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Exploring the Direct Rebound Effect of Energy Consumption: A Case Study

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Abstract: Technological innovation plays a crucial role for improving energy efficiency. But the excessive energy consumption has presented a significant challenge at the same time, which indicates that the direct energy rebound effect exists in China. Cobb-Douglas production function and Logarithmic Mean Divisia Index decomposition model are employed to analyze the rebound effect of energy consumption of all three main industries sector in China. The results show that total technological effect curve and total substitution effect curve fluctuated more significantly than total structure effect curve from 1991 to 2014.The first two curves were the most critical factors for the energy consumption intensity. Stabilizing energy prices, developing new and renewable energy and implementing policies related to energy conservation and emission reduction are effective measures to reduce energy consumption intensity. More attention should be paid to the growing demand for living energy consumption derived from the rapid development of the tertiary industry. The direct rebound effect of energy consumption in China showed an overall descending trend. This shows that technological effect has well prevented the growth of energy consumption. Direct energy rebound effect can be controlled effectively by means of formulating and implementing the corresponding energy related policies.

Keywords: energy rebound effect; energy intensity; Cobb-Douglas production function; Logarithmic Mean Divisia Index decomposition model

1. Introduction

Energy consumption issue has drawn a global public concern. It is well recognized that technological innovation is an effective approach to solve the conflicts between energy supply and demand so that energy efficiency can be improved [1]. In addition, the increase of energy efficiency is also a way to reduce the production cost [2]. With the rapid development of economy, the energy efficiency has been significantly improved globally, especially in developing countries. But the total energy consumption has kept increasing at the same time. It has been recommended that energy planning should focus on not only the improvement of energy efficiency but also other factors related to energy policies [3–5]. Energy consumption intensity decreased from 1568 thousand tce/billion RMB ("tce/billion RMB" means tons of standard coal equivalent consumed for 1 billion RMB output.) in 1978 to 403 thousand tce/billion RMB in 2014, with an average annual decline rate of 3.84%. By contrast, the total energy consumption rose from 571.44 million tce to 4.26 billion tce during the same period, with an average annual growth rate of 5.73% [6]. It shows that technological innovation contributes to the improvement of energy efficiency but the total energy consumption is not necessarily reduced. Therefore, it also indicates that the direct energy rebound effect still exists in China. To fulfill its carbon emission reduction commitments made in the "Paris Agreement", China needs to reduce the energy consumption by at least 110.4 million tce by 2020. This is a great challenge for China during its rapid urbanization. It is imperative to further analyze the direct energy rebound effect of all three industries sector.

Jevons first discovered that the steam engine would increase the energy consumption as well as the energy efficiency in 1865, which is named "Jevons paradox" [7]. Saunders [8] suggested in the K-B hypothesis that energy efficiency improvements might increase, rather than decrease the energy consumption. Cansino [9] found out that energy consumption can also be significantly increased driven by economic growth after an economic crisis. Hence, both energy efficiency and economic recovery can also lead to a significant increase of energy consumption. This phenomenon is known as the energy rebound effect. In terms of the mechanism, the energy rebound effect is divided into direct rebound effect, indirect rebound effect and economy-wide [10]. Energy efficiency increase will lead to decrease of energy products and services price. Hence, the rebound effect caused by the impact of price on direct energy consumption can be attributed to direct energy rebound effect, which is easily to be measured [11]. The computational models are usually related to the elasticity of energy services price and energy saving ratio. Assume the price of other goods or services do not change, the increase of energy efficiency will reduce extra energy consumption. It will increase the real income of consumers and lead to the increase of other energy services consumption. This phenomenon is called the indirect energy rebound effect [12]. The core of this model is to convert the rebound effect into the increase in re-consumption under the consideration of relative income after energy efficiency improvement. The calculation model is more comprehensive. Some factors need to be calculated in the model, such as energy service price elasticity, energy conservation efficiency, actual energy-saving investment, break-even input, total marginal energy intensity and different energy intensity, etc. In terms of input and output [13], the total energy rebound effect and direct rebound effect are usually calculated firstly. The difference between total energy rebound effect and direct rebound effect is indirect rebound effect. A number of studies have been conducted to examine the direct energy effects in various contexts. Freire [14] suggested that seven of the EU's 27member states have witnessed the direct energy rebound effect higher than 100%. Brockway et al. [15] pointed out that the UK and US had a low direct energy rebound effect nationwide between 1980 and 2010. Lin and Du [16] examined the direct energy rebound effect in China and found that direct energy rebound effect lay between 30% and 40% from 1981 to 2011. Shao et al. [17] argued that the energy rebound effect was stable and generally low before the reform and opening-up, which then fluctuated and declined. Li and Jiang [18] found that technological progress could significantly prevent the energy consumption growth while abolish energy subsidy policy would reduce the overall energy rebound effect by 1.53%. Zhou and Lin [19] analyzed the energy statistics of China from 1978 to 2004 and concluded that China's overall energy rebound effect ranged from 30% to 80% which showed a descending trend.

Similarly, the energy rebound effect has been examined in different industries sector. Liu and Lin [20] evaluated the impacts of the energy rebound effect in the Chinese construction industry. Their results showed that if the energy rebound effect did not exist, the total energy savings of the Chinese construction industry would have reached 27 million tce between 2003 and 2012. Lin and Li [21] calculated the energy rebound effect of the Chinese heavy industry. They concluded that if energy price and energy tax were reformed, China would achieve efficient energy conservation. Lu et al. [22] studied the energy rebound effect of 135 business divisions in China and found that enterprises could better reduce the energy rebound effect by means of improving the electricity consumption proportion to total energy consumption. Du et al. [23] revealed that the average energy rebound effect for the construction industry in China was about 59.5% during the period of 1990–2014. Wu et al.'s [13] empirical results based on the panel data of various industries sector in Taiwan showed that sectors with lower energy efficiency had higher direct rebound effects, while sectors with higher forward linkages generated higher indirect rebound effects. However, existing studies placed focus predominately on the energy rebound effect at the national level or the specific industry. By contrast, the energy rebound effect of the three industries sector is largely overlooked.

As the energy rebound effect theory is widely recognized, its methodologies have been studied extensively. Computable General Equilibrium (CGE) model, Logarithmic Mean Divisia Index (LMDI) decomposition model, Cobb-Douglas (C-D) production function model and Input-output methods have been applied for analyzing energy rebound effect. For example, González et al. [24] employed the LMDI decomposition model to examine the energy consumption of European countries and found that energy consumption in Europe could not be reduced by simply enhancing the energy efficiency. Chong et al. [25] employed the LMDI decomposition model to examine the energy consumption of Guangzhou Province and found that growth of GDP per capita and population are the most crucial factors driving the energy consumption growth. Saunders [8] adopted C-D production function and embedded constant elasticity of substitution (CES) production functions to simulate the relationship between energy efficiency and energy consumption. The findings showed that the improved energy efficiency would always lead to a growth in the energy consumption. Using IPAT model, Yu et al. [26] suggested that economic progress was the main driving force for energy consumption growth while technological innovation and structural reform could offset the increased energy consumption. Song et al. [27] found China's high-speed economic growth is still largely dependent on massive energy consumption. Wu et al. [13] developed an input-output model to investigate the energy rebound effect and concluded that most enterprises would witness a higher indirect rebound effect than the direct rebound effect. Using input-output model, Feng et al. [28] suggested that China's rapid urbanization and industrialization processes are among the main reasons for the large amount of energy consumption in China. With respects to the research methods, CD production function and LMDI model are two mathematical models that widely applied for the calculation of energy rebound effect [29,30]. The C-D production function is easy to calculate and measure the degree of improving productivity. Single factor can be decomposed into three kinds of factors with LMDI model and LMDI model can measure the influence of the three factors on the single factor. Therefore, LMDI model can effectively address the limitation of C-D production function in the aspect of data analysis. Based on this analysis, LMDI decomposition model and C-D production function are combined in this study to examine direct energy rebound effect of all three main industries sector in China from 1991 to 2014. Findings are helpful for analyzing the relationship among the substitution effect, technological effect, structure effect and total energy rebound effect. The issues associated with the current energy consumption policies of China can be identified and the corresponding countermeasures can be developed.

2. Methodology

The C-D production function can evaluate the rate of technical progress based on parameters such as economic output and energy input. It can reflect the input-and-output relationship between supplies and technologies by calculating the base ratio of progress. The LMDI decomposition model is commonly used quantitative estimation method in energy economics. In this research, LMDI decomposition model and C-D production function are used to construct a comprehensive evaluation model for studying direct energy rebound effect of all three industries sector in China from 1990 to 2014. According to the China Statistics Yearbook, the classification of three main industries sector is defined. The primary industries sector includes agriculture, forestry, animal husbandry and fishery. The secondary industries sector includes industry, construction. The tertiary industries sector includes transportation, warehousing and postal services, wholesale, retail and lodging, catering. Consequently, in-depth analysis is carried out on various factors that influence the energy intensity. These include: substitution effect, technological effect, structure effect and direct energy rebound effect. Figure 1 shows the design diagram of the research methods.

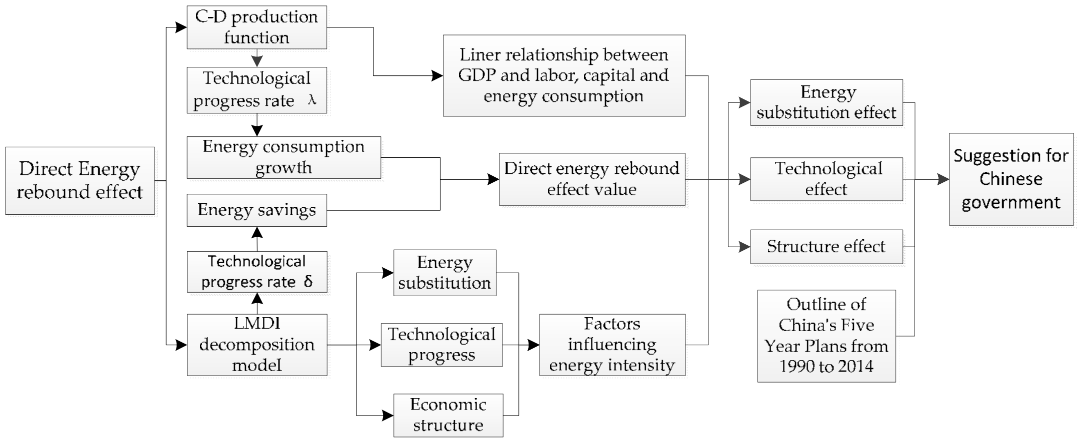

Figure 1. Design diagram of the research methods for China's direct energy rebound effect.

2.1. Model Development

The energy intensity can be represented as Equation (1).

$$I_t = \frac{E}{Y_t}, \tag{1}$$

where I_t represents energy intensity of the t-th year. E is the total energy consumption, Y_t is the economic output of the t-th year.

The total reduction in energy consumption from energy intensity reduction in the t-th year is Equation (2).

$$\Delta E_1 = (I_{t-1} - I_t)Y_t, \tag{2}$$

The decline in energy intensity induced by technological advances is ΔI, so the reduction in energy consumption due to technological advances is reduced as Equation (3).

$$\Delta E_2 = \lambda(I_t Y_t - I_t Y_{t-1}) = \lambda(Y_t - Y_{t-1})I_t, \tag{3}$$

In Equation (3), λ represents the technological progress rate.

The decline in energy intensity induced by technological advances is ΔI. The reduction in energy consumption due to technological advances is reduced as Equation (4).

$$\Delta E_1 = \left|\mathrm{E}'\ \mathrm{E}_t\right|\delta = \delta(I_{t-1}Y_t - I_t Y_t) = \delta(I_{t-1} - I_t)Y_t, \tag{4}$$

In Equation (4), δ represents the technological progress rate but it is different from λ which calculated by C-D production function.

According to Ang [31] and Wang and Zhou [32], the direct energy rebound effect is defined in Equation (5).

$$RE = \frac{\Delta E_2}{\Delta E_1} = \frac{I_t(Y_t - Y_{t-1})\lambda}{Y_t(I_{t-1} - I_t)\delta}, \tag{5}$$

where ΔE_1 represents energy savings derived from technological progress and ΔE_2 represents energy consumption growth. RE is the direct energy rebound effect, δ is the technological progress rate calculated by LMDI decomposition model and λ is the technological progress rate calculated by C-D production function.

According to Equation (5), when RE lies between 0 and 100%, direct energy rebound effect derived from economic progress is low and the overall energy consumption shows a downward trend; when direct energy rebound effect is higher than 100%, direct energy rebound derived from economic progress is significantly higher than energy savings derived from technological progress and the total energy consumption shows an upward trend. In addition, the larger RE means energy consumption shows the more obvious upward trend.

2.1.1. C-D Production Function

C-D production function was first proposed by Douglas [33] and was then constantly improved by other scholars [34–36]. The improved C-D production function model is built in this study to correlate economic output, energy input and technological progress with Gross Domestic Product (GDP), as defined in Equation (6).

$$Y_t = A_t F_t(L, K, E) = A_t L_t^{\alpha} K_t^{\beta} E_t^{\gamma}, \tag{6}$$

where A is technological progress of the t-th year, L is the labor input of the t-th year and α is the output elasticity of labor; K is the capital input of the t-th year and β is the output elasticity of capital; E is the energy input of the t-th year and γ is the output elasticity of energy.

Assume $A_t = A_0 e^{at}$, in which A_0 represents technological level of the base year.

Take logarithms of both sides of the above equations and then Equation (7) can be obtained.

$$LnY_t = LnA_0 + at + \alpha LnL_t + \beta LnK_t + \gamma LnE_t, \tag{7}$$

Set P_Y, P_L, P_K *and* P_E as the growth rates of output, labor input, capital input and energy input, respectively and P_A as a Solow Residual representing the technological progress rate. Then the above equation can be rewritten into Equation (8).

$$P_Y = P_A + \alpha P_L + \beta P_K + \gamma P_E, \tag{8}$$

Technological progress rate λ is defined in Equation (9).

$$\lambda = \frac{P_A}{P_Y} = \frac{P_Y - aP_{nL} - bP_K - gP_E}{P_Y}, \tag{9}$$

2.1.2. LMDI Decomposition Model Development

The direct energy rebound effect can be divided into energy substitution effect, energy technological effect and industrial structure effect [37,38]. LMDI decomposition model is employed to analyze direct energy rebound effect of all three main industries sector.

Direct energy rebound effect can be decomposed by Equation (10).

$$E = \sum_j \sum_k E_j = \sum_j \sum_k \frac{E_{j,k}}{E_j} \frac{E_j}{P_j} \frac{P_j}{P} P, \tag{10}$$

E represents the total energy consumption; $E_{j,k}$ represents the consumption of Type k energy in the j-th industry; E_j represents the energy consumption of the j-th industry; P_j represents the value added of the j-th industry; P represents GDP. j can be 1, 2, or 3, representing primary industries sector, secondary industries sector and tertiary industries sector, respectively. k can also be 1, 2, or 3, representing oil, coal and electricity, respectively.

Divide both sides of Equation (10) by P and then Equation (11) can be obtained.

$$I = \frac{E}{P} = \sum_j \sum_k \frac{E_{j,k}}{E_j} \frac{E_j}{P_j} \frac{P_j}{P} = \sum_j \sum_k N_{jk} T_j S_j, \tag{11}$$

I represents the energy intensity; N_{jk} represents the proportion of the consumption of Type k energy in the j-th industry, that is, the energy consumption structure; T_j represents the energy intensity of the j-th industry; S_j represents the proportion of the j-th industry in the whole economy, that is, the industrial structure.

For Equation (11), the time t can be differentiated and rewritten into the form of growth rate. Finally, the time is integrated from $t-1$ to t, as expressed in Equations (12) and (13).

$$C_{jk}^{t} = N_{jk}T_jS_j = \frac{E_{jk}}{P}, \tag{12}$$

$C_{jk}{}^{t}$ defines the ratio of energy consumption of the j-th industry to the GDP.

$$\begin{aligned}\Delta I &= I^t - I^{t-1} \\ &= \sum_j\sum_k\left(\frac{E_{jk}^t}{P} - \frac{E_{jk}^{t-1}}{P}\right) = \sum_j\sum_k\left(C_{jk}^t - C_{jk}^{t-1}\right) \\ &= \sum_j\sum_k\left(\frac{C_{jk}^t - C_{jk}^{t-1}}{\ln C_{jk}^t - \ln C_{jk}^{t-1}}\right)\ln\frac{C_{jk}^t}{C_{jk}^{t-1}} \\ &= \sum_j\sum_k\left(\frac{C_{jk}^t - C_{jk}^{t-1}}{\ln C_{jk}^t - \ln C_{jk}^{t-1}}\right)\ln\frac{N_{jk}^tT_j^tS_j^t}{N_{jk}^{t-1}T_j^{t-1}S_j^{t-1}} \\ &= \sum_j\sum_k\left(\frac{C_{jk}^t - C_{jk}^{t-1}}{\ln C_{jk}^t - \ln C_{jk}^{t-1}}\right)\ln\left(\frac{N_{jk}^t}{N_{jk}^{t-1}} + \frac{T_j^t}{T_j^{t-1}} + \frac{S_j^t}{S_j^{t-1}}\right)\end{aligned}, \tag{13}$$

Use the mean value theorem (in calculus) proposed to mark the following:

$$W(C_{jk}^{t}, C_{jk}^{t-1}) = \frac{C_{jk}^t - C_{jk}^{t-1}}{lnC_{jk}^t - lnC_{jk}^{t-1}}, \tag{14}$$

Then, $W(C_{jk}^{t}, C_{jk}^{t-1})$ can represent the weight of LMDI decomposition model. Equation (9) can be represented as Equation (14).

$$\begin{aligned}\Delta I &= \sum_j\sum_k w(C_j^t, C_j^{t-1})\ln\frac{N_{jk}^t}{N_{jk}^{t-1}} + \sum_j\sum_k w(C_j^t, C_j^{t-1})\ln\frac{T_j^t}{T_j^{t-1}} + \sum_j\sum_k w(C_j^t, C_j^{t-1})\ln\frac{S_j^t}{S_j^{t-1}} \\ &= \Delta I_N + \Delta I_T + \Delta I_S\end{aligned}, \tag{15}$$

ΔI represents the change in total energy intensity. LMDI decomposition model is used to decompose ΔI into ΔI_N, ΔI_T *and* ΔI_S, representing the energy intensity change caused by energy substitution effect, energy technological effect and energy industrial structure effect, respectively.

The technological progress effect δ can be solved by referring to the building method proposed by Wang and Zhou [32], as given by Equation (16).

$$\delta = (-1)^n\frac{\Delta I_T}{\Delta I} = (-1)^n\frac{\Delta I_T}{\Delta I_N + \Delta I_T + \Delta I_S}, \tag{16}$$

2.2. Data Sources

In this paper, data are mainly collected from official statistics while some data are calculated using formulas. Specific data sources are listed in Table 1.

Table 1. Data sources for direct rebound effect of China's energy consumption.

Index	Name	Remarks
Y	Economic output	National economic accounting (calculated by constant price based on the GDP index).
L	Number of employed persons	Number of employed persons specific to the three main industries sector.
K	Fixed capital stock	Refer to the methods of Shan [38] in "estimation of capital stock K in China, 1952–2006" research and calculate the Fixed capital stock according to the China statistical yearbook of fixed capital formation and fixed asset investment price index etc.
E	Total energy consumption	Total amount and structure of energy consumption. The three main industries sector include different types of energy consumption and consumption paths, shown in Table 2.
E_{jk}	Consumption of a specific type of energy in a specific industry	Oil balance sheet, coal balance sheet and electricity balance sheet. The consumption is converted to standard coal according to the conventional energy conversion coefficient. According to the China Statistical Yearbooks, the coal and oil consumption for power generation as well as coal consumption for oil refining are eliminated from the coal balance sheet and oil balance sheet.
P_j	Value added of a specific industry	The value added obtained after constant price index calculation is calculated based on the GDP composition provided by China Statistical Yearbook (2016).
P	GDP	National economic accounting (calculated by constant price based on the GDP index).

Table 2. The detailed energy consumption of different industries sector.

	The Types of Energy Sources	The Ways of Energy Consumption
The primary industries sector	Coal, coke, gasoline, kerosene, diesel, fuel oil, natural gas and electricity	Mechanical power, irrigation, etc.
The secondary industries sector	Coal, coke, crude oil gasoline, kerosene, diesel, fuel oil, natural gas and electricity	Manufacturing, energy conversion and power generation, building industry etc.
The tertiary industries sector	Coal, coke, gasoline, kerosene, diesel, fuel oil, natural gas and electricity	Transportation, storage, accommodation and catering, etc.

3. Calculation

3.1. Calculation of the Technological Progress Rate λ

The SPSS software is used to perform the ridge regression analysis for data shown in Table 3 (a) and (b). The elasticity coefficients obtained for labor, energy consumption and fixed capital input is α = 0.304, β = 0.257, γ = 0.406, respectively. The calculated variance is R^2 = 0.99. The fitting degree is higher and the residual difference of regression equation is 0.006. Therefore, the result of ridge regression is reasonable.

Hence, C-D production function is expressed by Equation (17).

$$Y_t = A_t L_t^{0.307} K_t^{0.271} E_t^{0.357}, \tag{17}$$

Equation (2) to Equation (5) is used to calculate China's technological progress rate. The calculation results are listed in Table 4.

Table 3. (a) Analysis process for direct rebound effect of China's energy consumption from 1990 to 2014. (b) Analysis process for direct rebound effect of China's energy consumption from 1990 to 2014.

Year	Gross Domestic Product (billion RMB)				Energy Consumption (ten thousand tons tce)				Number of Employed Persons (thousand)	Fixed Capital Stock (billion RMB)
	Primary Industries Sector	Secondary Industries Sector	Tertiary Industries Sector	Total	Primary Industries Sector	Secondary Industries Sector	Tertiary Industries Sector	Total		
1990	273.152	421.024	332.712	1026.888	4852.00	68,791.00	9061.00	98703	647,490	15,339.06
1991	268.869	464.919	386.499	1120.287	5099.00	72,691.00	10,000.00	103,783	654,910	16,247.13
1992	272.811	552.026	455.966	1280.803	5020.00	77,671.00	10,843.00	109,170	661,520	17,467.37
1993	281.714	674.362	503.582	1459.659	4781.00	82,540.00	12,941.00	115,993	668,080	19,277.08
1994	321.865	762.573	567.804	1650.592	5105.00	89,204.00	13,015.00	122,737	674,550	21,819.48
1995	358.860	856.870	617.019	1830.918	5505.00	97,526.00	12,400.00	131,176	680,650	24,916.52
1996	388.343	947.717	676.078	2012.138	5192.93	101,771.00	12,937.58	135,192	689,500	28,431.53
1997	394.055	1036.871	770.498	2201.424	5905.40	101,259.30	14,640.30	135,909	698,200	32,235.84
1998	408.305	1087.232	878.332	2373.869	5790.32	96,021.24	16,009.66	136,184	706,370	36,052.27
1999	411.315	1159.858	986.135	2554.754	5831.75	92,178.59	17,556.25	140,569	713,940	40,185.37
2000	407.212	1260.419	1102.521	2770.153	5787.12	91,066.61	18,531.32	146,964	720,850	44,455.64
2001	420.012	1344.038	1236.035	3000.084	6232.83	93,799.48	19,455.84	155,547	727,970	49,099.32
2002	435.250	1456.286	1381.018	3272.554	6514.29	103,791.30	20,883.78	169,577	732,800	54,290.34
2003	443.103	1642.725	1513.036	3602.467	6602.94	121,398.50	23,672.67	197,083	737,360	60,529.97
2004	511.326	1819.368	1633.071	3963.766	7680.00	146,503.00	27,763.00	230,281	742,640	68,511.53
2005	511.800	2073.672	1822.184	4412.068	6071.06	172,126.80	32,027.43	261,369	746,470	77,752.20
2006	528.179	2371.822	2082.818	4982.819	6330.71	188,706.20	35,128.43	286,467	749,780	88,801.71
2007	584.569	2661.777	2434.760	5675.431	6228.40	204,658.90	37,392.96	311,442	753,210	101,533.00
2008	640.891	2918.231	2663.119	6222.240	6013.13	213,114.70	40,422.17	320,611	755,640	114,844.43
2009	665.966	3119.166	3010.437	6795.569	6251.18	223,759.20	42,793.91	336,126	758,280	129,588.02
2010	713.023	3482.553	3309.926	7505.502	6477.30	237,328.10	46,575.79	360,648	761,050	149,667.56
2011	771.130	3806.427	3625.949	8203.506	6758.56	252,313.10	51,520.03	387,043	764,200	172,504.76
2012	830.140	4000.567	4000.566	8831.273	6784.43	258,630.20	56,651.34	402,138	76,704	197,114.34
2013	884.549	4184.964	4441.768	9511.281	8054.80	298,147.60	65,179.77	416,913	76,977	223,435.50
2014	961.066	4551.863	5048.238	10,561.167	8094.27	303,206.00	67,378.98	426,000	77,253	251,875.05

(a)

Table 3. *Cont.*

Year	Energy Consumption in the Primary Industries Sector Per Sources (ten thousand tons tce)			Energy Consumption in the Secondary Industries Sector Per Sources (ten thousand tons tce)			Energy-Specific Consumption in the Tertiary Industries Sector Per Sources (ten thousand tons tce)		
	Oil	Coal	Electricity	Oil	Coal	Electricity	Oil	Coal	Electricity
1990	1033.6	1494.72	426.8	5885.44	38,754.88	4938.30	2518.60	3709.39	384.5
1991	1068.2	1515.90	479.8	6176.86	40,429.73	5334.40	2921.40	3612.59	446.2
1992	1072.5	1261.51	522.4	6693.65	42,274.30	5912.90	3392.40	3437.80	514.2
1993	1063.5	1142.65	480.9	6586.43	44,929.00	6590.50	2822.40	3562.01	617.9
1994	1089.1	1271.99	530.6	7739.84	48,669.08	7132.70	3918.90	3872.19	730.1
1995	1203.2	1324.57	582.4	7651.35	52,485.05	7819.40	4587.80	3052.78	616.0
1996	1223.7	1367.80	618.3	8508.54	53,878.61	8226.50	5907.60	2914.60	786.4
1997	1256.3	1374.72	639.8	9215.02	52,131.71	8513.10	5907.60	2160.89	878.4
1998	1294.7	1372.08	623.5	9300.66	47,137.69	8594.80	6376.10	2226.45	1055.7
1999	1422.1	1238.18	660.4	9420.62	44,313.77	8975.00	7341.80	2098.54	1189.0
2000	1496.9	1175.47	673.0	10,405.92	47,464.14	10,164.40	7937.10	2352.65	1323.1
2001	1568.5	1141.15	762.4	10,027.15	40,277.21	10,589.60	8214.00	1880.17	1442.3
2002	1674.1	1157.78	776.2	11,077.68	42,196.83	11,957.30	7160.00	1877.03	1596.6
2003	1681.4	1200.87	876.4	11,986.20	53,339.85	14,089.50	9691.90	1875.03	1930.9
2004	2001.3	1606.01	808.9	13,616.55	63,332.16	16,476.40	11,641.00	1737.06	2221.6
2005	2072.9	1651.66	876.4	14,098.48	86,825.63	18,755.60	12,703.30	2997.35	2523.5
2006	2213.6	1647.67	947.0	14,701.19	76,588.84	21,518.80	14,049.00	1711.59	2870.6
2007	2130.3	1667.79	979.0	15,600.32	82,247.17	24,939.80	16,009.40	2883.36	3170.3
2008	1265.8	1086.22	887.1	16,237.58	93,331.05	25,755.90	15,999.60	3030.81	3502.2
2009	1308.1	1128.67	939.9	16,919.19	97,419.62	27,276.40	13,878.20	3285.14	3943.7
2010	1382.5	1531.74	976.5	20,487.66	125,917.38	31,355.00	18,138.50	3292.84	4478.3
2011	1466.3	1253.16	1012.9	20,069.93	107,785.89	35,263.40	19,401.50	3529.05	5104.6
2012	1537.9	1616.64	1012.6	20,076.18	148,422.09	36,840.60	21,473.83	3752.13	5690.5
2013	1650.3	1748.26	1026.9	20,306.48	148,623.83	39,912.00	22,884.68	6218.85	6275.4
2014	1659.3	1813.18	1076.5	22,880.12	168,309.97	42,051.86	24,888.57	5082.45	6409.5

(b)

Table 4. Results of China's technological progress rates from 1991 to 2014.

Year	Technological Progress Rate	Year	Technological Progress Rate
1991	0.48	2003	0.04
1992	0.59	2004	0.05
1993	0.48	2005	0.17
1994	0.42	2006	0.35
1995	0.29	2007	0.45
1996	0.33	2008	0.37
1997	0.43	2009	0.17
1998	0.35	2010	0.22
1999	0.28	2011	0.16
2000	0.32	2012	0.15
2001	0.27	2013	0.19
2002	0.21	2014	0.52

3.2. Calculation of Substitution Effect, Technological Effect, Structure Effect and Direct Energy Rebound of All Three Main Industries Sector in China

LMDI decomposition model is used to calculate substitution effect, technological effect and structure effect of all three main industries sector in China according to Equation (6) to Equation (14). The direct energy rebound effect is calculated according to Equation (5). The calculation results are listed in Tables 5 and 6.

Table 5. Summary of the calculation results of substitution effect, technological effect and structure effect.

Year	ΔI_N				ΔI_T				ΔI_S				ΔI
	Primary Industries Sector	**Secondary Industries Sector**	**Tertiary Industries Sector**	**Total Substitution Effect**	**Primary Industries Sector**	**Secondary Industries Sector**	**Tertiary Industries Sector**	**Total Technological Effect**	**Primary Industries Sector**	**Secondary Industries Sector**	**Tertiary Industries Sector**	**Total Structure Effect**	**Total Effect**
1991	−0.0038	−0.0407	−0.0282	−0.0726	0.0184	−0.2083	−0.0324	−0.2224	−0.0289	0.0574	0.0398	0.0683	−0.2268
1992	−0.0135	−0.0500	−0.0180	−0.0815	−0.0075	−0.4702	−0.0504	−0.5280	−0.0295	0.1687	0.0188	0.1579	−0.4516
1993	−0.0025	−0.0153	−0.1179	−0.1357	−0.0164	−0.5757	0.0407	−0.5514	−0.0200	0.2869	−0.0165	0.2504	−0.4367
1994	0.0014	0.0461	0.0948	0.1423	−0.0122	−0.1773	−0.0568	−0.2463	0.0019	0.0000	−0.0014	0.0004	−0.1035
1995	−0.0004	−0.0833	0.0079	−0.0758	−0.0058	−0.1035	−0.0633	−0.1726	0.0009	0.0488	−0.0099	0.0398	−0.2087
1996	0.0148	−0.0153	0.0506	0.0501	−0.0226	−0.2099	−0.0227	−0.2552	−0.0025	0.0231	−0.0014	0.0191	−0.1860
1997	−0.0169	−0.0190	−0.0860	−0.1219	0.0175	−0.3169	−0.0031	−0.3025	−0.0116	0.0000	0.0180	0.0064	−0.4181
1998	0.0037	−0.0546	−0.0052	−0.0562	−0.0079	−0.2967	−0.0169	−0.3215	−0.0057	−0.0826	0.0226	−0.0657	−0.4434
1999	0.0003	0.0115	0.0015	0.0133	0.0000	−0.2737	−0.0097	−0.2834	−0.0089	−0.0228	0.0174	−0.0142	−0.2843
2000	0.0019	0.2299	0.0144	0.2462	0.0003	−0.2339	−0.0240	−0.2577	−0.0114	0.0054	0.0128	0.0068	−0.0047
2001	−0.0044	−0.3141	−0.0222	−0.3407	0.0051	−0.0775	−0.0263	−0.0987	−0.0058	−0.0347	0.0139	−0.0265	−0.4659
2002	−0.0006	−0.0652	−0.0539	−0.1197	0.0010	0.0423	−0.0142	0.0290	−0.0058	−0.0135	0.0085	−0.0108	−0.1015
2003	0.0029	0.0840	0.0395	0.1265	−0.0005	0.0760	0.0119	0.0874	−0.0084	0.0512	−0.0017	0.0412	0.2550
2004	0.0011	−0.0581	−0.0056	−0.0627	0.0009	0.1957	0.0319	0.2284	0.0051	0.0149	−0.0074	0.0127	0.1785
2005	0.0298	0.2190	0.0051	0.2538	−0.0254	0.0767	0.0134	0.0647	−0.0115	0.0599	0.0010	0.0494	0.3679
2006	0.0002	−0.3750	−0.0277	−0.4025	0.0010	−0.1051	−0.0162	−0.1202	−0.0090	0.0314	0.0047	0.0271	−0.4955
2007	0.0009	0.0080	0.0406	0.0495	−0.0106	−0.0757	−0.0357	−0.1219	−0.0026	−0.0328	0.0099	−0.0255	−0.0980
2008	−0.0236	0.1231	−0.0213	0.0781	−0.0085	−0.1117	−0.0044	−0.1246	0.0000	0.0000	−0.0009	−0.0009	−0.0474
2009	0.0001	−0.0070	−0.0411	−0.0480	0.0000	−0.0380	−0.0220	−0.0600	−0.0025	−0.0459	0.0116	−0.0369	−0.1448
2010	0.0054	0.3745	0.0394	0.4193	−0.0017	−0.1141	−0.0033	−0.1191	−0.0016	0.0241	−0.0015	0.0210	0.3212
2011	−0.0041	−0.3199	−0.0076	−0.3315	−0.0017	−0.0601	0.0033	−0.0585	−0.0005	0.0000	0.0008	0.0003	−0.3898
2012	0.0049	0.4421	0.0010	0.4480	−0.0032	−0.0538	−0.0012	−0.0582	0.0000	−0.0516	0.0085	−0.0431	0.3467
2013	−0.0052	−0.2831	−0.0019	−0.2902	0.0051	0.2194	0.0128	0.2374	−0.0005	−0.0658	0.0110	−0.0553	−0.1081
2014	0.0010	0.2063	−0.0019	0.2054	−0.0035	−0.1480	−0.0339	−0.1854	−0.0010	−0.0455	0.0083	−0.0382	−0.0182

Table 6. Calculation results of China's direct energy rebound effect.

Year	GDP Growth Rate	Energy Consumption Growth Rate	Energy Intensity Growth Rate	Energy Savings Caused by Technological Progress	Energy Consumption Growth Caused by Technological Progress	Direct Energy Rebound Effect
1991	9.10%	5.15%	−3.62%	11,110.00	4275.22	64.05%
1992	14.33%	5.19%	−7.99%	22,367.77	5118.89	55.21%
1993	13.96%	6.25%	−6.77%	34,447.08	3875.91	38.47%
1994	13.08%	5.81%	−6.43%	84,429.38	11,760.30	16.40%
1995	10.92%	6.88%	−3.65%	19,564.77	12,070.23	40.14%
1996	9.90%	3.06%	−6.22%	25,243.91	10,059.61	25.92%
1997	9.41%	0.53%	−8.11%	10,220.81	9066.80	57.06%
1998	7.83%	0.20%	−7.08%	6567.38	2607.76	47.14%
1999	7.62%	3.22%	−4.09%	4110.84	4805.61	56.80%
2000	8.43%	4.55%	−3.58%	469,125.81	6095.19	97.37%
2001	8.30%	5.84%	−2.27%	1456.03	3348.46	270.29%
2002	9.08%	9.02%	−0.06%	316.99	721.89	990.54%
2003	10.08%	16.22%	5.58%	−1951.46	−7802.97	−42.22%
2004	10.03%	16.84%	6.19%	2116.70	−6883.74	82.78%
2005	11.31%	13.50%	1.97%	878.11	−3567.08	682.32%
2006	12.94%	9.60%	−2.95%	4743.37	7277.19	307.43%
2007	13.90%	8.72%	−4.55%	51,420.94	17,449.32	50.74%
2008	9.63%	2.94%	−6.10%	124,820.17	16,153.64	14.63%
2009	9.21%	4.84%	−4.01%	5678.90	−12,589.35	84.44%
2010	10.45%	7.30%	−2.85%	13,719.59	7047.24	88.23%
2011	9.30%	7.32%	−1.81%	5998.85	34,700.36	161.81%
2012	7.65%	3.90%	−3.49%	4173.37	−1726.54	131.51%
2013	7.70%	3.67%	−3.74%	56,622.44	−793.02	12.97%
2014	11.04%	2.18%	−7.98%	255,065.27	15,310.24	6.56%

4. Results and Discussion

4.1. Energy Substitution Effect

Energy substitution effect refers to the change in demand for consumption of an energy type that arises due to a change in the price of another energy type [39]. As shown in Figure 2, the primary industries sector displayed the smallest fluctuation in the energy substitution effect, followed by the tertiary industries sector. By contrast, secondary industries sector. witnessed the greatest fluctuation in the energy substitution effect, with the change trend basically synchronized with that of the total energy substitution effect. It can be observed the most significant fluctuations in the substitution effect due to oil and coal price fluctuations during the period of 2009–2014. According to statistics of the International Energy Agency shown (see Figure 3) [40], the global oil price began to rise dramatically since 2000 and fluctuated obviously between 2005 and 2010. With the change of oil prices, the substitution effect began to fluctuate. The West-East Gas Pipeline Project was completed in 2002, which has led to the price decrease and consumption increase of natural gas in China. According to China Statistical Yearbooks, coal demand began to surge since 2003 and the highest growth rate reached 18% in 2005. Since the financial crisis in 2008, the consumption of various types of energy has been decreasing, making the fluctuation of energy substitution effect temporarily slowing down. In 2001, the Chinese government proposed the energy system reform for the first time in the 10th Five-Year Plan in a bid to gradually optimize the energy structure, with a focus on reinforcing the power grid construction and actively developing hydropower (Table 7). The government then released a series of policies to promote the rapid development of new energies [41,42]. The proportion of non-fossil energy consumption gradually increased from 8% in 2009 to 11% in 2014 in China, leading to a very apparent fluctuation in the substitution effect from 2010 to 2014. Therefore, the energy price demand of end consumers fluctuates greatly in China. The reduction of energy prices will lead to excessively rapid growth in energy demand [43]. Hence, it will be beneficial to energy consumption by means of controlling energy substitution effect derived from the energy price fluctuations.

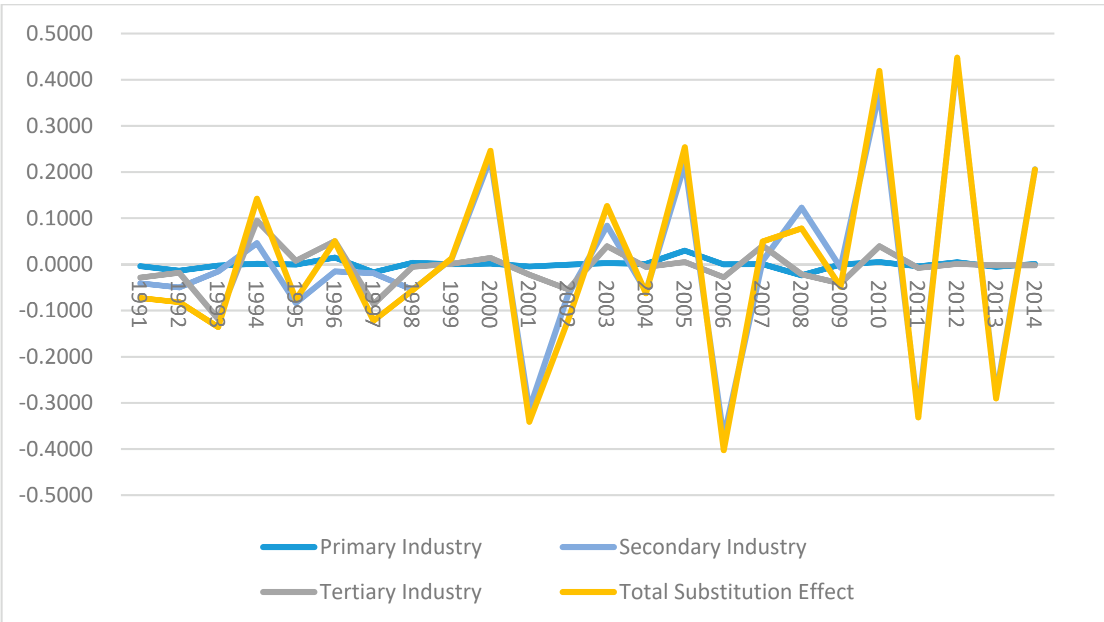

Figure 2. Energy substitution effect of all three main industries sector in China from 1991 to 2014.

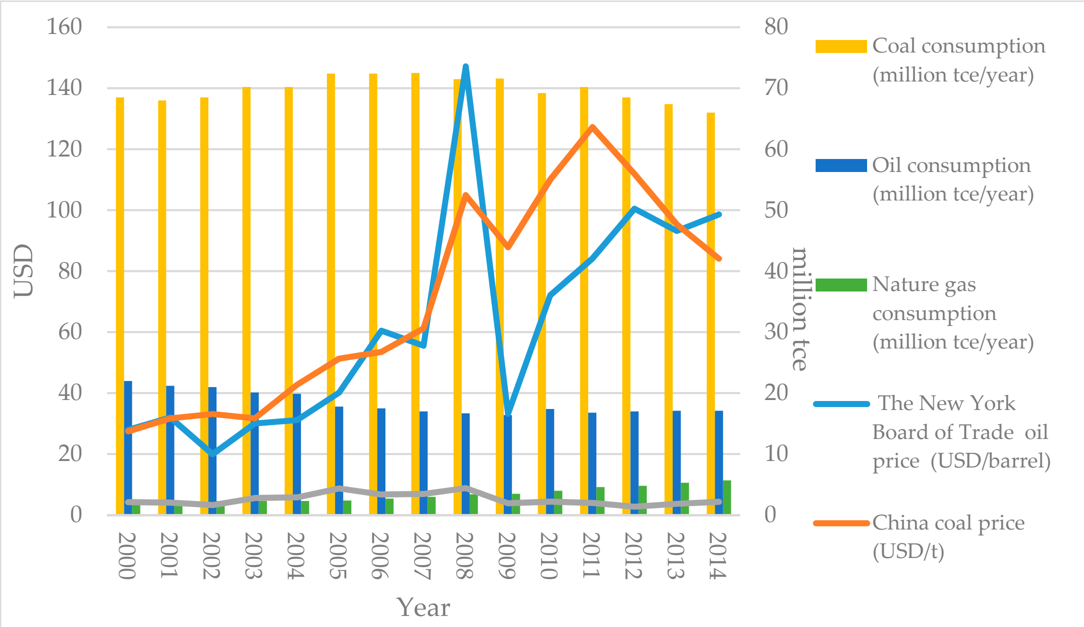

Figure 3. Energy price and energy consumption situation from 2000 to 2014.

Table 7. Policy evolution in terms of energy in China's Five-Year Plans.

Category	The Main Energy Policy Contents of China's Five-Year Plans
The 8th Five-Year Plan	Strengthen the construction of basic industries and infrastructure for energy. Adhere to the guidelines of stressing both development and conservation and plan to build, expand and rebuild a number of large and medium-sized power plants (including hydropower, thermal power and nuclear power), coal mines, oil fields and other key projects.
The 9th Five-Year Plan	First propose the sustainable development strategy, strengthen the environment and ecological protection and rationally develop and utilize resources. Actively develop marine resources. Improve the paid use system and price system of natural resources as soon as possible and establish an economic compensation mechanism for resource recovery.
The 10th Five-Year Plan	Strengthen infrastructure construction and develop resource strategies. Make great efforts to adjust the energy structure, take measures form all aspects to reduce oil consumption, vigorously develop clean coal technology and further develop hydropower and pithead large-unit thermal power.
The 11th Five-Year Plan	State that the inappropriateness of the economic structure is due to the extensive growth mode. The Outline proposes to promote the industrial structure optimization and upgrading so as to make the industry from big to strong. Give priority to the construction of a resource-saving and environment-friendly society, put forward clear tasks and measures and plan a number of environmental management key projects.
The 12th Five-Year Plan	First propose the development of circular economy: 1. Carry out recycling-oriented production; 2. Improve the resource recycling and recovery system; 3. Promote the green consumption mode; 4. Strengthen policy and technical support.
	The guideline polices are as follows: 1. simultaneously promote industrialization, urbanization and agricultural modernization; 2. Promote industrial upgrading through scientific and technological innovation; 3. Improve the energy conservation and emission reduction incentive and restraint mechanism to develop the economy.
The 13th Five-Year Plan	Build a modern energy system, further promote the energy revolution, focus on promoting the reform of energy production and utilization modes, optimize the energy supply structure, improve the energy efficiency, build a clean, low-carbon, safe and efficient modern energy system and maintain national energy security.

4.2. Technological Effect

Energy technological effect refers to the extent to which the use of advanced technologies influences energy consumption in a specific industry [44]. It can be observed from Figure 4 that the change trend of technological effect of China's all three industries sector is similar to that of energy substitution effect. Primary industries sector witnessed the smallest fluctuation in the technological effect; secondary industries sector witnessed the greatest fluctuation in the technological effect, with the change trend basically synchronous with that of total technological effect. This indicated that technological progress in secondary industries sector boosted the development of China's entire energy technologies and was to some extent the main driving force that influenced China's energy consumption from 1991 to 2014. Although the technological effect in China showed violent fluctuations, the technological progress has played a role in reducing the overall energy consumption intensity in China and prevented the growth of energy consumption to some extent from 1992 to 2002. However, since 2002–2006, the technological progress did not reduce but rather boost the energy consumption in China due to rapid economic expansion, leading to continuous growth in China's total energy consumption. To address this issue, the Chinese government decided to implement the *Notice of the Comprehensive Work Plan on Energy Conservation and Emission Reduction* since 2007, stimulating that energy consumption of per 10,000 RMB of GDP in 2010 should be reduced to less than 1 tce compared with 1.22 tce in 2005. Chinese government released the *Comprehensive Work Plan on Energy Conservation and Emission Reduction during the 12th Five-Year Plan Period* and *Comprehensive Work Plan on Energy Conservation and Emission Reduction during the 13th Five-Year Plan Period* to reduce the energy consumption intensity by eliminating backward production capacity and improving energy saving technology. As shown in Figure 4, the technological effect curve showed an overall downward trend under the strong impetus of policy although fluctuating between 2007 and 2014. It indicated that policy making promoted the improvements of energy conservation technologies, which slow down prevented the growth of energy consumption in China. Based on the above analysis, policy promotion is the direct factor and the indirect factor to reduce the intensity of energy consumption by promoting technological progress. In addition, since the change trend of the technological effect of secondary industries sector was synchronous with that of total technical effect, secondary industries sector is the key to control total technological effect. Therefore, secondary industries sector will remain the focus of efforts on energy conservation and emission reduction in China in the near future.

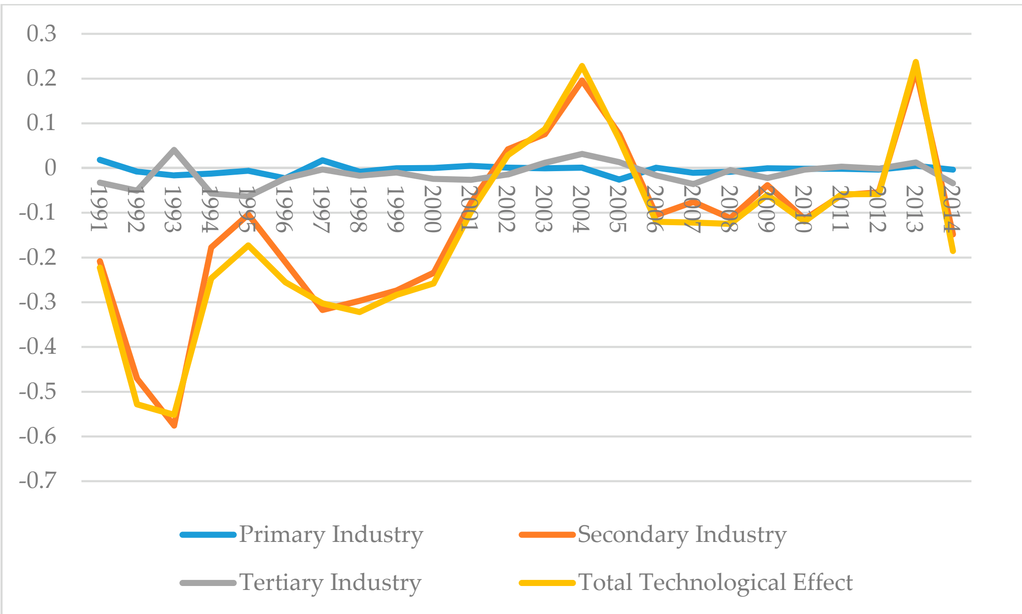

Figure 4. Energy technological effect of all three main industries sector in China from 1991 to 2014.

4.3. Structure Effect

Energy structure effect refers to the way how industrial structure change influences economic development and energy consumption, as well as the effects of the influence [45]. It can be observed from Figure 5 that, in the same year, secondary industry witnessed the largest GDP contribution rate, followed by tertiary industries sector and primary industries sector. Secondary industries sector was still the main factor influencing the economic development. In addition, due to the rapid development of tertiary industries sector, its structure effect has been gradually strengthened and has become another main factor influencing energy consumption changes. It can be observed from Figure 6 that the fluctuation of total structural effect was much lower than that of total substitution effect and total technological effect. Compared with substitution effect and technological effect, the change in industrial structure posed a weak impact on the energy consumption intensity. It can be observed from Table 5 that between total structure effect ΔI_S and total effect ΔI, either one was positive or the other was negative in most years. Therefore, the adjustment of industrial structure did not reduce the energy consumption intensity. Rather, it increased energy consumption per unit of output to some extent. It showed that the structure adjustment of manufacturing industry and construction industry as the industrial pillars did not make significant differences. As the research result of Guo [46], with technology and product price remaining unchanged, the adjustment of the industrial structure can reduce energy consumption per unit GDP by 2.7%. Therefore, the national policies of industry structure adjustment still need to be carried out persistently. As a result, the proportion of tertiary industry can be continuously increased so that the industrial structure can be improved. According to Wang et al. [47], with the rapid urbanization in China and the rapid development of tertiary industry, the structure of living energy consumption will change and the consumption of living energy will grow rapidly. Therefore, in order to mitigate the energy rebound effect, China government should pay more attention to the living energy consumption issues derived from tertiary industry.

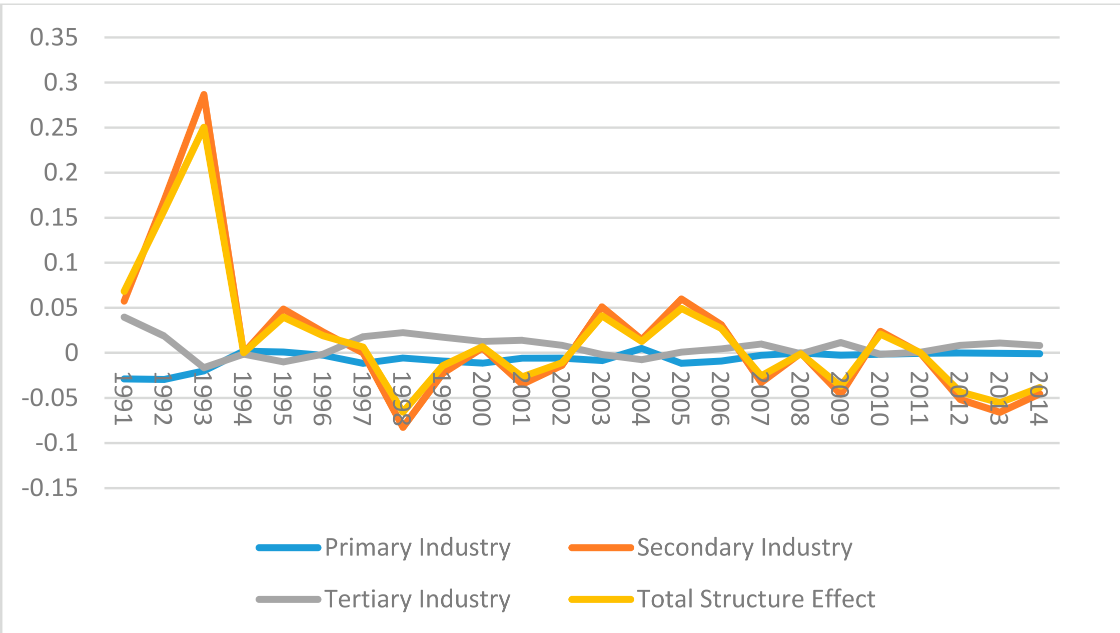

Figure 5. Structure effect of all three main industries sector in China from 1991 to 2014.

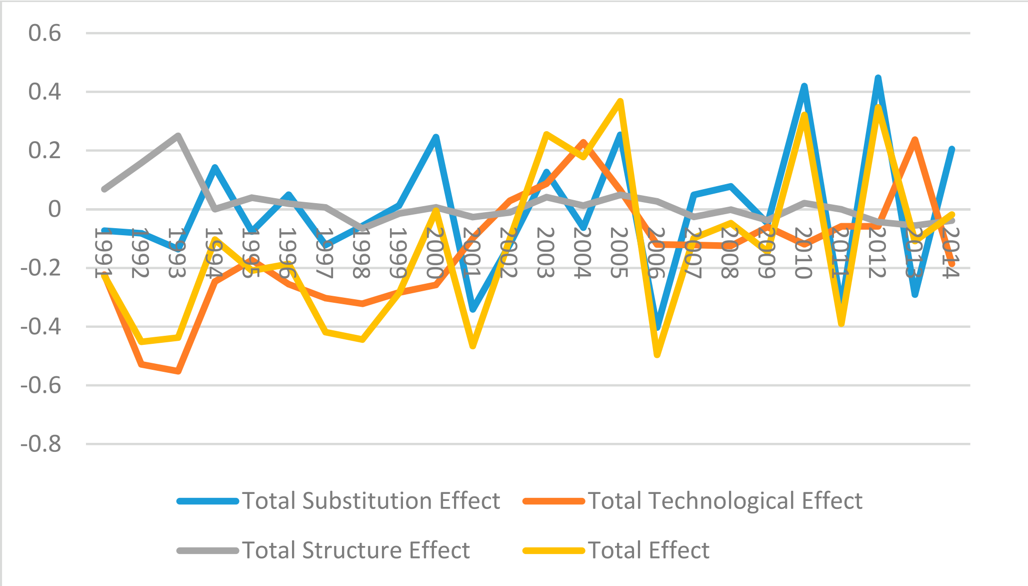

Figure 6. Comparison among total substitution effect, total technological effect and total structure effect in China from 1991 to 2014.

4.4. Direct Energy Rebound Effect

As shown in Table 6, Figures 7 and 8, the direct energy rebound effect curve in China showed an upward and then a downward trend. It increased from 64.05% in 1991 to 990.54% in 2001 and then dropped to 6.56% in 2014. Although the overall curve fluctuated, it is well observed that the technological progress effect suppressed the rapid growth of energy consumption. Results of the study were generally consistent with the analysis of Figure 4. Different magnitudes of direct energy rebound effect occurred in 1999–2006, 2011 and 2012. A possible reason is that during the period of 1991–2000, the Chinese government was trying to gradually shift from planned economy to market-oriented economy, as well as from the extensive development mode to intensive development mode (Table 7). Although the average annual growth rate of GDP reached 10.46%, that of energy consumption reached 4.08%. During this period, China's economy and energy consumption have been at a plateau and the direct energy rebound effect has always been below 100%. This is basically consistent with the findings of Brockway et al. [15]. The Chinese economy developed rapidly in the period of 2001–2006 due to the reform and opening up of China (Table 7). During this period, although the average annual growth rate of GDP reached 10.29%, that of total energy consumption reached 11.48%, which is much higher than the same period of energy consumption level. This suggested that the rapid economic development was exchanged with high energy consumption (Figure 7). During this period, the technological progress did not effectively prevent the growing demand for energy consumption but rather boosted rapid growth of energy consumption through economic effects, resulting in varying magnitudes of direct energy rebound effect (Table 6 and Figure 8). To address this issue, the Chinese government clearly stipulated in the *Outline of the 11th Five-Year Plan* to develop a resource-saving and environment-friendly society in a prominent position and commissioned a number of energy conservation and circular economy demonstration projects (Table 7). In 2007, the Chinese government released the *Notice by the State Council on Printing and Issuing the Comprehensive Work Plan on Energy Conservation and Emission Reduction* for the purpose of continuously promoting the energy conservation and emission reduction work in the entire society. Subsequently, it is stated in the *Outline of the 12th Five-Year Plan and Outline of the 13th Five-Year Plan* that efforts will be made not only develop the circular economy but also strengthen the construction of ecological civilization. Focus will be placed on: sustainable development and low-carbon development, further adjusting the industrial structure and energy structure, new energy development, improving the energy efficiency and building a low-carbon energy system (Table 7). Therefore, the direct energy rebound effect curve of China showed an overall downward trend from 2007 to 2014. However, the direct energy rebound effect was high in certain years. For example, it reached 161.81% in 2011. That is because the *Energy Conservation and Emission Reduction Plan is promoted* during the 11th Five-Year Plan period to strengthen the binding role of the energy conservation and emission reduction targets. In 2010, in order to achieve the energy conservation targets proposed in the 11th Five-Year Plan, the People's Bank of China and China Banking Regulatory Commission began to strictly examine the financing applications of high energy-consuming enterprises [48]. Therefore, the national fixed capital input dropped rapidly from 20% to 5%. The Chinese government also strengthened the examination on the energy conservation and emission reduction works conducted by enterprises, closing down the resource-wasting enterprises. However, these enterprises have already operated for a certain period of time and resulted in a large amount of energy rebound due to waste produced during the energy consumption. As a result, a large direct energy rebound effect occurred in the period of 2010–2012.

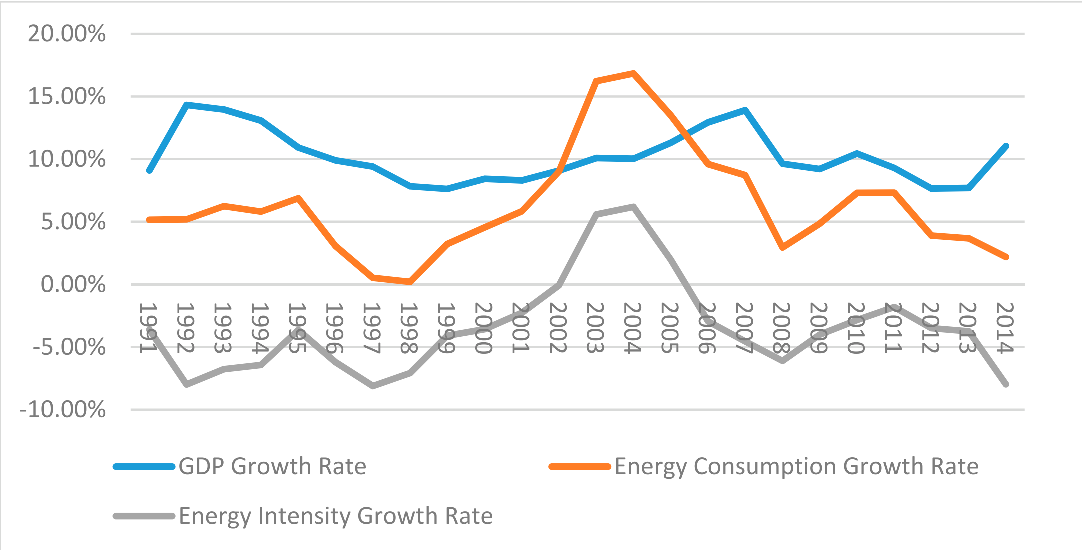

Figure 7. Growth rates of the GDP, energy consumption and energy intensity in China from 1991 to 2014.

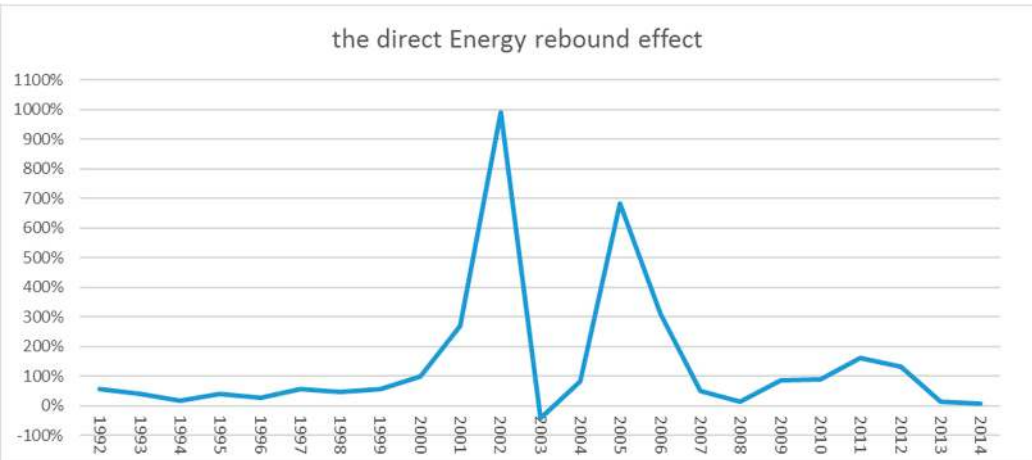

Figure 8. China's direct energy rebound effect from 1991 to 2014.

5. Conclusions

The technological progress of China has led to a constant decrease in the energy consumption intensity but the energy consumption has continued to rise at the same time. The energy consumption reduced by technological progress cannot offset the energy demand derived from economic effects. The direct energy rebound effect still exists in China.

LMDI decomposition model and C-D production function are employed to examine direct energy rebound effect of all three main industries sector. Affected by the fluctuations of energy price, China has witnessed a significant substitution effect. It is imperative for Chinese government to coordinate energy prices and develop new and renewable energies actively when developing energy related policies and plans. Technological effect of the secondary industry fluctuated significantly and its change trend was synchronous with total technological effect. The secondary industry will still be the focus of energy conservation and emission reduction in China. It can also be observed from the trend of total technological effect curve that energy conservation and emission reduction policies have boosted the development of energy conservation technologies, which prevented the rapid growth of energy consumption. The government should develop more stringent industrial energy conservation policies in reference to the current energy conservation and emission reduction policies as well as the status of the national industrial development. Compared with technological effect and substitution effect, structure effect posed a weak impact on energy intensity, which otherwise promoted the growth of energy consumption. The tertiary industry will occupy more important role with the progress of urbanization. The government should pay more attention to the expansion of living energy consumption.

The energy rebound curve of China showed an overall downward trend, indicating that technological effect well prevented the expansion of energy demand. Although different magnitudes of rebound effect occurred in certain years, there was a close relationship between the rebound effect and the policy guidance. The direct energy rebound effect can be controlled effectively as long as energy conservation and emission reduction policies are implemented strictly in all industries sector.

Duo to the absence of detail data of full employed workers and partial time workers, different kinds workers are not discussed in the CD production functions. This provides a future research potential to discuss the rebound effect combined with different situations.

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Author Contributions: The study was designed by Qingsong Wang, Xueliang Yuan and Zhenlei Gao. The data from yearbooks were retrieved by Zhenlei Gao and Hongrui Tang. The results were analyzed by Qingsong Wang and Zhenlei Gao. The policies related to the research are reviewed by Xueliang Yuan. Model design and English corrections were completed by Zhenlei Gao and Jian Zuo.

Conflicts of Interest: The authors declare no conflict of interest. The founding sponsors had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript and in the decision to publish the results.

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