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Decoupling and Decomposition Analysis of Carbon Emissions from Electric Output in the United States

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Abstract: The rapid growth of the electricity sector in the United States has been accompanied by a dramatic rise in CO_2 emissions. To understand the driving effects that contribute to the increase in CO_2 emissions during electricity generation, as well as the relationship between the emissions and electricity output, a novel decoupling index on the basis of the multilevel logarithmic mean divisia index (LMDI) method is presented in this paper. The results of our study indicate that, on the one hand, the electricity output effect played a crucial role in increasing CO_2 emissions. On the other hand, the energy mix effect and the conversion efficiency effect made a contribution to curbing the related CO_2 emissions in most of the years covered by our study. The power production structure effect and emission factor effect each played a negative role in the decoupling process. No decoupling was the main status during most of the years covered in our study, with a strong decoupling status being the least common state.

Keywords: CO_2 emissions; multilevel LMDI analysis; decoupling index; United States

1. Introduction

The ever-increasing focus on climate change has caused both growing concern and heated debates on the issue of greenhouse gases (GHGs) [1–5]. As demonstrated by the Intergovernmental Panel on Climate Change (IPCC), GHGs consist of anthropogenic emissions of carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), hydrofluorocarbons (HFCs), perfluorocarbons (PFCs), sulfur hexafluoride (SF_6), hydro chlorofluorocarbons (HCFCs), and chlorofluorocarbons (CFCs). Moreover, the increase in GHGs poses a threat to the economy and to society. As just one example, extreme weather has contributed to a decline in agriculture output. To curb GHG emissions, there is a desperate need to transform the world into a low-carbon energy environment [6–12]. The electricity sector burns 68% of global fossil fuels and produces 40% of global CO_2 emissions [13]. In addition, energy consumption in the electricity sector increased by 40% between 1990 and 2008 [13,14]. Thus, understanding the drivers of carbon emissions and the decoupling status of the electricity sector can facilitate not only the electricity sector, but also the movement of modern energy systems to a low–carbon model [15]. In this paper, we attempt to explore the drivers of carbon emissions and the decoupling status of electricity in the United States. To accomplish these goals, we use a novel decoupling index on the basis of the multilevel logarithmic mean divisia index (LMDI) method.

2. Literature Review

The issue of CO_2 emissions, the driving factors behind those emissions and the relationship between economic indicators, energy, and CO_2 emissions have all been discussed in previous studies [16–21]. As for the emissions caused by electricity generation, scientists have also focused their attention on the emissions of the electricity sector in various areas [10,20,22,23]. Ali found that carbon dioxide (CO_2) emissions coming from fossil fuel-fired power plants are a major focus for emissions abatement advocates, and created an optimization model to assess and explore Singapore's various CO_2 emission reduction strategies, particularly with regard to electricity generation in Singapore up to the year 2020 [24]. Fumitaka (2017) examines the relationship between renewable and non-renewable electricity consumption and economic development in three transition economies in the Baltic region. This study employs homogeneous and heterogeneous panel methods. Then, a unidirectional causality from the region's economic development to renewable electricity consumption was found [25]. Byun estimated Korean consumers' marginal utility and studied an appropriate generation mix, which was derived using the hierarchical Bayesian logit model in a discrete choice experiment, and found that consumers consider the danger posed by the source of electricity as the most important factor among the effects of electricity generation sources [26]. Cabral proposed an alternative method for applying the Moran's I test in exploratory analyses for spatial autocorrelation. Cabral found evidence which indicates that regional electricity consumption in Brazil is spatially dependent, presenting a spatial pattern of dissimilarity between regions to ensure consistent, unbiased and efficient estimates to obtain electricity use forecasts [27]. Da Silva (2017) assessed the main drivers of household electricity prices in the European Union (EU), throughout a period of deep sector transformation. This was accomplished by analyzing the long-term progress of household electricity prices across the EU, in relation to the variable of household electricity prices with variables related to sector liberalization. Da Silva did this by developing a dynamic model with panel data through the GMM proposal method [28]. When it comes to reducing carbon dioxide emissions and the use of renewable energy resources, Aquila analyzed long-term policies that have been applied in several countries. These policies include feed-in tariffs, shares with commercialization of certificates, auctions, and net metering. This study also discussed the main advantages and disadvantages of these incentive strategies from the perspective of renewable sources [29]. Some studies have taken the US as an example, exploring carbon emissions from different sources, such as land-use changes [15,30–33], farm operations [34], agriculture and forestry [35], and international trade [36]. Fatih Bayrak and Nidal Abu-Hamdeh published a comprehensive review of an exergy analysis and performance assessment relating to a wide range of solar electricity production. They also evaluated solar electricity options, including photovoltaics (PVs) and hybrid (PV/Twater or PV/Tair) solar collectors [37]. Scientists have also paid close attention to the emissions of the electricity sector in various areas [10,20,22,23]. Ciarreta, for example, proclaimed that no significant change in behavior was found for nuclear, hydropower and coal emissions. However, a change was observed with regard to combined cycle bidding strategies after the entry of renewable generators. The analysis showed that the massive expansion in the use of renewable energy sources made other power generators' behavior more competitive in the short run, but the effect was not persistent or prolonged [38].

In terms of the similarities and differences between structural decomposition analysis and index decomposition analysis based on the available information [39], Andreoni (2016) conducted a decomposition analysis of the energy-related CO_2 emissions of 33 countries [40]. Decoupling analysis has become a significant issue recently. Ren explored the impacts of industry structure, economic output, energy structure, energy intensity, and emission factors on the total carbon dioxide emissions from China's manufacturing industry. Ren also analyzed the decoupling elasticity of the manufacturing industry during the period from 1996 to 2010 [41]. Yu and Zhou (2017) discussed the environmental pressures caused by economic growth, which has occurred in cities undergoing rapid economic growth and a decoupling relationship in Chongqing, China [42].

Some researchers take the US as an example, exploring the carbon emissions from different sources, such as land-use change [30–33], farm operations [34], agriculture and forestry [35], and international trade [36]. The changes in carbon emissions in the US partly related to the extraction of natural gas from shale rock in the United States (US). The development of this new process is one of the landmark events in the 21st century [15,43,44] and is being heralded as a transition fuel which will lead to a low-carbon future [15,45–53]. Table 1 summarizes some typical studies of the US, which are closely related to our research. The main features of these studies include the methodology employed and the main findings [54–62].

Table 1. Summary of previous studies on the CO_2 emission in the US.

Study	Methodology	Content or Subject
Lakshmanan (1997) [59]	Divisia decomposition	U.S. transportation
Aldy (2005) [54]	Estimated EKCs	Pre-trade(production-based) and post-trade (consumption-based) CO_2 EKCs
Aldy (2006) [56]	Estimated EKCs and Kaya Identity	The relationship between economic development and energy consumption
Aldy (2006) [55]	Cross-sectional and stochastic convergence tests	State-level CO_2 emissions per capita—production (pre-electricity trade) CO_2 and consumption (post-electricity trade) CO_2
Lutsey (2008) [60]	Investigate three types of GHG policy actions	Local, state, and regional policy actions
Auffhammer (2012) [57]	Test the squared out-of-sample prediction error of aggregate CO_2 emissions	Compare the most common reduced form models used for emissions forecasting, point out shortcomings and suggest improvements
Baldwin (2013) [58]	Kaya Identity and a novel vector autoregression (VAR)	The evolution driving forces
Shahiduzzaman (2015) [61]	Decomposition models	Examines the changes in CO_2 emissions over business cycle phases
Shahiduzzaman (2017) [62]	LMDI decomposition	Make quantitative judgment of the challenge to achieve a reduction of net GHGs emissions by 26–28% below its 2005 level by 2025

Most previous studies have tended to decompose the energy-related CO_2 emissions of a sector from an economic aspect, using gross domestic product (GDP) or per capita GDP as one of the influencing factors. However, we conduct the research by using electricity production as the output of the electricity sector when launching our decomposition and decoupling analysis and research. In view of the characteristics of the electricity sector, a novel decoupling method was applied, in order to determine the relationship between emissions and the output of the electricity sector. The LMDI method was applied, in order to determine the influencing factors of the energy-related CO_2 emissions of the electric power generation, and in this paper, compare the attribution of each effect.

3. Methodologies and Data

3.1. Methodologies

3.1.1. Multilevel Index Decomposition for Decoupling

As stated above, a decomposition method can detect the driving factors behind the changes in carbon dioxide emissions and, even more significantly, in the overall trend of change. Based on an expanded Kaya identity and the research of Ang [63,64], the LMDI method was used in this paper. Meanwhile, both additive LMDI and multiplicative LMDI were applied to more precisely probe the factors driving the CO_2 emissions caused by electricity generation [65–68]. The total CO_2 emissions caused by electricity generation can be decomposed into five factors: (1) electric power production (electricity power output effect); (2) electricity power generation structure (structure effect); (3) the gross coal consumption rate (energy conversion efficiency effect); (4) energy mix (mix effect); and (5) CO_2 emission factors (emission factor effect).

First, the additive LMDI method is shown in Equation (1):

$$\Delta C = \sum\nolimits_i G \times \frac{G_0}{G} \times \frac{E_0}{G_0} \times \frac{E_i}{E_0} \times \frac{C_i}{E_i} \tag{1}$$

where ΔC represents the total energy-related CO_2 emissions from electricity generation in the US (Mt); G is the electric power production (Mtce); G_0 refers to fire power production (Mtce); E_0 and E_i are the energy consumption of thermal power generation (Mtce) and energy consumption by fuel type i (Mtce), and C_i represents the CO_2 emissions by fuel type i (Mt).

Equation (1) can also be stated as:

$$\Delta C = \sum\nolimits_i G \times S \times I \times M_i \times F_i \tag{2}$$

Here, S (G_0/G) means electricity power generation structure, and I (E_0/G_0) denotes the gross coal consumption rate; M_i (E_i/E_0) refers to the share of fuel i; F_i (C_i/E_i) represents the emission factor of fuel i:

$$\Delta C = C^t - C^0 = \Delta C_G + \Delta C_S + \Delta C_I + \Delta C_M + \Delta C_F \tag{3}$$

Each effect can be calculated as below:

$$\Delta C_G = \sum\nolimits_i W\left(C_i^t, C_i^0\right) \times ln\frac{G^t}{G^0} \tag{4}$$

$$\Delta C_S = \sum\nolimits_i W\left(C_i^t, C_i^0\right) \times ln\frac{S^t}{S^0} \tag{5}$$

$$\Delta C_I = \sum\nolimits_i W\left(C_i^t, C_i^0\right) \times ln\frac{I^t}{I^0} \tag{6}$$

$$\Delta C_M = \sum\nolimits_i W\left(C_i^t, C_i^0\right) \times ln\frac{{M_i}^t}{{M_i}^0} \tag{7}$$

$$\Delta C_F = \sum\nolimits_i W\left(C_i^t, C_i^0\right) \times ln\frac{{F_i}^t}{{F_i}^0} \tag{8}$$

where:

$$W\left(C_i^t, C_i^0\right) = \begin{cases} \frac{C_i^t - C_i^0}{\ln C_i^t - \ln C_i^0}, \ C_i^t \neq C_i^0 \text{ and } C_i^t C_i^0 \neq 0 \\ C_i^0, \ C_i^t = C_i^0 \\ 0, \ C_i^t C_i^0 \neq 0 \end{cases} \tag{9}$$

C^t and C^0stand for the CO_2 emissions in a target year and base year, respectively. The contribution of each effect is as follows: the electricity power output effect (ΔC_G), power production structure effect (ΔC_S), energy conversion efficiency effect (ΔC_I), energy mix effect (ΔC_M), and the emission factor effect (ΔC_F).

We applied the multiplicative LMDI to obtain a deeper analysis and identify the driving factors of the contribution of each effect, as follows:

$$\mathrm{D} = \mathrm{C_t}/\mathrm{C_0} = \mathrm{DG} \times \mathrm{DS} \times \mathrm{DI} \times \mathrm{DM} \times \mathrm{DF} \tag{10}$$

$$DG = \exp(\sum_i W' \times \ln \frac{G^t}{G^0}) \quad (11)$$

$$DS = \exp(\sum_i W' \times \ln \frac{S^t}{S^0}) \quad (12)$$

$$DI = \exp(\sum_i W' \times \ln \frac{I^t}{I^0}) \quad (13)$$

$$DM = \exp(\sum_i W' \times \ln \frac{{M_i}^t}{{M_i}^0}) \quad (14)$$

$$DF = \exp(\sum_i W' \times \ln \frac{{F_i}^t}{{F_i}^0}) \quad (15)$$

$$W' = \begin{cases} \frac{(C_i^t - C_i^0)/\left(lnC_i^t - lnC_i^0\right)}{(C^t - C^0)/(lnC^t - lnC^0)},\ C_i^t \neq C_i^0, C^t \neq C^0 \text{ and } C_i^t C_i^0 \neq 0 \\ \frac{C_i^0}{(C^t - C^0)/(lnC^t - lnC^0)},\ C_i^t = C_i^0 \\ 0,\ C_i^t C_i^0 \neq 0 \end{cases} \quad (16)$$

where DG, DS, DI, DM, and MF refer to the growth rates of CO_2 emissions corresponding to the electricity power production effect, power production structure effect, energy conversion efficiency effect, energy mix effect and emission factor effect, respectively.

3.1.2. Decoupling Index and Status Analysis

Previous researchers tended to focus on the relationship between environmental issues and economic factors (such as GDP). Since we chose the electricity sector as the object upon which to conduct the discussion, we presented a novel decoupling method for a theoretical framework, in order to analyze the relationship between the development of the electricity sector and the environmental changes, which is advanced on the basis of D. Diakoulaki [69]:

$$\Delta e_t = \Delta C - \Delta C_G = \Delta C_S + \Delta C_I + \Delta C_M + \Delta C_F \quad (17)$$

Here, Δe_t represents the efforts made by the government (or society) to decrease the level of carbon dioxide emissions. In addition, the changes in the CO_2 emissions caused by the output of the electricity sector can influence the decoupling status. If $\Delta C_G > 0$, then the decoupling index can be defined as the proposition of the output effect, which is shown in Equation (18), as follows:

$$\varphi_{tot} = -\frac{\Delta e_t}{\Delta C_G} = -\frac{\Delta C_S + \Delta C_I + \Delta C_M + \Delta C_F}{\Delta C_G} = -\frac{C_S}{C_G} - \frac{C_I}{C_G} - \frac{C_M}{C_G} - \frac{C_F}{C_G} = \varphi_S + \varphi_I + \varphi_M + \varphi_F \quad (18)$$

When $\Delta C_G < 0$, this means that the output effect has played a negative role, which also indicates that the reduction efforts did not outweigh the CO_2 emissions caused by the output effect. Therefore, extra efforts must be made. In this case, the decoupling can be calculated as Equation (19):

$$\varphi_{tot} = \frac{\Delta e_t - \Delta C_G}{\Delta C_G} = \frac{\Delta C_S + \Delta C_I + \Delta C_M + \Delta C_F - \Delta C_G}{\Delta C_G} = \varphi_S + \varphi_I + \varphi_M + \varphi_F + k \quad (19)$$

where φ_{tot} represents the fraction of the additional efforts needed to offset the total output effect. In both of the two situations, if $\varphi_t > 1$, this denotes strong decoupling efforts. If $0 < \varphi_t < 1$, this represents moderate decoupling efforts. When $\varphi_t < 0$, this indicates the existence of no decoupling efforts. Additionally, φ_S, φ_I, φ_M, and φ_F indicate the contribution to the total decoupling state of each effect [10,15,20].

3.2. Data

This study uses the energy-related electricity generation CO_2 emissions of each source data, as well as the data pertaining to the energy consumption of each source, as obtained from the Energy Information Administration (EIA) [70]. The electricity generation data are derived from the BP Statistical Review of World Energy [71]. It should be noted that, in order to make our findings more applicable to the electricity sector, we calculate from the type of coal (i = 1), oil (i = 2) and natural gas (i = 3), after the merger of various fuels.

4. Results and Discussion

4.1. Energy-Related Electricity CO_2 Emission

The changes in energy-related CO_2 emissions and carbon intensity (defined as the energy-related CO_2 emissions in electricity generation divided by the electricity produced) are shown in Figure 1. On the whole, annual energy-related CO_2 emissions from electricity generation, as well as the aggregate carbon intensity, were on the decrease during the period covered by our study. As for CO_2 emissions, the study span can be divided into two phases: 1990–2005 and 2006–2014. The corresponding emissions tended to increase during the first phase, while in the second phase, the emission levels began to show a decreasing trend. The annual growth rate of energy-related CO_2 emissions was 0.47%, and the carbon intensity decreased at an average change rate of 0.78%.

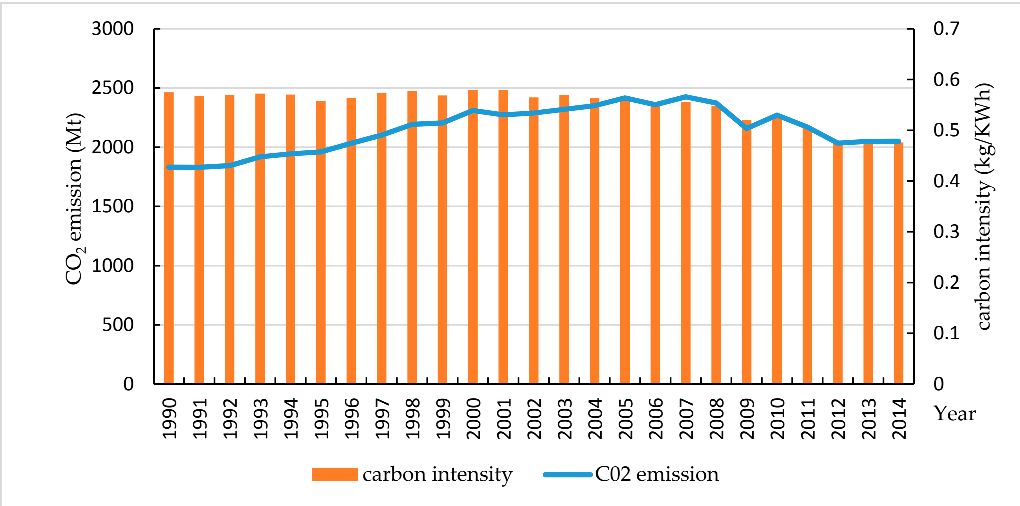

Figure 1. Energy-related CO_2 emissions and carbon emission intensity of electric sector during 1990–2014 (1990 is the baseline year).

4.2. Decomposition Results

The decomposition results shown in Figure 2 and Table 2 indicate to what extent the five effects influence the changes of carbon dioxide emissions. Various indicators posed different effects in the US in different years. Generally speaking, among the five factors, the electric power production effect played a positive role in the increase of CO_2 emissions. The energy mix effect and the conversion efficiency effect both contributed to curbing the related CO_2 emission in most years. However, the influence of the other factors varied from year to year. This finding implies that, when the electricity plants work, high levels of carbon dioxide emissions were still common. In other words, the increase in electricity generation directly contributed to an emissions growth trend in the US. However, the improvement of conversion efficiency can decrease the level of CO_2 emissions. As a consequence, a shift to less energy-intensive ways to generate power, and switching to low-emission fuels, are both feasible measures to combat climate change. In addition, the energy mix effect showed an ability to curb the increase in CO_2 emissions during most of the observed years, while the emission factor effect did not exert any significant influence, compared to other indicators, in most years. In general, the levels of CO_2 emissions increased between 1990 and 2014, except for the following periods: 1990–1991, 2000–2001, 2005–2006, 2007–2009, and 2010–2012. Moreover, the total change in CO_2 emission levels from 1990 to 2014 was 218.853 Mt. Additionally, since electricity output played a significant role in influencing the overall trend, the relationship between this effect and other effects should be determined. In addition, the additive LMDI and multiplicative LMDI results are not only a means to detect how the driving factors influence the overall changing trend of CO_2 emissions, but they also serve as the prerequisite and an indispensable part of the calculation and analysis of the decoupling index.

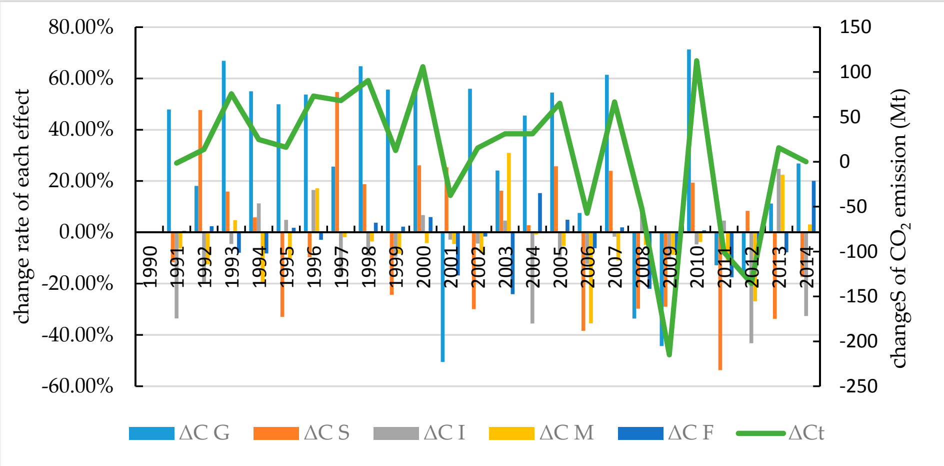

Figure 2. Decomposition of changes of electricity generation CO_2 emission in the US.

Table 2. Multiplicative LMDI decomposition of electricity CO_2 emissions.

Year	DG	DS	DI	DM	DF
1990–1991	1.0119	0.9971	0.9917	0.9984	1.0001
1991–1992	1.0038	1.0100	0.9960	0.9974	1.0005
1992–1993	1.0365	1.0086	0.9976	1.0025	0.9958
1993–1994	1.0161	1.0017	1.0033	0.9943	0.9976
1994–1995	1.0321	0.9793	1.0031	0.9934	1.0011
1995–1996	1.0267	0.9952	1.0081	1.0085	0.9986
1996–1997	1.0139	1.0299	0.9906	0.9990	1.0002
1997–1998	1.0372	1.0107	0.9949	0.9980	1.0021
1998–1999	1.0207	0.9911	0.9965	0.9969	1.0008
1999–2000	1.0296	1.0134	1.0034	0.9978	1.0030
2000–2001	0.9834	1.0085	0.9991	0.9985	0.9944
2001–2002	1.0322	0.9832	0.9975	0.9954	0.9991
2002–2003	1.0063	1.0043	1.0012	1.0081	0.9937
2003–2004	1.0227	1.0014	0.9827	0.9996	1.0076
2004–2005	1.0214	1.0101	0.9963	0.9980	1.0019
2005–2006	1.0021	0.9892	0.9965	0.9900	0.9982
2006–2007	1.0232	1.0090	0.9994	0.9959	1.0007
2007–2008	0.9910	0.9920	1.0026	0.9987	0.9941
2008–2009	0.9588	0.9728	0.9904	0.9918	0.9926
2009–2010	1.0446	1.0119	0.9971	0.9977	1.0005
2010–2011	0.9936	0.9735	1.0023	0.9944	0.9913
2011–2012	0.9880	1.0065	0.9671	0.9794	0.9954
2012–2013	1.0051	0.9850	1.0112	1.0101	0.9965
2013–2014	1.0074	0.9952	0.9910	1.0009	1.0056

4.3. Decoupling Index State

According to the decoupling index, the relationship between CO_2 emissions and the output of the electricity sector in the US from 1990 to 2014 has been analyzed. The decoupling results are shown in Table 3, and some insightful results have been acquired. According to the method presented in the decoupling effort index formulation section, we divide the decoupling effort indices into three states: strong decoupling, relative decoupling, and no decoupling. Generally speaking, the most common state is one of no decoupling. This "no decoupling" state occurred in 12 years of the study period. Since the decoupling index can test whether or not the development or generation of the electricity sector synchronizes with the protection of the environment, a no decoupling status indicates that the development of the electricity sector must rely, to a large extent, on the burning of fossil fuels.

Table 3. The Decoupling between CO_2 emissions and electricity output.

Year	φ_S	φ_I	φ_M	φ_F	φ_{tot}	Decoupling State
1990–1991	0.2446	0.7017	0.1315	−0.0113	1.0664	strong decoupling
1991–1992	−2.6367	1.0721	0.6918	−0.1312	−1.0041	no decoupling
1992–1993	−0.2377	0.0679	−0.0709	0.1187	−0.1219	no decoupling
1993–1994	−0.1063	−0.2055	0.3567	0.1501	0.1949	relative decoupling
1994–1995	0.6609	−0.0969	0.2098	−0.0361	0.7377	relative decoupling
1995–1996	0.1810	−0.3068	−0.3194	0.0536	−0.3915	no decoupling
1996–1997	−2.1343	0.6816	0.0736	−0.0122	−1.3914	no decoupling
1997–1998	−0.2900	0.1406	0.0549	−0.0582	−0.1527	no decoupling
1998–1999	0.4380	0.1705	0.1503	−0.0394	0.7194	relative decoupling
1999–2000	−0.4576	−0.1175	0.0739	−0.1042	−0.6054	no decoupling
2000–2001	0.5017	−0.0558	−0.0895	−0.3322	−1.0243	no decoupling
2001–2002	0.5345	0.0778	0.1451	0.0293	0.7868	relative decoupling
2002–2003	−0.6743	−0.1908	−1.2858	1.0017	−1.1493	no decoupling
2003–2004	−0.0603	0.7811	0.0193	−0.3358	0.4043	relative decoupling
2004–2005	−0.4727	0.1757	0.0963	−0.0901	−0.2908	no decoupling
2005–2006	5.0965	1.6399	4.7038	0.8235	12.2637	strong decoupling
2006-2007	−0.3907	0.0276	0.1784	−0.0318	−0.2165	no decoupling
2007–2008	−0.8852	0.2892	−0.1457	−0.6550	0.3966	relative decoupling
2008–2009	−0.6551	−0.2289	−0.1962	−0.1765	0.2567	relative decoupling
2009–2010	−0.2713	0.0663	0.0530	−0.0114	−0.1634	no decoupling
2010–2011	−4.1883	0.3582	−0.8807	−1.3671	5.0779	strong decoupling
2011–2012	0.5392	−2.7776	−1.7287	-0.3786	3.3457	strong decoupling
2012–2013	3.0044	−2.2055	−1.9993	0.6938	−0.5066	no decoupling
2013–2014	0.6484	1.2156	−0.1156	−0.7488	0.9995	relative decoupling

A strong decoupling status was the least common of the three decoupling states during our study period. This indicates that government efforts to curb the increase or even to reduce the levels of CO_2 emissions were greatly effective. The policies and measures taken by the government or society outweigh the emissions caused by the increased output of the electricity sector. In addition, because the decoupling index can also demonstrate and reflect the reactions of the government when confronted with environmental pressure, a strong decoupling status also indicates a relatively harmonious relationship between the government and environmental groups.

As for the contribution of each effect, the power production structure effect (ΔC_S) and emission factor effect (ΔC_F) played a negative role in the decoupling process. In other words, the more the thermal electricity plants use fossil fuels to generate electricity, the more likely that there will be a relationship. However, the degree of the influence of other effects varied from year to year during our study period. It should be noted that coal-fired generation still accounts for 70.83% of total electricity output. For this reason alone, finding methods to improve the degree of fuel conversion efficiency or of switching to low-carbon fuels is necessary.

5. Conclusions and Policy Implications

In this paper, we analyze the changes in CO_2 emissions from five different aspects, as well as the decoupling states, by using both additive and multiplicative LMDI methods and a decoupling index analysis. We applied a novel decoupling index to probe the relationship between the CO_2 emissions from electricity generation and electricity output. We also analyzed the changes of decoupling indicators by dividing the index into four factors (based on the LMDI approach), in order to investigate the factors that affect the decoupling process. We arrived at a number of conclusions.

By using the decomposition method to determine the driving factors that influenced the changes in the levels of energy-related CO_2 emissions in the United States, we found that the electricity output effect played a positive role in increasing the energy-related CO_2 emissions in the US. In addition, the energy mix effect and the conversion efficiency effect contributed to curbing the energy-related CO_2 emissions in the US during most of the years covered by our study. The power production structure effect and emission factor effect played a negative role in the overall decoupling process. Moreover, the electricity output effect played a crucial role in increasing CO_2 emissions.

According to the decoupling effort index, we came to the conclusion that a no decoupling status was the main status in most of the studied years (1990 to 2014), while a strong decoupling status was the least common state.

In view of the emission reduction targets of the US, effective measures and policies should be taken to achieve the goal of reducing greenhouse gas emissions by 28% by 2025. As such, some recommendations are put forward here, as follows:

(1) With the current rapid economic growth, the total demand for electricity is on the rise. Generally speaking, carbon emissions are proportional to the amount of thermal power plants, because thermal power plants contribute most of the carbon emissions. Measures pertaining to these thermal power plants are essential in view of this situation. For example, shutting down the smaller thermal power units would be an effective way to reduce emissions.

(2) Most of the thermal power plants in US generate electricity by burning coal. This coal has high carbon content and low combustion efficiency, thereby resulting in more carbon emissions. However, as far as the current status is concerned, thermal power remains in the dominant position. As such, the energy intensity effect should be treated as a key issue. As stated above, the energy intensity effect contributed to reducing CO_2 emissions. Studies on improving the efficiency of energy should be encouraged. Correspondingly, policies to improve energy efficiency and promote the use of renewable fuels or clean energy sources should be introduced and implemented. Moreover, developing a low-carbon economy and adjusting the industry structure are also sensible options.

(3) Though the electricity power generation structure effect did not seem to be the fundamental element influencing carbon emissions, upgrading the power generation structure could be a beneficial way to limit the growth of CO_2 emissions and diminish the harm being caused to the environment. There is no doubt that fossil fuels still provide the majority of energy consumption in electricity generation. This factor constricts the diminution of CO_2 emissions. As a consequence, measures to optimize the energy mix are urgently required to be put into practice. According to the US Energy Information Administration (EIA), US nuclear power was used to generate nearly 20% of all US electricity in 2015. However, the proportion of coal-fired electricity generation still cannot be adequately controlled when coal plays such a vital role in electricity generation. Therefore, improvements need to be made in the design of conventional power stations, and new combustion technologies need to be expanded in order to reach the efficiency target of producing more electricity from less coal possible.

(4) Generally speaking, opportunities for reducing CO_2 emissions were taken in some cases, as follows: energy efficiency, energy conservation, fuel switching, and carbon capture and sequestration.

As for power plants, increasing fuel costs could force energy-intensive power plants to make substantial efficiency improvements (in order to avoid the additional fuel costs). In addition, switching to renewable fuels helps power plants to reduce their potential environmental liabilities, by replacing fossil fuels with renewable fuels, such as hydropower and nuclear power. The amount of CO_2 emissions from electricity generation is extremely large. For this reason, additional policies and measures should be put into practice, as there is a desperate need for the current environmental state of the electric power sector to be improved.

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