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Refined Laspeyres Decomposition-Based Analysis of Relationship between Economy and Electric Carbon Productivity from the Provincial Perspective—Development Mode and Policy

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Abstract: The development of low-carbon electric power industry plays a vital role in sustainable economic development due to the supporting role of electricity in the Gross Domestic Product GDP. The electric carbon productivity indicator is introduced to investigate the provincial economic development and electric industry-related indicators. The refined Laspeyres decomposition technique is adopted to decompose provincial economic change into the quantitative influence of CO_2 emission, electric carbon productivity, and emission structure for the first-stage decomposition; the electric carbon productivity change is sub-decomposed into the influence of factors such as electricity-economic productivity, electricity import-export, and generation carbon efficiency. Through decomposition analysis for the research period of 2005 to 2015, scientific and reasonable suggestions are made for improvement of electric carbon productivity and provincial economic development: (1) The main obstacle to electric carbon productivity improvement is emissions from the power industry. (2) There is interaction between the green economic development mode and the low-carbon electric power industry. In others words, provincial future economy development mode formulation should consider not only economic and industrial factors but also power industry factors. (3) The issue of electric carbon productivity improvement and regional development mode is partially consistent with geographic locations, which is a comprehensive effect of economy level, power industry, energy resources, technological development level, environmental awareness, etc. (4) Due to the existence of regional protection, provincial local incentives should be promulgated to break the GDP-driven development mode to realize coordination among the economy, power industry, and the environment.

Keywords: electric carbon productivity; Laspeyres decomposition; sustainable economic development

1. Introduction

It is reported that carbon dioxide (CO_2), accounting for more than 80% of the total greenhouse gases (GHG) globally, comes primarily from the burning of fossil fuels [1,2]. Especially, coal-related CO_2 emissions at the combustion point of power generation make up the bulk of total emissions. About 37% of global electricity is generated by coal-based plants; and in China, this percentage was even higher at about 70% in 2015 [3,4].

In China, electricity is the backbone of the national and regional economy. Gross Domestic Product GDP increase is regarded as a key assessment indicator for economic development; therefore, more energy, especially electricity, is consumed to pursue an economic increase, ignoring environmental issues. The more electricity is generated by fossil-fueled power plants to support economic development, the more corresponding CO_2 emissions from fuel combustion will be. Therefore, the core of dealing with climate change is effectively controlling emissions from electricity generation and at the same time guaranteeing economic sustainable development. Due to the vast national territory, imbalanced economic development, and different power generation technologies, regional emission reduction responsibilities should be differentiated. Carbon productivity, defined as the amount of GDP produced per unit of carbon emission [5], is an effective indicator and an essential way to coordinate economic development and resource protection, as mentioned in the Climate Change Special Initiative Report by Mckinsey and Company [6]. According to the carbon productivity concept [5], carbon emission is regarded as a kind of input resource to support the economic output, denoting the economic benefits of per unit of CO_2 emissions. Carbon productivity is a scientific indicator, often used to measure a country's or a regional economic level and its developing stage [7]. It is also a reasonable indicator to evaluate national and/or the regional emission reduction responsibility. The current work focuses on electric carbon productivity to investigate provincial economic development and efficiency index from the aspect of the power industry in order to clarify provincial responsibility and provide targeted policy adjustment.

As for carbon productivity, there are several representative research works. He et al. [8] analyzed China's carbon productivity and estimated the carbon productivity growth rate for the time period of 2005–2020. Sun et al. applied the multi-dimensional decomposition technique to the electric carbon productivity (ECP) time series to explore the contribution of technological improvement and structure adjustment for each industrial sector [9]. Xian et al. applied the nonparametric directional distance function-based data envelopment analysis technique to carbon efficiency and productivity decomposition, and then evaluated the possibility of intensity reduction target in the 13th five-year plan through scenario design [10]. Lu et al. [11] designed a multi-dimensional log man divisia index model to investigate carbon productivity and the influencing factors, regional structure and industrial structure. Chen et al. [12] investigated the effect of impacts factors on electric carbon productivity change, based on logarithmic mean divisia index decomposition technique. Yu et al. [13] adopted a sequential meta-frontier luenberger productivity indicator to investigate the carbon productivity change for China's coal-fired power plants. Hu et al. [14] used the decomposition technique to explore the influential factors of carbon productivity for the Australian construction industry. Li et al. [15] decomposed the total factor carbon productivity for 36 sectors to reveal the possible sources of productivity changes during the period time of 2003–2015.

To the author's best knowledge, there is little research on the carbon productivity of electric power industry from a provincial aspect. In China, climate change policies are mainly determined by the central government and implemented by local governments, with equal importance to environmental improvement. There are 31 provinces and municipalities with diverse economic outputs, energy resources and consumption, technological improvement, etc. Therefore, it is imperative to research the provincial carbon productivity of the electric power industry to reveal the relationship between the low-carbon economic development and the electricity power industry from an efficiency angle. The current article attempts to investigate the economic development from the aspect of provincial carbon productivity of the electric power industry, and the relevant indicators (e.g., electricity consumption intensity, local electric power input and consumption, green power generation and carbon emission structure) using the decomposition technique. It also aims to reveal several efficacious measures for controlling CO_2 emissions and improving carbon productivity for the electric power industry to guarantee a balance of economic development and environmental protection.

Among the index decomposition methods, the Laspeyres decomposition technique, commonly used in energy consumption and emissions fields [16,17], is more suitable to compare different subjects, investigating one variable's change for a certain period of time by keeping other variables constant at the original value [18]. However, due to the left large residual interaction terms after the decomposition, which might make the decomposition analysis less meaningful and difficult in interpreting the decomposed results, Sun [19] proposed the refined Laspeyres index method with the ability of conducting complete decomposition based on the 'jointly created and equally distributed' principle, in which the residual terms are distributed equally to each variable. In this work, the refined Laspeyres technique is adopted to build the decomposition model and research the relationship between the economic development and carbon productivity of the electric power industry from a provincial aspect.

The remainder of this paper is structured as follows. The theory of refined Laspeyres-based decomposition technique is described is Section 2; Section 3 describes the data; in Section 4, the empirical results are presented, followed by a regional analysis and discussions of reasonable policy implications. Section 5 provides the key conclusions.

2. Material and Models

Carbon productivity from the angle of electric power industry (called electric carbon productivity, ECP) is defined as the amount of economic output produced per unit of CO_2 emissions of electricity power consumption from fossil-fueled plants generation, according to the usual concept of productivity [5,9]. In this part, a two-stage decomposition is applied.

2.1. First-Stage Decomposition

The first-stage decomposition for national GDP is as follows:

$$G = C \cdot \frac{G}{C} = C \cdot \frac{\sum_{i=1}^{n} \frac{G_i}{C_i} \cdot C_i}{C} = C \cdot \sum_{i=1}^{n} \frac{G_i}{C_i} \cdot \frac{C_i}{C} \tag{1}$$

where G is the total economic output for all the considered provinces; C is the total carbon emissions of electricity consumption from power plants' generation to support the considered provinces' economic development; G_i is the economic output of the ith province; C_i is the ith province's CO_2 emission for electricity generation, n is the number of provinces. Let $ECP_i = \frac{G_i}{C_i}$, $ES_i = \frac{C_i}{C}$, where ECP_i is the electric carbon productivity defined above for the ith province; EC_i is the ith province's emission structure.

Therefore, Equation (1) can be written as:

$$G = C \cdot \sum_{i=1}^{n} ECP_i \cdot ES_i \tag{2}$$

Let G_0 and G_t be the total economic output in year 0 and year t. Over a period [0, t], the change in the economy (ΔG) can be given by Equation (3) according to the Laspeyres decomposition technique. Reference [19] shows the concrete Laspeyres method.

$$\begin{aligned} \Delta G &= G^t - G^0 = C^t \cdot \sum_{i=1}^{n} ECP_i^t \cdot ES_i^t - C^0 \cdot \sum_{i=1}^{n} ECP_i^0 \cdot ES_i^0 \\ &= \Delta C \cdot \sum_{i=1}^{n} ECP_i^0 \cdot ES_i^0 + C^0 \cdot \sum_{i=1}^{n} \Delta ECP_i \cdot ES_i^0 + C^0 \cdot \sum_{i=1}^{n} ECP_i^0 \cdot \Delta ES_i \\ &+ \Delta C \cdot \sum_{i=1}^{n} \Delta ECP_i \cdot ES_i^0 + \Delta C \cdot \sum_{i=1}^{n} ECP_i^0 \cdot \Delta ESC_i + C^0 \cdot \sum_{i=1}^{n} \Delta ECP_i \cdot \Delta ES_i + \Delta C \cdot \sum_{i=1}^{n} \Delta ECP_i \cdot \Delta ES_i \end{aligned} \tag{3}$$

where ΔC is the change of carbon emission change for the whole country; ΔECP_i and ΔES_i represent the changes of the factors ECP_i and ES_i as the components of ΔG over the given period.

According to the 'jointly created and distributed equally' principle, terms affected by two or three variables should be divided into halves or trisections [19,20]. Therefore, the contributions of three factors ΔC, ΔECP_i, and ΔES_i in Equation (3) can be written as Equations (4)–(6).

$$CE_{1effect} = \Delta C \cdot \sum_{i=1}^{n} ECP_i^0 \cdot ES_i^0 + \frac{1}{2}\left(\Delta C \cdot \sum_{i=1}^{n} \Delta ECP_i \cdot ES_i^0 + \Delta C \cdot \sum_{i=1}^{n} ECP_i^0 \cdot \Delta ES_i\right) + \frac{1}{3}\Delta C \cdot \sum_{i=1}^{n} \Delta ECP_i \cdot \Delta ES_i \quad (4)$$

$$ECP_{effect} = C^0 \cdot \sum_{i=1}^{n} \Delta ECP_i \cdot ES_i^0 + \frac{1}{2}\left(\Delta C \cdot \sum_{i=1}^{n} \Delta ECP_i \cdot ES_i^0 + C^0 \cdot \sum_{i=1}^{n} \Delta ECP_i \cdot \Delta ES_i\right) + \frac{1}{3}\Delta C \cdot \sum_{i=1}^{n} \Delta ECP_i \cdot \Delta ES_i \quad (5)$$

$$ES_{1effect} = C^0 \cdot \sum_{i=1}^{n} ECP_i^0 \cdot \Delta ES_i + \frac{1}{2}\left(C^0 \cdot \sum_{i=1}^{n} \Delta ECP_i \cdot \Delta ES_i + \Delta C \cdot \sum_{i=1}^{n} ECP_i^0 \cdot \Delta ES_i\right) + \frac{1}{3}\Delta C \cdot \sum_{i=1}^{n} \Delta ECP_i \cdot \Delta ES_i \quad (6)$$

where $CE_{1effect}$, ECP_{effect} and $ES_{1effect}$ represent the effect of C, ECP_i and ES_i on the national economic change at first-stage decomposition.

2.2. Second-Stage Decomposition

Considering the different provincial electricity energy consumption, power generation and technological improvement, Equation (1) can be decomposed further as follows:

$$G = C \cdot \frac{\sum_{i=1}^{n} \frac{G_i}{E_{ci}} \cdot \frac{E_{ci}}{E_{gi}} \cdot \frac{E_{gi}}{C_i} \cdot C_i}{C} = C \cdot \sum_{i=1}^{n} \frac{G_i}{E_{ci}} \cdot \frac{E_{ci}}{E_{gi}} \cdot \frac{E_{gi}}{C_i} \cdot \frac{C_i}{C} \quad (7)$$

where E_{ci} is the electricity consumption of the ith province; E_{gi} is the electricity generation of the ith province; let $P_i = \frac{G_i}{E_{ci}}$, $Q_i = \frac{E_{ci}}{E_{gi}}$, $R_i = \frac{E_{gi}}{C_i}$, $S_i = \frac{C_i}{C}$, where P_i is the electricity-economic productivity, defined as the economic output per electricity consumption for the ith province; Q_i is the ratio of electricity consumption to electricity generation; R_i is the generation carbon efficiency, defined as the power generation per carbon emission; S_i is the emission structure. Equation (7) can be written as follows.

$$G = C \cdot \sum_{i=1}^{n} P_i \cdot Q_i \cdot R_i \cdot S_i \quad (8)$$

When time changes from 0 to t, the total economic change ΔG can be expressed as Equation (9)

$$\begin{aligned}
\Delta G &= G^t - G^0 = C^0 \cdot \sum_{I=1}^{N} P_i^0 \cdot Q_i^0 \cdot R_i^0 \cdot S_i^0 - C^t \cdot \sum_{I=1}^{N} P_i^t \cdot Q_i^t \cdot R_i^t \cdot S_i^t \\
&= \Delta C \sum_{I=1}^{N} P_i^0 \cdot Q_i^0 \cdot R_i^0 \cdot S_i^0 + C^0 \cdot \sum_{I=1}^{N} \Delta P_i \cdot Q_i^0 \cdot R_i^0 \cdot S_i^0 + C^0 \cdot \sum_{I=1}^{N} P_i^0 \cdot \Delta Q_i \cdot R_i^0 \cdot S_i^0 \\
&+C^0 \cdot \sum_{I=1}^{N} P_i^0 \cdot Q_i^0 \cdot \Delta R_i \cdot S_i^0 + C^0 \cdot \sum_{I=1}^{N} P_i^0 \cdot Q_i^0 \cdot R_i^0 \cdot \Delta S_i + \Delta C \cdot \sum_{I=1}^{N} \Delta P_i \cdot Q_i^0 \cdot R_i^0 \cdot S_i^0 \\
&+\Delta C \cdot \sum_{I=1}^{N} P_i^0 \cdot \Delta Q_i \cdot R_i^0 \cdot S_i^0 + \Delta C \cdot \sum_{I=1}^{N} P_i^0 \cdot Q_i^0 \cdot \Delta R_i \cdot S_i^0 + \Delta C \cdot \sum_{I=1}^{N} P_i^0 \cdot Q_i^0 \cdot R_i^0 \cdot \Delta S_i \\
&+C^0 \cdot \sum_{I=1}^{N} \Delta P_i \cdot \Delta Q_i \cdot R_i^0 \cdot S_i^0 + C^0 \cdot \sum_{I=1}^{N} \Delta P_i \cdot Q_i^0 \cdot \Delta R_i \cdot S_i^0 + C^0 \cdot \sum_{I=1}^{N} \Delta P_i \cdot Q_i^0 \cdot R_i^0 \cdot \Delta S_i \\
&+C^0 \cdot \sum_{I=1}^{N} P_i^0 \cdot \Delta Q_i \cdot \Delta R_i \cdot S_i^0 + C^0 \cdot \sum_{I=1}^{N} P_i^0 \cdot \Delta Q_i \cdot R_i^0 \cdot \Delta S_i + C^0 \cdot \sum_{I=1}^{N} P_i^0 \cdot Q_i^0 \cdot \Delta R_i \cdot \Delta S_i \\
&+\Delta C \sum_{I=1}^{N} \Delta P_i \cdot \Delta Q_i \cdot R_i^0 \cdot S_i^0 + \Delta C \sum_{I=1}^{N} \Delta P_i \cdot Q_i^0 \cdot \Delta R_i \cdot S_i^0 + \Delta C \sum_{I=1}^{N} \Delta P_i \cdot Q_i^0 \cdot R_i^0 \cdot \Delta S_i \\
&+\Delta C \sum_{I=1}^{N} P_i^0 \cdot \Delta Q_i \cdot \Delta R_i \cdot S_i^0 + \Delta C \sum_{I=1}^{N} P_i^0 \cdot \Delta Q_i \cdot R_i^0 \cdot \Delta S_i + \Delta C \sum_{I=1}^{N} P_i^0 \cdot Q_i^0 \cdot \Delta R_i \cdot \Delta S_i \\
&+C^0 \cdot \sum_{I=1}^{N} \Delta P_i \cdot \Delta Q_i \cdot \Delta R_i \cdot S_i^0 + C^0 \cdot \sum_{I=1}^{N} \Delta P_i \cdot \Delta Q_i \cdot R_i^0 \cdot \Delta S_i + C^0 \cdot \sum_{I=1}^{N} \Delta P_i \cdot Q_i^0 \cdot \Delta R_i \cdot \Delta S_i \\
&+C^0 \cdot \sum_{I=1}^{N} P_i^0 \cdot \Delta Q_i \cdot \Delta R_i \cdot \Delta S_i + \Delta C \cdot \sum_{I=1}^{N} \Delta P_i \cdot \Delta Q_i \cdot \Delta R_i \cdot S_i^0 + \Delta C \cdot \sum_{I=1}^{N} \Delta P_i \cdot \Delta Q_i \cdot R_i^0 \cdot \Delta S_i \\
&+\Delta C \cdot \sum_{I=1}^{N} \Delta P_i \cdot Q_i^0 \cdot \Delta R_i \cdot \Delta S_i + \Delta C \cdot \sum_{I=1}^{N} P_i^0 \cdot \Delta Q_i \cdot \Delta R_i \cdot \Delta S_i + C^0 \cdot \sum_{I=1}^{N} \Delta P_i \cdot \Delta Q_i \cdot \Delta R_i \cdot \Delta S_i \\
&+\Delta C \cdot \sum_{I=1}^{N} \Delta P_i \cdot \Delta Q_i \cdot \Delta R_i \cdot \Delta S_i
\end{aligned} \tag{9}$$

Total economic change ΔG is affected by emission change ΔC, electricity-economic productivity change for each province ΔP_i, the ratio of electricity consumption to generation change for each province ΔQ_i, generation carbon efficiency change for each province ΔR_i, emission structure change for each province ΔS_i, and the interaction terms of two, three, four and five factors. The interaction terms can be divided into halves, thirds and quarters, fifths of the residual terms. The contributions of ΔC, ΔP_i, ΔQ_i, ΔR_i ΔS_i in Equation (9) can be written as Equations (10)–(14).

$$\begin{aligned}
CE_{2effect} &= \Delta C \cdot \sum_{I=1}^{N} P_i^0 \cdot Q_i^0 \cdot R_i^0 \cdot S_i^0 \\
&+\frac{1}{2}\begin{pmatrix} \Delta C \cdot \sum_{I=1}^{N} \Delta P_i \cdot Q_i^0 \cdot R_i^0 \cdot S_i^0 + \Delta C \cdot \sum_{I=1}^{N} P_i^0 \cdot \Delta Q_i \cdot R_i^0 \cdot S_i^0 \\ +\Delta C \cdot \sum_{I=1}^{N} P_i^0 \cdot Q_i^0 \cdot \Delta R_i \cdot S_i^0 + \Delta C \cdot \sum_{I=1}^{N} P_i^0 \cdot Q_i^0 \cdot R_i^0 \cdot \Delta S_i \end{pmatrix} \\
&+\frac{1}{3}\begin{pmatrix} \Delta C \cdot \sum_{I=1}^{N} \Delta P_i \cdot \Delta Q_i \cdot R_i^0 \cdot S_i^0 + \Delta C \cdot \sum_{I=1}^{N} \Delta P_i \cdot Q_i^0 \cdot \Delta R_i \cdot S_i^0 + \Delta C \cdot \sum_{I=1}^{N} \Delta P_i \cdot Q_i^0 \cdot R_i^0 \cdot \Delta S_i \\ +\Delta C \cdot \sum_{I=1}^{N} P_i^0 \cdot \Delta Q_i \cdot \Delta R_i \cdot S_i^0 + \Delta C \cdot \sum_{I=1}^{N} P_i^0 \cdot \Delta Q_i \cdot R_i^0 \cdot \Delta S_i + \Delta C \cdot \sum_{I=1}^{N} P_i^0 \cdot Q_i^0 \cdot \Delta R_i \cdot \Delta S_i \end{pmatrix} \\
&+\frac{1}{4}\begin{pmatrix} \Delta C \cdot \sum_{I=1}^{N} \Delta P_i \cdot \Delta Q_i \cdot \Delta R_i \cdot S_i^0 + \Delta C \cdot \sum_{I=1}^{N} \Delta P_i \cdot \Delta Q_i \cdot R_i^0 \cdot \Delta S_i \\ +\Delta C \cdot \sum_{I=1}^{N} \Delta P_i \cdot Q_i^0 \cdot \Delta R_i \cdot \Delta S_i + \Delta C \cdot \sum_{I=1}^{N} P_i^0 \cdot \Delta Q_i \cdot \Delta R_i \cdot \Delta S_i \end{pmatrix} \\
&+\frac{1}{5}\left(\Delta C \cdot \sum_{I=1}^{N} \Delta P_i \cdot \Delta Q_i \cdot \Delta R_i \cdot \Delta S_i\right)
\end{aligned} \tag{10}$$

$CE_{2effect}$ represents the effect of national carbon emissions change from power generation on country's economic development. It can reflect the energy-specific electricity consumption situation, the availability of fuel switching options in electricity production, and technological improvements in power generation process.

$$
\begin{aligned}
ECE_{effect} &= C^0 \cdot \sum_{I=1}^{N} \Delta P_i \cdot Q_i^0 \cdot R_i^0 \cdot S_i^0 \\
&+\frac{1}{2}\left(\begin{array}{c} \Delta C \cdot \sum_{I=1}^{N} \Delta P_i \cdot Q_i^0 \cdot R_i^0 \cdot S_i^0 + C^0 \cdot \sum_{I=1}^{N} \Delta P_i \cdot \Delta Q_i \cdot R_i^0 \cdot S_i^0 \\ +C^0 \cdot \sum_{I=1}^{N} \Delta P_i \cdot Q_i^0 \cdot \Delta R_i \cdot S_i^0 + C^0 \cdot \sum_{I=1}^{N} \Delta P_i \cdot Q_i^0 \cdot R_i^0 \cdot \Delta S_i \end{array}\right) \\
&+\frac{1}{3}\left(\begin{array}{c} \Delta C \cdot \sum_{I=1}^{N} \Delta P_i \cdot \Delta Q_i \cdot R_i^0 \cdot S_i^0 + \Delta C \cdot \sum_{I=1}^{N} \Delta P_i \cdot Q_i^0 \cdot \Delta R_i \cdot S_i^0 + \Delta C \cdot \sum_{I=1}^{N} \Delta P_i \cdot Q_i^0 \cdot R_i^0 \cdot \Delta S_i \\ +C^0 \cdot \sum_{I=1}^{N} \Delta P_i \cdot \Delta Q_i \cdot \Delta R_i \cdot S_i^0 + C^0 \cdot \sum_{I=1}^{N} \Delta P_i \cdot \Delta Q_i \cdot R_i^0 \cdot \Delta S_i + C^0 \cdot \sum_{I=1}^{N} \Delta P_i \cdot Q_i^0 \cdot \Delta R_i \cdot \Delta S_i \end{array}\right) \\
&+\frac{1}{4}\left(\begin{array}{c} \Delta C \cdot \sum_{I=1}^{N} \Delta P_i \cdot \Delta Q_i \cdot \Delta R_i \cdot S_i^0 + \Delta C \cdot \sum_{I=1}^{N} \Delta P_i \cdot \Delta Q_i \cdot R_i^0 \cdot \Delta S_i \\ +\Delta C \cdot \sum_{I=1}^{N} \Delta P_i \cdot Q_i^0 \cdot \Delta R_i \cdot \Delta S_i + C^0 \cdot \sum_{I=1}^{N} \Delta P_i \cdot \Delta Q_i \cdot \Delta R_i \cdot \Delta S_i \end{array}\right) \\
&+\frac{1}{5}\left(\Delta C \cdot \sum_{I=1}^{N} \Delta P_i \cdot \Delta Q_i \cdot \Delta R_i \cdot \Delta S_i\right)
\end{aligned} \tag{11}
$$

ECE_{effect} represents the electricity-economic productivity change effect on economy, which can reflect the technological improvement and industrial adjustment of different provinces. The shift from highly electricity-intensive industrial sectors to high electricity-economic productivity sectors will result in lower electricity demand and emissions for certain economic output.

$$
\begin{aligned}
IO_{effect} &= C^0 \cdot \sum_{I=1}^{N} P_i^0 \cdot \Delta Q_i \cdot R_i^0 \cdot S_i^0 \\
&+\frac{1}{2}\left(\begin{array}{c} \Delta C \cdot \sum_{I=1}^{N} P_i^0 \cdot \Delta Q_i \cdot R_i^0 \cdot S_i^0 + C^0 \cdot \sum_{I=1}^{N} \Delta P_i \cdot \Delta Q_i \cdot R_i^0 \cdot S_i^0 \\ +C^0 \cdot \sum_{I=1}^{N} P_i^0 \cdot \Delta Q_i \cdot \Delta R_i \cdot S_i^0 + C^0 \cdot \sum_{I=1}^{N} P_i^0 \cdot \Delta Q_i \cdot R_i^0 \cdot \Delta S_i \end{array}\right) \\
&+\frac{1}{3}\left(\begin{array}{c} \Delta C \cdot \sum_{I=1}^{N} \Delta P_i \cdot \Delta Q_i \cdot R_i^0 \cdot S_i^0 + \Delta C \cdot \sum_{I=1}^{N} P_i^0 \cdot \Delta Q_i \cdot \Delta R_i \cdot S_i^0 + \Delta C \cdot \sum_{I=1}^{N} P_i^0 \cdot \Delta Q_i \cdot R_i^0 \cdot \Delta S_i \\ +C^0 \cdot \sum_{I=1}^{N} \Delta P_i \cdot \Delta Q_i \cdot \Delta R_i \cdot S_i^0 + C^0 \cdot \sum_{I=1}^{N} \Delta P_i \cdot \Delta Q_i \cdot R_i^0 \cdot \Delta S_i + C^0 \cdot \sum_{I=1}^{N} P_i^0 \cdot \Delta Q_i \cdot \Delta R_i \cdot \Delta S_i \end{array}\right) \\
&+\frac{1}{4}\left(\begin{array}{c} \Delta C \cdot \sum_{I=1}^{N} \Delta P_i \cdot \Delta Q_i \cdot \Delta R_i \cdot S_i^0 + \Delta C \cdot \sum_{I=1}^{N} \Delta P_i \cdot \Delta Q_i \cdot R_i^0 \cdot \Delta S_i \\ +\Delta C \cdot \sum_{I=1}^{N} P_i^0 \cdot \Delta Q_i \cdot \Delta R_i \cdot \Delta S_i + C^0 \cdot \sum_{I=1}^{N} \Delta P_i \cdot \Delta Q_i \cdot \Delta R_i \cdot \Delta S_i \end{array}\right) \\
&+\frac{1}{5}\left(\Delta C \cdot \sum_{I=1}^{N} \Delta P_i \cdot \Delta Q_i \cdot \Delta R_i \cdot \Delta S_i\right)
\end{aligned} \tag{12}
$$

The ratio of electricity consumption to electricity generation effect IO_{effect}, shown in Equation (12) reflects whether a certain province is an electricity-input region or an output region. The value of Q_i greater than 1 indicates that the province is an electricity power input area; otherwise, it is an electricity output area. If the value of Q_i equals to 1, it means the electricity demand of this region equals the electricity power production.

$$
\begin{aligned}
GCE_{effect} &= C^0 \cdot \sum_{I=1}^{N} P_i^0 \cdot Q_i^0 \cdot \Delta R_i \cdot S_i^0 \\
&+\frac{1}{2}\left(\begin{array}{c} \Delta C \cdot \sum_{I=1}^{N} P_i^0 \cdot Q_i^0 \cdot \Delta R_i \cdot S_i^0 + C^0 \cdot \sum_{I=1}^{N} \Delta P_i \cdot Q_i^0 \cdot \Delta R_i \cdot S_i^0 \\ +C^0 \cdot \sum_{I=1}^{N} P_i^0 \cdot \Delta Q_i \cdot \Delta R_i \cdot S_i^0 + C^0 \cdot \sum_{I=1}^{N} P_i^0 \cdot Q_i^0 \cdot \Delta R_i \cdot \Delta S_i \end{array}\right) \\
&+\frac{1}{3}\left(\begin{array}{c} \Delta C \cdot \sum_{I=1}^{N} \Delta P_i \cdot Q_i^0 \cdot \Delta R_i \cdot S_i^0 + \Delta C \cdot \sum_{I=1}^{N} P_i^0 \cdot \Delta Q_i \cdot \Delta R_i \cdot S_i^0 + \Delta C \cdot \sum_{I=1}^{N} P_i^0 \cdot Q_i^0 \cdot \Delta R_i \cdot \Delta S_i \\ +C^0 \cdot \sum_{I=1}^{N} \Delta P_i \cdot \Delta Q_i \cdot \Delta R_i \cdot S_i^0 + C^0 \cdot \sum_{I=1}^{N} \Delta P_i \cdot Q_i^0 \cdot \Delta R_i \cdot \Delta S_i + C^0 \cdot \sum_{I=1}^{N} P_i^0 \cdot \Delta Q_i \cdot \Delta R_i \cdot \Delta S_i \end{array}\right) \\
&+\frac{1}{4}\left(\begin{array}{c} \Delta C \cdot \sum_{I=1}^{N} \Delta P_i \cdot \Delta Q_i \cdot \Delta R_i \cdot S_i^0 + \Delta C \cdot \sum_{I=1}^{N} \Delta P_i \cdot Q_i^0 \cdot \Delta R_i \cdot \Delta S_i \\ +\Delta C \cdot \sum_{I=1}^{N} P_i^0 \cdot \Delta Q_i \cdot \Delta R_i \cdot \Delta S_i + C^0 \cdot \sum_{I=1}^{N} \Delta P_i \cdot \Delta Q_i \cdot \Delta R_i \cdot \Delta S_i \end{array}\right) \\
&+\frac{1}{5}\left(\Delta C \cdot \sum_{I=1}^{N} \Delta P_i \cdot \Delta Q_i \cdot \Delta R_i \cdot \Delta S_i\right)
\end{aligned} \tag{13}
$$

The generation carbon efficiency effect GCE_{effect}, shown in Equation (13) measures the electricity power generation per unit of carbon emissions, which reflects the availability of green generation in electricity production, and technological improvements in the energy conversion process.

$$
\begin{aligned}
ES_{2effect} &= C^0 \cdot \sum_{I=1}^{N} P_i^0 \cdot Q_i^0 \cdot R_i^0 \cdot \Delta S_i \\
&+\frac{1}{2}\begin{pmatrix} \Delta C \cdot \sum_{I=1}^{N} P_i^0 \cdot Q_i^0 \cdot R_i^0 \cdot \Delta S_i + C^0 \cdot \sum_{I=1}^{N} \Delta P_i \cdot Q_i^0 \cdot R_i^0 \cdot \Delta S_i \\ +C^0 \cdot \sum_{I=1}^{N} P_i^0 \cdot \Delta Q_i \cdot R_i^0 \cdot \Delta S_i + C^0 \cdot \sum_{I=1}^{N} P_i^0 \cdot Q_i^0 \cdot \Delta R_i \cdot \Delta S_i \end{pmatrix} \\
&+\frac{1}{3}\begin{pmatrix} \Delta C \cdot \sum_{I=1}^{N} \Delta P_i \cdot Q_i^0 \cdot R_i^0 \cdot \Delta S_i + \Delta C \cdot \sum_{I=1}^{N} P_i^0 \cdot \Delta Q_i \cdot R_i^0 \cdot \Delta S_i + \Delta C \cdot \sum_{I=1}^{N} P_i^0 \cdot Q_i^0 \cdot \Delta R_i \cdot \Delta S_i \\ +C^0 \cdot \sum_{I=1}^{N} \Delta P_i \cdot \Delta Q_i \cdot R_i^0 \cdot \Delta S_i + C^0 \cdot \sum_{I=1}^{N} \Delta P_i \cdot Q_i^0 \cdot \Delta R_i \cdot \Delta S_i + C^0 \cdot \sum_{I=1}^{N} P_i^0 \cdot \Delta Q_i \cdot \Delta R_i \cdot \Delta S_i \end{pmatrix} \\
&+\frac{1}{4}\begin{pmatrix} \Delta C \cdot \sum_{I=1}^{N} \Delta P_i \cdot \Delta Q_i \cdot R_i^0 \cdot \Delta S_i + \Delta C \cdot \sum_{I=1}^{N} \Delta P_i \cdot Q_i^0 \cdot \Delta R_i \cdot \Delta S_i \\ +\Delta C \cdot \sum_{I=1}^{N} P_i^0 \cdot \Delta Q_i \cdot \Delta R_i \cdot \Delta S_i + C^0 \cdot \sum_{I=1}^{N} \Delta P_i \cdot \Delta Q_i \cdot \Delta R_i \cdot \Delta S_i \end{pmatrix} \\
&+\frac{1}{5}\left(\Delta C \cdot \sum_{I=1}^{N} \Delta P_i \cdot \Delta Q_i \cdot \Delta R_i \cdot \Delta S_i \right)
\end{aligned} \tag{14}
$$

$ES_{2effect}$ represents effect of the emission structure change for different provinces on economic output.

In order to compare the contribution of each factor to the economic output for each province, the relative contribution for all the factors can be defined as Equations (15)–(20).

$$\alpha_i = \frac{CE_{effect}}{G_i^t - G_i^0}\ (i = 1, 2, \cdots, n) \tag{15}$$

$$\beta_i = \frac{ECP_{effect}}{G_i^t - G_i^0}\ (i = 1, 2, \cdots, n) \tag{16}$$

$$\chi_i = \frac{ES_{effect}}{G_i^t - G_i^0}\ (i = 1, 2, \cdots, n) \tag{17}$$

$$\delta_i = \frac{ECE_{effect}}{G_i^t - G_i^0}\ (i = 1, 2, \cdots, n) \tag{18}$$

$$\varepsilon_i = \frac{IO_{effect}}{G_i^t - G_i^0}\ (i = 1, 2, \cdots, n) \tag{19}$$

$$\eta_i = \frac{GCE_{effect}}{G_i^t - G_i^0}\ (i = 1, 2, \cdots, n) \tag{20}$$

where α_i, β_i, χ_i, δ_i, ε_i, η_i represents the relative contribution of *CE*, *ECP*, *ES*, *ECE*, *IO*, *GCE* to the economic output growth, respectively.

3. Data Source

The decomposition analysis covers the period of 2005–2015, which is consistent with China's 5-year Plan. The data of GDP (in 2005 constant price) are collected from China Statistical Yearbook (2006–2016) [21]. The data of total electricity power generation and consumption for each province and the whole country are obtained from China Electric Power Yearbook [4,22]. The CO_2 emissions from generation production can be calculated by multiplying standard coal consumption for power generation and the corresponding CO_2 emission coefficient per unit of standard coal. The conversion efficient adopted in current work is 2.4567 tCO_2/tce (ton of standard coal equivalent), which is recommended by the Energy Research Institute (ERI) of the National Development and Reform Commission (NDRC) [23]. And the data of standard coal consumption for power generation can be calculated by multiplying the generation amount and the average standard coal consumption per unit of power generation. The data of average standard coal consumption per unit of power generation for each province and the whole country are also obtained from China Electric Power Yearbook [22]. The adjusted GDP (G_i, unit: 10^8 Yuan), carbon emission from power generation (C_i, unit: 10^8 ton), electric carbon productivity (ECP_i, unit: 10^3 Yuan per ton), electricity-economic productivity (P_i, unit: Yuan per kWh), ratio of electricity consumption to electricity generation (Q_i), generation carbon efficiency (R_i, unit: kWh per ton) and the emission structure (EC_i, S_i) of each province in 2005 and 2015 are listed in Tables A1 and A2, respectively, in the Appendix A.

4. Results and Discussion

In this section, first-stage decomposition results and second-stage decomposition results for each province were presented.

4.1. First-Stage Decomposition Results and Analysis

It shows that the average values of the relative contribution for the three factors (CO_2 emission, electric carbon productivity, and emission structure), written as α_i, β_i and χ_i, are 60.091%, 47.201%, and −7.375%, respectively. The results show that the most important driving force of economic output is still the CO_2 emissions from power plants generation. As mentioned above, electricity is considered the backbone of Chinese economy's prosperity and progress, especially for the secondary industry-based national economy. The industrial sectors, especially the heavy industries such as cement, steel, chemicals etc., is the main electricity consumers in China, resulting in a major cause of pollution. In most stages of China's economic development, the growth rate of electricity consumption and the corresponding CO_2 emission from electricity generation is much higher than that of the economic output. China's GDP has grown from 100,280.1 billion Yuan in 2000 to 509,291.1 billion Yuan (in 2000 constant Yuan) in 2015 with an average annual growth rate of 11.59%; the corresponding electricity consumption has increased from 1347.2 TWh to 5802.0 TWh with an average annual growth rate of 22.04% during the same period [4,5]. Consequently, CO_2 emissions has increased from 0.1013 billion ton to 3.3056 billion ton, with an average annual growth rate of 26.16%. In fact, the Chinese central government has taken several measures to control CO_2 emissions from the power industry since the adoption of the Kyoto Protocol. These measures include constructing supercritical (SC) units, ultra-supercritical (USC) units, phasing out small thermal power units; developing substitutable energy such as solar, wind, biomass and geothermal for generation; using clean-coal resources and products, implementing Integrated Gasification Combined Cycle (IGCC), Combined Heat and Power (CHP), and carbon capture and storage (CCS) [24], etc. Actually, many papers, such as References. [8,10,12,13], have pointed to clean generation technology for power plants, high-capacity units with phasing out small ones, and so on. The different situation for provinces will be discussed in a later section.

As a part of the Paris agreement on climate change, China pledged that its emissions would peak no later than 2030. It is a fact that the high average growth rate of emissions from power industry has imposed enormous pressure on the Chinese government to improve the electric carbon productivity. Therefore, the intrinsical measure to control the generation CO_2 emission is to improve electric carbon productivity. According to the definition of electric carbon productivity, the improvement of electric carbon productivity implies the same economic output with less emissions, or the same emissions with more economic output. Less emissions from the power industry for the same economic output involves thermal power generation efficiency improvement, increasing the non-fossil energy share of power generation, CCS, etc. More economic output with the same emissions from power industry means the optimization of industrial structure, the improvement of energy intensity, etc. In the first-stage decomposition stage, the average relative contribution of electric carbon productivity to economic output is 47.201%, which means that the effect of electric carbon productivity on economy is obvious and improving electric carbon productivity is necessary.

From Appendix Table A3, the influence of emission structure is relatively low. And the relative contribution for each province manifests a difference. The low average contribution of emissions structure reflects the possible provincial protectionism for different regions, since most provinces pursue only economic development without considering the negative external effects of CO_2 emissions. Therefore, most provinces would like to build thermal power plants because of the short construction period, less initial investment, and less site selection constraints to meet the high electric demand. This phenomenon is consistent with certain published work, like References [11,25], which have pointed out the regional protectionism and the limited contribution of emissions' structures. From another angle, different provinces have different natural resources for power generation like coal and its products, water resources, and solar energy, etc., which might result in different power generation forms. For example, western provinces with abundant water resources should be encouraged to build hydroelectric power stations instead of thermal power plants, which might result in different CO_2 emissions for the same amount of electricity. Further analysis for provinces will be discussed in the next section.

4.2. Second-Stage Decomposition Results and Analysis

In this section, the second-stage decomposition is implemented for electric carbon productivity factor ECP_i of each province, which is decomposed into three sub-factors (P_i, Q_i, and R_i). The absolute results (ECE_{effect}, IO_{effect}, and GCE_{effect}) and relative results (δ_i, ε_i, and η_i) for each provinces are shown in Appendix Tables A4 and A5, respectively.

As mentioned above, the relative contribution of electric carbon productivity to economic output is obvious with average value of 47.201%. In other words, national and regional economic development has a great relationship with electricity carbon productivity. In the second-stage, the electricity carbon productivity is further decomposed to investigate the contribution of relevant sources (P_i, Q_i and R_i with the form of continuous multiplication) to productivity change. The average values of relative contribution for P_i, Q_i and R_i, shown as δ_i, ε_i, and χ_i in Appendix Table A5, are 14.919%, 1.336% and 30.747%, respectively. Further positioning to the electric power industry, the research revealed that generation carbon efficiency R_i had more effect on economic output, followed by electricity-economic productivity P_i and ratio of electricity consumption to electricity generation Q_i.

The generation carbon efficiency R_i is the ratio of the electricity generation amount to CO_2 emission. It has an obvious effect on electric carbon productivity improvement, which involves technical efficiency improvement, technology improvement, and increasing non-fossil fuel sources for electric power generation. Published papers like References [8,10,12] have stated similar ideas. Reference [8] stressed on renewable energy based power and clean coal generation with carbon capture for the climate change issue. Reference [10] demonstrated upgrading technology on electricity generation by using the data envelope analysis (DEA) technique. The main idea of Reference [12] for regional electric carbon productivity involved enhancing the efficiency of fossil energy utilization and reducing fossil generation share. In fact, technical efficiency improvement and technology improvement means less fuel consumption for the same amount of generated electricity, such as applying stringent efficiency standards on new capacity addition, phasing out small units with large-capacity and high-parameter units [26], advanced combustion technique, clean-coal technology, CCS, etc. As for the non-fossil fuel sources of electric power generation, promoting clean energy consumption in electric power generation has been included by the government into national strategic priorities [27]. The Chinese government announced at the 2015 Paris Climate Conference that the share of non-fossil fuels, as a part of its primary energy consumption, would be increased to about 20% by 2030 [28]. The wind power installed capacity will be increased from 95.81 Gigawatts (GW) to 200 GW, and the installed capacity of solar power from 28 GW to around 100 GW [29].

The electricity-economic productivity P_i makes 14.919% relative contribution to the electric carbon productivity factor ECP_i. Most literatures have focused on electricity intensity or energy intensity, defined as the ratio of total electricity or energy consumption to gross domestic product, which is a measure of the energy efficiency of a nation's economy. For example, in Reference [12], energy intensity is one of the decomposed indicators of research on electric carbon productivity change. The indicator P_i is the inverse of 'electric intensity', which represents the ratio of economic output to end-use electricity. It is also an efficiency index that shows the total electricity used to support economic and social activity. The electricity-economic productivity can reflect the adjustment of industrial structure and industrial electricity efficiency. In References [9] and [11], the industrial structure adjustment or optimization has been pointed out as an effective measure for carbon productivity and electric carbon productivity improvement. Industrial structure adjustment aims at reducing the disproportionate size of the secondary industry and increasing the proportion of the tertiary industry. It is a long-term and step-by-step process for different provinces with different levels of economic development, which will be discussed in the geographic homogeneity and heterogeneity section. Regions that rely on electricity-intensive industries such as aluminum and other metals' production have a high electricity demand for higher economic output. However, these regions show lower industrial electricity efficiency, thus reducing electricity-economic productivity. Improving industrial electricity efficiency could incentive these provinces to eliminate low-efficient and electricity-intensive equipments and introduce more efficient technology. Additionally, understanding the behavior of the electricity-economic productivity of each region could help local governments address economic development mode and energy policies in a more efficient way to include technological progress promotion, economic structure adjustment, and a more market-oriented economy reform.

The ratio of electricity consumption to electricity generation Q_i indicates that the provinces might be electricity exporting provinces ($Q_i < 1$) or electricity importing provinces ($Q_i > 1$). It is known that China's urban and industrial centers located along the eastern coast still face an electricity gap due to the concentration of power plants in the inland areas. The purpose of the West-East Electricity Transfer Project (WEETP), initiated in the 10th Five-Year Plan (2001–2005), was to reduce the electricity gap between the inland electricity supply and the growing electricity demand in eastern coastal areas. Therefore, the exporting or importing situation could affect the economic development model of the region. The detailed analysis for 30 provinces is discussed in the next section.

4.3. Geographic Homogeneity and Heterogeneity Analysis

In the 2015 Paris Climate Conference, the aim of which was to achieve a legally binding and universal agreement on climate, keeping global warming below 2 °C, the Chinese government submitted its climate action plan to the United Nations Framework Convention on Climate Change (UNFCCC), including peak emissions control, emission intensity reduction, and non-fossil fuels' share increase. In order to achieve the nationwide goal, each province should also implement its emissions reduction and productivity improvement for a reasonable economic development mode and policy regulation. Geographic homogeneity and heterogeneity analysis is important for national and provincial policy makers to fight climate change to achieve this final goal.

In this section, the relationship between the economy and CO_2 emissions in the power industry, electric carbon productivity, and emission structure will be discussed in order to explore the targeted economic development mode for different provinces. The mean values of each indicator's relative contribution (δ_i, ε_i, and χ_i) are used as criteria for classifying categories. If the relative contribution value of one indicator is more than the average value of this factor, 1 is assigned to this province; otherwise, 0 is assigned. Then, the state vector for each province can be obtained, leading to different categories, as shown in Appendix Table A4. The map of different provinces is painted accordingly with different colors, as shown as Figure 1, to observe geographic homogeneity and heterogeneity. The geographic difference is analyzed based on Appendix Table A6 and Figure 1. The possible reasons for regional difference could be analyzed; they include status of economic development, industrial structure, low-fossil-fuel area and fossil-fuel-dominated area, power generation technology and environmental protection, and technology gap for different categories, among others.

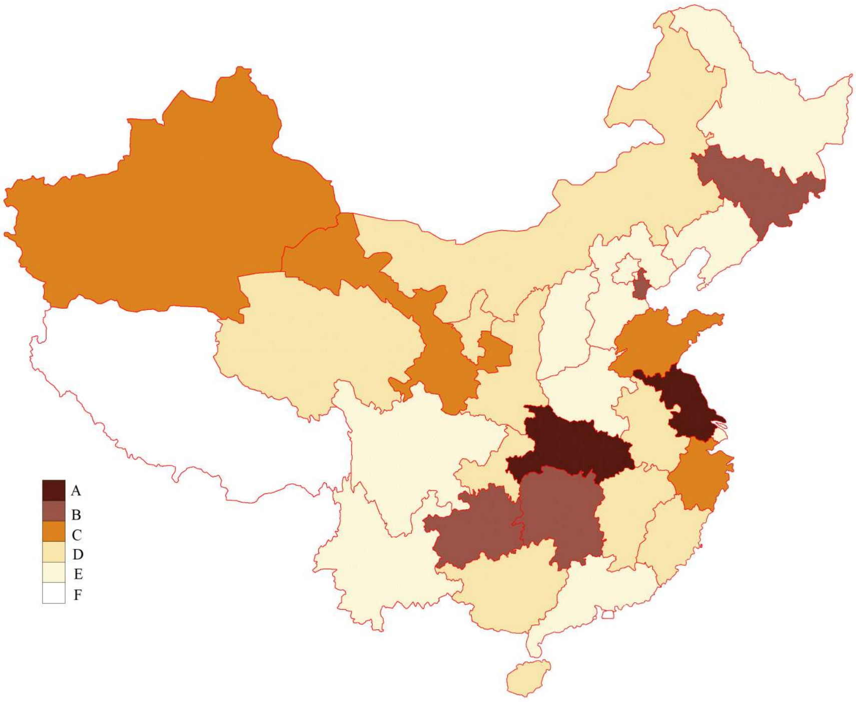

Figure 1. Geographic homogeneity and heterogeneity for 30 provinces.

Taking the first indicator (carbon emission change) as an example, if the relative contribution value of carbon emission change to the economic output is greater than the mean value of this factor, it means that the emission change effect is more obvious on the economy. Otherwise, if the relative contribution is smaller than the mean value, this factor has a relatively limited effect on economic output.

(1) Category A includes Jiangsu and Hubei provinces. The carbon emission change of these two provinces has a limited contribution to the economy, with 57.730% and 49.314%, respectively. The effect of electric carbon productivity and emission structure on economic output is 48.102%, −5.856% for Jiangsu and 47.488%, 2.917% for Hubei, respectively. These indicators can reflect the efficiency improvement in energy and electricity consumption, and also local governments' efforts to curb CO_2 emissions.

Jiangsu, a typical eastern-central coastal province, is the second-highest GDP province with 7738.828 billion Yuan in 2016. After years of industrial upgradation and structural reform, Jiangsu has shifted from a traditional manufacturing city that relies on labor and resources to a smart city focusing on intelligent manufacturing. From 2013 to 2016, the growth rate of the tertiary industry in Jiangsu Province was higher than that of the secondary industry. By 2016, the output value of the tertiary industry was close to 50%. Although it has a higher GDP with relatively high electricity consumption, high energy efficiency and reasonable industrial structures offers low CO_2 emissions, resulting in lower α_i and higher β_i.

Hubei province in central China is located at the junction of the Yangtze River Economic Belt from the east to the west. Its GDP (3652.295 billion Yuan) in 2017 ranks second among the six provinces in central China and seventh among all provinces in China. Hubei's economy focuses on the development of advanced and emerging manufacturing industries; promoting smarter networking and digitization of the manufacturing industry. Additionally, the Three Gorges Dam, the world's largest hydroelectric power station in terms of installed capacity, is in this province. The province's hydropower generation ranks third in China with 145.92 billion kWh in 2017. It is a key factor helping improve the electric carbon productivity in the province.

(2) Tianjin, Jilin, Hunan, Guizhou belong to Category B. Similar to Category A, the provinces in Category B show relative a lower contribution of carbon emission change to the economy with α_i value of 53.557%, 58.286%, 51.420%, and 44.873%, respectively. The reasons for a low α_i for Tianjin,

Jilin, and Hunan are similar to that of Jiangsu and Hubei, with relatively high economic output and electricity consumption, but higher efficiency. The establishment of Tianjin Binhai New Area (TBNA), is home to industrial clusters with distinct advantages of secondary and tertiary industries. Industrial clusters are taking shape in the processing, manufacturing and service industries with high efficiency and productivity, which has a great influence on the change of Tianjin's development mode.

On the other hand, Guizhou needs to be viewed as a different group. Guizhou's economy ranked 25th out of 30 Chinese provinces with 1177.7 billion Yuan in 2016. The proportion of primary, secondary, and tertiary industry is 15.17%, 40.17%, and 44.66%, respectively. Electric-power generation is the main pillar of Guizhou's economy. Although most electricity is generated from coal-fired thermal plants, the province's abundant water resources have been used to develop a number of hydroelectric facilities. The main characteristics of Guizhou are low-level economic development without a heavy industry pillar, limited energy consumption with lower efficiency, and abundant hydroelectric power generation.

For the second-stage decomposition, the contribution of electricity-economic productivity to the economy is 36.439%, 49.515%, 35.666%, and 35.472% respectively. P_i is also an efficiency index, showing a reasonable industrial structure and high-efficiency for industries. The contribution of generation carbon efficiency to the economy of these provinces is 12.821%, 20.234%, 21.321% and 28.570%, respectively, which is lower than the average value. As for Q_i, Tianjin and Hunan belong to the electricity importing regions; while Jilin and Guizhou belong to the electricity exporting regions. The relative contribution of Q_i is 22.5%, 6.054%, 12.492%, and 0.78%, respectively. If the value of Q_i in 2015 was larger than that of 2005, IO_{effect} and ε_i have a positive value. For electricity importing regions (Tianjin and Hunan), it means a larger gap between electric power generation and electricity consumption. For electricity exporting regions (Jilin and Guizhou), it means a proportion of delivered electricity to local total electric power generation decreased; in other words, local electricity consumption to total power generation increased.

(3) Shandong, Zhejiang, Gansu and Xinjiang are classified as Category C. Shandong and Zhejiang should be considered as one group; while Gansu and Xinjiang should be grouped separately. In the same category, the common characteristic of these provinces is that the relative contribution of emission to economy is higher than the average value with 62.852%, 68.446%, 61.491%, and 68.972%, respectively. However, the relative contribution of electric carbon productivity to economy is lower than the average value with 20.227%, 37.041%, 32.822% and −92.434%, respectively. For second-stage decomposition, the relative contributions of P_i, Q_i, and R_i to economic output (written as δ_i, ε_i and η_i) for these four provinces are −62.806%, 11.022%, 16.055%, −130.256%; 63.201%, 5.456%, −9.180%, −17.601; 15.875%, 20.850%, 25.947%, 46.241%, respectively.

Shandong and Zhejiang are two rich provinces in China's coastal regions, with GDP of 6802.4 billion Yuan and 4725.1 billion Yuan in 2016. Higher economic output resulted in higher energy, especially electricity consumption, and even more emissions. In addition, the tertiary industry proportion of Zhejiang and Shandong was 48.0% and 52.7%, respectively, in 2017, which is higher than that of the secondary industry. The steady adjustment of industrial structure and relatively reasonable power generation structure made a relatively lower contribution of β_i and δ_i to the economy of these two provinces.

Gansu and Xinjiang are two western parts in China with relative lagging economic development. With China's Western Development Strategy, these two provinces could consume more energy and electricity to boost their economic development. Gansu and Xinjiang are primary provinces for wind power development, with installed capacity of 12.77 million kWh and 17.76 million kWh, respectively. Furthermore, the hydroelectric power generation for Gansu and Xinjiang ranks 9th and 11th in China with 28.62 billion kWh and 20.40 billion kWh. These two situations offer a steady value of electric carbon productivity and electricity-economic productivity, which are lower than average contribution rates.

Additionally, Zhejiang and Shandong are electricity importing regions, while Gansu and Xinjiang are electricity exporting regions. The values of ε_i are positive for Zhejiang, Shandong, and negative for Gansu and Xinjiang. This means that the average growth rate of electricity consumption is lower than the average growth rate of power generation for Zhejiang and Shandong, which might result in a larger electricity gap in the future. It is the opposite situation for Gansu and Xinjiang, which means more generated electricity would be delivered.

(4) Category D includes Inner Mongolia, Anhui, Jiangxi, Fujian, Chongqing, Ningxia, Shaanxi, Hainan, Qinghai, and Guangxi, based on first-stage decomposition. For second-stage decomposition, three sub-groups are divided to differentiate the in-depth heterogeneity.

The relative contribution of carbon emission change and electric carbon productivity change to the economy (written as α_i, β_i) are lower than the corresponding average value. The contribution of emission structure to economic output χ_i is higher than the average value. These provinces are sub-divided into three groups according to the second-stage decomposition results in Appendix Table A5. Group one includes Inner Mongolia, Anhui, and Jiangxi. Group two includes Fujian, Chongqing, Shaanxi, and Ningxia. Hainan, Qinghai, and Guangxi are regarded as Group 3.

For Group 1, although significant economic development has been made in these three provinces, similar economic output and steady energy consumption has resulted in a lower contribution of CO_2 emission to the economy. The proportion of the secondary industry in these regions was 48.7%, 48.1%, and 47.7%, respectively, in 2016, which is higher than the tertiary proportion (42.5%, 41.3%, and 42.0%). In addition, Inner Mongolia, Anhui, and Jiangxi belong to natural resources-based regions dominated by heavy industries, which results in lower energy efficiency and lower electric carbon productivity. The contribution of emission structures to the economy is higher than the average value, which affirms industrial structure adjustment effect and local government efforts for environmental policy implementation. As for the power industry, the values of δ_i, ε_i, η_i are −10.265%, 7.576%, 9.105%; −8.412%, −12.406%, −1.063%; 11.964%, 15.925%, and 20.993%, respectively. For example, Inner Mongolia with the largest wind power production capacity, is an important power generation supply base that transfers electricity to other provinces in China. However, due to wind instability, wind generation is bundled with the support of conventional thermal power generation. The contribution of electricity-economic productivity and generation carbon efficiency is lower than average values, which indicates that it is challenging for these three provinces to implement industrial structure adjustment and power generation efficiency improvement.

For Group 2, the contribution of electricity-economic productivity to the economic output (δ_i) for these provinces is 17.438%, 24.397%, 30.114%, and 16.43, respectively; the value of η_i is 15.735%, 27.434%, −3.606%, and 19.804%, respectively. It shows that satisfactory improvement has been made for industrial structure adjustment and electricity consumption efficiency for the end user; however, further improvement for generation carbon efficiency is needed. In this group, Ningxia is considered a special province. In 2005, Ningxia was an electricity-importing region with 30.288 billion kWh generation and 28.763 billion kWh electricity consumption. However, in 2015, Ningxia's electricity generation reached 116.6 billion kWh, surpassing its consumption (87.83 billion kWh) and essentially becoming a typical electricity exporting region. It is a less-developed province in the northwest, but with a well-developed wind-power and solar-power industry of 15.5 billion kWh and 7.6 billion kWh, respectively, which accounts for 11% and 5% of the total power generation. The coal industry is one of the pillar industries of Ningxia, accounting for more than 90% of its energy. The province now has a national largescale coal base, a coal chemical industry base, and a 'West-East Power Transmission' thermal power base. In the future, possible economic development will be based on the improvement of electric carbon productivity and generation carbon efficiency.

For Group 3, the values of δ_i, ε_i, η_i are −10.475%, 3.198%, and 16.272%; 10.828%, 14.653%, and −11.561%; 3.017%, 28.857%, and 40.229%, respectively. The main characteristics of these provinces are a relatively low economic development and electricity (energy) consumption. Hainan is a typical region with the largest share of primary sector in its GDP and a high proportion of tertiary industry.

The power generation amount is basically equal to electricity consumption. Its future models focus on tertiary development based on renewable energy generation. However, for Qinghai and Guangxi, the secondary proportion to regional GDP was 48.6% and 45.1% in 2017. These two provinces are rich in natural resources, which has a great influence on shaping the industry structure. As for the power industry, Guangxi maximizes the use of its water resources for hydro power generation; while Qinghai makes efforts in wind power generation and power transmission lines construction for the West-East Electricity Transfer Project. Future development would be an efficiency-improvement based economic model with renewable energy generation adjustment and electric lines construction.

(5) Category E includes Beijing, Shanghai, Guangdong, Sichuan, Yunnan, Hebei, Shanxi, Liaoning, Heilongjiang, and Henan. The main feature for this category is the obvious emissions effect and productivity effect on economy. Based on the first-stage and second-stage decomposition results, these provinces are sub-divided into four groups, representing possible future differentiated development modes.

Beijing and Shanghai belong to the same group. These two provinces' economy ranks among the most developed and prosperous cities in China with tertiary proportion as high as 80.6% and 69.8%, respectively. These two provinces are electricity importing regions with high economic development. The contribution of electricity-economic productivity to economic output is 44.467% and 42.59%, respectively, which is higher than the average values. This means that these two provinces have tried to improve electricity-carbon productivity and clean generation. Beijing has shut down all coal-fired power plants to realize renewable energy generation in 2018 and increase the proportion of imported electricity energy. Shanghai's coal-fired Waigaoqiao No. 3 Power Plant is being championed as a model of high efficiency. The future economic development mode focuses on the modern services sector and high-tech industries by relying on imported-electricity support.

It is reasonable to classify Guangdong, Liaoning, and Shanxi into one group. The reasons are as follows. The values of δ_i, ε_i and η_i for these four provinces are 22.142%, 41.441%, and 25.394%; 49.381%, −1.107%, and −2.831%; 21.050%, 33.486%, and 26.892%, respectively. The tertiary proportion of these regions is 52.6%, 51.6% and 55.7%, respectively, higher than the secondary industry proportion with 42.8%, 39.3% and 39.3%, respectively. Shanxi, the most important coal supply base in China, has started closing down small coal mines since 2000, which could lead to different development modes due to adjustment of the coal industry. Guangdong is a typical electricity-importing region, dominated by thermal power generation for its heavy, new and high technology industries. Shanxi plays an important role as a long-distance provider of electricity; it supplies coal to local thermal power plants for generation and transmits electricity to other parts of the country through ultra-high voltage transmission lines. Ningxia is still one of the major bases of coal mining and thermal power generation in northern China with a relative low-level economy. Therefore, future development for this group lies in sustainable development, based on the improvement of electricity-economic productivity and generation carbon efficiency.

As for Hebei and Henan, heavy industry dominated regions, the proportion of the secondary industry is 47.6% for these two regions, compared with the tertiary proportion of 41.5% and 41.8%. Due to the coal-dominated energy system, thermal power generation accounted for 90.53% and 95.15% of the total generation in 2015, respectively. Therefore, considering the lower productivity and efficiency, future development for these two regions should be sustainable and green with optimization of industrial and energy structures, and improvement in electricity-economic productivity and power generation efficiency. Hebei province, an integral part of the Jing-Jin-Ji (Beijing-Tianjin-Hebei) Economic Zone, plays a vital role in Beijing's green economic development.

Heilongjiang, Sichuan, and Yunnan belong to one group, because a main characteristic of all three is the certain proportion of primary industry with 17.4%, 12%, and 15.1%, respectively; and a higher proportion of tertiary industry with 54.0%, 45.4%, and 45.1%, respectively, compared with 28.6%, 42.6%, and 39.8% for secondary industry proportion in 2016. The contribution of generation carbon efficiency to the economy is 38.598%, 39.376%, and 15.273%, which is higher than the average value. In Yunnan and Sichuan, hydroelectric power generation dominated the power industry with its water resources. Thus, future development emphasis for these regions should be urbanization and sustainable economic development based on green power generation.

5. Conclusions

Electric carbon productivity, an indicator combining economic output, electricity generation and consumption, carbon emission, and generation efficiency, can measure a region's effectiveness and effort in coping with increased climate change risks and provide reasonable economic development. The aim of the current work is to investigate the relationship between economy and power industry related indicators from a provincial perspective and provide targeted development modes and policies. Considering different economies, technology, resources, provincial development and policy should be differentiated based on the research results. The two-stage refined Laspeyres index decomposition technique is adopted to decompose Chinese GDP change into the quantitative influence of CO_2 emission, electric carbon productivity, and emission structure in first-stage decomposition; electric carbon productivity change is sub-decomposed into the effect of electricity-economic productivity factor, electricity input-output factor, and generation carbon efficiency factor in the second-stage decomposition. For the research period of 2005 to 2015, the results reveal several important measures to improve electric carbon productivity and secure a reasonable future development mode:

(1) The most important driving force of economic growth is CO_2 emissions from the power industry due to the supporting role of electricity to the GDP, of which high growth rate becomes a main obstacle to the improvement of electric carbon productivity.

(2) Improving electric carbon productivity involves electricity-economic productivity improvement, electricity importation or exportation situation, and power generation efficiency. Different factors have different effects on different provinces, which is basically consistent with economic development levels, energy resources, and technological improvement.

(3) Electricity-economic productivity is an indicator of consumption, which could measure technological improvement and industrial optimization. Provinces with relatively low electricity-economic productivity need to eliminate low-efficiency and electricity-intensive equipments, introduce more efficient technology, and make more market-oriented economy reforms.

(4) The ratio of electricity consumption to electricity generation is a new indicator introduced in current work, which identifies the electricity importation or exportation situation. Provinces might be electricity importing or exporting regions, which results in different power industry developments and economic development modes.

(5) Carbon efficiency, as most literatures point out, is a key factor influencing carbon productivity. As for the power industry, improving generation carbon productivity involves technical efficiency improvement, such as CCS, USC, IGCC, non-fossil fuel sources for electric power generation, and clean-coal generation technology, among others.

(6) Emission structures for provinces have a limited effect on economic output. The low average contribution of emission structures might be a result of the possible provincial protectionism in different regions. A possible reason is that local governments pursue high economy speed at the expense of external environmental impacts. Different local incentives should be promulgated for provincial emission reduction share.

(7) Provincial future economy development mode formulation should consider not only economic and industrial factors but also factors of the power industry.

Electric carbon productivity can describe a general view of economic development and environmental protection. Research on provincial electric carbon productivity and economy could measure provincial low-carbon development performance. Furthermore, this research can be applied to other regions or industrial sectors to clarify the scientific emission reduction responsibility and ascertain reasonable sustainable development modes for different regions or sectors. It can also be used as a scientific indicator for international negotiations to determine different countries' emission reduction share. The improvement of carbon productivity can also measure a region's or a country's effort in coping with the global climate change.

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Appendix A

Table A1. The original data for parameters in 2005.

NO.	Provinces	G_i	C_i	ECP_i	EC_i	P_i	Q_i	R_i	S_i
1	Beijing	6969.52	1730.33	40.2786	0.0095	12.22	2.66	1.2414	0.0095
2	Tianjin	3905.64	3124.01	12.502	0.0172	10.18	1.04	1.1844	0.0172
3	Hebei	10,012.11	12,193.77	8.2108	0.0670	6.67	1.12	1.1045	0.0670
4	Shanxi	4230.53	12,095.48	3.4976	0.0664	4.47	0.72	1.0825	0.0664
5	Inner Mongolia	3905.03	7749.87	5.0388	0.0426	5.85	0.71	1.2088	0.0426
6	Liaoning	8047.26	7750.76	10.3825	0.0426	7.25	1.24	1.1569	0.0426
7	Jilin	3620.27	3324.12	10.8909	0.0183	9.57	0.87	1.3055	0.0183
8	Heilongjiang	5513.70	5630.44	9.7927	0.0309	9.92	0.93	1.0639	0.0309
9	Shanghai	9247.66	6378.89	14.4973	0.0350	10.03	1.24	1.1699	0.0350
10	Jiangsu	18,598.69	18,355.50	10.1325	0.1008	8.48	1.03	1.1550	0.1008
11	Zhejiang	13,417.68	9584.81	13.9989	0.0526	8.17	1.14	1.5001	0.0526
12	Anhui	5350.17	5578.18	9.5912	0.0306	9.19	0.91	1.1513	0.0306
13	Fujian	6554.69	4180.92	15.6776	0.0230	8.66	0.97	1.8584	0.0230
14	Jiangxi	4056.76	2778.12	14.6025	0.0153	10.35	1.12	1.2598	0.0153
15	Shandong	18,366.87	16,884.33	10.8781	0.0927	15.41	0.63	1.1253	0.0927
16	Henan	10,587.42	12,462.73	8.4953	0.0684	7.83	0.98	1.1097	0.0684
17	Hubei	6590.19	4291.73	15.3556	0.0236	8.35	0.61	3.0081	0.0236
18	Hunan	6596.10	3705.40	17.8013	0.0203	9.78	1.05	1.7272	0.0203
19	Guangdong	22,557.37	15,425.60	14.6233	0.0847	8.44	1.17	1.4779	0.0847
20	Guangxi	3984.10	2270.49	17.5473	0.0125	7.81	1.15	1.9599	0.0125
21	Hainan	918.75	601.93	15.2634	0.0033	11.26	0.95	1.4287	0.0033
22	Chongqing	3467.72	1739.38	19.9365	0.0096	9.97	1.47	1.3580	0.0096
23	Sichuan	7385.10	3914.84	18.8644	0.0215	7.83	0.93	2.5978	0.0215
24	Guizhou	2005.42	5271.13	3.8045	0.0289	4.12	0.60	1.5345	0.0289
25	Yunnan	3462.73	2667.55	12.9809	0.0146	6.21	0.90	2.3259	0.0146
26	Shaanxi	3933.72	3773.59	10.4243	0.0207	7.62	0.97	1.4083	0.0207
27	Gansu	1933.98	2952.53	6.5502	0.0162	3.95	0.97	1.7030	0.0162
28	Qinghai	543.32	561.41	9.6778	0.0031	2.63	0.97	3.8017	0.0031
29	Ningxia	612.61	2450.77	2.4997	0.0135	2.02	1.05	1.1736	0.0135
30	Xinjiang	2604.19	2997.60	8.6876	0.0165	8.40	1.00	1.0352	0.0165

Table A2. The original data for parameters in 2015.

NO.	Provinces	G_i	C_i	ECP_i	EC_i	P_i	Q_i	R_i	S_i
1	Beijing	17,098.51	2276.17	75.1197	0.0069	17.95	2.26	1.8496	0.0069
2	Tianjin	12,286.92	4406.80	27.8817	0.0133	15.35	1.33	1.3638	0.0133
3	Hebei	22,144.21	16,953.82	13.0615	0.0513	6.97	1.38	1.3572	0.0513
4	Shanxi	9484.76	18,363.48	5.165	0.0556	5.46	0.71	1.3380	0.0556
5	Inner Mongolia	13,247.78	28,268.16	4.6865	0.0855	5.21	0.65	1.3878	0.0855
6	Liaoning	21,299.42	10,209.29	20.8628	0.0309	10.73	1.23	1.5858	0.0309
7	Jilin	10,448.09	4392.65	23.7854	0.0133	16.03	0.93	1.6027	0.0133
8	Heilongjiang	11,206.29	6493.55	17.2576	0.0196	12.90	0.97	1.3783	0.0196
9	Shanghai	18,665.27	6115.82	30.5197	0.0185	13.28	1.71	1.3424	0.0185
10	Jiangsu	52,092.41	31,458.48	16.5591	0.0952	10.18	1.16	1.4069	0.0952
11	Zhejiang	31,862.18	16,601.61	19.1922	0.0502	8.97	1.20	1.7902	0.0502
12	Anhui	16,348.91	15,070.06	10.8486	0.0456	9.97	0.80	1.3683	0.0456
13	Fujian	19,301.50	8577.62	22.5022	0.0259	10.42	0.98	2.1952	0.0259
14	Jiangxi	12,424.80	6185.41	20.0873	0.0187	11.43	1.11	1.5876	0.0187
15	Shandong	46,807.08	35,743.42	13.0953	0.1081	9.15	1.11	1.2923	0.1081
16	Henan	27,490.46	19,089.87	14.4005	0.0577	9.55	1.13	1.3405	0.0577
17	Hubei	21,954.08	8074.98	27.1878	0.0244	13.18	0.71	2.9177	0.0244
18	Hunan	21,472.67	5678.32	37.8152	0.0172	14.83	1.16	2.2066	0.0172
19	Guangdong	54,095.51	21,924.25	24.6738	0.0663	10.19	1.40	1.7282	0.0663
20	Guangxi	12,483.74	4264.84	29.2713	0.0129	9.35	1.01	3.0927	0.0129
21	Hainan	2750.94	1736.01	15.8463	0.0053	10.10	1.06	1.4746	0.0053
22	Chongqing	11,677.02	3622.61	32.2337	0.0110	13.34	1.28	1.8854	0.0110
23	Sichuan	22,327.71	3430.98	65.0768	0.0104	11.21	0.62	9.3530	0.0104
24	Guizhou	7802.79	8593.64	9.0797	0.0260	6.65	0.61	2.2470	0.0260
25	Yunnan	10,118.25	2272.70	44.5208	0.0069	7.03	0.56	11.2333	0.0069
26	Shaanxi	13,389.20	9781.05	13.6889	0.0296	10.96	0.92	1.3506	0.0296
27	Gansu	5044.81	5646.33	8.9347	0.0171	4.59	0.89	2.1749	0.0171
28	Qinghai	1795.73	1070.21	16.7792	0.0032	2.73	1.15	5.3541	0.0032
29	Ningxia	2163.28	7827.68	2.7636	0.0237	2.46	0.75	1.4896	0.0237
30	Xinjiang	6927.79	16,476.73	4.2046	0.0498	3.21	0.87	1.5045	0.0498

Table A3. First-stage decomposition results for each province.

NO.	Provinces	$CE_{1effect}$	α_i (%)	ECP_{effect}	β_i (%)	ES_{effect}	χ_i (%)
1	Beijing	6899.036	68.112	7216.735	71.248	−3960.06	−39.096
2	Tianjin	4488.791	53.557	5942.287	70.9	−2094.09	−24.985
3	Hebei	9228.416	76.066	7265.82	59.889	−4377.55	−36.082
4	Shanxi	3892.836	74.09	2586.827	49.233	−1222.17	−23.261
5	Inner Mongolia	4596.450	49.198	−597.599	−6.396	5332.462	57.076
6	Liaoning	8356.106	63.055	9728.283	73.409	−4840.15	−36.524
7	Jilin	3979.681	58.286	5146.466	75.375	−2303.37	−33.735
8	Heilongjiang	4956.332	87.066	4730.887	83.106	−4024.6	−70.699
9	Shanghai	8595.508	91.271	10,667.8	113.275	−9853.21	−104.625
10	Jiangsu	19,335.884	57.73	16,111.16	48.102	−1961.55	−5.856
11	Zhejiang	12,624.567	68.446	6831.975	37.041	−1037.08	−5.623
12	Anhui	5793.122	52.671	1252.138	11.384	3955.657	35.965
13	Fujian	6940.725	54.451	4304.669	33.771	1444.531	11.332
14	Jiangxi	4392.322	52.489	2414.798	28.857	1535.773	18.353
15	Shandong	17,875.111	62.852	5752.506	20.227	4777.324	16.798
16	Henan	10,617.491	62.814	9472.8	56.042	−3220.16	−19.051
17	Hubei	7576.592	49.314	7296.072	47.488	448.211	2.917
18	Hunan	7649.579	51.42	9549.419	64.191	−2287.93	−15.379
19	Guangdong	21,753.717	68.976	19,236.42	60.994	−9502.29	−30.13
20	Guangxi	4411.165	51.898	3825.181	45.004	245.986	2.894
21	Hainan	992.558	54.173	65.739	3.588	799.455	43.634
22	Chongqing	4002.521	48.756	3270.323	39.837	958.036	11.67
23	Sichuan	9286.226	62.146	18,274.09	122.295	−12583.8	−84.214
24	Guizhou	2601.478	44.873	3695.569	63.746	−498.119	−8.592
25	Yunnan	4279.951	64.307	8397.399	126.172	−5978.7	−89.831
26	Shaanxi	4529.065	47.899	2141.981	22.653	2788.402	29.49
27	Gansu	1912.871	61.491	1021.037	32.822	181.396	5.831
28	Qinghai	618.341	49.372	574.693	45.887	34.81	2.779
29	Ningxia	728.647	46.989	129.268	8.336	691.886	44.619
30	Xinjiang	2982.092	68.972	−3996.46	−92.434	5321.904	123.09
	Average	6863.239	60.091	5743.609	47.201	−1374.3	−7.375

Table A4. Second-stage absolute decomposition results for each province.

NO.	Provinces	CE_{effect}	ECE_{effect}	IO_{effect}	GCE_{effect}	ES_{effect}
1	Beijing	6855.677	4504.087	−1949.53	4663.134	−3944.38
2	Tianjin	4344.307	3054.057	1885.83	1074.555	−1977.47
3	Hebei	9120.035	715.313	3351.578	3240.521	−4295.35
4	Shanxi	3866.686	1334.255	−148.741	1412.993	−1210.96
5	Inner Mongolia	4606.181	−959.055	−785.93	1117.796	5363.758
6	Liaoning	8184.9	5491.839	−146.73	4437.673	−4715.52
7	Jilin	3873.965	3380.79	413.383	1381.547	−2221.87
8	Heilongjiang	4882.887	2197.216	383.603	2168.442	−3939.56
9	Shanghai	8344.739	4011.007	4650.517	1982.423	−9571.08
10	Jiangsu	19,068.09	6082.816	3691.559	6541.649	−1890.39
11	Zhejiang	12,559.67	2032.902	1006.243	3845.709	−1000.03
12	Anhui	5808.671	833.275	−1364.49	1751.579	3969.7
13	Fujian	6897.662	2222.791	121.377	2005.705	1499.275
14	Jiangxi	4371.139	761.881	−88.923	1756.672	1567.27
15	Shandong	18,747.73	−17,862	17,974.49	4514.974	5065.061
16	Henan	10,455.78	3601.867	2552.955	3428.548	−3136.11
17	Hubei	7511.725	5842.767	1919.207	−409.638	499.829
18	Hunan	7447.844	5305.817	1208.335	3171.766	−2257.19
19	Guangdong	21,413.53	6983.127	6613.466	5813.299	−9285.28
20	Guangxi	4400.791	1383.085	−982.663	3419.349	279.078
21	Hainan	988.836	−191.916	198.381	55.27	781.619
22	Chongqing	3976.135	2002.817	−994.039	2252.147	972.241
23	Sichuan	9581.354	5883.86	−6987.98	19,427.63	−12,962.3
24	Guizhou	2523.543	2056.418	45.223	1656.32	−484.135
25	Yunnan	4706.941	1016.465	−3981.03	11,470.59	−6557.44
26	Shaanxi	4549.661	2847.38	−403.141	−340.92	2802.499
27	Gansu	1909.703	499.44	−285.561	807.177	180.073
28	Qinghai	612.535	40.054	183.517	361.411	54.894
29	Ningxia	739.008	254.78	−456.524	307.096	706.311
30	Xinjiang	3124.744	−5631.76	−760.994	1999.29	5592.324

Table A5. Second-stage relative decomposition results for each province.

NO.	Provinces	α_i (%)	δ_i (%)	ε_i (%)	η_i (%)	χ_i (%)
1	Beijing	67.684	44.467	−19.247	46.037	−38.941
2	Tianjin	51.833	36.439	22.5	12.821	−23.594
3	Hebei	75.173	5.896	27.626	26.710	−35.405
4	Shanxi	73.592	25.394	−2.831	26.892	−23.047
5	Inner Mongolia	49.302	−10.265	−8.412	11.964	57.411
6	Liaoning	61.763	41.441	−1.107	33.486	−35.583
7	Jilin	56.738	49.515	6.054	20.234	−32.541
8	Heilongjiang	85.776	38.598	6.739	38.092	−69.205
9	Shanghai	88.608	42.59	49.381	21.050	−101.630
10	Jiangsu	56.93	18.161	11.022	19.531	−5.644
11	Zhejiang	68.094	11.022	5.456	20.85	−5.422
12	Anhui	52.812	7.576	−12.406	15.925	36.092
13	Fujian	54.113	17.438	0.952	15.735	11.762
14	Jiangxi	52.236	9.105	−1.063	20.993	18.729
15	Shandong	65.92	−62.806	63.201	15.875	17.81
16	Henan	61.857	21.309	15.104	20.284	−18.554
17	Hubei	48.892	38.029	12.492	−2.666	3.253
18	Hunan	50.064	35.666	8.122	21.321	−15.173
19	Guangdong	67.897	22.142	20.97	18.433	−29.441
20	Guangxi	51.776	16.272	−11.561	40.229	3.283
21	Hainan	53.97	−10.475	10.828	3.017	42.66
22	Chongqing	48.435	24.397	−12.109	27.434	11.843
23	Sichuan	64.121	39.376	−46.765	130.015	−86.747
24	Guizhou	43.529	35.472	0.78	28.57	−8.351
25	Yunnan	70.722	15.273	−59.815	172.347	−98.526
26	Shaanxi	48.117	30.114	−4.264	−3.606	29.639
27	Gansu	61.389	16.055	−9.18	25.947	5.789
28	Qinghai	48.909	3.198	14.653	28.857	4.383
29	Ningxia	47.657	16.43	−29.44	19.804	45.549
30	Xinjiang	72.272	−130.256	−17.601	46.241	129.344

Table A6. Classified results for 30 provinces based on state vector.

Category	State Vector	Provinces
A	(0 1 1)	Jiangsu, Hubei
B	(0 1 0)	Tianjin, Jilin, Hunan, Guizhou
C	(1 0 1)	Zhejiang, Shandong, Gansu, Xinjiang
D	(0 0 1)	Inner Mongolia, Anhui, Fujian, Jiangxi, Hainan, Chongqing, Shaanxi, Qinghai, Ningxia, Guangxi
E	(1 1 0)	Beijing, Shanghai, Guangdong, Sichuan, Yunnan, Hebei, Shanxi, Liaoning, Heilongjiang, Henan
F	-	This region is not considered due to the absence of data.

References

1. Foster, V.; Bedrosyan, D. *Understanding CO_2 Emissions from the Global Energy Sector (Report No. 85126)*; World Bank: Washington, DC, USA, 2014. Available online: http://documents.worldbank.org/curated/en/873091468155720710/Understanding-CO2-emissions-from-the-global-energy-sector (accessed on 10 September 2018).
2. Ali, H.; Sanjaya, S.; Suryadi, B.; Weller, S.R. Analysing CO_2 emissions from Singapore′s electricity generation sector: Strategies for 2020 and beyond. *Energy* **2017**, *124*, 553–564. [CrossRef]
3. Coal & Electricity. World Coal Association. Available online: https://www.worldcoal.org/coal/uses-coal/coal-electricity (accessed on 10 September 2018).
4. CEC (China Electric Council). *China's Electric Power Statistical Yearbook*; China′s Electric Power Press: Beijing, China, 2016.
5. Kaya, Y.; Yokobori, K. *Environment, Energy and Economy: Strategies for Sustainability*; Book well Publications: Delhi, India, 1999.
6. Beinhocker, E.; Oppenheim, J.; Irons, B. The Carbon Productivity Challenge: Curbing Climate Change and Sustaining Economic Growth [EB]. 2008. Available online: http://www.mckinsey.com/mgi (accessed on 15 September 2018).
7. Wang, K.; Xian, Y.; Wei, Y.-M.; Huan, Z. A decomposition and disaggregation analysis based on global Luenberger productivity indicator and endogenous directional distance function. *Ecol. Indic.* **2016**, *66*, 545–555. [CrossRef]
8. He, J.; Deng, J.; Su, M. CO_2 emission from China's energy sector and strategy for its control. *Energy* **2010**, *35*, 4494–4498. [CrossRef]
9. Sun, W.; He, Y.; Gao, H. Electric Carbon Productivity Analysis of China's Industrial Sector Using Multi-Dimensional Decomposition. *Pol. J. Environ. Stud.* **2016**, *25*, 1699–1708. [CrossRef]
10. Xian, Y.; Wang, K.; Shi, X.; Zhang, C.; Wei, Y.-M.; Huang, Z. Carbon emissions intensity reduction target for China's power industry: An efficiency and productivity perspective. *J. Clean. Prod.* **2018**, *197*, 1022–1034. [CrossRef]
11. Lu, J.; Fan, W.; Meng, M. Empirical Research on China′s Carbon Productivity Decomposition Model Based on Multi-Dimensional Factors. *Energies* **2015**, *8*, 3093–3117. [CrossRef]
12. Chen, G.; Hou, F.; Chang, K. Regional decomposition analysis of electric carbon productivity from the perspective of production and consumption in China. *Environ. Sci. Pollut. Res.* **2018**, *25*, 1508–1518. [CrossRef] [PubMed]
13. Yu, Y.; Qian, T.; Du, L. Carbon productivity growth, technological innovation, and technology gap change of coal-fired power plants in China. *Energy Policy* **2017**, *109*, 479–487. [CrossRef]
14. Hu, X.; Liu, C. Carbon productivity: A case study in the Australian construction industry. *J. Clean. Prod.* **2016**, *112*, 2354–2362. [CrossRef]
15. Li, W.; Wang, W.; Wang, Y.; Ali, M. Historical growth in total factor carbon productivity of the Chinese industry-A comprehensive analysis. *J. Clean. Prod.* **2018**, *170*, 471–485. [CrossRef]
16. Quan, L. Factors Analysis and Empirical Study on Energy Consumption in China: Based on Laspeyres Index Decomposition. *Technol. Econ.* **2011**, *30*, 83–86.

17. Sun, J.; Zhao, R.; Huang, X.; Chen, Z. Research on Carbon Emission Estimation and Factor Decomposition of China from 1995 to 2005. *J. Nat. Resour.* **2010**, *25*, 1284–1295.
18. Gürkan, K.A. Sectoral decomposition analysis of Turkish CO_2 emissions over 1990–2007. *Energy* **2011**, *36*, 2419–2433.
19. Sun, J.W. Accounting for energy use in China, 1980–94. *Energy* **1998**, *23*, 835–849. [CrossRef]
20. Sun, J.W. Changes in energy consumption and energy intensity: A complete decomposition model. *Energy Econ.* **1998**, *20*, 85–100. [CrossRef]
21. NBSC (National Bureau of Statistics of China). *China Statistics Yearbook 2006–2016*; China Statistics Press: Beijing, China, 2016.
22. CEC (China Electric Council). *China's Electric Power Statistical Yearbook 2006–2015*; China′s Electric Power Press: Beijing, China, 2015.
23. Standards Press of China. *General Principles for Calculation of the Comprehensive Energy Consumption (Chinese National Principle, GB/T 2589-2008)*; Standards Press of China: Beijing, China, 2008.
24. Lu, Q.; Chen, Y.; Tian, C.; Zheng, X.-Q.; Li, J. Strategic deliberation on development of low-carbon energy system in China. *Adv. Clim. Chang. Res.* **2016**, *7*, 26–34. [CrossRef]
25. Ming, M.; Niu, D.; Gao, Q. Decomposition Analysis of Chinese Provincial Economic Growth through Carbon Productivity Analysis. *Environ. Prog. Sustain. Energy* **2014**, *33*, 250–255. [CrossRef]
26. Yang, L.S.; Lin, B.Q. Carbon dioxide-emission in China's power industry: Evidence and policy implications. *Renew. Sustain. Energy Rev.* **2016**, *60*, 258–267. [CrossRef]
27. National Development and Reform Commission (NDRC). *The 13th Five-Years-Plan for Renewable Energy Development. NDRC Directive [2016] 2619*; Chinese Edition; National Development and Reform Commission (NDRC): Beijing, China, 2016. Available online: http://www.ndrc.gov.cn/zcfb/zcfbtz/201612/t20161216_830264.html (accessed on 10 September 2018).
28. Bjorn, L. Impact of current climate proposals. *Glob. Policy* **2016**, *7*, 109–118.
29. INDC (Intended Nationally Determined Contribution). *China's Intended National Determined Contribution: Enhanced Actions on Climate Changes*; United Nations Framework Convention on Climate Change (UNFCCC): Paris, France, 2015.

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