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Have Market-oriented Reforms Decoupled China's CO_2 Emissions from Total Electricity Generation? An Empirical Analysis

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Abstract: Achieving the decoupling of electric CO_2 emissions from total electricity generation is important in ensuring the sustainable socioeconomic development of China. To realize this, China implemented market-oriented reforms to its electric power industry at the beginning of 2003. This study used the Tapio decoupling index, the Laspeyres decomposition algorithm, and decoupling-related data from 1993 to 2012 to evaluate the effect of these reforms. Several conclusions can be drawn based on the empirical analysis. (1) The reforms changed the developmental trend of the decoupling index and facilitated its progress towards strong decoupling. (2) The results forecasted through fitting the curve to the decoupling index indicate that strong decoupling would be realized by 2030. (3) Limiting the manufacturing development and upgrading the generation equipment of the thermal power plants are essential for China to achieve strong decoupling at an early date. (4) China should enhance regulatory pressures and guidance for appropriate investment in thermal power plants to ensure the stable development of the decoupling index. (5) Transactions between multiple participants and electricity price bidding play active roles in the stable development of the decoupling index.

Keywords: Tapio decoupling index; Laspeyres decomposition; electric power industry; CO_2 emissions; China

1. Introduction

On 15 March 2015, the Central Committee of the Chinese Communist Party and the State Council promulgated a document entitled "Further strengthening the institutional reform of electric power industry" [1]. Following this document, six subsidiary documents were also released on 26 November 2015 [2]. Thus, the second round of market-oriented reforms for the electric power industry in China will enter the implementation phase in 2016. The current study aims to evaluate the effect of the first round of reforms in 2003 and develop recommendations to guide the present ones.

As a dual economy, the economic growth of China is greatly dependent on energy consumption, especially electricity. The causality between them has been proved by many researchers [3,4]. To support economic growth, China developed a large electric power system. In 2014, total electricity generation of China was as high as 5649.58 TWh, accounting for 24% of the world's total electricity generation [5].

Owing to the natural resource endowment (with coal being more available than other energy resources) and the historical development of China, electricity generated by its thermal power plants accounts for the single largest portion of the country's total electricity generation. Since the foundation of the People's Republic in 1949, this share has never been lower than 75% [6]. Following the economic development of China, the electric power industry has always been the single most important contributor to the CO_2 emission growth generated in the country and throughout the world. Since the adoption of the Kyoto Protocol at the end of 1997, the emission growth from the electric power industry has accounted for approximately 41% of the total growth in China and 24% in the world [5,6]. After years of increase, the CO_2 emission scale from the electric power industry in China is now already very large. If viewed as a country, China's electric power industry is presently the third largest CO_2 emitter in the world, contributing approximately 35.34 billion tons or 10.15% of the total global amount in 2012 [5,6].

Energy-related CO_2 emissions are the most important contributors of greenhouse effect aggravation, which is listed among the most important problems faced by the scientific and political sectors [7]. Moreover, pollutants accompanying energy-related CO_2 emissions have heavily affected the local environment in China. At present, less than 1% of the 500 largest cities in China meet the air quality standards recommended by the World Health Organization; in fact, seven of these cities are ranked among the ten most polluted cities in the world [8]. Studies have shown that fossil energy combustion in China is the single most important contributor of air pollution and accounts for approximately 70% of the country's total [9,10]. Therefore, managing the relationship between electric CO_2 emissions and total electricity generation is an important issue for the sustainable development of China's economy and environment.

China implemented market-oriented reforms to its electric power industry at the beginning of 2003. One of the main goals of these reforms is to weaken the coupling extent between electric CO_2 emissions (or fossil energy consumption) and total electricity generation. This means that the growth of total electricity generation should result in a minimal increase in CO_2 emission. To achieve this, China designed the reforming policy of "separation of plant and grid, price bidding for use of grid" [11] to introduce competition among the power plants, thus improving their generating efficiencies. Before the reforms, all the electricity sectors (generation, transmission, and distribution) of China were "vertically integrated" [11], in which planning, investment, and operation of the electric sectors were legally managed together by administrational orders. After the reforms, the "vertically integrated" management system was dismantled to allow equal access to the transmission grid for all the plants through competition. The state-owned generation assets were allocated to five large generation corporations which were given full management authority [12]. More investors were permitted to enter the electricity generation industry to ensure electricity supply and maintain competition in electricity bidding [13]. Furthermore, renewable energies, especially wind and photovoltaic power, were developed in subsequent years to decrease the generation share of fossil energy [14].

At present, the effect of the market-oriented reforms in 2003 have attracted the attention of some researchers. Zhao and Ma measured the impact of the reforms on the operational efficiency of 34 large power plants [15]. Zeng *et al.* analyzed the influence of the reforms on the electricity supply demand situation [16]. Judith and Kentish evaluated the contribution of these reforms to the development of renewable power [17]. Some other similar researches have performed the same kinds of analyses [18–20]. However, most of these studies only focused on certain aspects of these reforms; few concentrated on the comprehensive effect of the relationship between electric CO_2 emissions and total electricity generation.

The Environmental Kuznets Curve (EKC) hypothesis has been widely used to measure the relationship between environmental degradation extent and economic growth or welfare level. However, EKC analysis usually requires that economic growth or welfare level is reflected by per capita indicator (e.g., per capita income) [21]. Furthermore, long-term observations or large panel data are essential for EKC analysis to simulate the "natural" development of the above relationship [22].

As this research focuses on the impact of the market-oriented reforms to China's electric power industry in 2003 to the relationship between electric CO_2 emissions and total electricity generation, EKC analysis is not adopted in this paper.

Decoupling refers to undoing the traditional link between two indicators. For the past several years, decoupling analysis has already been used to evaluate the strategies and actions of different regions and sectors to achieve the sustainable development of the economy and environment [23–25]. In this study, decoupling theory is used to analyze the correlation between electric CO_2 emissions and the total quantity of electricity generated in China. At present, two main decoupling indicators can quantify the correlation extent between the two variable changes, namely: the Organization for Economic Co-operation and Development (OECD) algorithm [26,27] and the Tapio algorithm [28]. The present study adopts the latter indicator to facilitate the following decomposition analysis.

Aside from measuring the decoupling extent, knowing what caused these changes is also important, *i.e.*, the changes of the decoupling extent should be decomposed to the quantitative impacts of different factors. The Logarithmic Mean Divisia Index [29] and Laspeyres [30] decomposition models are the widely used methods to solve this problem. These two models have similar functions but have fine differences in terms of the applicable conditions. The former cannot incorporate with negative values that lead to imaginary decomposition results (caused by logarithmic operation) and, as such, cannot be explained, whereas the latter does not have this limitation. Given that the calculated results of the decoupling index may be negative values, the latter is selected as the decomposition algorithm for the present study.

The remainder of this paper is organized as follows: Section 2 introduces the research methods and data used in this study, namely, the Tapio decoupling index, the Laspeyres decomposition algorithm, and decoupling-related data. Section 3 presents the modeling results. Section 4 discusses the abovementioned results. Section 5 concludes the study and proposes policy recommendations.

2. Methods and Data

2.1. Tapio Decoupling Index

According to the definition of Tapio [28], the decoupling index (D) of electric CO_2 emissions (CE) from total electricity generation (TE) can be written as

$$D_{(CE,\ TE)} = \frac{\frac{\Delta CE}{CE}}{\frac{\Delta TE}{TE}} \tag{1}$$

where $D_{(CE,\ TE)}$ is the TE elasticity of CE. According to the concrete values of $D_{(CE,\ TE)}$, ΔCE, and ΔTE, eight logical categories can be distinguished, as shown in Figure 1.

The growth rates of CE and TE can be coupled, decoupled, or negatively decoupled. In order to avoid interpreting slight changes as significant, a $\pm$20% variation of the elasticity values around 1.0 are still regarded as a coupling [28]. When the changes of CE and TE are both in a positive or negative direction, the coupling has two cases: expansive coupling and recessive coupling. For similar reasons, decoupling and negative decoupling have three cases each, namely, weak, strong, and recessive.

In the present study, category III (strong decoupling) is the expected result, that is, the electric CO_2 emissions decrease when the total electricity generation increases. One of the main goals of these reforms at the beginning of 2003 is to prompt the development of $D_{(CE,\ TE)}$ in the direction of strong decoupling.

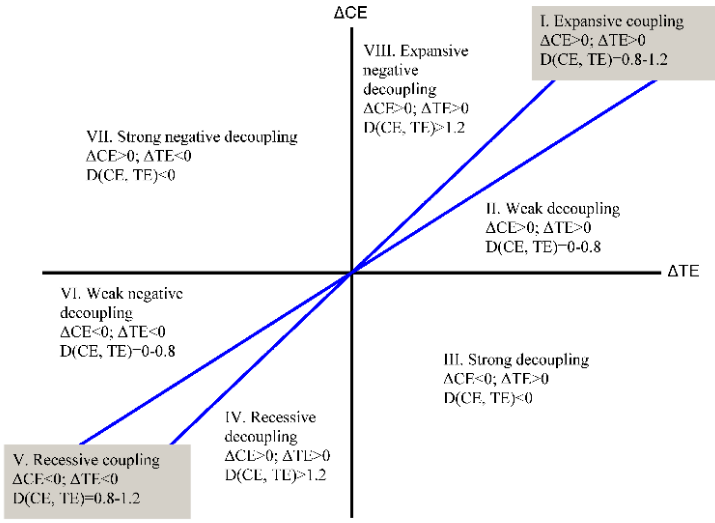

Figure 1. Categories of coupling and decoupling (modified from [28,31]).

2.2. Laspeyres Decomposition

According to the definition of the decoupling index of electric CO_2 emissions from total electricity generation, Equation (1) can further be written as

$$D_{(CE,\ TE)} = \frac{\frac{\Delta CE}{CE}}{\frac{\Delta EF}{EF}} \cdot \frac{\frac{\Delta EF}{EF}}{\frac{\Delta CF}{CF}} \cdot \frac{\frac{\Delta CF}{CF}}{\frac{\Delta TE}{TE}} \tag{2}$$

where EF and CF are the electricity generated by fossil energy and the installed generation capacity of fossil energy, respectively.

Let $D_{(CE,\ EF)} = \frac{\frac{\Delta CE}{CE}}{\frac{\Delta EF}{EF}}$, $D_{(EF,\ CF)} = \frac{\frac{\Delta EF}{EF}}{\frac{\Delta CF}{CF}}$, and $D_{(CF,\ TE)} = \frac{\frac{\Delta CF}{CF}}{\frac{\Delta TE}{TE}}$, Equation (2) is then written as

$$D_{(CE,\ TE)} = D_{(CE,\ EF)} \cdot D_{(EF,\ CF)} \cdot D_{(CF,\ TE)} \tag{3}$$

Equation (3) is an identical equation. That is, the changes of $D_{(CE,\ TE)}$ should be attributed to the effects of $D_{(CE,\ EF)}$, $D_{(EF,\ CF)}$, and $D_{(CF,\ TE)}$ changes, which are denoted as $ED_{(CE,\ EF)}$, $ED_{(EF,\ CF)}$, and $ED_{(CF,\ TE)}$, respectively. Thus,

$$\Delta D_{(CE,\ TE)} = ED_{(CE,\ EF)} + ED_{(EF,\ CF)} + ED_{(CF,\ TE)} \tag{4}$$

According to the "jointly created and equally distributed" principle [32], the decomposition algorithm of each influence factor should be written as

$$\begin{aligned} ED_{(CE,\ EF)} &= \Delta D_{(CE,\ EF)} \cdot D_{(EF,\ CF)} \cdot D_{(CF,\ TE)} + \tfrac{1}{2} \cdot \Delta D_{(CE,\ EF)} \cdot \Delta D_{(EF,\ CF)} \cdot D_{(CF,\ TE)} \\ &+ \tfrac{1}{2} \cdot \Delta D_{(CE,\ EF)} \cdot D_{(EF,\ CF)} \cdot \Delta D_{(CF,\ TE)} + \tfrac{1}{3} \cdot \Delta D_{(CE,\ EF)} \cdot \Delta D_{(EF,\ CF)} \cdot \Delta D_{(CF,\ TE)} \end{aligned} \tag{5}$$

$$\begin{aligned} ED_{(EF,\ CF)} &= D_{(CE,\ EF)} \cdot \Delta D_{(EF,\ CF)} \cdot D_{(CF,\ TE)} + \tfrac{1}{2} \cdot \Delta D_{(CE,\ EF)} \cdot \Delta D_{(EF,\ CF)} \cdot D_{(CF,\ TE)} \\ &+ \tfrac{1}{2} \cdot D_{(CE,\ EF)} \cdot \Delta D_{(EF,\ CF)} \cdot \Delta D_{(CF,\ TE)} + \tfrac{1}{3} \cdot \Delta D_{(CE,\ EF)} \cdot \Delta D_{(EF,\ CF)} \cdot \Delta D_{(CF,\ TE)} \end{aligned} \tag{6}$$

and

$$\begin{aligned} ED_{(CF,\ TE)} &= D_{(CE,\ EF)} \cdot D_{(EF,\ CF)} \cdot \Delta D_{(CF,\ TE)} + \tfrac{1}{2} \cdot \Delta D_{(CE,\ EF)} \cdot D_{(EF,\ CF)} \cdot \Delta D_{(CF,\ TE)} \\ &+ \tfrac{1}{2} \cdot D_{(CE,\ EF)} \cdot \Delta D_{(EF,\ CF)} \cdot \Delta D_{(CF,\ TE)} + \tfrac{1}{3} \cdot \Delta D_{(CE,\ EF)} \cdot \Delta D_{(EF,\ CF)} \cdot \Delta D_{(CF,\ TE)} \end{aligned} \tag{7}$$

The positive and negative values of $ED_{(CE,\ EF)}$, $ED_{(EF,\ CF)}$, and $ED_{(CF,\ TE)}$ mean contributions to the increase and decrease of $D_{(CE,\ TE)}$, respectively. Equations (5)–(7) are complete decomposition algorithms [32], that is, the summation of $ED_{(CE, EF)}$, $ED_{(EF, CF)}$, and $ED_{(CF, TE)}$ should be equal to the change of $D_{(CE, TE)}$.

2.3. Data Selection

The time period covered by the samples spans from 1993 to 2012, because the latest available decoupling-related data were from 2012, and the present study sought to balance the sample size before and after the market-oriented reforms in the beginning of 2003.

For the variables used in Equations (1)–(7), *TE*, *EF*, and *CF* were selected directly from the *China Statistical Yearbook* [6]. However, because China has never released its CO_2 emission data from the electric power industry, *CE* had to be obtained by converting the consumed fossil energies.

The fossil energy consumption data of the electric power industry in China was selected from the *China Energy Statistical Yearbook* [33]. The present study includes all consumed fossil energies, namely, coal, crude oil, fuel oil, and diesel oil.

When estimating CO_2 emissions by conversion, the net heating data of different fossil energies serve as the important intermediate values. Net heating factors usually have fine differences between different countries. The present study adopted a Chinese national standard called "General Principles for Calculation of Total Production Energy Consumption" (GB/T 2589-2008) [34].

Using the selected fossil energy consumption data and the mean net heating factors offered by the above Chinese national standard, the net heating values of each fossil energy for each year were obtained. The Intergovernmental Panel on Climate Change (IPCC) has proposed CO_2 emission factors that can measure the CO_2 emissions by using the net heating values.

Then, the CO_2 emissions from each fossil energy for each year were obtained. By adding emission data of a year together, the CO_2 emissions from the electric power industry in China for that year were obtained. All data used for calculating the decoupling index and the decomposition results are listed in Table 1.

Table 1. Annual data of CO_2 emissions (*CE*), total electricity generation (*TE*), electricity generated by fossil energy (*EF*), and installed generation capacity of fossil energy (*CF*).

Year	1993	1994	1995	1996	1997	1998	1999	2000	2001	2002
CE	779.5	829.4	922	1004.2	1021.2	1019.7	1076.2	1140	1220	1395.9
TE	838.3	928.1	1007.7	1079.4	1134.5	1166.2	1239.3	1355.6	1480.8	1654.0
EF	683.9	745.9	804.3	877.7	924.1	944.1	1020.5	1114.2	1183.4	1338.1
CF	138.0	148.7	162.9	178.9	192.4	209.9	223.4	237.5	253.0	265.6
Year	**2003**	**2004**	**2005**	**2006**	**2007**	**2008**	**2009**	**2010**	**2011**	**2012**
CE	1667.1	1876.3	2090.5	2389.6	2608.2	2694.5	2858.7	3064.4	3476.3	3534
TE	1910.6	2203.3	2500.3	2865.7	3281.6	3466.9	3714.7	4207.2	4713	4987.6
EF	1580.4	1795.6	2047.3	2369.6	2722.9	2790.1	2982.8	3331.9	3833.7	3892.8
CF	289.8	329.5	391.4	483.8	556.1	602.9	651.1	709.7	768.3	819.7

The unit of *CE*, *TE*, *EF*, and *CF* are million tons, billion kWh, billion kWh, and million kW, respectively.

3. Results

Using Equation (1) and the data shown in Table 1, the annual results of $D_{(CE, TE)}$ before and after the market-oriented reforms were obtained. Similarly, the annual results of $D_{(CE, EF)}$, $D_{(EF, CF)}$, and $D_{(CF, TE)}$ were also calculated as the intermediate values for decomposition. These results are all listed in Table 2.

Table 2. Annual results of $D_{(CE,\ TE)}$, $D_{(CE,EF)}$, $D_{(EF,CF)}$, and $D_{(CF,TE)}$.

Year	1993	1994	1995	1996	1997	1998	1999	2000	2001
$D_{(CE,\ TE)}$	0.5974	1.3009	1.2543	0.3316	−0.0525	0.884	0.6317	0.7598	1.2327
$D_{(CE,\ EF)}$	0.7057	1.426	0.9771	0.3205	−0.0678	0.6843	0.646	1.1292	1.1029
$D_{(EF,\ CF)}$	1.168	0.8201	0.9339	0.6972	0.2387	1.2541	1.4531	0.9542	2.6376
$D_{(CF,\ TE)}$	0.7249	1.1124	1.3746	1.4838	3.2463	1.0300	0.6729	0.7051	0.4237
Year	**2003**	**2004**	**2005**	**2006**	**2007**	**2008**	**2009**	**2010**	**2011**
$D_{(CE,\ TE)}$	0.819	0.8471	0.9788	0.6305	0.5859	0.8527	0.5427	1.1179	0.2849
$D_{(CE,\ EF)}$	0.9214	0.8142	0.909	0.6135	1.3417	0.8823	0.6147	0.8926	1.0765
$D_{(EF,\ CF)}$	0.9938	0.7463	0.6664	0.9985	0.2931	0.8635	1.3008	1.8216	0.2307
$D_{(CF,\ TE)}$	0.8944	1.394	1.6158	1.0292	1.4899	1.1192	0.6787	0.6876	1.1471

The year values above refer to the starting year of the annual change. For example, 0.5974 in line 2, row 2 is the value of $D_{(CE,\ TE)}$ from 1993 to 1994.

Using data in Table 2, the annual changes of $D_{(CE,\ EF)}$, $D_{(EF,\ CF)}$, and $D_{(CF,\ TE)}$ were easily calculated. The annual decomposition results of $ED_{(CE,\ EF)}$, $ED_{(EF,\ CF)}$, and $ED_{(CF,\ TE)}$ were obtained by inputting these annual changes and data in Table 2 into Equations (5)–(7). Table 3 lists the decomposition results.

Table 3. Decomposition results of $ED_{(CE,\ EF)}$, $ED_{(EF,\ CF)}$, and $ED_{(CF,\ TE)}$.

Year	1993	1994	1995	1996	1997	1998	1999	2000
$ED_{(CE,\ EF)}$	0.6497	−0.4907	−0.7639	−0.4036	1.0592	−0.0439	0.4001	−0.0256
$ED_{(EF,\ CF)}$	−0.3487	0.1689	−0.2181	−0.1109	0.5282	0.1129	−0.3058	1.0614
$ED_{(CF,\ TE)}$	0.4025	0.2752	0.0592	0.1304	−0.651	−0.3213	0.0338	−0.563
Year	**2003**	**2004**	**2005**	**2006**	**2007**	**2008**	**2009**	**2010**
$ED_{(CE,\ EF)}$	−0.1056	0.1006	−0.3205	0.5726	−0.3385	−0.256	0.2965	0.1619
$ED_{(EF,\ CF)}$	−0.2446	−0.1037	0.3391	−0.8883	0.8356	0.2985	0.2682	−1.4481
$ED_{(CF,\ TE)}$	0.3783	0.1348	−0.3669	0.2711	−0.2303	−0.3525	0.0106	0.453

The year values above refer to the starting year of the decomposition analysis. For example, 0.6497 in line 2, row 2 is the quantitative effect of $D_{(CE,\ EF)}$ on the change from $D_{(CE,\ TE)}$, 1993 to $D_{(CE,\ TE)}$, 1994.

The summation of values from line 2 to line 4 of Table 3 is 0.6350. This result is equal to the change of $D_{(CE,\ TE)}$ from 1993 to 2002. In addition, the summation of line 6 to line 8 is equal to the $D_{(CE,\ TE)}$ change of 2003 to 2012. Thus, Equations (5)–(7) are proven to be complete decomposition algorithms.

4. Discussion

4.1. Outlier Analysis

Based on the threshold values shown in Figure 1 and data in Table 2, the classification result of the decoupling indicator $D_{(CE,\ TE)}$ for each year was obtained. The results are shown in Table 4.

Table 4. Classification results of $D_{(CE,\ TE)}$.

Year	1993	1994	1995	1996	1997	1998	1999	2000	2001
Category	II	VIII	VIII	II	III	I	II	II	VIII
Year	**2003**	**2004**	**2005**	**2006**	**2007**	**2008**	**2009**	**2010**	**2011**
Category	I	I	I	II	II	I	II	I	II

As shown in Table 4, most of the decoupling results belonged to categories I (expansive coupling) and II (weak decoupling). Although the decoupling classification results in 1994, 1995, and 2001 belonged to category VIII (expansive negative coupling), as their concrete values (1.3009, 1.2543, and

1.2327 for 1994, 1995, and 2001, respectively) approached the threshold (1.2), they had no difference to category I in essence. The only outlier was the decoupling result for 1997, which not only belonged to a category distinct from other samples but also was significantly smaller than others.

In the second half of 1997, a severe financial crisis broke out in Southeast Asia. China's exports were affected and appeared abnormal in 1998. From 1990 to 1997, the average annual increase rate of China's export was 16.68%. However, this rate was only 0.56% from 1997 to 1998 [6]. Manufactured goods accounted for over 85% of China's total exports, and most of which were electricity intensive. Therefore, the total electricity generation in the country by 1998 was also greatly affected and only increased by 2.08%, which was much lower than the average annual increase rate from 1990 to 1997 (8.98%) [6]. For the above reasons, the relative excess generation capacity appeared temporarily in 1998.

At that time, the market-oriented reforms had not yet been implemented. This meant that the electric power industry in China still adopted a "vertically integrated" management system [11]. The grid company bought electricity from power plants at a fixed price. The purchase prices of hydropower, thermal power, and nuclear power were about 0.2–0.4, 0.3–0.5, and 0.43 Yuan, respectively. When the excess generation capacity appeared in 1998, the dispatch department of the grid company first bought electricity from the hydropower, large thermal power, and nuclear power plants. When arranging the generation plan, the dispatch department did not take the small thermal power plants into account because of their higher generation cost (mainly caused by low generation efficiency). As a result, CO_2 emissions from thermal power plants decreased by 1.5 million tons in 1998, although the electricity generation increased by 20 billion kWh (Table 1).

Aside from the development of non-fossil energy generation, controlling the output increase of manufactured goods and upgrading the generation equipment of the thermal power plants are important for decoupling CO_2 emissions from total electricity generation according to the outlier analysis.

4.2. Trend Analysis

To demonstrate the development trend of $D_{(CE,\ TE)}$ before and after the reforms, two linear equations were obtained by using the ordinary least squares algorithm to fit its annual results listed in Table 2. They are

$$D_{(CE,\ TE),x} = -6.7210 + 0.0038x \tag{8}$$

where x = 1993–2001, and

$$D_{(CE,\ TE),x} = 66.7702 - 0.0329x \tag{9}$$

where x = 2003–2011, respectively.

The distribution, classification, and linear curve fitting results of $D_{(CE,\ TE)}$ before and after the reforms are shown in Figure 2 to analyze the development trend of decoupling extent of electric CO_2 emissions from total electricity generation.

As shown in Figure 2, the outlier (1997) is located just in the middle position of the samples which are used to estimate the fitting curve before the reforms. Owing to this special position, it has no effect on the slope of the fitting curve, although increases the fitting error of Equation (8). Figure 2 shows that the fitted curve before the reforms presents a slight upward trend, whereas the curve after the reforms is downward. Thus, the market-oriented reforms in China in 2003 have changed the developmental trend of the extent of decoupling electric CO_2 emissions from total electricity generation.

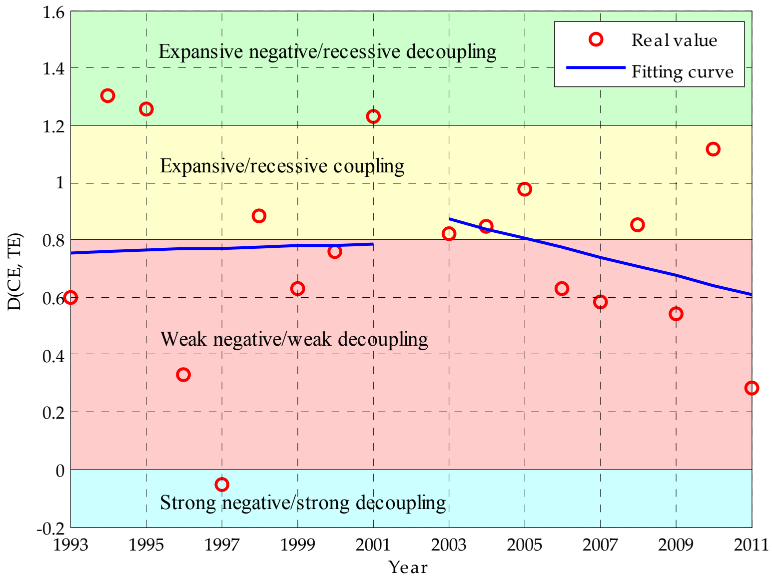

Figure 2. Distribution, classification, and curve fitting results of $D_{(CE,\,TE)}$.

The future decoupling extent can be forecasted by extrapolating the fitting curve after the reforms. Table 5 shows the forecasting results.

Table 5. Forecasting results of $D_{(CE,\,TE)}$.

Year	**2012**	**2013**	**2014**	**2015**	**2016**	**2017**	**2018**	**2019**	**2020**	**2021**
$D_{(CE,\,TE)}$	0.575	0.543	0.51	0.477	0.444	0.411	0.378	0.345	0.312	0.279
Year	**2022**	**2023**	**2024**	**2025**	**2026**	**2027**	**2028**	**2029**	**2030**	**2031**
$D_{(CE,\,TE)}$	0.246	0.214	0.181	0.148	0.115	0.082	0.049	0.016	−0.017	−0.05

The forecasting results of $D_{(CE,\,TE)}$ show that the electric CO_2 emissions of China will decouple from total electricity generation by 2030. Hence, with the growth of the total electricity generation, electric CO_2 emissions in China will increase with a progressively slower rate before 2030. The rate of increase in electric CO_2 emissions will reach 0 by 2030 at the same time that the emission amount reaches its peak. After 2030, the projected results of $D_{(CE,\,TE)}$ will be less than 0. Thus, electric CO_2 emissions will decrease, even if the total electricity generation increases.

China has once claimed that its CO_2 emissions will stop growing by the 2030s and then decrease gradually [35,36]. Considering that the electric power industry is the single most important CO_2 emitter in the country, the above forecasting results show that this goal may well be achieved.

4.3. Decomposition Result Analysis

According to Equation (4), the change of $D_{(CE,\,TE)}$ can be decomposed to the effects of the changes of $D_{(CE,\,EF)}$, $D_{(EF,\,CF)}$, and $D_{(CF,\,TE)}$. Figure 3 uses a histogram to demonstrate the above decomposition results.

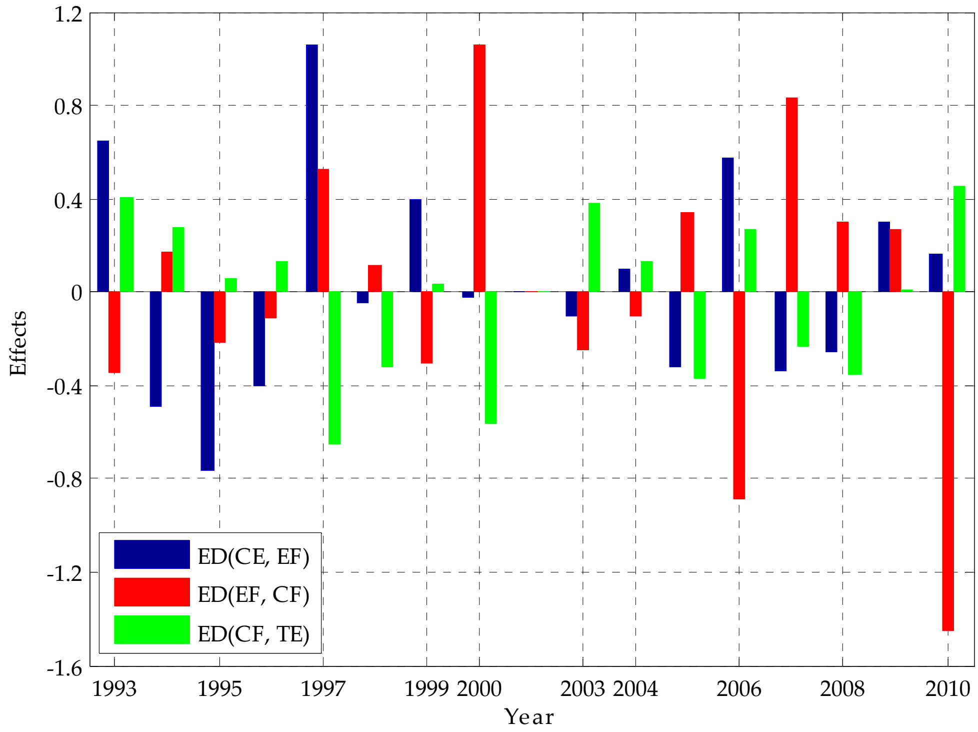

Figure 3. Annual decomposition results of $ED_{(CE,\,EF)}$, $ED_{(EF,\,CF)}$, and $ED_{(CF,\,TE)}$.

As shown in Figure 3, the amplitude of $ED_{(CF,\,TE)}$ was not significantly affected by the reforms, whereas the amplitudes of $ED_{(CE,\,EF)}$ and $ED_{(EF,\,CF)}$ were different.

Using data in Table 3, the present study illustrates that the variance of $ED_{(CE,\,EF)}$ after the reforms (0.0931) is much smaller than that before the reforms (0.3345); this difference implies that the quantitative relationship between electric CO_2 emissions and electricity generated by fossil energy became more stable after the market-oriented reforms in 2003. To achieve this effect, the generating efficiency of thermal power plants should remain relatively stable after the reforms. Although the unified electricity bidding market was not yet complete, the market-oriented reforms in 2003 partly changed the traditional planned electricity dispatch and partly introduced competition into the arrangement of the generation plan. This change allowed the generating efficiency to become more stable than before, thus reducing the variance of $ED_{(CE,\,EF)}$. The document "Further strengthening the institutional reform of electric power industry," as promulgated by the Central Committee of the Chinese Communist Party and the State Council on 15 March 2015, clearly indicated that China must encourage the transactions between multiple participants [1]. Furthermore, a unified electricity price bidding market is also expected to be completed in the future. These policies shall further enhance the influence of market competition in electricity dispatch and ultimately help to more steadily decouple electric CO_2 emissions from total electricity generation.

Contrary to $ED_{(CE,\,EF)}$, the variance of $ED_{(EF,\,CF)}$ after the reform (0.4775) is larger than that before the reforms (0.2029). This difference means that the quantitative relationship between the electricity generated by fossil energy and installed generation capacity of fossil energy became more unstable after the reforms. As a result, relative surplus and shortage of thermal power generation capacity appeared more frequently and with a greater impact. After the market-oriented reforms in 2003, more investors were permitted to build new thermal power plants. Moreover, the existing investors were granted more investment autonomy. The above results prove that investments in the thermal power industry are more disordered than before, and the effect of the market mechanism for this issue is not satisfactory.

Keeping $ED_{(CE,\,EF)}$, $ED_{(EF,\,CF)}$, and $ED_{(CF,\,TE)}$ steady helps $D_{(CE,\,TE)}$ to decrease steadily until electric CO_2 emissions decoupling from total electricity generation as is expected in the future. At present, the key is to enhance regulation and guidance relating to investments made in the thermal power industry. Furthermore, transactions between multiple participants and electricity bidding play active roles in this process.

5. Conclusions

At the beginning of 2003, China implemented market-oriented reforms to its electric power industry. One of the main goals of these reforms is to achieve the decoupling of electric CO_2 emissions from total electricity generation.

The current study used the Tapio decoupling index, Laspeyres decomposition algorithm, and decoupling-related data from 1993 to 2012 to evaluate the effect of the reforms. Several conclusions can be drawn from empirical analysis. (1) The market-oriented reforms in 2003 changed the developmental trend of the decoupling index from upward to downward. As expected, the present development trend of decoupling index is directed towards strong decoupling. (2) The future decoupling index can be forecasted by trend extrapolation of the fitting curve. According to the forecasting results, strong decoupling can be realized by 2030. After 2030, the electric CO_2 emissions will decrease, even if the total electricity generation increases. (3) Given that manufacturing consumes a large share of electricity, limiting its development can reduce the usage of inefficient thermal power plants and help China to achieve strong decoupling at an early date. Furthermore, upgrading the generation equipment of thermal power plants has a similar effect. (4) At present, the main uncertainty of the decoupling index development comes from the disorder of investments in thermal power plants. Therefore, China should enhance existing regulation and guidance for these investments. (5) Transactions between multiple participants and electricity bidding can further enhance the influence of the market in electricity dispatch, and ultimately help the decoupling index to develop smoothly.

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