 19 industries in Beijing from 2013 to 2016.

Table 5. Total carbon dioxide emissions in Beijing (2013–2016) (unit: 10,000 tons).

Industry	2013	2014	2015	2016
Agriculture, Forestry, Animal Husbandry, Fishery	251.33	239.22	225.74	218.01
Mining	57.88	59.30	47.15	40.34
Manufacturing	2597.06	2502.57	2355.16	2326.65
Production and Supply of Electricity, Gas and Water	4245.20	4109.56	3886.07	3916.32
Construction	313.28	308.79	295.85	296.63
Wholesale and Retail	488.35	506.68	524.61	556.16
Transportation, Warehousing and Postal Services	2468.11	2594.01	2659.29	2784.53
Accommodation and Catering	676.46	701.72	721.31	689.08
Information Transmission, Software and Information Technology Services	363.10	402.55	457.77	508.05
Finance	165.60	187.08	187.60	182.44
Real Estate	939.56	939.54	950.21	976.13
Leasing and Business Services	480.39	538.51	506.91	529.34
Scientific Research and Technical Service	404.47	409.01	446.86	497.18
Water Conservancy, Environment and Public Facilities Management	132.49	154.47	154.13	162.73
Inhabitant Service, Repair and Other Service	97.85	83.34	78.03	79.97
Education	526.37	564.37	578.47	559.95
Healthcare and Social Work	200.44	215.57	216.67	222.02
Culture, Sport and Entertainment	162.04	174.94	196.69	207.68
Public Administration, Social Security and Social Organization	310.00	313.25	305.74	295.60

Source: Own elaboration.

The added values of the 19 industries were also sourced from the Beijing Statistical Yearbook (2014–2017).

4. Empirical Analysis

4.1. Trends in Carbon Productivity

Based on Equation (3), we calculate the carbon productivities of the 19 industries from 2013 to 2016, and we present the results in Table 6. From Table 6, the finance industry distinguished itself among the 19 industries, and it ranked first over the four consecutive years from 2013 to 2016.

Although the average carbon productivity of the 19 industries in Beijing showed a steady upward trend (Figure 4), the increase was not prominent, and the annual growth rate was about 4.89%. The carbon productivity of the primary industry was the lowest and its change was tiny over the four years, and the carbon productivity declined slowly after 2014. The carbon productivity of secondary industry was far below the average level, and formed a trend of gradual improvement, and then a sharp decline, with carbon productivity falling 13.38% in 2015–2016. The carbon productivity of tertiary industry was outstanding; it was not only much higher than the primary, secondary, and average values, but also increased steadily from 2013 to 2016, with an average annual growth rate of 6.21%.

Table 6. The carbon productivities of 19 industries in Beijing (2013–2016) (unit: 10,000 yuan per ton).

Industry	2013	2014	2015	2016
Agriculture, Forestry, Animal Husbandry, Fishery	0.6446	0.6751	0.6326	0.6064
Mining	3.0165	3.0305	3.2303	1.8443
Manufacturing	1.0920	1.1715	1.2429	1.3500
Production and Supply of Electricity, Gas and Water	0.1533	0.1820	0.1933	0.2072
Construction	2.6787	2.9499	3.2513	3.4572
Wholesale and Retail	4.7931	4.7586	4.4839	4.2666
Transportation, Warehousing and Postal Services	0.3533	0.3656	0.3702	0.3810
Accommodation and Catering	0.5541	0.5184	0.5512	0.5796
Information Transmission, Software and Information Technology Services	5.2368	5.3064	5.3343	5.5227
Finance	17.7725	17.9489	20.9302	23.4093
Real Estate	1.4257	1.415	1.5138	1.7136
Leasing and Business Services	3.2678	3.1662	3.4935	3.4728
Scientific Research and Technical Service	4.4087	4.9434	4.9819	5.0525
Water Conservancy, Environment and Public Facilities Management	0.9133	0.8921	1.1821	1.2561
Inhabitant Service, Repair and Other Service	1.4297	1.8599	1.8301	1.9970
Education	1.5799	1.6468	1.8072	2.0952
Healthcare and Social Work	2.0799	2.1756	2.6699	2.8673
Culture, Sport and Entertainment	2.7808	2.6907	2.6849	2.7220
Public Administration, Social Security and Social Organization	1.8797	1.8416	2.4050	2.7493

Source: Own elaboration.

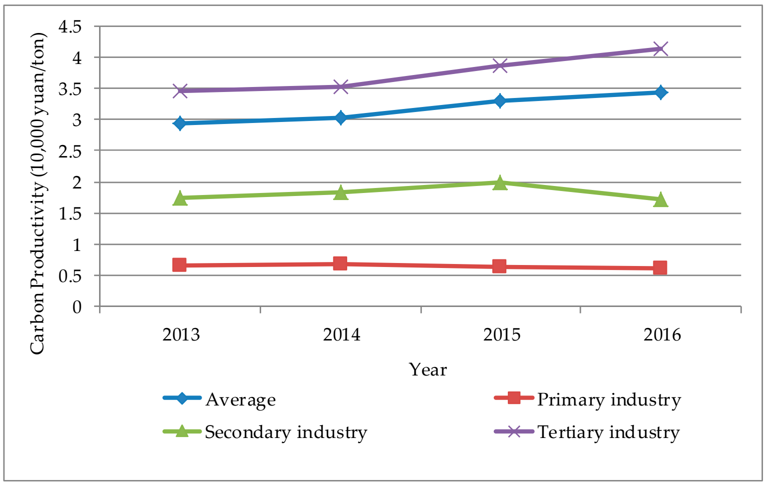

Figure 4. Carbon productivities of different industries in Beijing (2013–2016).

In the secondary industries, the carbon productivity of mining declined significantly in 2016. In the tertiary industries, the carbon productivity of finance was excellent, and increased steadily in 2013–2016, with the average carbon productivity reaching 200,200 yuan/ton, far exceeding the average value of 32,500 yuan/ton in the other Beijing industries. Its added value had an extraordinary performance and developed very well. Coupled with lower carbon dioxide emissions, finance had the best carbon productivity. Information transmission, software, and information technology services, as well as the scientific research and technology services, closely followed finance; their carbon productivities improved steadily in 2013–2016, with average carbon productivity of 53,300 yuan/ton and 48,400 yuan/ton, respectively. The carbon productivity of wholesale and retail slowed during the study period.

4.2. Decomposition Factors of Carbon Productivity Change

The change in carbon productivity is computed and decomposed according to Equation (7). The change effect of *CP*, *EP*, and *CE* is displayed in Tables 7 and 8.

Table 7. Change effect of carbon productivity in Beijing (2013—2016).

Industry	Sector	2013–2014	2014–2015	2015–2016
Primary Industry	Agriculture, forestry, animal husbandry, fishery	0.030	–0.043	–0.026
Secondary Industry	Mining	0.014	0.199	–1.386
	Manufacturing	0.079	0.071	0.107
	Production and Supply of Electricity, Gas and Water	0.029	0.011	0.014
	Construction	0.272	0.302	0.206
	Average Value	0.099	0.146	–0.265
Tertiary Industry	Wholesale and Retail	–0.034	–0.275	–0.217
	Transportation, Warehousing and Postal Services	0.012	0.005	0.011
	Accommodation and Catering Services	–0.035	0.032	0.029
	Information Transmission, Software and Information Technology Service	0.069	0.028	0.188
	Finance	0.176	2.982	2.479
	Real Estate	–0.011	0.099	0.200
	Leasing and Business Services	–0.102	0.327	–0.021
	Scientific Research and Technology Services	0.535	0.038	0.071
	Water Conservancy, Environment and Public Facilities Management	–0.021	0.290	0.074
	Residential Services, Repairs and Other services	0.430	–0.030	0.167
	Education	0.067	0.160	0.288
	Healthcare and Social Work	0.096	0.494	0.198
	Culture, Sport and Entertainment	–0.090	–0.005	0.037
	Public Administration, Social Security and Social Organization	–0.038	0.563	0.344
	Average Value	0.075	0.336	0.275

Source: Own elaboration.

Table 8. The change effect of *EP* and *CE* in different industries (2013–2016).

Industry	**Change Effect of *EP***			**Change Effect of *CE***		
	2013–2014	**2014–2015**	**2015–2016**	**2013–2014**	**2014–2015**	**2015–2016**
Agriculture, forestry, animal husbandry, fishery	0.045	–0.018	0.016	–0.015	–0.025	–0.042
Mining	0.540	0.217	–1.402	–0.526	–0.018	0.016
Manufacturing	0.088	0.078	0.145	–0.009	–0.007	–0.038
Electricity, Gas and Water Production and Supply	0.024	–0.003	0.008	0.005	0.014	0.006
Construction	0.228	0.250	0.175	0.044	0.052	0.031
Wholesale and Retail	0.010	–0.295	–0.308	–0.044	0.020	0.091
Transportation, Warehousing and Postal Services	0.010	0.006	0.011	0.002	–0.001	0.000
Accommodation and Catering Services	–0.042	0.028	0.063	0.007	0.004	–0.034
Information Transmission, Software and Information Technology Service	0.068	0.062	0.300	0.001	–0.034	–0.112
Finance	0.051	3.549	2.947	0.125	–0.567	–0.468
Real Estate	–0.029	0.115	0.243	0.018	–0.016	–0.043
Leasing and Business Services	–0.271	0.330	–0.083	0.169	–0.003	0.062
Scientific Research and Technology Services	0.508	0.253	0.040	0.027	–0.215	0.031
Water Conservancy, Environment and Public Facilities Management	–0.017	0.333	0.105	–0.004	–0.043	–0.031
Residential Services, Repairs and Other services	0.588	0.032	0.189	–0.158	–0.062	–0.022
Education	0.089	0.154	0.375	–0.022	0.006	–0.087
Healthcare and Social Work	0.143	0.476	0.343	–0.047	0.018	–0.145
Culture, Sport and Entertainment	–0.058	0.056	0.110	–0.032	–0.061	–0.073
Public Administration, Social Security and Social Organization	–0.056	0.569	0.468	0.018	–0.006	–0.124

Source: Own elaboration.

Given the change effect in carbon productivity in different years, overall, carbon productivity in Beijing tended to improve. In 2013–2014, only seven out of the 19 industries' changes were negative, and only four industries' changes were negative in 2014–2015 and 2015–2016.

From the industrial structure perspective, carbon productivities in the primary industry turned negative in 2014; in the secondary industry, they became negative as of 2015; while the tertiary industry's carbon productivity changes were always positive in 2013–2016. The carbon productivity of the tertiary industry consistently grew.

The carbon productivity of agriculture, forestry, animal husbandry, and fishery (the primary industry) decreased remarkably during 2014–2016. In the secondary industries, only mining negatively changed in 2015–2016, showing that, except for the mining industry, the carbon productivity of all other industries improved year over year from 2013 to 2016. Although the overall average change in carbon productivity was positive in tertiary industries, the carbon productivities of several industries were in decline, such as the wholesale and retail industry, which had negative changes in carbon productivity over the three years. The carbon productivity of wholesale and retail was dropping. This was the only industry out of the 19 industries with a negative three-year change. After a decline in 2013–2015, the carbon productivity in culture, sports, and entertainment began to rise in 2015–2016, whereas changes in carbon productivity for leasing and business services constantly fluctuated.

What caused these changes in carbon productivity in the different industries? Previous analysis showed that changes in carbon productivity can be decomposed into the change in *EP* and the change in *CE*. Therefore, the relationship of these two factors with changes in carbon productivity is discussed in the following stage.

As seen from Table 8, the average contributions (average change effect) of the *EP* of the 19 industries in 2013–2014, 2014–2015, and 2015–2016 were 0.101, 0.326, and 0.197, respectively. They were all positive, indicating that the change effect of the energy productivity on carbon productivity increased continuously. Although the average contribution ratio dropped from 3.124 to 0.623 in 2013–2015, it rebounded rapidly to 1.382 in 2015–2016. Overall, a strong correlation was observed between the change in *EP* and the change in *CP* in the industries.

Table 9 presents the change effect of *EP* and *CE* in detail from the industrial structure. The change effect of *EP* in the tertiary industry was positive throughout 2013–2016, which meant that the change in *EP* in the tertiary industry positively promoted carbon productivity. The change in *EP* in the secondary industry acted as a stimulus of carbon productivity in 2013–2015, whereas the effect was reversed in 2015–2016. The change effect in *EP* in the primary industry was generally lower by comparison. Specifically, mining and manufacturing in the secondary industries, as well as accommodation and catering, real estate, leasing, and business services in the tertiary industries, contributed considerably to the energy productivity change effect in 2013–2016. Consequently, changes in the carbon productivity in these industries were mainly due to changes in energy productivity. Thus, an improvement in the energy productivity of these industries could improve carbon productivity.

Table 9. Change effect of *EP* and *CE* in the industrial structure (2013–2016).

Industry	Change Effect of *EP*			Change Effect of *CE*		
	2013–2014	**2014–2015**	**2015–2016**	**2013–2014**	**2014–2015**	**2015–2016**
Primary	0.045	–0.018	0.016	–0.015	–0.025	–0.042
Secondary	0.22	0.136	–0.269	–0.122	0.010	0.004
Tertiary	0.071	0.405	0.343	0.004	–0.069	–0.068

Source: Own elaboration.

From the change effect of *CE*, the contributions of the 19 industries in 2013–2016 were generally lower, and the change effect of *CE* slightly influenced the change in carbon productivity. Further analysis indicated that the average contribution of the change effect of *CE* was –0.02 in 2013–2014, –0.05 in 2014–2015, and –0.05 in 2015–2016. Though its absolute average contribution ratio was slightly higher in 2013–2014, it was fairly low in 2014–2015 and 2015–2016, with corresponding ratios of 0.38 and –0.38, respectively.

In terms of industrial structure, the average change effects in *CE* in the primary, secondary, and tertiary industries were –0.03, –0.04, and –0.04, respectively, which was a rather miniscule contribution. Therefore, the change in *CE* was less well-correlated to the change in carbon productivity.

4.3. Coefficient of Carbon Productivity Change

To further verify the relationship among the change in *CP*, *EP*, and *CE*, we used correlation analysis and the results are shown in Table 10. The change in *EP* was strongly positively correlated with the change in *CP*, and a weak correlation with no significant difference was found with the change in *CE.* There was no significant correlation between the changes in *EP* and *CE*. The change in energy productivity was a result of the improvement in energy efficiency. Energy efficiency can be promoted through various methods, such as introducing low-carbon technology, improving the application efficiency of existing equipment, and optimizing energy consumption structures. Overall, the improvement in energy productivities in different industries is a significant factor, and this improvement plays a vital role in the carbon productivity change in Beijing. Thus, the improvement of energy productivity could markedly improve carbon productivity.

Table 10. Coefficient of carbon productivity change.

Index	Correlation	*p*-Value (Significance Level: 0.05)
Changes between energy productivity and carbon productivity	0.995	0.031
Changes between carbon energy consumption and carbon productivity	–0.719	0.245
Changes between energy productivity and energy consumption per unit carbon emissions	–0.784	0.213

Source: Own elaboration.

4.4. Discussion on the Improvement of Carbon Productivity

Carbon productivity is important for measuring emission performance and sustainable development over time [56]. Carbon productivity is an indicator that reflects a country's contribution to curbing global climate change [57,58]. Therefore, an improvement in the carbon productivity in Beijing is beneficial, not only to China's ecological civilization and low-carbon economy, but to the global temperature target of the Paris Agreement.

Given these empirical results, there are several approaches that could be applied to enhance carbon productivity in Beijing.

The carbon productivity of the primary industry was the lowest, and its change was small over four years (2013–2016), which indicates that the level of economic output in the primary industry per unit of carbon emissions is low. The main reason for this finding is evident when comparing 2014 with 2016, as carbon emissions were reduced by 8.87%, but the added value decreased by 18.14%. The primary industry could improve its carbon productivity by increasing its industrial added value. For example, in agriculture, it is necessary to accelerate structural adjustments, highlight the ecological function of agriculture, raise the income of urban agriculture farmers, and improve rural economic development.

Improvements in carbon productivity in the secondary industries could be realized by enhancements in energy productivity. Secondary industries are mainly energy-intensive and carbon-intensive [59]; an efficient approach would be to improve the energy productivity. The secondary industries produced 20.8% of the total added value, with 45.81% of the total carbon emissions. The transformation of drivers of economic growth, reductions in energy consumption, and enhancements in energy efficiency should be urgently promoted. An improvement in secondary industry carbon productivity is crucial to the sustainable and green development of the Beijing economy.

The mining industry performed the worst in terms of secondary industry carbon productivity. Compared with 2015, carbon emissions and added value decreased by 14.44% and 51.15% in 2016, respectively, which caused a sharp drop in carbon productivity. In addition, the global mining slump and the promotion of ecological civilization construction in Beijing accelerated the decline in the carbon productivity of mining. Therefore, for mining, reducing carbon emissions through technical improvements, introducing new technologies or a combination of newly developed industries, and adapting to high quality economic development are all possible solutions.

The increase in carbon productivity in the tertiary industries was steady from 2013 to 2016, especially in finance, information transmission, software and information technology service, and scientific research and technology service. The total added value of these three industries accounted for 35.28% of the 19 industries, whereas the ratio of the total carbon emissions was only 7.05%. Furthermore, the tertiary industry produced 78.49% of the total added value, with 52.63% of the total carbon emissions. The energy use efficiency of the tertiary industry was highest among the three industries. The superiority of the tertiary industry was evident. Tertiary industries have simultaneously improved their added value and reduced their carbon dioxide emissions. The stable development of carbon productivity in the tertiary industry, especially in the service industry, will help guarantee Beijing's sustainable and green development.

However, in the wholesale and retail industry, an increase in carbon emissions of 3.75% occurred from 2013 to 2014, 3.54% from 2014 to 2015, and 6.01% from 2015 to 2016, whereas the changes in added value were 3%, −2.44%, and 0.88%, respectively. Carbon emissions grow faster than added value, and carbon productivity thus cannot be rescued from decline. In wholesale and retail, the energy consumption structure, the consumption of high pollution energy, and carbon emissions must be urgently optimized in order to improve carbon productivity. For those industries, such as accommodation and catering, real estate, and leasing and business services, carbon productivity could be hugely improved through energy-saving and emission-reduction.

5. Conclusions and Policy Implications

In this paper, we investigated the carbon productivities of 19 industries in Beijing from 2013 to 2016, and we discussed the holistic trend in carbon productivity in these different industries. To explore the changes in carbon productivity, we used the LMDI factor decomposition method to highlight the change effects of carbon productivity into the change effect of energy efficiency and energy consumption per unit of carbon emissions. We found that the overall carbon productivity of Beijing was growing year over year, and that the growth rate in the tertiary industries was particularly high. A change in the energy efficiency remarkably affects the carbon productivity change, whereas the change effect in energy consumption per unit of carbon emissions was not significant. In terms of industrial structure, the change effect of energy efficiency contributed more to the secondary and tertiary industries, and the change effect of energy consumption per unit of carbon emissions was low in all three industries.

The carbon productivity of Beijing could be further promoted in all 19 industries by the improvement in energy productivity. In order to improve energy productivity, these industries should not only transform their industrial structure and introduce energy-saving technologies, but also optimize the structure of energy consumption, and employ clean and renewable energy in the production process, so that their carbon productivities can be promoted.

Emphasis should be put on bringing the carbon productivity advantage of the tertiary industry into full play. Accelerating economic development and improving the environmental quality in the tertiary industry are vital for realizing the optimization of capital core functions and sustainable development in Beijing.

More attention should be paid to the differences in carbon productivity in various industries. Policy-makers should create more detailed policies to support the improvement of carbon productivity in certain industries, especially for those that are not improving.

Confronted with traditional industries, policy-makers should contemplate and act prudently when implementing a strategic orientation for Beijing and constructing an ecological capital. They should help and guide these industries to further improve their energy productivities and increase their carbon productivities.

6. Remarks

Our study is not without limitations, however, and future research is thus warranted. First, employing different carbon productivity decomposition methods to compare the research results would be valuable. Among these methods, the metafrontier function [28,30,33–35,60] is widely used in carbon productivity. The econometric model [29] and the spatial panel data model [27,61] are also conducted for decomposition. The differences between the models, and which method is most accurate, may be the focus of future work. Second, some novel factors could be incorporated into the decomposition model. With the optimization of China's energy consumption structure, the proportion of coal consumption to total energy consumption declines, and clean energy consumption increases continuously [62]. Clean energy, such as natural gas and renewable energy, is playing an increasingly important role in China [10,12]. These clean energies have not yet been incorporated into the decomposition model to explore their effects on the improvement of carbon productivity. If a specific improvement approach for each industry can be presented according to their different rates of energy consumption, this will compensate for limitations of the study. The third limitation is how the research results link to the regional reduction target. The objective of carbon productivity improvement is to protect the environment and to enhance economic levels, and finally reach sustainable development. Therefore, quantifying the relationships between carbon productivity improvement and emission reduction targets is of great importance [63].

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