ISSN 1749-3889 (print), 1749-3897 (online)
International Journal of Nonlinear Science
Vol.26 (2018) No.2, pp.67-75

Grey Correlation Analysis of Energy Consumption and CO_2 Emissions in China's Industrial Sector

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(Received 12 March 2018, accepted 19 June 2018)

Abstract: As the problem of global warming becomes more prominent, excessive CO_2 emissions have received increasing attention. As a major contributor to CO_2 emissions, the industrial sector needs to explore ways to reduce CO_2 emissions. In this paper, the influence of energy consumption on CO_2 emissions in China's industrial sector is studied by using the grey relational analysis method from 2005 to 2014. The results show that energy consumption in the industrial sector has an important impact on CO_2 emissions. From the perspective of industrial sector, the industry of Petroleum and Nuclear Fuel Processing and Coking (PNFPC) has the largest degree of grey correlation between energy consumption and CO_2 emissions. It indicates that the industry has the greatest impact on CO_2 emissions. From the perspective of the types of energy consumption, the grey correlation degree between coal consumption and CO_2 emissions is the largest, indicating that the increase in coal consumption is an important cause for the increase in CO_2 emissions. The overall research is conducive to clarifying the impact of energy consumption on CO_2 emissions in specific industrial sectors, as well as the impact of fossil energy consumption on industrial CO_2 emissions. It provides theoretical basis for the formulation of government policy.

Keywords: Energy consumption; Carbon dioxide emissions; Industrial sector; Grey relational analysis

1 Introduction

Global warming has become the most attractive issue in the past 30 years and has attracted widespread attention all over the world [1]. The greenhouse gases that cause the global warming are mainly carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O) and hydrofluorocarbons (HFCS), perfluorocarbon (PFCS), sulfur hexafluoride (SF_6), etc. Among them, CO_2 accounts for 80% of the total greenhouse gases emissions, and its warming effect is the largest, reaching 63% [2, 3]. Reducing CO_2 emissions has become a global consensus. In 2014, China's total energy consumption (4.26 Gtce) and CO_2 emissions (9.76 Gt, the world's largest) accounted for 23% and 27.5% of the world's total, respectively [4]. In response to global warming, the Chinese government has announced a phased carbon reduction target in the framework of the Paris agreement. By 2030, China's CO_2 emissions per unit of GDP fell by 60-65% compared to 2005. By around 2030, China's CO_2 emissions will reach a peak, and strive to reach its peak as soon as possible. As an important basic industry of China's national economy, industry is not only vital in economic development, but also crucial to China's total energy consumption. In 2015, 68% of total energy consumption can be attributed to industrial activities [5]. China's industrial energy consumption structure is dominated by fossil energy, and the consumption of fossil energy will generate large amounts of CO_2 emissions [6]. Therefore, as the major contributor to CO_2 emissions, industrial energy conservation and emission reduction continues to be the focus of China's energy strategy [7]. The detailed analysis of the relationship between energy consumption and CO_2 emissions in specific industrial sectors will help clarify the status and characteristics of industrial CO_2 emissions, and effectively achieve regional emission reduction targets.

Many scholars have studied the relationship between industrial energy consumption and CO_2 emissions. Li (2012) used an improved STIRPAT model to empirically analyze the influencing factors of CO_2 emissions in 39 industries in China's industry. The results showed that energy consumption factors had the greatest impact on CO_2 emissions [8]. Ou yang (2015) and Nan (2016) used the co-integration method to explore the determinants of CO 2 emissions in China's industrial

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IJNS.2018.10.15/1015

sector. Results indicated that the industrial energy consumption had a positive impact on industrial CO_2 emissions and long-term co-integration relationship [9, 10]. Wang (2016) analyzed CO_2 emissions from industrial energy consumption in China using carbon emission factors from 2001 to 2011. It was found that China's industrial energy consumption and CO_2 emissions had positive effects [11]. Wu (2016) calculated CO_2 emissions from industrial energy consumption in Inner Mongolia from 2003 to 2012. The results showed that energy consumption led to CO_2 growth, and different fossil fuels had different effects on CO_2 emissions [12]. Some researchers also went deep into specific departments to study the relationship between them. Wen (2011) used logarithmic mean Divisia index (LMDI) to decompose the influence factors of CO_2 emissions in China's steel industry. The results indicated that the contribution of energy consumption factors to the reduction of CO_2 emissions was the most [13]. Based on factor decomposition method, Fan (2013) studied the key factors that affected the change of CO_2 emissions in China's chemical industry from 1996 to 2007. The results showed that the growth of energy consumption in chemical industry increased CO_2 emissions [14]. Hu (2018) took the manufacture of non-metallic mineral products as the research object, and studies energy consumption and CO_2. The results showed that energy consumption and CO_2 emissions were increasing rapidly, and energy consumption was excessively dependent on coal [15].

Most studies have decomposed the factors affecting industrial CO_2 emissions and obtained the relationship between industrial energy consumption and CO_2 emissions. However, direct research on the relationship between fossil energy consumption and industrial CO_2 emissions is less. China's industrial structure and the leading industries are different. Statistical data is limited and the gray scale is large. Therefore, the grey relational grade model is used to study and analyze the relationship between fossil energy consumption and CO_2 emissions in various industries. The rest of the article is as follows: Section 2 measures industrial CO_2 emissions; the methodology and results are introduced in Section 3. At last, Section 4 draws conclusions.

2 Measurement of industrial CO_2 emissions

2.1 Data sources

In this paper, the classification and energy consumption data of industrial sectors are derived from *China Statistical Yearbook*. The reference coefficients of various energy conversion into standard coal are derived from *China Energy Statistics Yearbook* [16]. The related calculation parameters of CO_2 emissions from fossil energy consumption are referred to Cheng [17].

2.2 Calculation method of industrial CO_2 emissions

The various fossil energy contain different amounts of heat. In order to compare and study the total amount of energy consumption, the energy consumption data is converted into standard coal. The formula for energy consumption under standard coal is as follows:

$$E = \sum_{i=1}^{n} \sum_{j=1}^{m} E'_{ij} \times \alpha_j \tag{1}$$

where E denotes the industrial energy consumption under standard coal; n indicates the number of sectors; m indicates the number of fossil fuels; E' represents the energy consumption data; i means the classification of sectors; j means the types of fossil fuel; α is the coefficient of standard coal.

The calculate of CO_2 emissions is based on direct energy consumption method provided by Intergovernmental Panel on Climate Change (IPCC) [18]. The formula for estimating CO_2 emissions caused by various fossil energy consumption is as follows:

$$CO_2 = \sum_{j=1}^{m} CO_{2j} = \sum_{j=1}^{m} E'_j \times NCV_j \times CEF_j \times COF_j \times 44/12 \tag{2}$$

where CO_2 represents the industrial CO_2 emissions (unit: Mt); j is the type of fossil fuel; m is the number of fossil fuel; E' represents the energy consumption data; NCV represents the low calorific value; CEF denotes carbon content provided by IPCC; COF means the rate of carbon oxidation and 44/12 is the conversion coefficient from carbon to carbon dioxide.

The consumption data of eight types of fossil fuels is compiled by *China Statistical Yearbook*. The calculation parameters of CO_2 emissions and the reference coefficient of fossil fuels conversion into standard coal are summarized in Table 1.

Table 1: Carbon emission coefficients of various fossil fuels

Fossil fuel	Low calorific (kJ/kg)	carbon content (kgC/GJ)	The rate of carbon oxidation	Carbon emissions coefficients (tC/t)	Coefficient of standard coal (kgce/kg)
Coal	20908	25.8	0.913	0.4925	0.7143
Coke	28435	29.2	0.928	0.7705	0.9714
Crude oil	41816	20.0	0.979	0.8187	1.4286
Gasoline	43070	18.9	0.980	0.7977	1.4714
Diesel	42652	20.2	0.982	0.8461	1.4571
Fuel oil	41816	21.1	0.985	0.8691	1.4286
Kerosene	43070	19.5	0.986	0.8281	1.4714
Natural gas	38931 (kJ/m^3)	15.3	0.990	0.5896 (tC/m^3)	1.3300 $(kJce/m^3)$

2.3 Analysis of CO_2 emissions in China's industrial sector

This paper studies 23 industrial sectors. Fig.1 shows the total energy consumption and CO_2 emissions in China's industrial sectors from 2005 to 2014. Fig.2 shows the percentage of CO_2 emissions in various industries.

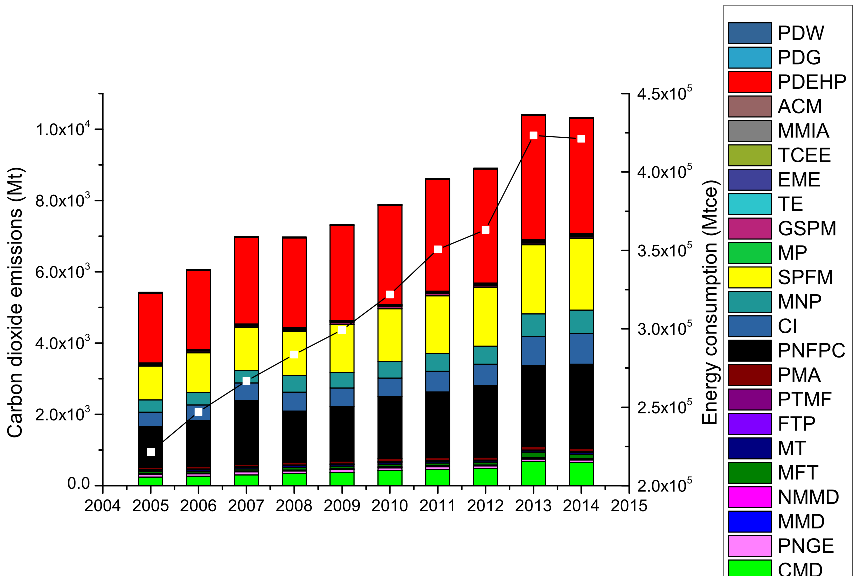

Figure 1: CO_2 emissions and energy consumption in China's industrial sector

Combined with the changes in energy consumption and CO_2 emissions in the industrial sector, the trend of energy consumption and CO_2 emissions in the industrial sector is roughly the same, and it has always maintained the positive correlation and common growth. The average annual growth rate of both total energy consumption and CO_2 emissions are 6.64%. From Fig.2, we find that the CO_2 emissions of PDEHP is the largest, followed by PNFPC. Their total CO_2 emissions exceed 50% of total CO_2 emissions. Sectors with larger carbon dioxide emissions also include SPFM, CI, MNP and CMD. This shows that China's industrial carbon dioxide emissions are highly concentrated in a few industrial sectors. Futher research on the relationship between energy consumption and CO_2 emissions in industrial sector is the top priority. It provides a theoretical basis for the adjustment of industrial structure and the formulation of carbon emission reduction policies.

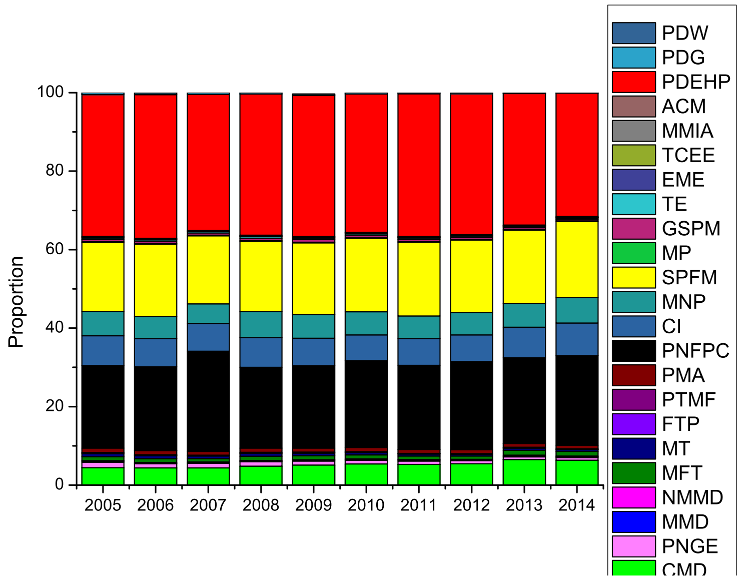

Figure 2: The annual proportion of CO_2 emissions in China's industrial sector

Table 2: Grey correlation degree between energy consumption and CO_2 emissions in various industrial sector

Industry	Abbreviations	Correlation degree	Sort
Coal Mining and Dressing	CMD	0.7814	13
Petroleum and Natural Gas Extraction	PNGE	0.7908	10
Metals Mining and Dressing	MMD	0.7009	21
Nonmetal Minerals Mining and Dressing	NMMD	0.7774	14
Manufacture of Foods and Tobacco	MFT	0.7861	11
Manufacture of Textile	MT	0.7758	15
Manufacture of Textile Wearing Apparel, Footwear, Caps,Leather, Fur, Feather and Its products	FTP	0.7458	16
Processing of Timbers and Manufacture of Furniture	PTMF	0.8880	6
Paper printing and Manufacture of Articles for Culture, Education and Sports Activities	PMA	0.8776	7
Petroleum and Nuclear Fuel Processing and Coking	PNFPC	0.9554	1
Chemical Industry	CI	0.8456	9
Nonmetal Mineral Products	MNP	0.9143	3
Smelting and Pressing of Ferrous Metals	SPFM	0.9336	2
Metal Products	MP	0.8598	8
General and Special Purpose Machinery	GSPM	0.7333	18
Transportation Equipment	TE	0.8900	5
Electrical Machinery and Equipment	EME	0.7011	20
Telecommunication, Computer and other Electronic Equipment	TCEE	0.7172	19
Manufacture of Measuring Instruments and Apparatuses	MMIA	0.6780	23
Arts and Crafts and other Manufacturing (Including Scrap and Waste)	ACM	0.7851	12
Production and Distribution of Electric and Heat Power	PDEHP	0.9042	4
Production and Distribution of Gas	PDG	0.6819	22
Production and Distribution of Water	PDW	0.7387	17

3 Methodology and results

The grey system theory was first proposed by Chinese scholar professor Deng Julong in 1982. The study of grey theory includes grey relational analysis, grey prediction, grey decision making and grey prediction control. Gray correlation analysis is distinguished by the geometric similarity of time series. The correlation order is determined by correlation degree and correlation matrix. It is a quantitative analysis method of dynamic process development trend among various factors. This method has no requirement on the quantity and regularity of samples, and the results are consistent with the qualitative analysis results [19]. Grey correlation analysis can make up for the defects caused by the systematic analysis of mathematical statistical methods. It has been widely used in systems science, environmental science and other fields [10, 20–24]. Xie (2017) studied the influencing factors of project cost by grey correlation analysis, and the results showed that the grey correlation degree between the influence factors of construction drawing budget and project cost was the largest [20]. Lee (2011) used grey relational analysis to evaluate the energy performance of 47 government office buildings in Taiwan. Results indicated that this method could evaluate and sort the energy performance of buildings reasonably and effectively [21]. Liu (2013) conducted a grey correlation analysis on the per capita energy ecological footprint, per capita energy footprint and environmental investment elasticity coefficient from 1978 to 2010 in Shanghai. The results showed that the negative impact of energy consumption on the ecosystem was greater than the active impact of environmental protection on the ecosystem [22]. Nan (2016) adopted grey correlation analysis to quantitatively analyze the relationship between energy consumption and environmental quality in various industrial sector. Results found that the grey correlation degree between manufacturing energy consumption and industrial CO_2 emissions was the largest [10]. Chai (2012) and Zhou (2014) analyzed the relationship between energy consumption and CO_2 emissions in various industries in China. The results showed that the increase of energy consumption was an important reason for the increase of CO_2 emissions [23, 24]. In this paper, the relationship between energy consumption and CO_2 emissions in China's industrial sector is studied by grey correlation analysis.

3.1 Grey correlation analysis

The grey correlation analysis of energy consumption and CO_2 emissions in the industrial sector is carried out in this paper from 2005 to 2014. It provides a theoretical basis for the adjustment of industrial structure. The main steps are as follows:

1. Determine the reference and comparison series. From 2005 to 2014, the amount of CO_2 emissions per year is a reference series, and the energy consumption of various sector each year is a comparison series. The reference series are set to

$$X_0 = \{X_0(k)|k = 1, 2, ..., 10\} \tag{3}$$

and the comparison series are set to

$$X_i = \{X_i(k)|i = 1, 2, ..., 23; k = 1, 2, ..., 10\} \tag{4}$$

2. Dimensionless processing of reference series and comparison series is carried out by means of averaging method.

$$Z_i = X_i(k)/X_i(1)(i = 1, 2, ..., 23; k = 1, 2, ..., 10) \tag{5}$$

3. Calculate the absolute difference between the reference series and the comparison series.

$$\Delta_i(k) = |Z_i(k) - Z_0(k)|(i = 1, 2, ..., 23; k = 1, 2, ..., 10) \tag{6}$$

4. Calculate the correlation coefficient.

$$\zeta_i(k) = (\Delta_{min} + \rho\Delta_{max})/(\Delta_i(k) + \rho\Delta_{max}) \tag{7}$$

5. Calculate the correlation degree.

$$R_i = 1/10 \sum_{k=1}^{10} \zeta_i(k) \tag{8}$$

where i is the industry category; k is the year k; Δ_{min} represents the minimum absolute difference; Δ_{max} represents the maximum absolute difference; ρ represents the resolution coefficient.

In this paper, the value of ρ is 0.5. The greater the degree of association, the greater the effect of the comparison series on the reference series.

3.2 Results

Table 3: Grey correlation degree between consumption of various fossil energy and industrial CO_2 emissions

Fossil fuel	Correlation degree	Sort
Coal	0.9678	1
Coke	0.9539	2
Crude oil	0.9235	3
Gasoline	0.7187	5
Diesel	0.5627	8
Fuel oil	0.6277	7
Kerosene	0.6766	6
Natural gas	0.7270	4

According to the steps of grey correlation analysis, we can calculate the grey correlation degree between energy consumption and CO_2 emissions in various industrial sector from 2005 to 2014 (Table 2). In the same way, we can calculate the grey correlation degree between consumption of various fossil energy and industrial CO_2 emissions (Table 3). Table 4 and Table 5 show the grey correlation degree between consumption of various fossil energy and industrial CO_2 emissions in various industrial sector.

Table 4: Grey correlation degree between consumption of various fossil energy and industrial CO_2 emissions in various industrial sector

Industry	Coal	Sort	Coke	Sort	Crude oil	Sort	Gasoline	Sort
CMD	0.8123	8	0.7666	14	0.6793	20	0.7010	18
PNGE	0.6954	19	0.5291	23	0.9132	4	0.6171	21
MMD	0.6676	20	0.8562	3	0.7021	17	0.7971	7
NMMD	0.8097	10	0.7519	17	0.0000	22	0.8162	2
MFT	0.8034	12	0.7946	10	0.7567	14	0.7996	5
MT	0.7268	16	0.7899	11	0.6982	18	0.6874	19
FTP	0.8102	9	0.7597	15	0.7873	9	0.8070	3
PTMF	0.8261	6	0.8024	8	0.9160	3	0.7772	12
PMA	0.9070	3	0.7310	20	0.7851	13	0.7535	15
PNFPC	0.8480	5	0.7837	12	0.9889	1	0.6140	22
CI	0.8173	7	0.8571	2	0.9649	2	0.7252	17
MNP	0.8758	4	0.7683	13	0.7631	12	0.7840	10
SPFM	0.9076	2	0.8919	1	0.8775	6	0.6478	20
MP	0.7712	13	0.8279	6	0.7686	11	0.7270	16
GSPM	0.6622	21	0.8339	5	0.8255	7	0.7870	9
TE	0.7289	15	0.8548	4	0.8841	5	0.8025	4
EME	0.5452	23	0.8018	9	0.7975	8	0.7990	6
TCEE	0.7059	17	0.6733	21	0.7405	15	0.7566	14
MMIA	0.8085	11	0.8055	7	0.7069	16	0.7815	11
ACM	0.7001	18	0.7579	16	0.6596	21	0.5723	23
PDEHP	0.9195	1	0.7510	18	0.7722	10	0.8653	1
PDG	0.5951	22	0.6732	22	0.6890	19	0.7947	8
PDW	0.7427	14	0.7509	19	0.0000	23	0.7590	13

From the perspective of industrial sector, the gray correlation degree between CO_2 emissions and energy consumption in some industries is very large, which shows that the increase of energy consumption is an important reason for the increase of CO_2 emissions.

Combined with the Fig.2 and Table 2, we find that the grey correlation degree between energy consumption and CO_2 emissions of PNFPC, SPFM, MNP, and PDEHP is greater than 0.9. Meanwhile, their contribution to the total amount of CO_2 emissions is very high, over 80%. It indicates that energy consumption in these industries is closely related to CO_2 emissions. It is worth noting that TE, PTMF, PMA, and MP have the characteristics of high correlation and low emissions, which indicates that the development of these industries contributes greatly to carbon emission reduction.

From the perspective of energy consumption types, coal consumption and CO_2 emissions have the largest grey correlation degree. It indicates that coal consumption has the greatest impact on industrial CO_2 emissions.

From the perspective of the combination of industrial sector and energy consumption types, the grey correlation degree of various fossil energy and sector is quite different. The coal consumption of PDEHP, SPFM, and PMA have a large grey correlation degree with CO_2 emissions. The grey correlation degree between coke consumption and CO_2 emissions of SPFM, CI, MMD and TE are relatively large. For crude oil consumption, the grey correlation degree of PNFPC, CI, PTMF and PNGE with CO_2 emissions are relatively large. PDEHP's gasoline consumption and CO_2 emissions has a larger grey correlation degree. The grey correlation degree between kerosene consumption and CO_2 emissions of TE and CMD are relatively large. The grey correlation degree between fuel consumption and CO_2 emissions of CI and MMIA are relatively large. For natural gas consumption, PNGE, CI, TCEE, GSPM and PDG have a larger grey correlation degree with CO_2 emissions. Specifically, the energy consumption of these industries are the main source of industrial CO_2 emissions. In order to reduce CO_2 emissions, we should focus on controlling fossil energy consumption in these sectors, developing new energy sources, and adjusting the energy consumption structure of these sectors.

Table 5: Grey correlation degree between consumption of various fossil energy and industrial CO_2 emissions in various industrial sector

Industry	Diesel	Sort	Fuel oil	Sort	Kerosene	Sort	Natural gas	Sort
CMD	0.8699	2	0.7499	8	0.6757	19	0.9134	6
PNGE	0.6269	22	0.6091	18	0.8167	4	0.9681	1
MMD	0.7551	10	0.7508	7	0.7285	15	0.7748	19
NMMD	0.7174	16	0.7521	5	0.7155	17	0.6803	23
MFT	0.7470	11	0.7692	3	0.7506	10	0.8253	16
MT	0.6706	21	0.6231	17	0.7289	14	0.8797	9
FTP	0.8090	5	0.6454	13	0.7433	11	0.7612	21
PTMF	0.6806	19	0.7516	6	0.6779	18	0.8596	11
PMA	0.6983	17	0.6803	10	0.7828	8	0.7678	20
PNFPC	0.7584	9	0.5495	21	0.8109	5	0.8080	17
CI	0.8302	3	0.6289	16	0.9274	1	0.9644	2
MNP	0.7974	8	0.7921	1	0.7794	9	0.9082	7
SPFM	0.8013	7	0.7575	4	0.7371	12	0.8517	14
MP	0.8037	6	0.6662	11	0.8055	6	0.7817	18
GSPM	0.8192	4	0.7739	2	0.7198	16	0.9228	4
TE	0.8908	1	0.7403	9	0.8443	3	0.8566	12
EME	0.7304	13	0.6391	14	0.7353	13	0.8604	10
TCEE	0.7340	12	0.5561	20	0.6645	20	0.9487	3
MMIA	0.7283	15	0.6087	19	0.8950	2	0.8558	13
ACM	0.7284	14	0.6582	12	0.7890	7	0.7398	22
PDEHP	0.6921	18	0.5220	22	0.6393	21	0.8397	15
PDG	0.6722	20	0.4610	23	0.6022	23	0.9190	5
PDW	0.6013	23	0.6387	15	0.6052	22	0.8964	8

4 Conclusion

Energy conservation and emission reduction is an important part of China's sustainable development strategy. The industrial sector contributes the most to CO_2 emissions. Research on the main influencing factors of industrial CO_2 emissions is the key to energy saving and emission reduction. This paper makes an empirical study on the relationship between energy consumption and CO_2 emissions in industrial sector and draws the following conclusions: energy consumption is an important factor affecting industrial CO_2 emissions. Coal consumption has the greatest impact on industrial CO_2 emissions. The grey correlation degree between energy consumption and CO_2 emissions of PNFPC, SPFM, MNP and PDEHP are greater than 0.9. At the same time, they account for a high proportion of carbon dioxide emissions, more than 80%. In addition, PE, PTMF, PMA and MP have the characteristics of high correlation and low emission. The development of these industries have made a great contribution to carbon emission reduction. In order to achieve the goals of energy saving and emission reduction, the state should vigorously promote the flow of production factors from high energy consumption industries to high technology, low energy consumption industries and technology intensive industries. It is necessary to strengthen the transformation of traditional production technology, accelerate the integration of industrialization and informatization, and promote industrialization and informatization. The development of wind power photovoltaic equipment industry, smart grid, new materials and other new industries.

Acknowledgements

This work is supported by the Student research projects of Jiangsu University (Grant No.16A305) and the National Natural Science Foundation of China (Nos.71673116).

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