Comprehensive Evaluation of Carbon Emission Reduction Maturity of Typical Megacities

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Abstract. Addressing climate change by reducing carbon emissions has become the consensus of all countries in the world. Urban carbon emissions account for more than 80% of the total carbon emissions, which is a key link in reducing carbon emissions. A systematic evaluation of the maturity of low-carbon city construction can help improve the targeted reduction of carbon emissions by low-carbon measures. Select three key indicators such as output value energy consumption intensity, energy consumption carbon emission intensity and output value carbon emission intensity, use the grey correlation analysis method to calculate the grey correlation coefficient between the indicators, and further construct the development index, coordination index and coordinated development Based on the data of seven typical megacities from 2008 to 2017, a comprehensive evaluation of the urban carbon emission reduction maturity was carried out. The results show that there is inconsistency between the development index and coordination index of carbon emission reduction maturity in some years, but the overall carbon emission reduction development index, coordination index and coordination development index show a continuous growth trend, indicating that the maturity of emission reduction has been steadily improved.

Keywords: Maturity Model · Urban Carbon Emission Reduction · Grey Correlation · Relative Coordinated Development Index

1 Introduction

As the main source of greenhouse gas emissions, cities will directly affect the development of low-carbon economy and the realization of the "emission peak and carboon neutrality". Therefore, the evaluation of urban carbon emission reduction development has forward-looking significance.

Ref. [1] draws on the project management maturity model, constructs a management maturity evaluation model for college teachers' training programs abroad, and uses AHP and grey theory to evaluate project management maturity. Ref. [2] introduces the

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maturity model into the field of industrial carbon emission reduction analysis, constructs a maturity measurement index, and conducts a comprehensive evaluation of carbon emission reduction in 30 provinces and 38 industrial sectors in China. Ref. [3] develops a digital maturity model by means of literature research and expert review, and evaluates the digital maturity of an enterprise by constructing key process areas, primary indicators, and secondary indicators. Ref. [4] aims to assess the digital maturity of MSEs, using the Brazilian context as a research model, digital maturity was shown to be statistically correlated with innovation and business revenue. Ref. [5] proposes 23 specific criteria based on triple bottom line (environmental, economic, and social aspects) to assess the maturity of carbon market, and puts forward a novel multi-criteria decision approach, which integrates subjective weights and objective weights. Ref. [6] introduces a method for assessing LCC performance by using Capability Maturity Model (CMM), this method identifies LCC maturity grade through assessing the performance of individual LCC dimensions which contributes to overall performance.

Based on the above research, this paper takes the data of seven typical megacities in China from 2008 to 2017 as examples, and selects the total carbon emission, carbon emission intensity, and output value energy consumption intensity that are closely related to carbon emission reduction as key evaluation indicators. The carbon emission reduction development degree, coordination degree, and coordinated development degree index are formed, and the carbon emission reduction maturity model is formed, and the carbon emission reduction situation of seven typical megacities and the carbon emission reduction situation of typical megacities in China are comprehensively evaluated.

2 Carbon Emission Reduction Assessment Indicators

In order to accurately complete the assessment of carbon emission reduction maturity, this paper comprehensively considers the impact of various factors on carbon emission reduction, and establishes a comprehensive index system. The key indicators reflecting urban carbon emission reduction include the following three, acoording to the [7, 8]:

The first is the total amount of carbon emissions, which refers to the total greenhouse gas emissions of a certain region in a certain period of time. Controlling the total amount of carbon emissions is the key to realizing dual control as soon as possible.

The second is carbon emission intensity, which refers to the carbon emission per unit of GDP and is mainly used to measure the relationship between the economic development level of a country, region or city and carbon emission. The factors affecting carbon emission intensity are not single factors, and different conclusions can be drawn according to different analysis angles.

The third is the energy consumption intensity of output value, which is the main indicator reflecting the level of energy consumption and the status of energy conservation and consumption reduction.

3 Construction of Carbon Emission Reduction Maturity Model

The concept of maturity mainly emphasizes the description of the degree of development of things, in addition to the comprehensive description and measurement of the degree of coordination and development of things. The degree of development is the degree of realization of things from a low-level stage to a high-level stage, reflecting the level achieved by the system in the process of changing from small to large, from simple to complex. The degree of coordination refers to the degree of integration between the internal subsystems of a thing to adapt to each other, cooperate with each other and promote each other. The degree of coordinated development can reflect the comprehensive effect of the development level of comprehensive things and the level of coordination. This paper will analyze the relative maturity and overall maturity of carbon emission reduction, and provide an empirical basis for urban development to scientifically formulate carbon emission reduction strategies.

3.1 Modelling of Carbon Emission Reduction Development Levels

The relative development index is introduced to measure the development level of carbon emission intensity to compare the final effect of carbon emission reduction. According the [9], the grey relational degree analysis method is often used to study the correlation problem, consider using the grey relational degree to analyze the relative development index of carbon emission reduction. The overall development degree is introduced to measure the average development level of carbon emission reduction to compare the overall effect of carbon emission reduction in different years.Please note that the first paragraph of a section or subsection is not indented. The first paragraphs that follows a table, figure, equation etc. does not have an indent, either.

Relative Development Index. The research object is typical megacities, and the carbon emission intensity development of different cities in m years is compared. The reference sequence of carbon emission intensity is $C_0 = (c_0(1), c_0(2), ..., c_0(m))$, and the comparison sequence of the carbon emission intensity of the jth city is $C_j = (c_j(1), c_j(2), ..., c_j(m))$, the gray correlation coefficient of carbon emission intensity in the i year can be calculated as:

$$\varepsilon(i) = \frac{\min\left|C_0(i) - C_j(i)\right| + \rho \max\left|C_0(i) - C_j(i)\right|}{\left|C_0(i) - C_j(i)\right| + \rho \max\left|C_0(i) - C_j(i)\right|} \tag{1}$$

where $\left|C_0(i) - C_j(i)\right|$ denotes the absolute difference in carbon emission intensity in year i; $\min\left|C_0(i) - C_j(i)\right|$ denotes the minimum absolute difference of carbon emission intensity in year i; $\max\left|C_0(i) - C_j(i)\right|$ denotes the maximum absolute difference of carbon emission intensity in year i; ρ represent the resolution coefficient, generally 0.5. The relative development index is positively correlated with the carbon emission reduction maturity, that is, the larger the relative development index, the better the carbon emission reduction development of the city.

Overall Development Index. The overall development index of carbon emission reduction of typical megacities in year i can be calculated by the arithmetic mean of the relative development index of carbon emission reduction:

$$\mu_i = \frac{1}{m}\sum_{i=1}^{m}\varepsilon(i) \tag{2}$$

where μ_i denotes the overall development index of carbon emission reduction of typical megacities in year i.

3.2 Modeling of Carbon Emission Reduction Coordination Levels

The relative coordination degree is introduced to measure the coordination level relationship between the energy consumption intensity of output value and the energy consumption carbon emission intensity, so as to compare the coordination among the driving factors of carbon emission reduction. The overall coordination degree is introduced to measure the coordination degree of carbon emission reduction development level to compare the overall coordination of carbon emission reduction in different years, according to [10]. In this paper, the evaluation model of the actual state and the ideal state of the Euclidean distance measurement system is used to construct the overall coordination index model in the urban carbon emission reduction maturity model.

Carbon Emission Reduction Relative Coordination Index. The geometric mean of energy consumption per unit of GDP and energy consumption emission intensity is expressed as the relative coordination degree of carbon emission reduction, it can be calculated as:

$$\varphi(i) = \sqrt{\tau(i) \times \upsilon(i)} \tag{3}$$

where $\tau(i)$ denotes the gray correlation coefficient of energy consumption per unit of GDP; $\upsilon(i)$ denotes the gray correlation coefficient of energy consumption emission intensity. Among them, the calculation method of $\tau(i)$ and $\upsilon(i)$ is calculated with the gray correlation degree of carbon emission intensity. Similarly, it can be seen that the larger the relative coordination index of carbon emission reduction, the higher the maturity of carbon emission reduction.

Overall Coordination Index of Carbon Emission Reduction. The overall coordination level can be calculated by the Euclidean distance and Chebyshev distance between the actual and ideal values of carbon emission intensity, according to [11, 12]:

$$D_i = 1 - \sqrt{(d_i)^2 / \sum_{j=1}^{n} (h_j)^2} \tag{4}$$

$$d_i = \sqrt{\sum_{j=1}^{n} \left[c_0(i) - c_j(i)\right]^2} \tag{5}$$

$$h_j = \max_{1 \le i \le m} \left\{ \left| c_0(i) - c_j(i) \right| \right\} \tag{6}$$

where d_i denotes the Euclidean distance between the actual and ideal carbon emission intensity; h_j denotes the Chebyshev distance between the actual and ideal carbon emission intensity; D_i denotes the overall coordination index of carbon emission reduction.

3.3 Modelling of Coordinated Development Level of Carbon Emission Reduction

Considering that there is a mismatch between the relative development trend of carbon emission reduction and the relative coordination trend, that is, the situation of low development level, high coordination degree or high development level and low coordination degree in economic development. The relative coordinated development degree is introduced to measure the degree of harmonious development between the relative development level of carbon emission reduction and the relative coordination level, so as to compare the comprehensive balance between the development level of carbon emission reduction and the coordination level. The degree of harmonious development between the overall development level and the coordination level is measured to compare the comprehensive balance between the overall development level and coordination level of carbon emission reduction.

Relative Coordinated Development Index. Due to the inconsistency between the relative development index and the relative coordination index of urban carbon emission reduction, it is impossible to comprehensively, objectively and effectively reflect the real situation of urban carbon emission reduction based on the relative coordination index. Index to conduct a comprehensive and objective analysis of carbon emission reduction. Using the geometric mean of the relative development index and the relative coordination index as the relative coordinated development index of carbon emission reduction, it can be calculated as:

$$\theta(i) = \sqrt{\varepsilon(i) \times \varphi(i)} \tag{7}$$

where $\theta(i)$ denotes the relative coordinated development index of carbon emission reduction in year i, which is positively correlated with carbon emission reduction maturity.

Overall Coordinated Development Index. In the same year, there may be inconsistencies between the overall development level and overall coordination level of carbon emission reduction in typical megacities, resulting in a comprehensive evaluation of the overall maturity of carbon emission reduction using the overall development index or overall coordination index alone. There is one-sidedness. Therefore, the overall coordinated development index of carbon emission reduction is constructed by the aggregate of the overall coordination index and the overall development index. The details are as follows:

$$T_i = \sqrt{\mu_i D_i} \tag{8}$$

where Ti denotes the overall coordinated development index of carbon emission reduction of typical megacities in year i, which is positively correlated with carbon emission reduction maturity.

4 Comprehensive Evaluation of Urban Carbon Emission Reduction and Electricity-Related Maturity

First, the data related to carbon emissions in typical megacities from 2008 to 2017 were sorted out, including energy consumption, GDP, carbon emissions, etc., and the carbon emission intensity, output value energy consumption intensity, and energy consumption carbon emission intensity of each city Calculate; calculate and analyze the carbon emission reduction maturity of each city from 2008 to 2017 with the help of the maturity model, and evaluate the carbon emission reduction maturity of the city.

4.1 Data Processing

Raw Data. Find the relevant data required for carbon emission reduction assessment from the China Energy Statistical Yearbook over the years, as shown in Fig. 1, according to Ref. [13, 14].

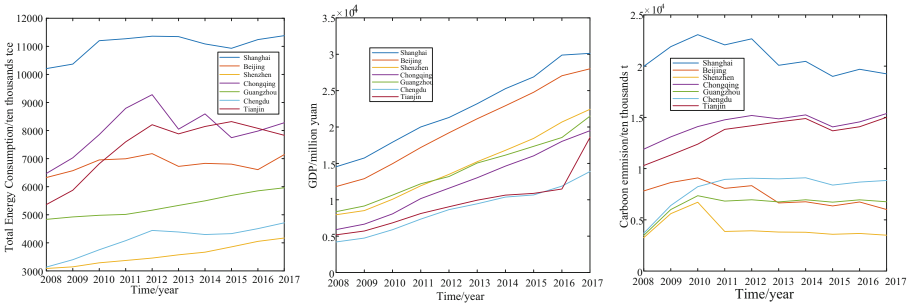

Fig. 1. Energy consumption, GDP, carbon emissions, etc. of typical megacities from 2008 to 2017.

Indicator Data. The raw data is processed according to the constructed carbon emission maturity model, and the urban carbon emission intensity, output value energy consumption intensity, and energy consumption carbon emission intensity can be further obtained. As shown in Fig. 2. Carbon emission intensity, output value energy consumption intensity, and energy consumption carbon emission intensity are calculated from the ratio of carbon emission to carbon emission intensity, the ratio of energy consumption to GDP, and the ratio of carbon emission to energy consumption in a certain period.

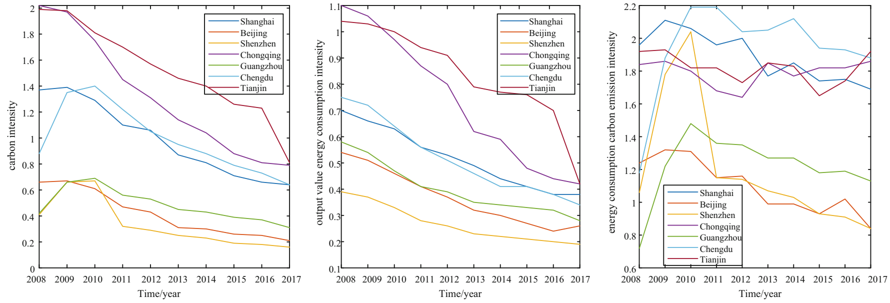

Fig. 2. Carbon emission intensity, output value energy consumption intensity, and energy consumption carbon emission intensity of typical megacities from 2008 to 2017.

4.2 Evaluation and Analysis of Urban Carbon Emission Reduction Maturity

Relative Development Level of Carbon Emission Reduction. The relative development level of carbon emission reduction of each city calculated according to formula (1) is shown in Table 1.

Table 1. Relative development level of carbon emission reduction in typical megacities from 2008 to 2017

city	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017
Shanghai	0.57	0.56	0.63	0.82	0.88	0.81	0.74	0.64	0.60	0.59
Beijing	0.46	0.45	0.52	0.80	0.95	0.67	0.64	0.57	0.56	0.50
Shenzhen	0.70	0.34	0.34	0.92	0.79	0.67	0.62	0.54	0.52	0.49
Chongqing	0.49	0.50	0.61	0.84	1.00	0.79	0.71	0.60	0.57	0.56
Guangzhou	0.81	0.58	0.54	0.76	0.84	0.89	0.83	0.73	0.69	0.59
Chengdu	0.83	0.58	0.55	0.69	0.90	0.93	0.82	0.72	0.66	0.59
Tianjin	0.62	0.63	0.73	0.81	0.95	0.93	0.87	0.75	0.73	0.52

As can be seen from Table 1, since 2008, the relative development level of carbon emission reduction in each city has shown an increasing trend. Only in some years the relative development index has decreased, especially in 2012 or 2013. Significant growth occurred.

Relative Coordination Level of Carbon Emission Reduction. The relative coordination level of carbon emission reduction of each city calculated according to formula (3) is shown in Table 2.

From Table 2, it can be seen that the relative coordination index of carbon emission reduction also peaked in 2012 or 2013, and then declined in a small range. Showing an upward trend. Comparing Table 1 and Table 2, it can be seen that the relative development level of carbon emission reduction in each city is positively correlated with the relative

Table 2. Relative coordination level of carbon emission reduction in typical megacities from 2008 to 2017.

city	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017
Shanghai	0.61	0.61	0.66	0.83	0.90	0.84	0.78	0.68	0.64	0.61
Beijing	0.51	0.50	0.57	0.78	0.93	0.73	0.68	0.59	0.60	0.53
Shenzhen	0.52	0.41	0.42	0.89	0.90	0.71	0.65	0.58	0.55	0.50
Chongqing	0.56	0.58	0.67	0.71	0.78	0.76	0.74	0.64	0.62	0.59
Guangzhou	0.42	0.65	0.61	0.84	0.84	0.78	0.75	0.74	0.73	0.62
Chengdu	0.42	0.61	0.62	0.75	0.91	0.78	0.67	0.75	0.69	0.63
Tianjin	0.67	0.67	0.75	0.82	0.81	0.90	0.88	0.77	0.74	0.54

coordination level, but there are still cases where the relative development level rises and the relative coordination level declines. For example, Guangzhou City From 2008 to 2010, the relative development level rose as a whole while the relative coordination level declined as a whole.

Relatively Coordinated Development Level of Carbon Emission Reduction. The relative coordinated development level of each city's carbon emission reduction calculated according to formula (7) is shown in Table 3.

Table 3. Relatively coordinated development level of carbon emission reduction in typical megacities from 2008 to 2017.

city	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017
Shanghai	0.59	0.58	0.64	0.82	0.89	0.82	0.76	0.66	0.62	0.60
Beijing	0.48	0.47	0.54	0.79	0.94	0.70	0.66	0.58	0.58	0.51
Shenzhen	0.60	0.37	0.38	0.90	0.84	0.69	0.63	0.56	0.53	0.49
Chongqing	0.52	0.54	0.64	0.77	0.88	0.77	0.72	0.62	0.59	0.57
Guangzhou	0.58	0.61	0.57	0.80	0.84	0.83	0.79	0.73	0.71	0.60
Chengdu	0.59	0.59	0.58	0.72	0.90	0.85	0.74	0.73	0.67	0.61
Tianjin	0.64	0.65	0.74	0.81	0.88	0.91	0.87	0.76	0.73	0.53

As can be seen from Table 3, 2012 or 2013 was still regarded as the turning point of carbon emission reduction development from 2008 to 2017, and the relative coordinated development level reached the maximum in that year, and the overall relative coordinated development level of carbon emission reduction during the research period rise.

The Overall Maturity of Carbon Emission Reduction in Typical Megacities. The overall development level, overall coordination level, and overall coordinated development level of each city calculated according to formula (2), (4)–(6), (8) are shown in Table 4.

Table 4. The overall maturity of carbon emission reduction in typical megacities from 2008 to 2017.

year	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017
level of development	0.64	0.52	0.56	0.81	0.90	0.81	0.75	0.65	0.68	0.76
level of coordination	0.37	0.07	0.13	0.76	0.87	0.73	0.65	0.49	0.42	0.47
level of coordinated development	0.49	0.19	0.27	0.78	0.88	0.77	0.70	0.56	0.51	0.63

It can be seen from Table 4 that from 2008 to 2017, the overall trend showed an increase. Although there was a slight decline from 2012, in the following years, each index began to recover as a whole, and it has never been lower than 2008.

5 Conclusion

This paper constructs the carbon emission reduction maturity model of typical megacities, and analyzes the carbon emission reduction of typical megacities from 2008 to 2017 from the three indexes of carbon emission reduction development level, coordination level and coordinated development level. It can be seen that the carbon emission reduction maturity of most cities shows an upward trend in terms of relative development, relative coordination or relative coordination. Considering that the relative development level of carbon emission reduction and the coordinated development level of carbon emission reduction are out of sync in some years, the urban carbon emission reduction maturity is further evaluated through the relative coordinated development index of carbon emission reduction. The overall maturity of carbon emission reduction The index also shows an upward trend in carbon emission reductions across typical megacities.

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