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Article

Evaluation of a Low-Carbon City: Method and Application

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Abstract: Many cities around the World have established the development objective of becoming a low-carbon city. Evaluation of such a city is important for its progress. A new evaluation framework of urban low-carbon development level is proposed in this paper, which integrates synthetic evaluation based on a bottom-up idea and analytical diagnosis based on a top-down idea. Further, set pair analysis is combined for synthetic evaluation and analytical diagnosis by comparing urban low-carbon development levels of different cities, through which the comprehensive state of urban low-carbon development level can be obtained and limiting factors identified. Based on the proposed framework and set pair analysis, low-carbon development levels of 12 Chinese cities are compared. Some suggestions are provided, based on results of overall situations of urban low-carbon development level and concrete performances of various factors and specific indicators. We conclude that both synthetic evaluation and analytical diagnosis are important for evaluation of urban low-carbon development level. The proposed framework and method can be widely applied in the evaluation of different cities over a long-term period.

Keywords: low-carbon city; evaluation framework; synthetic evaluation; analytical diagnosis; set pair analysis

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1. Introduction

Since the concept of a "low-carbon economy" was put forward in the UK white paper "*Our Energy Future: Creating a Low Carbon Economy*" in 2003 [1], this concept has been considered and pursued as a hopeful development pattern for reducing carbon emissions and coping with the challenges of climate change [2]. As one of the biggest contributors to carbon emissions [3,4] and the basic unit of economic development and administrative management, cities always play important roles in the development of a low-carbon economy.

In fact, many cities have adopted measures to reduce carbon emissions, ranging from overall planning and macro policy aspects to concrete measures in specific fields. For example, Tokyo, London, New York and Wuxi have initiated comprehensive planning programs of a low-carbon city [5–9]. Berlin, Copenhagen, Barcelona and Hangzhou have established a series of policies of low-carbon city construction regarding energy usage structure, industrial structure, public transportation, building design, household consumption, and public awareness [7,9–11]. Malmo, Baoding, Jilin and Shanghai have established concrete measures in specific fields, such as exploiting new energy, adjusting energy supply modes, regulating industrial structure, and developing low-carbon demonstration areas [9,11–14].

It is reported that about 1,050 cities in the United States, 40 cities in India, and more than 100 cities in China have established an objective of low-carbon development and made efforts to reduce carbon emissions [12,15,16]. This indicates that the low-carbon city has become a new goal of urban development. With this background, problems of low-carbon city evaluation are important to confirm whether a city is indeed low-carbon or, if not, the approximate gap between its present state and the low-carbon objective, and whether low-carbon city construction is proceeding properly.

As the United Nations Human Settlements Programme claimed, there is no globally accepted definition of city, and there are no globally accepted standards for recording emissions from sub-national areas [17,18]. It is easily understandable that there is no globally accepted definition of a low-carbon city. Certain evaluation indictors of the low-carbon city have been established based on different understandings and emphases, such as macro-level economic indicators, macro-level *per capita* indicators, end-use sectoral indicators [19,20], as well as indicators of carbon emissions, carbon source control, carbon capture, and human development [2,21–23]. Although without unified definition and standards, it has become gradually acknowledged that multiple indicators should be considered for evaluation of a low-carbon city covering economic development, social progress, energy structure, living consumption, and environmental quality. Some scholars have used these indicators to comprehensively evaluate urban low-carbon development based on a weighted sum model [2,20,22], whereas others have analyzed urban low-carbon construction only at the scale of concrete indicators [23]. In fact, both comprehensive evaluation and concrete analysis are necessary for low-carbon city evaluation. Only in this way can overall low-carbon states be understood and corresponding detailed limiting factors be identified, which are both important for improved urban low-carbon development in the future. Therefore, a method that can perform both comprehensive evaluation and concrete analysis is needed. Moreover, it should fit the characteristics of low-carbon city evaluation indicators, *i.e.*, with no fixed assessment standard because of new and dynamic features of the low-carbon city.

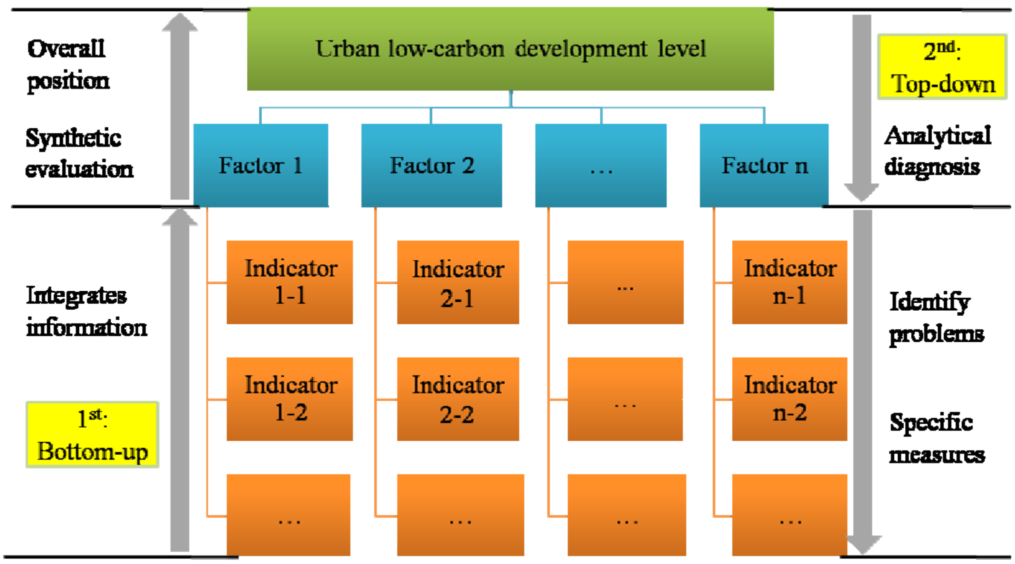
Based on these demands, we propose herein a new framework for evaluation of urban low-carbon development level, integrating comprehensive evaluation and concrete analysis. Furthermore, set pair analysis, a powerful tool when various factors of study objects must be integrated and relationships among different objects require analysis [24,25], is introduced into the evaluation of development level. Choosing 12 Chinese cities as case studies, the proposed framework and method are applied, based on which further suggestions for low-carbon city construction are put forth.

2. Methodology

2.1. Assessment Framework of Urban Low-Carbon Development Level

First, regarding the low-carbon city as a predicted development goal more than as a fixed, existing status [1], we focus on the concept of urban low-carbon development level, which emphasizes both the existing foundation and future potential of low-carbon city development. Second, assuming no fixed, acknowledged assessment standard for a low-carbon city, comparison among different cities is highlighted, which can give understandable results and improve the low-carbon level of multiple cities as a whole. To understand the overall low-carbon development level of cities and identify specific limiting factors, a novel relative assessment framework of urban low-carbon development level (Figure 1) is established upon integrating both bottom-up and top-down ideas.

Figure 1. Assessment framework of urban low-carbon development level.



As shown in Figure 1, synthetic assessment based on the bottom-up idea is conducted first. During this process, information about multiple factors and indicators is integrated to determine the comprehensive performance of the urban low-carbon development level. It gives the relative position of the assessed city among other cities, in terms of urban low-carbon development level. Detailed analysis is done subsequently, especially for cities with relatively weak comprehensive performance of urban low-carbon development level. During this stage, the condition of various factors and indicators is investigated, based on which key problems of the cities are identified and corresponding regulatory measures suggested.

Aside from the bottom-up and top-down ideas, there are two key points for implementation of the assessment framework. These are methods that can compare at different scales (e.g., objective, factor, and indicator scales) and a multi-scale assessment indicator system (e.g., objective, factor, and indicator scales). These two aspects will be introduced in the following sections.

2.2. Assessment Model of Urban Low-Carbon Development Level

2.2.1. Set Pair Analysis

Ground on fuzzy set and vague set, set pair analysis was proposed by Zhao [24] and extensively applied in multi-attribute assessment [26–28]. With clear expressions, simple calculation and understandable biophysical implications, this analysis can be used on different scales of comprehensive evaluation and detailed analysis, which is consistent with the bottom-up and top-down ideas. Compared with the commonly used evaluation method named weighted sum model [2,20,22] that defines the evaluation standard by researchers, set pair analysis emphasizes intrinsic relationships among different objects and generates reference sets from different objects, thus it is well suited to dynamic relative evaluation when there is no fixed standard of urban low-carbon development level. Additionally, describing relationships among different objects from aspects of identity, contrary, and discrepancy, set pair analysis maintains relatively more information and is favorable to overcome the partial property in the process of evaluation [26,28].

For the problem of assessment for urban low-carbon development level, the problem space Q based on set pair analysis can be defined as:

$$Q = \{S, M, H\} \tag{1}$$

$$S = \{s_k\} \quad (k = 1, 2, ..., q) \tag{2}$$

$$M = \{m_r\} \quad (r = 1, 2, ..., l) \tag{3}$$

$$H = (h_{kr})_{q \times l}, \tag{4}$$

where S is the assessed interval set composed of the selected cities, and s_k means the k^{th} city. M is the indicator set of urban low-carbon development level, and m_r denotes the r^{th} indicator. If a larger value of m_r expresses a better situation, $m_r \in M_1$ and is called a positive indicator; conversely $m_r \in M_2$ and is called a negative indicator. H is the decision-making matrix about problem Q, and h_{kr} is the attribute value of indicator m_r in the interval s_k.

Then, the optimal evaluation set that equals the assessment standard, marked as $u = \{u_1, u_2, \ldots u_l\}$, is generated by collecting the best value of each indicator of urban low-carbon development level. The worst evaluation set is marked as $v = \{v_1, v_2, \ldots v_l\}$. u_r and v_r respectively denote the best and worst values of the indicator m_r. For $m_r \in M_1$, the comparative interval is $[v_r, u_r]$. In the domain $X_r = \{h_{kr}, u_r, v_r\}$, the identity and contrary degree of the set pair $\{h_{kr}, u_r\}$ is defined as follows:

$$a_{kr} = \frac{h_{kr}}{u_r + v_r} \tag{5}$$

$$c_{kr} = \frac{h_{kr}^{-1}}{u_r^{-1} + v_r^{-1}} = \frac{u_r v_r}{(u_r + v_r) h_{kr}}, \tag{6}$$

where a_{kr} is the identity degree indicating the approximate degree between h_{kr} and u_r, whereas c_{kr} is the contrary degree denoting the approximate degree between h_{kr} and v_r. For $m_r \in M_2$, the identity and contrary degree of the set pair $\{h_{kr}, u_r\}$ is obtained by exchanging the equations of a_{kr} and c_{kr} in Equations (5) and (6).

Next, the average identity degree and contrary degree are calculated in the comparative interval s_k, *i.e.*, $[U,V]$, via Equations (7) and (8):

$$a_k = \sum_{r=1}^{n} w_r a_{kr} \quad (7)$$

$$c_k = \sum_{r=1}^{n} w_r c_{kr} \quad (8)$$

where a_k is the average identity degree representing the proximity between s_k and U, c_k is the average contrary degree that indicates the proximity between s_k and V, and ω_r is the weight of indicator m_r.

Finally, the approximate degree between s_k and U, marked as r_k, is calculated by:

$$r_k = \frac{a_k}{a_k + c_k} \quad (9)$$

Based on these procedures, a relative approximate degree of urban low-carbon development level to the optimal evaluation set is obtained by integrating information of multiple factors and indicators. Thus a synthetic evaluation based on the bottom-up idea is completed, through which the overall positions of different cities is defined. Set pair analysis can also be used as the scales of factor and concrete indicator to perform analytical diagnosis based on the top-down idea, when the indicator set M is different from that of the synthetic evaluation. This can identify the major problems of the cities in terms of urban low-carbon development level.

2.2.2. Information Entropy Weight

The main intention of introducing set pair analysis is to understand the relative low-carbon development level of different cities by integrating the relative situations of multiple indicators. It determines that those indices changing greatly with different assessment objects impact more notably on the final evaluation results and should possess larger weights. Therefore, the information entropy weight, which is usually confirmed by each indicator's differentiation ability for various assessment objects, was adopted to calculate the weight of those indicators [27,29]:

$$\omega_r = \left(1 + \frac{1}{\ln q}\sum_{k=1}^{q}\frac{g_{kr}}{g_r}\ln\frac{g_{kr}}{g_r}\right) \Big/ \left(n + \frac{1}{\ln q}\sum_{r=1}^{l}\sum_{k=1}^{q}\frac{g_{kr}}{g_r}\ln\frac{g_{kr}}{g_r}\right) \quad \left(\sum_{r=1}^{l}\omega_r = 1, 0 \le \omega_r \le 1\right) \quad (10)$$

$$g_r = \sum_{k=1}^{q} g_{kr} \quad (11)$$

$$g_{kr} = \begin{cases} h_{kr}/h_r^* & (\mathrm{h_r^*{=}max(h_{kr}),\ m_r \in M_1}) \\ h_r^*/h_{kr} & (\mathrm{h_r^*{=}min(h_{kr}),\ m_r \in M_2}) \end{cases}, \quad (12)$$

where ω_r is the weight of indicator m_r; g_r is the integrated value of m_r for interval set S; and g_{kr} is the standardized value calculated from raw data of m_r for interval s_k.

2.3. Multi-layer Indicator System of Urban Low-Carbon Development Level

The indicator system of urban low-carbon development level was initially established according to principal characteristics and multiple objectives of the low-carbon city (new urban development pattern with higher resource productivity, less carbon emission and pollution, better quality of life, and more development opportunity than traditional patterns) [30] and related assessment indicators [2,19–23]. Based on correlation analysis and component analysis of indicators as well as data availability and accuracy, the indicator system was slightly adjusted. Ultimately, 15 indicators of urban low-carbon development level formed the indicator set M, based on which the foundation and potential of developing low-carbon cities was measured.

As shown in Table 1, the 15 indicators are organized from aspects of economic development and social progress (M_1–M_5), energy structure and usage efficiency (M_6–M_8), living consumption (M_9–M_{11}) and development surroundings (M_{12}–M_{15}), according to focused items of each aspect. We thereby formed a multi-layer indicator system of urban low-carbon development level, which includes objective, factor and indicator layers. This makes possible a simultaneous synthetic evaluation (integrating various indicators and factors into the comprehensive objective) and concrete diagnosis (related analysis at scales of factors and indicators, according to the synthetic evaluation results).

Table 1. Indicators of urban low-carbon development level and indicator weights.

Objective	Factor	Concerns	Indicator	Weight
Urban low-carbon development level	Economic development and social progress	Economic amount, structure, and development speed; urbanization and civilization level	M_1 *Per capita* GDP/Yuan	0.0480
			M_2 GDP growth rate/%	0.0133
			M_3 Proportion of tertiary industry to GDP/%	0.0123
			M_4 Urbanization rate/%	0.0280
			M_5 R&D as a percentage of GDP/%	0.0391
	Energy structure and usage efficiency	Urban energy structure, relationship among energy use, economic growth, and carbon emission	M_6 Proportion of non-coal energy/%	0.1161
			M_7 Carbon productivity/(10^4 Yuan/t)	0.0213
			M_8 Elasticity coefficient of energy consumption	0.2270
	Living consumption	Residents' living consumption mode and related impact of carbon emission	M_9 Angel's coefficient/%	0.0010
			M_{10} Number of public transportations vehicles per 10,000 persons/Vehicle	0.0852
			M_{11} *Per capita* carbon emission/t	0.0459
	Development surroundings	Situations of carbon sink and investment for environmental protection	M_{12} *Per capita* public green areas/m^2	0.2921
			M_{13} Forest coverage/%	0.0449
			M_{14} Coverage rate of green area in built-up area/%	0.0112
			M_{15} Proportion of investment for environmental protection to GDP/%	0.0148

2.4. Study Sites

Twelve cities—Shanghai, Baoding, Tianjin, Chongqing, Hangzhou, Shenzhen, Beijing, Guangzhou, Qingdao, Suzhou, Zhuhai, and Kunming—were selected to constitute the assessed interval set *S*, while considering factors such as efforts of low-carbon city construction, economic development level, social civilization degree, environmental quality and data availability. Indicator data were collected in 2009.

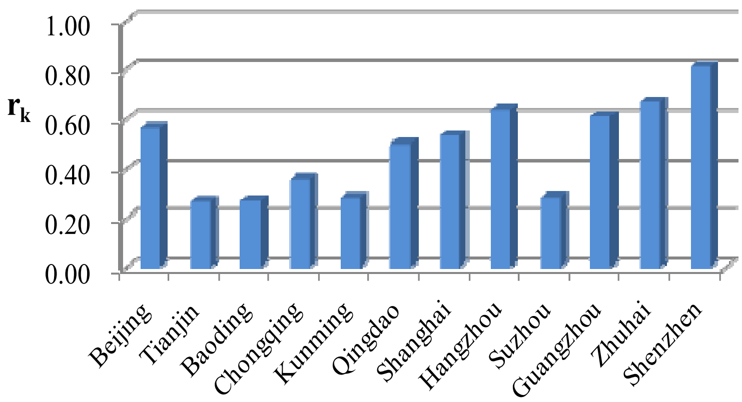
3. Results

The 2009 indicator data for the assessed cities were compiled from national and local yearbooks, statistical surveys, and official government websites. According to these data, the information entropy weight of each indicator was derived (Table 1). Subsequently, with the set pair analysis, we conducted the synthetic evaluation based on the bottom-up idea and detailed analysis based on the top-down idea, in terms of urban low-carbon development level.

3.1. Overall Situations of Urban Low-Carbon Development Level

As indicated in Figure 2, the 12 cities had different grades in terms of low-carbon development level in 2009. Shenzhen, Zhuhai and Hangzhou ranked in the highest grade when their relative approximate degrees of urban low-carbon development level to the optimal evaluation set (r_k) exceeded 0.6. Tianjin, Baoding, Kunming, Suzhou and Chongqing ranked in the lowest grade when r_k was less than 0.4. Guangzhou, Beijing, Shanghai and Qingdao ranked in the medium grade when r_k was 0.4–0.6. It should be pointed out that 0.4 and 0.6 do not represent any fixed gradation standard for urban low-carbon development level, but are used according to the results of this case. The results of synthetic evaluation based on set pair analysis produced a clear order of different cities. This demonstrates that this evaluation can define overall city positions when accurate grading of the cities according to a specific standard is less important.

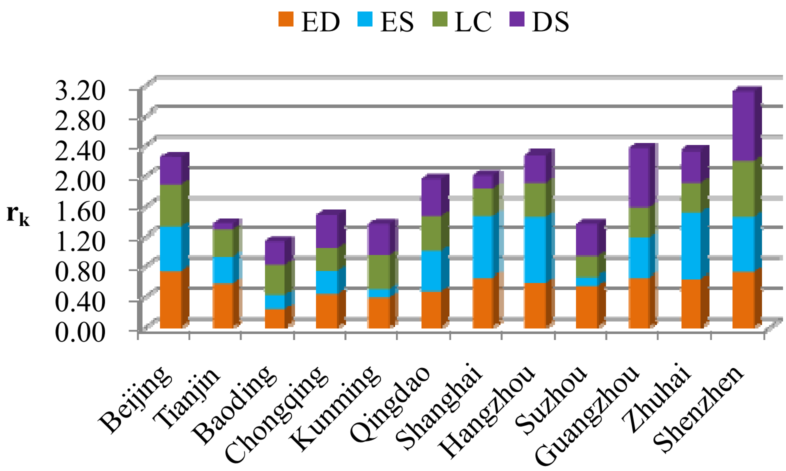
Figure 2. Relative urban low-carbon development levels of 12 cities in 2009.



3.2. Performance of Each Factor of Urban Low-Carbon Development Level

Based on a procedure similar to synthetic evaluation, the performance of various factors for the assessed cities was also obtained by set pair analysis (Figure 3). For the factor of economic development and social progress, Beijing, Shenzhen, Shanghai, Guangzhou and Zhuhai performed relatively well, whereas Baoding, Kunming and Chongqing performed relatively poorly. With respect to energy structure and usage efficiency, Zhuhai, Hangzhou, Shanghai and Shenzhen ranked at a relatively high level, Kunming, Suzhou and Baoding at a relatively low level, and the other cities ranked at a middle level. For the factor of living consumption, Shenzhen and Beijing performed slightly better than other cities, but most cities showed a medium performance. For the factor of development surroundings, the situations of Shenzhen and Guangzhou were strong, those of Tianjin and Shanghai were weak, and those of other cities were at a medium level.

Figure 3. Relative performance of each factor of urban low-carbon development level, for 12 cities in 2009 (ED, economic development and social progress; ES, energy structure and usage efficiency; LC, living consumption; and DS, development surroundings).



For cities with a high urban low-carbon development level, like Shenzhen, Zhuhai and Guangzhou, each factor of this level performs well in a balanced way. The situation is especially so for Shenzhen. For cities of low development level, like Tianjin, Baoding, Kunming and Suzhou, some factors performed weakly. For Tianjin city, which had the lowest development level, the factor of development surroundings had the worst performance of all assessed cities. Levels of energy structure and usage efficiency were lowest for Kunming and Suzhou.

3.3. Concrete Situations of Specific Indicators

According to the above results, we conclude that cities with relatively low urban low-carbon development levels mainly perform poorly in two factors, *i.e.*, development surroundings and energy structure and usage efficiency. To further diagnose the problems of these cities, detailed analysis is conducted with a focus on the concrete indicators of the two factors, as indicated in Figures 4 and 5. Regarding the four indicators of development surroundings, the levels of *per capita* public green areas, coverage rate of green area within built-up area, and forest coverage are relatively low, especially for the first two, taking Tianjin city as an example. Regarding the factor of energy structure and usage efficiency, the levels of carbon productivity and elasticity coefficient of energy consumption are relatively low, especially that of the latter, again taking Tianjin city as the example.

Figure 4. Relative situations of each indicator of development surroundings, for 12 cities in 2009. (**a**) *Per capita* public green areas, (**b**) forest coverage, (**c**) coverage rate of green area within built-up area, and (**d**) proportion of investment for environmental protection to GDP.

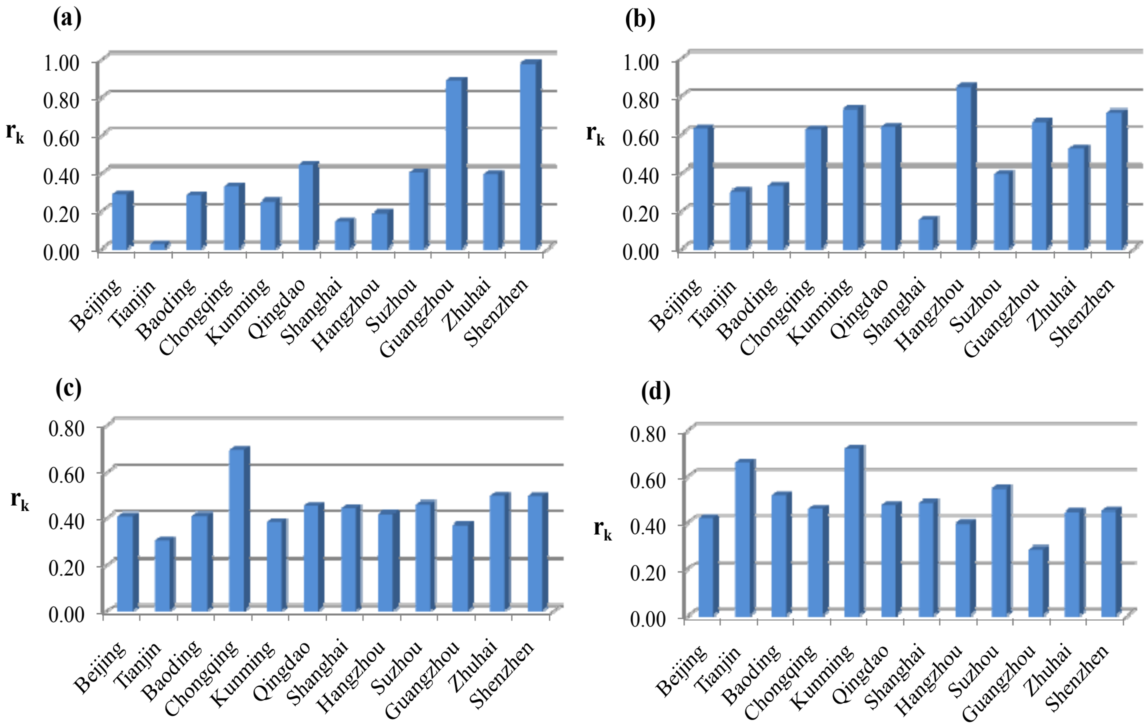
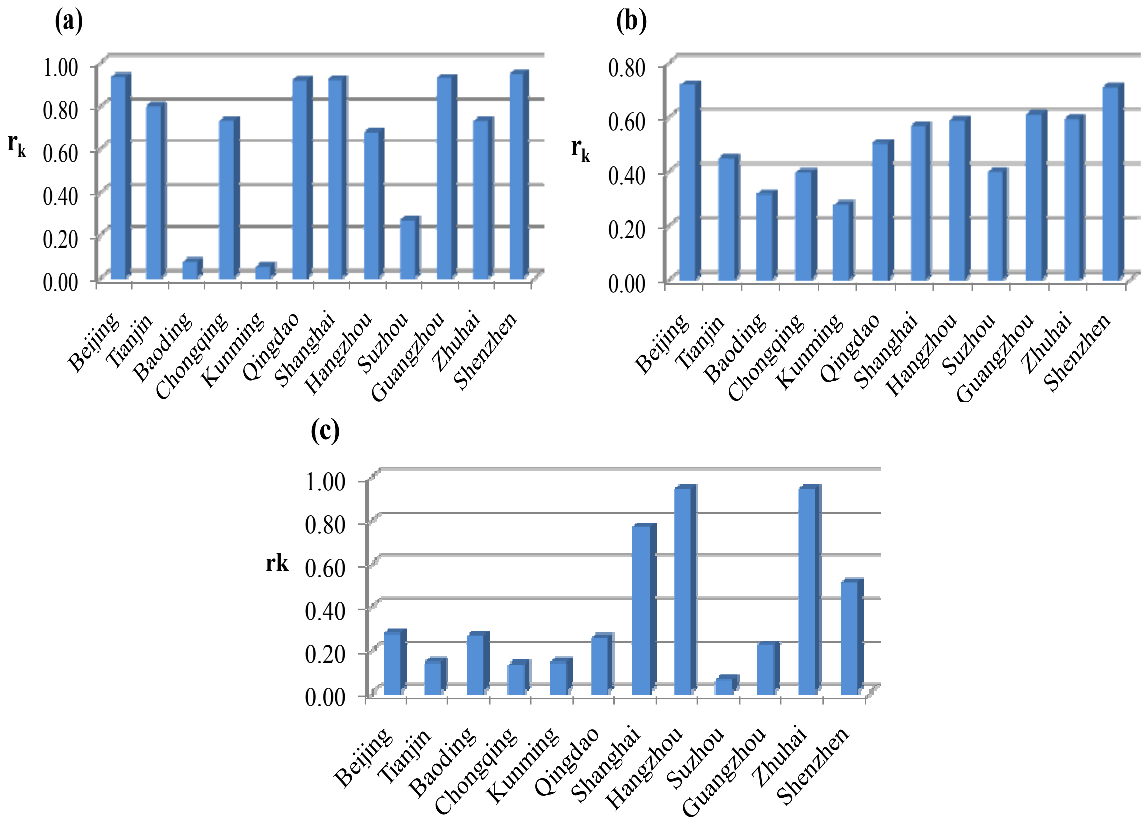


Figure 5. Relative situations of each indicator of energy structure and usage efficiency, for 12 cities in 2009. (**a**) Proportion of non-coal energy, (**b**) carbon productivity, (**c**) elasticity coefficient of energy consumption.



Based on these analyses, suggestions for improving urban low-carbon development level can be put forward. Taking Tianjin city, for instance, we suggest that more attention be paid to the construction of green areas to enlarge its carbon sink capacity and improve the development surroundings for low-carbon city realization. Meanwhile, measures such as improving energy usage efficiency by adopting clean energy, transforming production techniques, and recycling materials and energy should be taken. This would reduce the elasticity coefficient of energy consumption and achieve a harmonious relationship between energy use, economic growth, and carbon emission.

4. Discussion

4.1. Selection of Indicators of Urban Low-Carbon Development Level

Undoubtedly, the indicator selection has a direct impact on the final evaluation results of urban low-carbon development level. As described above, various factors, including characteristics of the low-carbon city, related existent indicators, data availability and accuracy, as well as correlation analysis and component analysis of indicators, are all considered during indicator selection. We should attempt to attain the most scientific result. However, we usually have to balance various considerations, especially for concepts closely linked to actual management.

Table 2 shows correlation analysis results of the 15 indicators of urban low-carbon development level. The first indicator (M_1, *per capita* GDP) has relatively high correlation with several other indicators like M_7 and M_{11}, and the seventh indicator (M_7, carbon productivity) has high correlation with several other indicators like M_1, M_5 and M_6. These results cause us to reconsider the selection of M_1 and M_7. However, given the vital indicating role of M_7 for the low-carbon city and the important meaning of M_1 in actual urban management, we ultimately retained the two indicators.

Table 2. Correlation matrix for 15 indicators of urban low-carbon development level.

	M_1	M_2	M_3	M_4	M_5	M_6	M_7	M_8	M_9	M_{10}	M_{11}	M_{12}	M_{13}	M_{14}	M_{15}
M_1	1.000	−0.094	0.495	0.681	0.470	0.632	0.802	−0.306	−0.317	0.350	0.725	0.449	0.096	0.397	−0.069
M_2	−0.094	1.000	−0.278	−0.103	−0.158	−0.029	−0.194	0.354	−0.149	0.157	0.126	0.118	−0.050	0.055	−0.052
M_3	0.495	−0.278	1.000	0.585	0.704	0.692	0.621	−0.394	−0.315	0.162	0.128	0.168	0.180	0.019	−0.008
M_4	0.681	−0.103	0.585	1.000	0.584	0.586	0.704	−0.200	−0.292	0.455	0.294	0.522	0.010	0.224	−0.084
M_5	0.470	−0.158	0.704	0.584	1.000	0.545	0.719	−0.432	−0.409	0.325	0.065	0.224	0.069	0.384	−0.074
M_6	0.632	−0.029	0.692	0.586	0.545	1.000	0.736	−0.312	−0.477	0.432	0.211	0.509	−0.022	0.212	−0.112
M_7	0.802	−0.194	0.621	0.704	0.719	0.736	1.000	−0.413	−0.517	0.495	0.211	0.566	0.221	0.423	−0.224
M_8	−0.306	0.354	−0.394	−0.200	−0.432	−0.312	−0.413	1.000	0.096	0.022	−0.055	0.039	−0.009	−0.257	−0.166
M_9	−0.317	−0.149	−0.315	−0.292	−0.409	−0.477	−0.517	0.096	1.000	−0.207	0.048	−0.262	0.141	−0.263	0.414
M_{10}	0.350	0.157	0.162	0.455	0.325	0.432	0.495	0.022	−0.207	1.000	0.039	0.904	0.256	0.226	−0.012
M_{11}	0.725	0.126	0.128	0.294	0.065	0.211	0.211	−0.055	0.048	0.039	1.000	0.077	−0.105	0.264	0.129
M_{12}	0.449	0.118	0.168	0.522	0.224	0.509	0.566	0.039	−0.262	0.904	0.077	1.000	0.259	0.271	−0.130
M_{13}	0.096	−0.050	0.180	0.010	0.069	−0.022	0.221	−0.009	0.141	0.256	−0.105	0.259	1.000	−0.065	−0.177
M_{14}	0.397	0.055	0.019	0.224	0.384	0.212	0.423	−0.257	−0.263	0.226	0.264	0.271	−0.065	1.000	−0.032
M_{15}	−0.069	−0.052	−0.008	−0.084	−0.074	−0.112	−0.224	−0.166	0.414	−0.012	0.129	−0.130	−0.177	−0.032	1.000

The results of principal component analysis shown in Table 3 also aid this decision making. Good component extraction was not achieved from this analysis, which means that correlation between the 15 indicators is not significant, but acceptable. With the dynamic development of low-carbon city, certain modifications and supplements to the present indicators based on the academic progress in related subjects is still necessary to obtain a more scientific evaluation result in the future.

Table 3. Total variance explained for principal component analysis of the 15 indicators.

Component	Initial Eigenvalues		
	Total	% of Variance	Cumulative %
1	5.523	36.822	36.822
2	1.957	13.043	49.865
3	1.574	10.493	60.358
4	1.389	9.263	69.621
5	1.041	6.937	76.558
6	0.986	6.572	83.131
7	0.727	4.845	87.976
8	0.547	3.648	91.624
9	0.387	2.579	94.202
10	0.322	2.149	96.351
11	0.253	1.686	98.037
12	0.169	1.129	99.166
13	0.071	0.476	99.642
14	0.043	0.287	99.929
15	0.011	0.071	100.000

4.2. Management Implication based on Evaluation of Urban Low-Carbon Development Level

The evaluation of urban low-carbon development level based on the bottom-up and top-down ideas provides management implications from various viewpoints, as indicated in Table 4. Both ideas are important for actual urban management, and they should refer to each other.

Since the optimal evaluation set based on set pair analysis is generated from the *status quo* of the selected cities, the evaluation results may change with time and selected cities. For example, though Shenzhen ranked at the highest level among the 12 cities in the study period, it may decline in the future if other cities develop vigorously. Moreover, although Shenzhen performed relatively well against the other Chinese cities, it may perform poorly relative to other cities internationally. The results of set pair analysis will impel every city to continuously improve their low-carbon levels. These qualifications suggest that set pair analysis-based studies of different city sets or over a long term will shed more light on the evaluation of urban low-carbon development level.

Table 4. Management implications based on evaluation of urban low-carbon development level.

Ideas	Focus	Results	Management implications
Bottom-up	Integrated urban low-carbon development level	Group 1 with relative high level: Shenzhen, Zhuhai, and Hangzhou Group 2 with medium level: Guangzhou, Beijing, Shanghai, and Qingdao Group 3 with relative low level: Tianjin, Baoding, Kunming, Suzhou, and Chongqing	Those cities with relative low levels of low-carbon development should realize the gap and learn from those with relative high levels. The orders based on relative urban low-carbon development levels will change with time and assessed cities, which requires every city to develop continuously.
Top-down	Concrete limiting factors of urban low-carbon development level	Mainly constrained by economic development and social progress: Baoding Mainly constrained by energy structure and usage efficiency: Kunming and Suzhou Mainly constrained by living consumption: Chongqing Mainly constrained by development surroundings: Tianjin	Measures focused on different factors should be taken for different cities to improve the urban low-carbon development level. In order to reach a relative high urban low-carbon development level, each factor should develop well in a balanced way.

4.3. Possible Further Analysis of Urban Low-Carbon Development Level

As a development pattern of sustainable city, the low-carbon city should pursue not only the objective of carbon emission reduction but also other objectives for sustainable development, including economic development, reduction of conventional emissions, comfortable living environment, social justice, and low-carbon lifestyle [30]. However, the concrete focuses for different types of cities may differ with natural condition, resources endowment, and socio-economic situation. Based on the preliminary evaluation results among different cities, more detailed analysis could be conducted on certain specific type of cities (e.g., economy-limited city, resource-limited city, or environment-limited city) in the future to obtain more effective management options.

Since each method has its own advantages and disadvantages, how to reasonably define the indicator weights is always an open question. Further discussion is deserved to check the feasibility and uncertainty that exists in incorporating different methods such as information entropy, the correlation coefficient method, the Delphi method, and the analytic hierarchy process in confirming indicator weights. Moreover, regarding the inadequate recognition of various complexity and uncertainties within urban ecosystems, set pair analysis could be combined with other uncertainty methods like fuzzy-stochastic programming model [31] and mixed fuzzy interval-stochastic programming method [32] to incorporate more elements of uncertainty and quantify the uncertainty of evaluation more accurately.

5. Conclusions

Both comprehensive measure and concrete analyses are needed for evaluation of the low-carbon city. A new evaluation framework of urban low-carbon development level that integrates synthetic evaluation and analytical diagnosis by integrating bottom-up and top-down ideas was proposed. Set pair analysis was also used to do a synthetic evaluation and analytical diagnosis based on comparison among different cities. This produced understandable results and improves the low-carbon level of multiple cities as a whole. Through synthetic evaluation based on the bottom-up idea, various data were integrated to obtain a comprehensive state of urban low-carbon development level, which assigns an assessed city a ranking among different cities in terms of urban low-carbon development level. Through analytical diagnosis based on the top-down idea, situations of specific factors and indicators were investigated, which identified key problems of the cities.

The proposed framework and method was used to evaluate the low-carbon development level for 12 Chinese cities. Varying management implications were furnished by the synthetic evaluation and analytical diagnosis, which are both important for construction of the low-carbon city. The evaluation results may change with time and selected cities. However, the results give impetus to every city to learn from each other and continuously improve their low-carbon levels. Further studies of different cities or over a long term, based on set pair analysis, are helpful in comprehensive and dynamic evaluation of urban low-carbon development level.

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Conflict of Interest

The authors declare no conflict of interest.

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