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Model and methods for comprehensive measurement of the low-carbon status of China's oil and gas enterprises

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Abstract: This paper establishes a model that would allow China's oil and gas enterprises to scientifically evaluate and measure their low-carbon level and status. It considers various characteristics of China's oil and gas enterprises and the implications of low-carbon development, and is based on an overall analysis of factors that influence the reduction of carbon emissions. In view of low-carbon economic theories and the general principles of an evaluation index system, a comprehensive system for measuring the low-carbon status of China's oil and gas enterprises has been developed. This measurement system is comprised of four main criteria (energy structure, energy utilization, carbon emissions and utilization, and low carbon management) as well as thirty indexes. By the Delphi method and the analytical hierarchy process (AHP), the weight of the rules hierarchy and indexes hierarchy were determined. The standardized indexes were then integrated using a linear weighted sum formula, and a comprehensive formula for index measurement was established. Taking into account the status of low-carbon development in the petroleum and petrochemical industry at home and abroad, an evaluation criterion is proposed comprising four levels: ideal low-carbon, economical low-carbon, medium-carbon and high-carbon, whose values were organized within the settings of [0, 1].

Key words: Oil & gas enterprises, low-carbon, measurement, evaluation, index system, AHP

1 Introduction

In recent years China's oil and gas production enterprises have achieved substantial results in increasing oil and gas supply, improving energy efficiency, limiting greenhouse gases emissions, and developing clean energy. However, due to limited resources, China's enterprises are still facing challenges in energy utilization. These challenges include a poor oil and gas consumption ratio, inferior energy efficiency, a heavy reliance on foreign oil, and increased greenhouse gas-emissions. To improve China's pattern of energy consumption and to guarantee the supply of oil and gas, China's petroleum enterprises have made great efforts in the development of oil and gas resources and in maintaining a rapid growth of oil and gas production. However, with increasing difficulties in oilfield development and the rise of oil and gas production, energy consumption and greenhouse gases emissions are still showing an upward trend. In the midst of the reduction of greenhouse gases emission and the pursuit of low-carbon development worldwide, the problem for China's petroleum enterprises is how to ensure energy conservation and emission reduction while keeping their high growth in oil and gas production. It is an urgent problem for China to find a balance between the supply of "high-carbon" products and "low-carbon" development .To solve this problem, it is necessary to first study the major factors influencing the low-carbon development of China's petroleum enterprises, and then use this research to create a comprehensive evaluation index system with multiple criteria, indexes, and layers. Subsequently, based on comprehensive assessment, to understand the current status and phase of low-carbon development in China's oil and gas enterprises and the difference between China and foreign countries, and then to investigate the development potentials of China's oil and gas enterprises. A large number of studies of the evaluation index system for energy efficiency and sustainable development have been reported abroad. These index systems include the sustainable energy index system (IAEA, 2005), the low-carbon efficiency index (Andress et al, 2010), and the energy efficiency index system (Streimikiene and Šivickas, 2008). However, in China only a very few studies are related to the comprehensive evaluation of low-carbon development. These

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mainly focus on national or regional low-carbon development, such as low-carbon economic development (Fu et al, 2010), low-carbon social evaluations (Ren et al, 2010), low-carbon urban evaluations (Ma et al, 2010; Grubb and Jamasb, 2008; DTI, 2003), energy conservation and emissions reduction (He and Chen, 1999; Zhang et al, 2008; ADB, 2011), as well as oil and gas security and risk assessment etc. (ERI, 2008; Liu et al, 2006; Zhang and Wang, 2003). However, studies related to low-carbon evaluation systems and methods for oil and gas enterprises have not been reported.

2 Low-carbon development and its influencing factors

2.1 Low-carbon development for China's oil & gas enterprises

The "low-carbon" concept first appeared in the literature in the late 1990s (Kinzig and Kammen, 1998). It was first officially used in the White Paper *Our Energy Future—Creating a Low Carbon Economy* issued by the British government in 2003. This document describes an economic development model with decreased energy consumption, reduced pollution, and increased energy efficiency, all in order to create a higher standard of living. For China's oil and gas enterprises, low-carbon developments should embody the following four aspects. 1) Rapid development of natural gas resources and increases of the output of natural gas, coal bed methane (CBM), shale gas, and tight gas on a large scale, all of which are comparatively realistic choices for optimizing energy consumption. 2) To promote innovations in energy utilization techniques, to improve energy utilization efficiency, to decrease high-carbon energy (e.g., coal) consumption, and to reduce carbon emissions at their source and in the period of utilization. 3) To strengthen R&D of low-carbon technology, such as carbon dioxide capture utilization and storage (CCUS). 4) To study policies and establish standards to promote enterprise development in low-carbon economy.

2.2 System theory based influencing factors of low-carbon development

The system is a functional organic whole composed of several interrelated and mutually restrained factors (Ma et al, 2009). The basic method of System Theory is to regard its objects of study as a system, then to investigate the relationship among the system, factors and environments and their changing rules. By understanding of system characteristics, regulating of system structure and coordinating of the relationship among factors, system optimization can be improved (Wei and Zeng, 1995).

For China's oil and gas enterprises, low-carbon development is an extremely complicated system, which embodies not only the multidisciplinary nature of low-carbon development itself but also the complexity of oil and gas enterprises: Firstly, low-carbon development is a more sustainable or green development mode related to energy, environment and economics. Secondly, oil and gas production is related to the reservoir engineering system, oil production engineering system, and the surface engineering system. Thus, study of the factors that influence this system should be focused on "oil and gas production" and "low-carbon development".

China's oil and gas production enterprises are now faced with decreasing their energy consumption and carbon emissions while increasing the outputs of oil and gas constantly to meet the rapid growth of oil and gas consumption. On the one hand, to improve China's energy consumption patterns and meet the demand for oil and gas, China's petroleum industry is forced to greatly increase oil and gas production. With the rapid development of economy in China, the demand for oil and gas is increasing significantly, and China's reliance on foreign oil and natural gas is forecast to exceed 80% and 30%[1] respectively in 2030, when the security of oil and gas supply in China is threatened. On the other hand, China's oil and gas enterprises are facing the challenges of increasing exploitation difficulties as their mainland oilfields decline into the mid-late periods of production, resulting in increasing energy consumption and high greenhouse gas emissions. These challenges are as follows: 1) with the increase of low-yield inefficient wells and a rise in water content, large amount of fluid and water are extracted during the production process, this will result in more and more waste water discharging because of the restriction on reinjection of waste water. 2) Special reservoirs, such as low-yield, low permeability, heavy oil and high-sulfur natural gas are increasing. 3) With increasing tertiary oil recovery, thermal recovery technologies, such as steam assisted gravity drainage (SAGD), are used. 4) Hydrocarbon gas emissions from oil and gas production and gathering systems. 5) Fossil fuel combustion plants (especially coal-fired thermal recovery boilers for thermal recovery of heavy oil) will result in more carbon dioxide emissions. In order to find a balance between the supply of "high-carbon" products and the development of a "low-carbon" mode, it is crucial to simultaneous develop and utilize clean energy sources, improve energy efficiency, reduce greenhouse gases emissions, while increasing the supply of oil and gas.

As a consequence, the principles that define the evaluation system for the low-carbon development of China's oil and gas enterprises should at the very least be comprised of energy structure, energy utilization, carbon emissions and utilization, as well as low-carbon management. These four factors make up the major framework for evaluating low-carbon development.

3 Model for comprehensive measurement of the low-carbon status of China's oil and gas enterprises

3.1 Principles of selection of indexes

The following factors are to be strongly considered when selecting indexes: Firstly, systematic and scientific indexes are

[1]IEA. World Energy Outlook: 2011. Paris International Energy Agency. 2010. 59-271.

highly recommended so as to reflect the measurable reality of low-carbon development. Secondly, the availability and reliability of indexes should be considered. The third factor is to ensure that the selected indexes are highly representative and largely independent each other.

3.2 Indexes selection

Taking into account the above studies on the implications and restricted factors of the low-carbon development of China's oil and gas enterprises, a comprehensive low-carbon measurement system should include the following four types of indexes as a rule hierarchy: 1) *Energy structure*, including the supply structure and the consumption structure of energy products, a relatively essential factor in the development of a low-carbon system. Energy structure is a priority index in improving energy structure and reducing greenhouse gases, also an enterprise's contributions towards the optimization of the structure of national energy consumption. 2) *Energy utilization*, including total energy consumption, energy consumption intensity, and energy utilization efficiency etc., which is used to evaluate a system's efficiency in energy production and utilization. A higher energy utilization level indicates more effective energy consumption and fewer carbon emissions. 3) *Carbon emissions and utilization*, including carbon emissions gross, source, intensity, reduction and utilization. This index can evaluate an enterprise's ability to reduce greenhouse gas emissions and to deal with them via "end-of-pipe treatment"; it also embodies an enterprise's environmental and social responsibilities. 4) *Low-carbon management*, which involves low carbon related strategies and plans, management systems, standards and information systems. It can provide useful support for an oil and gas enterprise to adapt to the low-carbon development, to improve the overall management efficiency and enhance core competitiveness.

Based on the principles of index selection, and using the four types of indexes described above as a rule hierarchy, in this work, we first established a comprehensive low-carbon measurement system for China's oil and gas enterprises. Then we conducted a principal component analysis (PCA) and an independent check to the indexes chosen, and rejected any invalid, unmeasured or unavailable indexes, and finally selected thirty indexes as the index hierarchy of the comprehensive low-carbon measurement system.

3.3 Establishment of an integrated model for a low-carbon measurement system

In this study, we established a comprehensive measurement system model by using AHP, consisting of a target hierarchy, a rule hierarchy and an index hierarchy. It is based on the achievements not only from low-carbon development of China's oil and gas enterprises, but also from the comprehensive evaluation status at home and abroad.

Comprehensive measurement of low-carbon for oil and gas enterprises (denoted as A) is set as the target hierarchy; energy structure (B_1), energy utilization (B_2), carbon emission and utilization(B_3), and low-carbon management(B_4) are all arranged in the rule hierarchy; and the thirty indexes (C_{ij}, i=1, 2, 3, 4; j=1, 2, ···, 9) are designated as the index hierarchy (Table1).

4 Integrated measurement method

4.1 Determination of the index weight by using AHP

Scientific and reasonable index weights can lead to accurate comprehensive evaluation. A few methods, such as AHP, fuzzy comprehensive evaluation (FCE) (Dong and Zeng, 2006), principal component analysis (PCA) (Wang, 2010; Zhang et al, 2005) etc., are used to determine the weight of each index based on subjective and objective analysis (Du et al, 2008). Different evaluation objects or phases should use different evaluation index systems or weights (Nielsen, 2005). In order to determine the index weight of low carbon development for China's oil and gas enterprises, we applied the AHP method. According to AHP principles, it is necessary to determine target hierarchy, rule hierarchy and index hierarchy, and then convert the abstract problems into mathematical ones by constructing a hierarchical structure model, and finally each layer's results were integrated into a value. The following is a brief introduction to the operation and calculation processes with the help of the AHP software (0.5.2 version).

4.1.1 Design of comparative judgment matrixes

According to the established hierarchical model for the index system, a questionnaire about a comparison of the importance between two indexes within the same hierarchy was designed, and the questionnaire was separately delivered to 8 low-carbon experts, 6 petroleum experts, and 6 natural gas experts for assigning values to each index with a scale of 1-9 by the Delphi method (Xu, 2008) (Table 2). Then, a new forecast table was prepared based upon the preliminary statistical results of their feedback. This new table was then sent to each expert for a second-round of judgment until a general consensus was reached. Finally, the results were summarized so as to construct a comparative judgment matrix R for rule hierarchy B towards target hierarchy A (Table 3), as well as four comparative judgment matrixes T_k (T_1, T_2, T_3 and T_4, which are not to be listed) for index hierarchy C towards rule hierarchy B. $R=\{b_{ij}\}$, $T_k=\{t_{ij}\}$, where b_{ij} and t_{ij} denote respectively the elements of matrix R and T, which is in line i, column j, also b_{ij} and $t_{ij}>0$, $b_{ij}=1/b_{ji}$, $t_{ij}=1/t_{ji}$.

4.1.2 Level single sort and consistency check

Hierarchical Single Arrangement involves the calculations of the maximum eigenvalue ($\lambda_{\max}$) of each judgment matrix and its corresponding eigenvector (W: relative weight of each factor towards the rule). It also involves a consistency check through the terms of consistency index (CI), random index (RI) and consistency ratio (CR). The calculation is as follows:

1) To calculate the eigenvector of the judgment matrix by using the asymptotic normalization coefficient (ANC):

Table 1 Integrated measurement model for low-carbon development for Chinese oil and gas enterprises

Target hierarchy	Rule hierarchy	Index hierarchy (C_{ij})
Comprehensive measurement of low-carbon for oil and gas enterprises, A	Energy structure, B_1	Supply ratio of petroleum products, C_{11} Supply ratio of conventional natural gas, C_{12} Supply ratio of non-conventional natural gas, C_{13} Supply ratio of renewable energy, C_{14} Ratio of coal consumption to total energy consumption, C_{15} Ratio of oil consumption to total energy consumption, C_{16} Ratio of gas consumption to total energy consumption, C_{17} Ratio of power consumption to total energy consumption, C_{18}
	Energy utilization, B_2	Total energy consumption per RMB 10,000 output value, C_{21} Total energy consumption for crude oil/gas production, C_{22} Total energy consumption for crude oil/gas fluid production, C_{23} Total energy consumption for oil/gas equivalent production, C_{24} Ratio of non-materials energy consumption to self-produced capacity, C_{25} Total energy consumption per unit crude oil transportation, C_{26} Total energy consumption per unit gas transportation, C_{27} Mechanical pumping system efficiency, C_{28}
	Carbon emission and utilization, B_3	Carbon emissions per RMB 10,000 output value, C_{31} Carbon emissions per tonne petroleum production, C_{32} Carbon emissions per tonne liquids production, C_{33} Carbon emissions per unit natural gas production, C_{34} Carbon emissions for oil/gas equivalent production, C_{35} Recycle rate of natural gas emission, C_{36} Recycle rate of associated natural gas, C_{37} Ratio of fuel combustion emissions to utilization, C_{38} Ratio of fugitive emissions to total emissions, C_{39}
	Low carbon management, B_4	Low-carbon development strategies and plans, C_{41} Low-carbon technologies research and development, C_{42} Low-carbon standards development and execution, C_{43} Low-carbon management system, C_{44} Low-carbon database, C_{45}

Table 2 Grading rules for AHP

Relative importance comparison	Extremely important	Very important	Apparently important	Slightly important	Equally important
Scale	9	7	5	3	1

Notes: 2, 4, 6, 8 are between two neighboring importance.

Table 3 Comparative judgment matrix R for rule hierarchy B towards target hierarchy A

	B_1	B_2	B_3	B_4	W_i
B_1	1.0000	1.4918	0.6703	3.3201	0.2875
B_2	0.6703	1.0000	0.3679	1.4918	0.1659
B_3	1.4918	2.7183	1.0000	4.9530	0.4509
B_3	0.3012	0.6703	0.2019	1.0000	0.0957

Notes: W_i is the weight for rule hierarchy index B_i towards target hierarchy A.

$W=[W_1, W_2, \cdots, W_n]^T$, where W is the weight corresponding to each criterion or index.

2) λ_{max} value is calculated by Eq. (1):

$$\lambda_{max} = \frac{1}{n}\sum_{i=1}^{n}\frac{(AW)_i}{\omega_i} \quad (1)$$

where $(AW)_i$ here is the number i factor of the vector (AW).

3) Consistency check: Firstly, to calculate CI by Eq. (2), "n" is the order of a judgment matrix. The smaller the CI, the greater the consistency;

$$CI = \frac{\lambda_{max} - n}{n-1} \quad (2)$$

Then, to divide CI by RI (Table 4) to obtain the CR, i.e. $CR=CI/RI$.

Finally, consistency check: if $CR<0.10$, it means that the judgment matrix is consistent, otherwise more adjustments should be made until satisfactory consistency is achieved.

Table 4 Random Index reference value

Order	1	2	3	4	5	6	7	8	9
RI	0.00	0.00	0.58	0.90	1.12	1.24	1.32	1.41	1.45

4.1.3 Calculation of the comprehensive weight

The comprehensive weight vector is the weight vector of the index hierarchy and rule hierarchy on the target hierarchy, and calculated by Eq. (3), Table 5 is the calculation of comprehensive weight using the AHP software.

$$W=\sum_{j=1}^{4}W_{bj}\times W_{ci} \tag{3}$$

where W_{bj} is the weight vector of the first-class index hierarchy towards the target hierarchy, and W_{ci} is the weight vector of the second-class index towards the first-class index.

Table 5 Index weight of comprehensive measurement system for low-carbon development

Target hierarchy	Rule hierarchy W_{bj}	Index hierarchy	Weight to rule hierarchy, W_{ci}	Comprehensive weight, W
Comprehensive measurement of low-carbon for oil and gas enterprises, A λ_{max}=4.0150 CR=0.0056	W_{b1}=0.2875 λ_{max}=8.1569 CR=0.0159	C_{11}	0.1543	0.0444
		C_{12}	0.1115	0.0321
		C_{13}	0.0659	0.0190
		C_{14}	0.0612	0.0176
		C_{15}	0.1748	0.0503
		C_{16}	0.1663	0.0478
		C_{17}	0.1263	0.0363
		C_{18}	0.1396	0.0401
	W_{b2}=0.1659 λ_{max}=9.5737 CR=0.0491	C_{21}	0.1750	0.0290
		C_{22}	0.0786	0.0130
		C_{23}	0.1282	0.0213
		C_{24}	0.1311	0.0217
		C_{25}	0.0860	0.0143
		C_{26}	0.1311	0.0217
		C_{27}	0.0576	0.0096
		C_{28}	0.0752	0.0125
		C_{29}	0.1371	0.0227
	W_{b3}=0.4509 λ_{max}=8.1865 CR=0.0189	C_{31}	0.1024	0.0462
		C_{32}	0.1567	0.0707
		C_{33}	0.0818	0.0369
		C_{34}	0.1962	0.0885
		C_{35}	0.0591	0.0267
		C_{36}	0.1962	0.0885
		C_{37}	0.1454	0.0655
		C_{38}	0.0621	0.0280
	W_{b4}=0.0957 λ_{max}=5.0643 CR=0.0144	C_{41}	0.2296	0.0220
		C_{42}	0.1365	0.0131
		C_{43}	0.3291	0.0315
		C_{44}	0.1312	0.0126
		C_{45}	0.1736	0.0166

4.2 Standardization of indexes

As each index may be different from others in attribute, unit, order of magnitude, positive or negative, so it is necessary to standardize each of the indexes of the measurement system, making these indexes into a uniformed evaluation system that can be compared with each other. Index standardization involves quantifying of the qualitative indexes and standardization (non-dimensionalization) of the index value.

4.2.1 Quantifying of qualitative indexes

The conventional methods for quantifying of qualitative indexes usually include the brainstorming, fuzzy, and grey methods etc., which are synthetically used in most applications (Shi, 2006). In this study, we first define the qualitative indexes, then grade them and separate them into different ranks and finally assign values to each grade.

4.2.2 Standardization of the index value

The standardization of the index value (also called the non-dimensionalization) is a method used to eliminate the dimensional effect of original variables by the use of a mathematical formula. Because of the difference of indexes in their units and orders of magnitude, it is necessary to make each index standardized so as to acquire more accurate and reasonable evaluation results. Considering the relationship between the objects and their evaluation values, a linear approach was used here to standardize these indexes, as Eq. (4):

$$N_i=\frac{C_{i\,\max}-C_i}{C_{i\,\max}-C_{i\,\min}}\quad (i=1,\,2,\,3,\,\cdots,30) \tag{4}$$

where N_i, C_i, $C_{i\max}$, and $C_{i\min}$ are the standard values of index i, actual value of enterprise i, best and worst value of index i within the industry.

4.3 Synthesizing indexes value

There are many methods for synthesizing indexes value. The most commonly used methods include the linear weighting, the multiplicative synthesis and the mixed addition and multiplication synthesis methods. In this paper, the linear weighting method (as shown in Eq. (5)) (Ma et al, 2010) was used for synthesizing each index value.

$$M=\sum_{j=1}^{4}\left(W_{bj}\times\sum_{i=1}^{30}\left(N_i\times W_{ci}\right)\right) \tag{5}$$

where W_{bj} is the weight vector of the first-class index hierarchy towards the target hierarchy, N_i is a standardized non-dimensional index, and W_{ci} is the corresponding weighted index.

By Eq. (5), we can either benchmark each index one by one or evaluate each level horizontally or vertically, or combine the indexes of two different levels to make a comprehensive measurement for low-carbon development for China's petroleum industry. By making comparisons between the M value and evaluation criteria, the comprehensive low-carbon development level of an enterprise can be ultimately determined.

4.4 Evaluation criteria

The evaluation criteria are determined based on the implications of low-carbon development for China's oil & gas enterprises, Chinese governmental policies and requirements, and average and advanced levels of domestic and foreign industries, which includes four levels: "high carbon", "medium carbon", "economical low carbon" and "ideal low carbon". Table 6 shows the four different levels proportionately assigned within the settings of [0, 1]. This standard may be regularly updated with reference to the development of each index.

Table 6 Low-carbon economy evaluation criteria

Level	Composite index	Description			
		Ratio of natural gas production to overall energy consumption	Energy utilization efficiency level	Ratio of carbon control and utilization	Low carbon management system
I Ideal low carbon	0.75-1.00	≥60%	Internationally advanced	≥80%	Systemic and effective
II Economical low carbon	0.50-0.75	40%-60%	Overall a leading level in China, partial internationally advanced	50%-80%	Need to improve
III Medium carbon	0.25-0.50	30%-40%	Advanced in China	30%-50%	Preliminary
IV High carbon	0.00-0.25	≤30%	Below average in China	≤30%	None

5 Conclusions

1) It is of utmost importance for China's oil and gas enterprises to expand the scale of natural gas utilization, improve energy efficiency, achieve key technology of carbon dioxide control and utilization, and promote low-carbon management, while they increase oil and gas supply continuously.

2) According to the implications and restricted factors, by using of AHP, PCA, as well as independent checks, a comprehensive system of low-carbon development for China's oil and gas enterprises was established, comprising energy structure, energy utilization, carbon emissions and utilization and low carbon management, as well as thirty indexes.

3) Constructed five scientific judgment matrixes according to the characteristics of Chinese oil and gas enterprises and the extensive research of specialists, determined the index weights both the rule hierarchy towards the target hierarchy, and that the index hierarchy towards the rule hierarchy. We quantified the qualitative indexes and standardized the index values. These indexes were subsequently synthesized by applying the weighted linear method, and finally the formula for the measurement indexes of low-carbon development in Chinese oil and gas enterprises were obtained.

4) Taken into consideration relevant national low-carbon policies and requirements, average and advanced levels of domestic and foreign industry, a comprehensive low-carbon evaluation criteria were designed using four evaluative criteria: ideal low carbon, economical low carbon, medium carbon and high carbon, all of which are categorized within the settings of [0, 1] proportionately. An enterprise, whose composite index is within 0.75-1.00, is assigned an ideal low-carbon level; and that when the value is within0.50-0.75, an economical level of low-carbon development is in progress.

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