Comprehensive Evaluation of Low-carbon Economic Development in Guangdong Province Based on Weighted GRA-TOPSIS Method

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Abstract: Firstly, the connotation of regional low-carbon economy development is deeply analyzed, and the evaluation index system reflecting regional low-carbon economic progress level is constructed. Secondly, the grey correlation analysis is introduced to judge the correlation degree of all samples, with the index weight determined by method of entropy; then the TOPSIS method is used for data calculation and sample ranking. Using the above steps, a comprehensive estimation for low-carbon economic development in Guangdong province is exerted from dimensions of vertical and horizontal. The results show the low-carbon economy in Guangdong possesses a good level of development, and most of the evaluation values are in the forefront of coastal regions China, also the trend of its low-carbon economy is getting better and better year by year. However, the shortness of low-carbon consciousness and the backwardness of ecological benefits have also restricted the growth potential of low-carbon economic progress in Guangdong. The research conclusions can provide a reference for the low-carbon capacity elevation in Guangdong as well as the coordinated progress for low-carbon economy in other regions.

Keywords: weighted grey correlation analysis; the TOPSIS method; low-carbon economic progress;

1 Introduction

For the past few years, under the international background of global warming and energy crisis, the implement of low-carbon economy has turned into a common understanding of all countries. As the second largest economy in the world, China has always attached great importance to low-carbon emission reduction. In 2015, the party made a clear proposal for low-carbon economy in the fifth Plenary Session of the 18th CPC Central Committee. However, the country's carbon emissions have been in the first place of all countries for many years. Therefore, it is very urgent for China to form a low-carbon production mode with high efficiency so as to realize the low-carbon transformation successfully as soon as possible.

Guangdong province is a strong economic province in the coastal areas of China. In 2017, it realized GDP 8.99 trillions, accounting for 10.5% of the total GDP in the country, which ranks first in the country. The position has been kept for 29 years. Therefore, it is obvious that the economic level of Guangdong has an important impact on the national economic development. However, Guangdong has poor energy endowments; the coal, the oil and other industrial energy are very scarce. In 2014, Guangdong's external dependence on energy supply was over 80%.[1]At the same time, the high energy consumption industry in Guangdong province occupies a high proportion in economy, the proportion of the second industries was around 60% before 2012; this proportion has been reduced in recent years, but is still at a high level. Under the highly unbalanced situation of energy supply and energy consumption, the low-carbon economic mode has become one strategic choice for the economic progress in Guangdong. In 2011, Guangdong became the first pilot of the country's Low-carbon Province. In 2016, the 13th Five-year Plan of Guangdong explicitly proposed the transformation and upgrading of regional energy resources, and low-carbon economy will become its strategic focus in the future. However, the researchers generally believe that the low-carbon economy in Guangdong is in good condition and lacks the necessity of research. This leads to the lack of theoretical reference to the progress practice of this new economic mode in Guangdong, and also makes it difficult for other regions to learn from the successful experience of the province. So, what is the real condition for low-carbon economic progress in case of high yield GDP in Guangdong? In comparison with other provinces, how to locate the position of Guangdong’s low-carbon economic progress level? How to improve the low-carbon economic growth capacity of Guangdong in a more comprehensive way? Based on the above background, this paper makes a synthetically estimation for the low-carbon economic progress level of Guangdong on the basis of extensive data research.[1]

The methods used to research low-carbon economic development can be divided into two categories: One is based on the whole factor production theory, using DEA and other methods to assess efficiency of regional resource utilization and emission cutting. Wu Qi incorporated all energy with environmental efficiency index into the energy efficiency research framework, and constructed a DEA energy efficiency evaluation model that can deal with non-expected outputs.[2] Based on the Meta-frontier theory Wu Qiaosheng integrates the undesired output of SO_2 emissions into the DEA model.[3] Chen Xiaohong synthesized the dual goals of GDP growth and CO_2 emission control, and constructed the dynamic programming model using SBM-DEA method.[4] General factor production is aimed at quantifying the state and ability for low-carbon economic progress of the region, and is not affected by human subjective factors; however, the DEA method regards all the random interference terms as the efficiency factor, which seriously affects the credibility of the evaluation results. Another kind of assessment method lies in comprehensive evaluation of low-carbon progress in the region. Fu Jiafeng built an evaluation index system and the corresponding computational model with dimensions of low-carbon production, expenditure, assets, legislation and circumstance; then he got the semi-quantitative assessment results.[5] Qu Xiaoe introduced the people's life with one comprehensive evaluation index system for the first time, and evaluated the growth level to low-carbon economy in Shanxi Region.[6] Li Yunyan used fuzzy comprehensive evaluation method to deal with the low-carbon development indexes; and the whole development trend was predicted.[7] The purpose of comprehensive evaluation for regional low-carbon progress is to roundly assess all comprehensive levels of low-carbon economy, including regional economy, energy, carbon emission and environment. However, the method generally needs to combine the expert opinion to carry on the integration of different levels of indexes, with strong subjective assumption.

Combined with the above methods, this study proposes a comprehensive evaluation model based on entropy weight-grey correlation-TOPSIS. The model firstly gives weight to each evaluation index quantitatively by entropy weight method. Secondly, the positive and negative ideal values of each evaluation index are determined and the relationship between them is judged using the grey correlation analysis, then the geometric shape similarity of the data column is compared. Thirdly, the Euclidean distance, which indicates the similarity scale between the actual and ideal scheme of evaluation unit, is obtained using the TOPSIS analysis method. Finally, the evaluation results of grey relation and TOPSIS are synthesized, and the ranking of each evaluation unit is given. Based on the improved grey relational-TOPSIS multi-attribute evaluation method, this paper comprehensively evaluated the progressive level for low-carbon economy in Guangdong from dimensions of vertical and horizontal. This research approach not only enhances the credibility of the evaluation results, but also avoids the subjective assumption, so it can give more reasonable evaluation results. This paper is composed of five parts. The first part is introduction. And the second part introduces current situations of energy consumption and carbon emission in Guangdong. Then the author constructs an index-system and evaluation model for low-carbon economic development in the third part. In the fourth part horizontal and vertical evaluations are analyzed. And the final part is the conclusion.

2 Current Situations of Energy Consumption and Carbon Emission in Guangdong Province

2.1 Current situation of energy consumption in Guangdong

One typical characteristic of low-carbon economic progress comes from the continuous decline of carbon emissions as well as energy consumption. [8] But the largest economic province in China, Guangdong, is also one of the regions with the largest energy consumption in the country. In 2016 its total amount of primary energy consumption reached 271,579,000 tons of standard coal, up 5.84% over the previous year, and the total amount of final energy consumption reached 307,299,000 tons of standard coal, up 4.58% over the last year. Since 2011, the annual total energy consumption in Guangdong has been relatively stable, and the annual average growth rate is about 3%, which is in the forefront of the country. The primary energy consumption of Guangdong mainly includes raw coal, crude oil, natural gas, electricity and so on; among them, the raw coal occupies half of total consumption. In 2011, the consumption of raw coal reached 105,243.000 tons, and its share remained at 50.2%; but since 2011, the proportion has fallen year

[1] The data in this section comes from Statistical Yearbook of Guangdong Province (2011-2016).

by year, and the proportion of raw coal consumption in 2016 has dropped to 40%. The proportion of crude oil consumption in Guangdong has been stable and kept at about 27% since 2011, the ratio was 26.9% in 2016; but the total consumption of crude oil was increasing. Natural gas, electricity and other renewable energy are the future energy. The consumption of natural gas has risen from 6.4% in 2011 to 8.1% in 2016, the consumption of electricity and other energy has risen from 16.4% in 2011 to 25.6% in 2016.The trend of the data can reflect the policy orientation of energy consumption in Guangdong. In the long run, with the development of solar technology and bio power technology, electric power and other renewable low-carbon energy will gradually replace crude oil and even raw coal. Meanwhile, because of regional reasons, Guangdong has a high degree of dependence on external development, for example, raw coal and crude oil are purchased nearly 100% outside; and benefited from the prosperity of foreign trade, many low-end industrial enterprises that have been the setting sun industry abroad are attracted here; also the economic growth and the pace of life in Guangdong are extremely rapid. All these make Guangdong the problem of serious emissions and serious contamination more badly than other provinces, which have caused tremendous pressure for its low-carbon economic development.[2]

2.2 Current conditions of carbon emission in Guangdong

The synthesis report of the United Nations Intergovernmental Panel on Climate Changing (IPCC) points out the worsen of carbon emissions mainly comes from the burning of fossil fuels [9], so most of the test research on carbon emissions is on account of energy utilization measurement. Renewable energies such as tidal energy, solar energy and wind energy does not generate carbon emissions. Therefore, these study only selects coal, oil, natural gas along with their respective coefficients to calculate Guangdong's carbon emissions. The calculation formula is as follows:

$$E = \sum_i E_i = \sum_i \frac{C_i}{C} * \frac{E_i}{C_i} * C = \sum_i R_i * Coe_i * C \tag{1}$$

Among them, E is the total amount of carbon emissions (tons); E_i is carbon emissions (tons) for class i energy consumption; C is the total amount of energy consumption (ton standard coal); C_i is the consumption of class i energy (tons of standard coal); R_i is an energy consumption rate of category i(%); Coe_i is the carbon emission coefficient (ton / ton standard coal) for class i energy, the IPCC statistics of various energies carbon emission coefficients are shown in the following table(See table 1).

Table 1 Emission coefficients of various energies（IPCC）[9]

Energy Type	Raw Coal	Crude Oil	Natural Gas	Electricity
Emission Coefficient	0.7559	0.5857	0.4483	0

Guangdong is a forerunner area of Chinese economy; the problem of resource consumption and environmental pollution is more serious here. It is a big energy consumption province, and also a big carbon emission province. According to the formula (1), the total carbon emissions in Guangdong increased from 9.661 billion tons to 13.367 million tons from 2008 to 2016, and the annual average growth rate was up to 4.63%; also the per capita carbon emissions in the province increased from 1.012 tons to 1.215 tons. From the energy variety, the carbon emissions from coal still account for most of the total carbon emissions in Guangdong. The data showed that in 2014, the carbon emission rate of coal, oil and gas in Guangdong was 58.1%, 25.5% and 4.9% respectively. In 2016, the total consumption proportion with crude oil and raw coal of Guangdong was still up to 66.3%. Therefore, although the current carbon emission in Guangdong is considerable, the emission reduction potential is huge. The introduction of new energy and the use of emission reduction technology can significantly reduce its carbon emissions. Meanwhile, the 12th Five-Year Plan calls for a reduction in carbon emissions per unit of GDP of Guangdong by more than 45% from 2005 levels by 2020[10], so the task of reducing emissions in Guangdong is very arduous.

3 Construction of Index System and Evaluation Model for Low-carbon Economic Development

3.1 Construction of low-carbon Economic evaluation index system

One core for low-carbon economic development lies in the comprehensive consideration of the low-carbonization level of its economy, resources, environment and technology. [11] The evaluation index should keep consistence with present indexes internationally and stately. At the same time, we should consider the efforts made by areas about their low-carbon economic transition. Accordingly the evaluation system should have the characteristics of applicability, dynamics and foresight [12]. On account of foregoing requirements, the model built here includes three hierarchies: the goal level, criterion level and index level. Goal level means the low-carbon economic development level under

2 The data in this section comes from Statistical Yearbook of Guangdong Province (2016).

framework of sustainable development; criterion level is formed with four aspects: low-carbon economic index, low-carbon energy index, low-carbon ecological index as well as low-carbon technical index; in different criterion layer, the indexes are selected in light of the layer's target, and then 20 specific indexes are obtained after the expert group screening (See table 2). The index system fully refers to previous research findings, which can reflect the intensity and trend of economic progress originating from regional low-carbon actions; also it can be used in the horizontal contrast of regions; so the index system has a strong theoretical and practical value.

Table 2 Evaluation index system for the regional low-carbon economic progress

Goal level	Criterion level	Index level	Code	Index Interpretation	Index Impact
Low-carbon economic development level in the region	Low-carbon economic indicators	Per capita GDP	EC1	Yuan per person	P
		GDP growth rate	EC2	%	P
		Industrial structure	EC3	%， proportion of the third industry	P
		Carbon productivity	EC4	Million Yuan / ton，Carbon emissions /GDP	P
		Level of urbanization	EC5	%，Proportion of urban population	P
		Engel coefficient	EC6	%，Food expenditure to the total consumption.	N
	Low-carbon energy indicators	Total energy consumption	EG1	Million tons of standard coal	N
		Coal consumption rate	EG2	%	N
		Renewable energy consumption rate	EG3	%，proportion of electricity and new energy to the total amount of energy consumption.	P
		Energy carbon emission coefficient	EG4	T / T standard coal，proportion of carbon emissions to general energy consumption.	N
		Energy conversion rate	EG5	Ten thousand Yuan / ton standard coal，GDP of unit energy consumption.	P
		Per capita carbon emissions	EG6	Ton per person	N
	Low-carbon ecological indicators	Emission of smoke (powder)	EO1	Million tons	N
		Forest coverage rate	EO2	%	P
		Per capita afforestation area	EO3	Hectare / 10000 people	P
		Effective utilization rate of industrial solid waste	EO4	%	P
	Low-carbon technical indicators	Investment rate of R&D	TE1	%，the proportion of R&D in Enterprises above the scale accounts for the proportion of GDP.	P
		Patent authorization	TE2	Thousands of items，number of valid patents approved in the year.	P
		Proportion of fixed assets investment in Low-carbon industry	TE3	%，the fixed assets of the information industry, financial industry and research service industry occupied the total fixed assets investment.	P
		Number of employees in scientific and technical industry	TE4	Ten thousand people.	P

Note: P represents positive and N represents negative.

(1) Low-carbon economic indexes

The ultimate objective of low-carbon economy is to achieve sustainable social and economic progress; so low-carbon economic indexes indicate all results from low-carbon economic implement, and reflect the economic and social benefits of a region during course of low-carbon economic development.. Specifically, it includes six indexes. Per capita GDP and GDP growth rate respectively measure the absolute level and relative level of economic development. Industrial structure refers to the proportion relationship between industries in economic development, and it describes the mode of economic growth. Carbon productivity refers to the production of economic output by unit carbon emissions; it measures the output efficiency of energy consumption. The essence of urbanization is the transformation of human life style and production mode, so the level of urbanization is the significant symbol of regional low-carbon economic progress. The Engel coefficient indicates the richness of the people's life and represents the consumption structure of non-industrial groups.

(2) Low-carbon energy indexes

Low-carbon energy indexes measure the consumption efficiency as well as exploitation capacity for energy of a region. All use of low-carbon energy directly affects the amount of carbon emissions, and then determines the implementation effect of low-carbon economy. Specifically, it also includes six indexes. The total energy consumption and renewable energy consumption rate account for the absolute capacity of carbon sources consumption as well as a relative level to zero-carbon source consumption, of which renewable energy refers to the electricity and other energy sources. Coal consumption is listed separately as coal is the main source of energy in Guangdong province and other coastal provinces; also coal has the highest carbon emission coefficient and the lowest efficiency, which is the main source of current carbon emission. The overall energy carbon emission coefficient reflects the differences in energy consumption structure in different regions. Energy conversion rate refers to the economic output of unit energy consumption and measures source utilization efficiency. Per capita carbon emissions reflect the carbon consumption of each person, and can be used to measure regional emission level more directly.

(3) Low-carbon ecological indexes

The emission of smoke (powder) is used to measure the environmental damage of industrial pollutants; presently the domestic haze weather has become a social problem which is widely concerned in China, and the smoke (powder) dust is the main culprit of haze. Forests and green spaces are carbon absorbers and converters; the higher the forest coverage, the stronger the ability to capture and store regional carbon dioxide, which means the region would have a higher carbon sink capacity. The per capita afforestation area is an indicator of the regional low-carbon economic transformation initiative: the more the per capita afforestation area, the stronger the initiative of the low-carbon economic transformation. Under the current situation of shortage of resources, the recycling of industrial solid waste can take both economic and ecological goals into account; the higher the utilization rate, the greater of the economic sustainability potential, and the greater of the successful probability for low-carbon economy implementation.

(4) Low-carbon technical indexes

These are used to measure the basic conditions of regional low-carbon economy implementation, and they also determine the potential and speed of regional transformation to the new economic mode. Four specific indexes are selected. Total investment rate of R&D reflects a growth potential to the regional technological capacity. Index of effective patents number reflects achievements of regional technical progress; the more the number, the stronger the regional low-carbon competitiveness. Some technology industries that have zero carbon emission and a promotion effect to this new economic mode are selected as the low-carbon industry. The proportion of fixed assets investment in low-carbon industry reflects the government's importance to the low-carbon economic transformation; and the higher the proportion, the stronger the regional low-carbon technology innovation capability. The R&D industry practitioners are the driving force of low-carbon technology R&D, the more the number, the higher the success rate of low-carbon technology adoption.

3.2 Model Construction

Suppose that there are m evaluation units in the low-carbon economic evaluation system $A_i, i\in M=\{1,2,...m\}$, each unit has n evaluation indexes $F_j, j\in N=\{1,2,...n\}$. The evaluation matrix is supposed as $X=(x_{ij})_{m*n}$, inside, x_{ij} denotes attribute value of the jth index in the ith unit. Then the evaluation procedures of the GRA-TOPSIS model are shown below.

(1) Standardized matrix obtaining. Because of the differences in dimension, magnitude, and positive and negative orientation of each index, the original data are standardized by the method of range method. The standardized matrix is supposed as $Y=(y_{ij})_{m*n}$.

For the positive index

$$y_{ij}=[x_{ij}-\min_i(x_{ij})]/[\max_i(x_{ij})-\min_i(x_{ij})] \quad (2)$$

For the negative index,

$$y_{ij}=[\max_i(x_{ij})-x_{ij}]/[\max_i(x_{ij})-\min_i(x_{ij})] \quad (3)$$

(2) Ideal solution calculation. According to the method of entropy, the index weight is determined as $w=(w_1,w_2,...,w_n)$; on this basis, the weighted normalized decision matrix is calculated as $Z=(z_{ij})_{m*n}$, inside that $z_{ij}=w*y_{ij}, i\in M, j\in N$;

After the weighted normalized matrix analyzed, a positive ideal solution Z^+ along with the negative ideal solution Z^- is obtained.

$$Z^+=(z_1^+,z_2^+,...,z_n^+),\quad Z^-=(z_1^-,z_2^-,...,z_n^-), \quad (4)$$

inside that $z_j^+=\max_i(z_{ij})=w_j$, $z_j^-=\max_i(z_{ij})=0$。

(3) Grey relational degree calculation. The grey correlation coefficient matrix between actual value and ideal solution in each evaluation unit is calculated. The positive and the negative ideal solution correlation matrix are expressed as $R^+=(r_{ij}^+)_{m*n}$, $R^-=(r_{ij}^-)_{m*n}$ respectively.

Inside that：

$$\begin{aligned} r_{ij}^+ &= [\min|z_j^+-z_{ij}|+\rho\max|z_j^+-z_{ij}|]/[|z_j^+-z_{ij}|+\rho\max|z_j^+-z_{ij}|] \\ &= \rho w_j/(w_j-z_{ij}+\rho w_j) \end{aligned} \quad (5)$$

$$\begin{aligned} r_{ij}^- &= [\min|z_j^--z_{ij}|+\rho\max|z_j^--z_{ij}|]/[|z_j^--z_{ij}|+\rho\max|z_j^--z_{ij}|] \\ &= \rho w_j/(z_{ij}+\rho w_j) \end{aligned} \quad (6)$$

In the formulas(5)(6), $\rho\in(0,\infty)$ is the distinguish coefficient。The smaller the value of ρ , the greater the resolution distinguish ability. Generally the range of ρ is (0, 1), and the specific value can be determined according to situation. When $\rho \le 0.5463$, it will has the best distinguish ability, generally $\rho = 0.5$;

Then the grey relational degree between actual value and ideal solution in each evaluation unit is calculated. $r_i^+ = \sum_{j=1}^{n} r_{ij}^+ / n$, and $r_i^- = \sum_{j=1}^{n} r_{ij}^- / n$。 （7）

(4) Distance analysis between the evaluating and ideal scheme. Calculating the Euclidean distance of each evaluating unit to the positive and negative ideal solution d_i^+ 和 d_i^-：

$$d_i^+ = \sqrt{\sum_{j=1}^{n}(z_{ij} - z_j^+)^2}, \quad d_i^- = \sqrt{\sum_{j=1}^{n}(z_{ij} - z_j^-)^2}$$

Dimensionless treatment of correlation degree r_{ij}^+, r_{ij}^- and Euclidean distance d_i^+, d_i^- are carried out respectively：

$$R_i^+ = r_i^+ / \max r_i^+, \quad R_i^- = r_i^- / \max r_i^-; \quad D_i^+ = d_i^+ / \max d_i^+ \quad D_i^- = d_i^- / \max d_i^-; \qquad (8)$$

Then we combine Euclidean distance with the degree of association. Supposed $S_i^+ = \alpha R_i^+ + \beta D_i^-$, $S_i^- = \alpha R_i^- + \beta D_i^+ \ i \in M$, inside that α and β reflect the degree of preference of the decision-makers on the position and shape; and $\alpha, \beta \in [0,1]$, $\alpha + \beta = 1$, The decision maker can determine the value of α and β according to his own preference. S_i^+ is the comprehensive reflection of proximity degree between the evaluating unit and the ideal scheme; the higher the value of S_i^+ is, the better the scheme is. S_i^- is the comprehensive reflection of deviation degree between the evaluating unit and the ideal scheme; and the higher of its value is, the worse the scheme is.

(5) Similarity scale calculation and evaluating result acquisition. The similarity scale of each scheme is calculated as $C_i^+ = S_i^+ / (S_i^+ + S_i^-) \ i \in M$ .The greater the similarity scale, the better the scheme; on the other hand, the smaller the similarity scale, the worse the scheme. [13]

4 Comprehensive Evaluation of Low-carbon Economic Development Level in Guangdong Province

4.1 vertical evaluation of low-carbon economic development

Based on the above evaluation system, the vertical development situation about low-carbon economy in Guangdong is calculated for 2012-2016. The data of all indexes can be seen in the following table.

Table 3 all index data for low-carbon economic evaluation in Guangdong Province during 2012-2016 years

Unit	EC1	EC2	EC3	EC4	EC5	EC6	EG1	EG2	EG3	EG4
2012	53943.51	8.20	47.30	4.46	67.40	36.90	24080.97	46.4	20.1	53.15
2013	58694.84	8.50	48.83	4.65	67.76	35.00	24930.93	46.4	20.0	53.86
2014	63231.86	7.80	48.99	5.12	68.00	34.30	25636.29	43.7	22.9	51.67
2015	67114.53	8.00	50.61	5.58	68.71	34.50	25662.31	42.7	24.1	50.83
2016	72290.25	7.50	52.59	5.95	69.20	34.18	27157.91	39.7	25.6	49.23
Unit	**EG5**	**EG6**	**EO1**	**EO2**	**EO3**	**EO4**	**TE1**	**TE2**	**TE3**	**TE4**
2012	2.37	1.28	32.8	57.7	10.15	84.62	2.08	153598	2.84	62.91
2013	2.51	1.26	35.4	58.2	13.06	84.98	2.31	170430	2.40	65.24
2014	2.65	1.24	45	58.69	14.13	96.37	2.39	179953	2.67	67.62
2015	2.84	1.20	34.8	58.88	36.99	90.98	2.47	241176	2.72	68.02
2016	2.98	1.22	28.2	58.98	27.78	87.42	2.53	259032	2.52	73.52

Data sources:《Statistical Yearbook of Guangdong Province(2011-2016)》.

Entropy weight method is commonly used to obtain weights objectively. According to the information entropy of each index, the weight is determined. Its principle is mature and the solution process is simple. Set the entropy of the j index to be $H_j = -k\sum_{i=1}^{m} f_{ij} \ln f_{ij}$,and $f_{ij} = y_{ij} / \sum_{i=1}^{m} y_{ij}$, $k = 1/\ln n$（Assume when $f_{ij} = 0$, $f_{ij} \ln f_{ij} = 0$), then entropy weight of the j index is:

$$w_j = (1 - H_j) / (n - \sum_{j=1}^{n} H_j). \qquad (9)$$

As a result, the weight values of each evaluation index are calculated in the follow table.

Table 4 the low-carbon economy evaluation index weight of Guangdong during 2012-2016 years

Index	EC1	EC2	EC3	EC4	EC5	EC6	EG1	EG2	EG3	EG4
Weight	0.0668	0.0428	0.0503	0.0525	0.0451	0.0389	0.0651	0.0531	0.0485	0.0502
Index	**EG5**	**EG6**	**EO1**	**EO2**	**EO3**	**EO4**	**TE1**	**TE2**	**TE3**	**TE4**

Weight	0.0360	0.0407	0.0609	0.0547	0.0323	0.0683	0.0456	0.0422	0.0701	0.0359

It can be seen from the calculation that the overall difference of each weight is not so large. After ranking index weight, we can find that index TE3, EO4, EC1 and EG1 have relatively larger weight. It indicates that the low-carbon technology level, the carbon sink construction, the energy endowment and the human life style have greater influence on the regional low-carbon economic development level.

After calculating the weight of indexes, the grey correlation degree between every evaluating unit and its perfect scheme as well as an Euclidean distance from every evaluating element to the perfect scheme can be calculated through steps (3), (4) and (5) respectively, and then the dimensionless processing is carried out. The results are as follows:

$$R^+ = \{0.6523, 0.7358, 0.8172, 0.8235, 1.0000\},$$

$$R^- = \{1.0000, 0.7726, 0.6348, 0.6703, 0.6351\},$$

$$D^+ = \{1.0000, 0.8501, 0.7086, 0.6813, 0.6052\},$$

$$D^- = \{0.5892, 0.6726, 0.7083, 0.7877, 1.0000\}$$

When α=β=0.5, the step (5) is combined with gray correlation and Euclidean distance, and the results are as follows:

$$S^+ = \alpha R_i^+ + \beta D_i^- = \{0.6208, 0.7042, 0.7628, 0.8056, 1.0000\},$$

$$S^- = \alpha R_i^- + \beta D_i^+ = \{1.0000, 0.8114, 0.6717, 0.6758, 0.6202\}$$

By the similarity scale formula, it can be calculated:

$$C^+ = \{0.3830, 0.4646, 0.5318, 0.5438, 0.6172\}$$

The similarity scale evaluation criterion of TOPSIS method is that the greater the close degree, the higher the low-carbon progress standard. Therefore, a ranking of each evaluation unit can be obtained by the low-carbon economic progress standard in each year: Then a vertical evaluation conclusion is obtained:2012<2013<2014<2015<2016.

Guangdong's regional economic development mode is constantly improving the traditional extensive mode, turning to a low-carbon economy attributed with lower consumptions, less pollutions and fewer emissions.

4.2 Horizontal evaluation of low-carbon economy development

On the basis of longitudinal comparison of one region, horizontal comparison of low-carbon economic progress level to distinct areas can be made to find problems in the region and learn advanced experience from other regions. This study selected 10 eastern coastal provinces for the sample to explore the difference of low-carbon economic development level in 2016(See table 5), which include: Guangdong(GD), Fujian(FJ), Zhejiang(ZJ), Shanghai(SH), Jiangsu(JS), Shandong(SD), Hebei (HB), Tianjin(TJ), Beijing(BJ), and Liaoning(LN); all of their data are shown in table 5.

Table 5 Low-carbon economic evaluation index data of coastal regions of eastern China in 2016

Unit	EC1	EC2	EC3	EC4	EC5	EC6	EG1	EG2	EG3	EG4
GD	73511.15	7.5	52.59	5.95	69.20	34.18	27157.9	39.72	25.56	49.23
FJ	74369.08	8.4	42.91	3.87	63.60	34.25	12362.7	62.89	6.15*	60.29
ZJ	84528.37	7.6	51.06	3.70	67.10	29.04	20275.6	62.82	7.72	62.94
SH	116440.7	6.9	69.81	4.65	87.90	25.53	11712.4	39.49	12.68	51.76
JS	96747.44	7.8	50.35	3.02	67.70	28.31	31053.8	76.03	7.11	82.45
SD	68386.94	7.6	46.72	2.54	59.00	28.19	38722.8	76.88	3.47	69.16
HB	42932.33	6.8	41.50	1.52	53.30	26.8	29794.4	85.01	3.22	70.72
TJ	114503.1	9.1	56.48	3.21	82.90	30.7	8244.7	51.31	10.45	67.48
BJ	118127.6	6.8	80.23	9.15	86.50	21.48	6961.7	9.81	25.58	40.32
LN	50815.21	-3	51.52	1.66	67.40	27.49	19924.8*	61.78*	1.55*	66.15

Unit	EG5	EG6	EO1	EO2	EO3	EO4	TE1	TE2	TE3	TE4
GD	2.98	1.2	28.17	58.98	27.77	87.42	2.53	25.90	2.52	42.373
FJ	2.34	1.9	23.79	68	59.03	69.48	1.35	6.71	2.08	10.225
ZJ	2.33	2.3	18.23	61.1	5.48	88.81	1.98	22.15	1.86	32.185
SH	2.41	2.5	7.95	16.2	1.63	95.71	1.74	6.42	2.92	9.867
JS	2.49	3.2	47.17	22.8	3.83	91.53	2.15	23.10	2.87	45.189
SD	1.75	2.7	87.38	16.73	14.75	84.3	2.08	9.81	2.76	24.176
HB	1.07	2.8	125.68	31.1	78.09	55.52	0.96	3.18	2.18	8.297
TJ	2.17	3.6	7.81	9.87	5.95	98.99	1.95	3.97	3.82	7.834
BJ	3.69	1.3	3.45	42.3	8.77	86.33	0.99	10.06	4.06	5.114
LN	1.12	3	64.91	40.9	32.53	41.03	1.09	2.51	1.85	4.925

Data sources: China Statistical Yearbook (2012-2016), China Energy Statistical Yearbook (2015-2016) and other Annual Statistical Yearbooks published in 2017 by the provinces.

In the above table, the structure and data of the index system are the same as that of table 2, only slightly different in D4 (the number of employees in the research technology industry).Due to the difference between provincial and national statistical accounting methods, this data has different meanings in the Statistical Yearbook of Guangdong Province and China Statistical Yearbook. Therefore, we select the number of researchers in Guangdong Province in Table 2, and select the number of research developers in the above scale enterprises here. As table 2 and table 5 have their own research independence, and table 5 analyses the comparative evaluation of cross section data, this difference does not affect the evaluation results. In Table 5, very few index values are missing in 2016. Based on the data of 2012 -2015, we use the moving average method to get the predicted value of 2016, and use it as the statistical value of missing data. The missing data are identified with * in table 5.

Similarly, the weight of index is determined by entropy weight method. Then, by using grey relational analysis, the relation degree is judged through comparing the geometry similarity of data columns. Next, the Euclidean distance is calculated to get the degree of proximity and deviation between each evaluation unit and the ideal plan. Finally, we get the similarity scale of 10 regions in the eastern coastal area based on the grey relational analysis and TOPSIS analysis results.

$$C^{+} = \{0.6843, 0.5796, 0.5842, 0.7014, 0.4911, 0.4680, 0.3876, 0.6462, 0.7361, 0.3928\}$$

In Figure 2, we can see that the top three levels of low-carbon economic progress are Beijing, Shanghai as well as Guangdong.

It can be seen that the low-carbon economic progress standard in Guangdong lies in the high level among coastal regions, and has better comparative advantages compared with other sample provinces. But at the same time, the development of Guangdong province is not ideal for some low-carbon indicators, such as EC1, EG1, TE3. EC6 index ranks near the worst in the sample. Therefore, the progress for low-carbon economy in Guangdong continues to have greater promotion space. Further, from the evaluation data, we can see the progress for low-carbon economy among coastal regions is very uneven. The similarity scale of high level regions (such as Beijing and Shanghai) is almost two times than that of low level provinces, such as Liaoning and Hebei. Guangdong's successful experience and progress principles should be summarized in a timely manner, which will coordinate the low-carbon economy development in coastal areas and further improve the economic level of this province. So it is necessary to make a more thorough inquiry into the evaluation index system of Guangdong province.

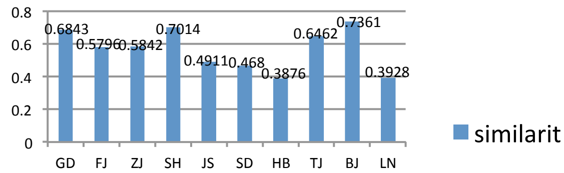

Figure 2 Low-carbon economic progress in 10 coastal regions

(1) Aspect of economic outputs. Guangdong's per capita GDP(73511) and GDP growth rate(7.5), industrial structure(52.59), carbon productivity (5.95), urbanization level(69.2) and Engel's coefficient(34.18) rank the 7th, 6th, 4th, 2nd, 4th and 9th respectively in the sample regions. The large amount of GDP and the slow growth of GDP indicate the economic development of Guangdong is in a mature and stable period, which predicates that the energy consumption will be in a stable state in the next few years. The low per capita GDP and low Engel coefficient show that the living standard in the province needs to be improved, which would affect the society's confidence to the progress for low-carbon economy. A reason may lie in the excessive gap between rich and poor or the unreasonable consumption structure. Higher carbon productivity indicates Guangdong has a high level of low-carbon technology and better social production efficiency which is due to its enthusiasm for new technology adoption and resource intensive utilization. These data also show the low-carbon economic progress of this region needs to take steps such as the industrial structure optimizing, the third industry proportion increasing, and the high carbon emission industry dependence reducing.

(2) Aspect of energy consumption. The indicators of Guangdong's total energy consumption (27157), coal consumption rate (39.72), the proportion of renewable energy consumption (25.6), energy carbon emission coefficient (49.23), and energy conversion rate (2.98), per capita carbon emissions (1.2) rank the 7th, 3rd, 2nd, 2nd, 2nd and 1st respectively in the sample regions. As a whole, Guangdong has a good control over the energy consumption. The strong technical strength of the province has promoted the efficiency and economic contribution of the unit energy. Meanwhile according to the data in Table 2, Guangdong is gradually reducing the consumption of coal energy in recent years, while the consumption

rate of renewable energy, such as electricity, is increasing year by year. These practices greatly reduce carbon emissions, and are strategically significant for future development. The trend of coal consumption rate and renewable energy proportion, combined with low-carbon practices in recent years, indicate that government policy guidance and low-carbon regulations in the region play a vital effect. All index data also indicate that Guangdong has a high energy utilization efficiency, which may also benefits from the positive attitude of the province to new energy adoption and the scientific and reasonable energy consumption structure.

(3) Aspect of ecological protection. Ecological protection includes some significant measures to the realization of low-carbon transformation, and these measures provide a guarantee to the sustainable progress of regional boom. The indexes of Guangdong's smoke (dust) emissions (28.17), forest coverage rate (58.98), per capita afforestation area (27.77), and industrial solid waste effective utilization rate (87.42) ranked the 6th, 3rd, 4th and 6th respectively in the sample regions. These reflect the group consciousness of low-carbon activities, and the practice in this area is not so ideal in Guangdong. The average level of smoke (dust) emission and industrial solid waste effective utilization shows that the enterprises have poor low-carbon initiative and lack of necessary environmental awareness. The forest coverage rate and the per capita afforestation area are at the middle level of the sample, which indicates that the carbon sequestration capacity of Guangdong still has great lifting space; yet the low-carbon economy, which lacks ecological support, will have greater vulnerability. Therefore, the lower carbon ecological benefits should be promoted in Guangdong Province in the next stage, so as to ensure more efficient completion of economic benefits.

(4) Aspect of technology inputs. Such indexes can reflect the potential for the low-carbon progress of the region; also this is an advantage to low-carbon economic development of Guangdong. The R&D investment rate (2.53), the amount of patent licensing (25.90), the proportion of low-carbon technical fixed assets investment (2.52), and the number of R&D employees (42.373) in Guangdong are ranked the 1st, 1st, 6th and 2nd respectively. The rate of R&D investment shows the vitality of technological innovation, the amount of patent empowerment reflects progress of a region's annual low-carbon technology, and all employee numbers in the science and technology industry reflects the intrinsic motivation to promote the progress of low-carbon technology. These index values of Guangdong are all high in the forefront showing its bright future in low-carbon economy. Then we can look at the data of Hebei and Liaoning, and their technical input indexes are all in the end, which directly lowers their overall level of the new economic progress (ranked 9th and 10th respectively). Therefore, the accumulation of low-carbon technologies along with an enhancement in R&D investment can be an important measure to improve the low-carbon capability in the backward regions. However, the lower investment in low-carbon industry of Guangdong still shows that the government lacks enough attention to the low-carbon transformation. In the next phase, the province needs to effectively schedule the related resources to ensure the rapid growth of low-carbon capacity in the region.

5 Conclusions

This paper constructs an evaluation index system for the regional low-carbon economic progress, and then the empirical evaluation of development level to low-carbon economy is conducted for Guangdong region from dimensions of vertical and horizontal.

Guangdong province has a high standard of low-carbon economic progress, and also the increasingly good tendency is showed. Compared with other coastal provinces and cities, Guangdong has a higher comparative advantage in low-carbon economic development, including scientific energy composition, reasonable industrial structure, clear policy orientation and strong technical foundation power. All of these indicate that Guangdong has a promising low-carbon economy. Whereas many worries still exist, such as low-carbon awareness, low-carbon ecological benefits, low-carbon input and so on. These problems constraint the sustainable growth of the low-carbon economy in Guangdong and will become the focus of future work. Some relevant countermeasures are put forward here.

Firstly, the government should implement effective policy guidance and establish a legal system to ensure the low-carbon economic development. The government can introduce policies or guide funds to the low-carbon industry. It can give preferential treatment to low-carbon enterprises in terms of tax, water, electricity and land. What is more, the law can be used to strictly restrict the high energy consumption and high pollution industries to a lower development level. Moreover, we can advocate low-carbon consumption throughout the entire society by enhancing public low-carbon awareness.

Secondly, implementation of low-carbon policy should be put into practice. Low-carbon promotion funds as well as the application of special funds should all be effectively guaranteed. Other capital ensuring measures can also be adopted. As regards of human resources, regional government or other organizations can cultivate excellent talents in low-carbon development on their own. On the other hand, they can cooperate with research institutions and universities to ensure their investment to meet the progress requirements to low-carbon projects.

Thirdly, some advanced low-carbon technologies should be explored or exploited to strengthen regional low-carbon technology strength. A strategic roadmap can be formulated according to current situation, show all routes and directions for low-carbon technology development clearly, and increase the R&D strengths and the promotion efforts of low-carbon technologies. At the same time, various enterprises, institutions and other organizations can also be encouraged to implement specific technical exploration and demonstration projects to advance low-carbon development. Through the implementation with these measures, we will gradually establish diversified low-carbon technology systems in the region, for instance of power conservation technology, clean energy technology, energy efficiency technology and emission reduction technology, so as to provide strong support for the regional industrial structure optimization.

Fourthly, we should strengthen low-carbon propagation along with inter regional exchanging and cooperation promoting. Any progress to low-carbon economy requires not only efforts of government, but also, more importantly, to allow the whole society to join in the process of low carbon-economy building. We can make use of various media, such as television, newspapers, and images, to make the masses realize the importance and urgency of coping with climate change. In addition, the progress of low-carbon economy has become one consistent goal for regional development. In order to expand low-carbon economy more efficiently, all relevant departments should strengthen cooperation and exchanges between provinces, and actively learn from the low-carbon experience of advanced provinces, so as to enhance the regional low-carbon development capacity as soon as possible.

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