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Research

Keywords: green economy, low-carbon development, system coupling, coordination mechanism, innovation

Posted Date: January 6th, 2021

DOI: <https://doi.org/10.21203/rs.3.rs-139426/v1>

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System Coupling and Coordinating Evaluation of Green Low-carbon Development in Coal Enterprises^{*}

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Abstract: Green low-carbon development is the direction for coal enterprises to cope with overcapacity, industrial restructuring and enterprise transformation. Based on the connotation of green low-carbon development, this paper deconstructed the green low-carbon development of coal enterprises into a process of coupling and coordinated development of green low-carbon system (GLCS) and innovation development system (IDS) from a systematic perspective, further deconstructed the green low-carbon system into two subsystems of environment (ES) and resources(RS), and deconstructed the innovation development system into two subsystems of innovation (IS) and growth(GS), built the coupling and coordination evaluation model and grey relational degree model of green low-carbon development of coal enterprises, and made an empirical analysis of China Shenhua Energy Company Limited ("CSEC") and China National Coal Group Corp ("CNCGC") in 2010-2017. The empirical analysis showed that the coupling and coordinating level of GLCS and IDS of CSEC and CNCGC is both not high, but there are differences in evolutionary trends and causes, and the coupling and interaction mechanism needs to be strengthened; the coupling coordination degree between ES and IS is good, and between RS and GS is the worst in CSEC, and the coupling coordination degree between RS and GS is highly correlated with the coupling coordination degree between GLS and IDS, and improving the level of IS is an important direction for CSEC; But in CNCGC the coupling coordination degree between subsystems fluctuates greatly, and there is no persistent good and persistent bad coupling, but in the past two years, the level of coupling coordination among subsystems has a rising trend, and the level of RS and the degree of coupling coordination between ES and IS have the highest correlation with the degree of coupling coordination between GLS and IDS. Coal enterprises should improve the interaction mechanism among subsystems, strengthen the driving role of green innovation, and promote green low-carbon development.

Key words: green economy; low-carbon development; system coupling; coordination mechanism; innovation.

I. Introduction

Tackling climate change has been a global issue of wide concern to the international community, and China, as a responsible developing country, has made a great deal of effort in this regard. As early as in the "Twelfth Five-Year Plan", China has made it an important task of its economic and social development to actively respond to global climate change; the report at the 18th National Congress of the Communist Party of China (CPC) proposed "vigorously promoting green, circular and low-carbon development"; and in the report at the 19th CPC National Congress, to accelerate the reform of the ecological civilization system, build a beautiful China, speed up the establishment of a legal system and policy guidelines for green production and consumption, and establish a sound economic system of green and low-carbon circular development is proposed. GLCS has become the new development model in China nowadays. According to the *Global Coal Market Report (2018-2023)* published by IEA, coal is still the core and main fuel of the global energy system, and coal remains the main energy for many countries. As coal is widely used and produced in China, China will not change its main energy source of coal for a long time to come. Therefore, the clean and efficient use of coal, and the establishment of GLCS have become exceptionally important, and coal enterprises, as main bodies of the micro-economy, shoulder important responsibilities. In recent years, the effect of GLCS of coal enterprises and how to better develop GLCS in the future have been the focus of research and attention. Therefore, the GLCS of coal enterprises needs to realize the coordinated development of green low-carbon and innovation growth, and to stimulate innovation growth with green low-carbon.

This paper examines the GLCS problem of coal enterprises from the perspective of system coupling and

^{*} **Fund project:** This research was funded by National Natural Science Foundation of China, grant number 71774105.

coordinating. Current research on the coupling and coordinated development of economic, environmental, energy and innovation systems are mostly at the macro and meso degrees, with binary, ternary and quintessential system theories. From the point of view of the coupling of two systems, researchers constructed an “economic growth system - environmental protection system”^[1] (Wu Yuming and Zhang Yan, 2008), “Science and technology innovation system - beautiful China construction system”^[2] (Pan Sunan et al., 2019), “tourism resource development system - ecological system”^[3] (Cheng Hui et al., 2019), “science and technology innovation - sustainable development system”^[4] (Zhao Chuansong et al., 2018), “innovation ability - economic development”^[5] (Li Erling and Cui Zhizhen, 2018) and other coupling and coordinating models, and conducted evaluation studies of the development of regional coupling and coordinating in China. From a three-system coupling perspective. From the perspective of ternary system coupling, the “energy-economy-environment, 3E” system coupling model was constructed. Zhao et al. (2008) conducted an empirical evaluation of 3E system coupling and coordinating in Inner Mongolia Autonomous Region^[6]; Lu Jin (2017) measured the coupling and coordinating degrees of the four economical regions of China and discussed the changing characteristics and differences in regional three-system interactions from two spatial and temporal dimensions^[7]; Tan Feifei constructed a composite system coupling model of “socio-economic-environmental” sustainable development, and used the system coupling degree model and HP filter to analyze the coupling and coordinating properties and system stability of three economic circles in China in depth^[8]. From the perspective of five-system coupling, Fan Yuxian and Yuan Xiaoling (2017) integrated ecological civilization construction into the “four-in-one” construction proposed in the 18th National Congress of CPC, constructed a “five-in-one” coupling and coordinating model, and empirically measured the coupling and coordinating degrees of the “five-system” of ecological economy, ecological politics, ecological culture, ecological society, and ecological environment in China from 1995 to 2014 and in each province in 2013^[9]. Research on the development of coupling and coordinating between environmental, economic, innovation, and energy systems from macro- and meso-perspectives has been relatively well established, but at the micro-firm degree, as micro-economic agents, firms are the practitioners of GLCS. Schaltegger & Synnestvedt (2002) argued that the relationship between environmental performance and economic performance is “inverted U-shape” and that enterprises can achieve win-win situations for both economic and environmental performance, and that improving environmental performance does not just increase an enterprise’s costs and reduce its profits^[10]. Wagner M (2008) verified this relationship through an empirical analysis of enterprises in a number of European countries and concluded that the choice of corporate sustainability strategy has a moderating effect on the relationship between sustainable development strategy of enterprises and economic performance^[11]. Through an empirical analysis of 19 listed coal enterprises from 2012-2018, Fan Baoxue and Wang Wenjiao (2019) found that the environmental protection investment and green technology innovation of coal enterprises have a significant contribution to their financial performance, and there is a mutually reinforcing relationship between environmental protection investment and green technology innovation of coal enterprises. When the two work together on financial performance, they will have a more powerful effect on it^[12]. However, few studies have examined the relationship and developmental effects of business environment, innovation and business growth from a coupling and coordinating perspective. Wu Chao (2018) studied the construction of the green innovation efficiency improvement model in China’s heavy pollution industry, proposing that the green innovation system is the integration of innovation subsystem and green subsystem, and the results of the study found that the green innovation efficiency of the coal mining and washing industry is low, technological innovation and environmental improvement have not reached an effective state, and the traditional inherent development structure has not been really broken. What’s more, as the main body of technological innovation, enterprises’ dealing with overcapacity has not triggered a real increase in the innovative power of green technology in coal enterprises. Thus, there are many difficulties in the green development of coal industry^[13]. Therefore, this paper takes coal enterprises as the object of study and evaluates the coupling and coordinating situation of GLCS of coal enterprises by constructing a coupling and coordinating model of GLCS in coal enterprises. By constructing a grey correlation model, this paper measures the correlation between the coupling and coordinating degree of green low-carbon and IDS, as well as the development degree of each subsystem and the coupling and coordinating degree among subsystems. In addition, this paper explores the coupling and coordinating state causes and paths of improvement of GLCS in coal enterprises.

II. Coupling Mechanism of GLCS of coal enterprises

2.1 Deconstruction of Connotation of GLCS

Since the concept of “sustainable development” was put forward in 1980, how to balance economic development, environmental protection and the sustainable use of resources to achieve sustainable development has been a hot spot of all the society circles. As society develops and the global environment changes, a series of sustainable development paradigms such as green economy, green development, circular development, low-carbon economy and low-carbon development have been proposed one by one. The report at the 18th CPC National Congress also proposed “vigorously promoting green development, circular development and low-carbon development”, among which, green development is concerned with environmental protection, a development model that balances economic development and ecological environment protection, as well as the prosperity of the current economy and the development of future generations; circular development addresses the issue of material flow, namely, resource recycling and comprehensive utilization; and the core of low-carbon development is aimed at energy use, namely, the pursuit of high resource productivity with less resource consumption and less pollution to bring more output^[14] (Kang Yanbing, 2015). For China, it is not only necessary to continue to solve the problem of regional environmental pollution, but also to deal with the global problem of climate change, therefore, the concept of GLCS is proposed, and it is of great academic value and practical significance to study how to realize GLCS. As a new concept, the connotation of GLCS is underdeveloped. According to Fang Shijiao and Ding Zhao (2011) who first proposed the connotation of GLCS, GLCS is a pattern of economic development guided by the idea of sustainable development, and through green technological innovation, institutional innovation, industrial transformation, new energy development and other means, it can reduce the consumption of high-carbon energy such as coal and oil, and reduce greenhouse gas emissions, so as to achieve a win-win situation for both economic and social development and ecological environmental protection. Its connotation includes three aspects: first, the essence is to change the existing energy consumption, economic development mode and human life style; second, GLCS focuses on the development and utilization of green and low-carbon technologies; third, GLCS has the triple benefits of promoting economy, stabilizing employment and reducing emissions, which will become a new economic growth point and ensure the sustainable development of society and economy^[15]. Although many scholars have conducted researches on GLCS since then, most of them decomposed GLCS into green and low-carbon development or biased towards either of them to understand it (Zhang La’e and Duan Jinjun (2015) ^[16]), thus, the existing research is biased.

This paper believes that GLCS is an organic combination of green development and low-carbon development, which not only focuses on protecting the ecological environment, but also takes into account saving resources, improving energy efficiency and reducing emissions, and at the same time aims to achieve coordinated development of economic development, environmental protection and resource utilization, and its essential goal is to achieve coordinated development of economic development, environmental protection and efficient utilization of resources, with green innovation as an important means. Therefore, system coupling and coordinating theory is an effective way to solve the GLCS problem. Therefore, based on the perspective of system, the GLCS connotation is deconstructed as the coupling and coordinating development of the two subsystems of GLCS and IDS, and GLCS is deconstructed as two subsystems of ES and RS, and IDS is deconstructed as two subsystems of IS and GS in this paper.

2.2 Coupling Mechanism of GLCS System

The GLCS of coal enterprises refers to a sustainable development mode that realizes the harmonious development of environmental and economic performance of coal enterprises by improving energy efficiency, and reducing energy consumption and emissions through technological innovation and other means. Therefore, this paper deconstructs the GLCS of coal enterprises as a coupling and coordinating relationship between GLCS and IDS, i.e., the efficient development of both GLCS and IDS is the goal of the GLCS of coal enterprises. GLCS refers to a series of actions taken by coal enterprises in the process of production and operation to reduce the impact on the environment and improve the utilization rate of resources and energy. It is the interaction and organic combination of a series of actions and elements to achieve the goal of energy conservation and environmental protection, reflecting the environmental protection skill performance of coal enterprises. The IDS, which is the synergy between research and innovation and efficient and high-quality growth of a coal enterprises, reflects the innovative economic performance of the coal enterprises. GLCS and IDS promote and drive each other. The green and low-carbon of coal enterprises is the inevitable requirement of coal enterprises in dealing

with climate change, government environmental regulation and green transformation. If coal enterprises improve the degree of GLCS, it promotes enterprises to improve innovation degree and economic performance, and the improvement of enterprise innovation degree and economic performance will in turn promote the improvement of GLCS degree for enterprises. There is a two-way interactive relationship between the two, and the development of coupling and coordinating is formed.

Based on the meaning of GLCS, it is not only concerned with environmental protection, but also energy issues of resource productivity, so this paper deconstructs GLCS as two subsystems of ES and RS. The IDS and innovation technology degree of coal enterprises are the technical support of the whole system and provides technical support for degrees of other systems. The economic performance growth of enterprises is the primary goal of enterprise development and the economic guarantee of sustainable development of enterprises. Therefore, this paper deconstructs IDS into two subsystems of IS and GS, the coupling mechanism is shown in Figure 1. The environment sub-system is mainly concerned with the impact of coal enterprises on environmental pollution, which is mainly measured by three indicators: capital investment in environmental protection, SO₂ emissions and COD emissions, among which, the requirement to reduce emissions can lead to an increase in the degree of technological innovation, but increased investment in environmental protection will lead to increased costs for companies^[17](Walley & Whitehead, 1994), constraining the development of systems for the growth of coal enterprises; the resource subsystem is mainly concerned with the energy efficiency and resource consumption of the coal enterprises, which is measured by three indicators: the comprehensive energy consumption of per unit production value, the comprehensive utilization rate of waste-water and the recovery rate of the coal mine, reducing energy consumption and improving energy efficiency to the requirements of the technology degree of the coal enterprises, and promoting the IDS of coal enterprises. At the same time, lower energy consumption and higher energy efficiency will save costs for enterprise development and promote sustainable development of enterprises. The innovation sub-system is the technical support of the whole system and provides technical support for the environment sub-system and the resource sub-system, which is measured by three indicators: R&D investment, number of talents and number of patents granted; the growth sub-system focuses on the economic performance of the coal enterprises, which is the primary purpose of enterprise development and the economic guarantee for the development of other systems. Therefore, from the four aspects of profitability, solvency, operating capacity and growth capability, this paper selects four indicators, namely rate of return on total assets (ROA), current ratio, total asset turnover rate and operating income growth rate, to measure the growth capability of coal enterprises.

Figure 1 The coupling mechanism of the GLCS system of coal enterprises

III. Evaluation Model of the Coupling and Coordinating Degree of GLCS of Coal Enterprises

The coupling and coordinating model can reflect the degree of interaction and influence between different

systems, including the degree of coupling and coordinating. The coupling degree is taken from the concept of physics, reflecting the degree of interaction between two (or more than two) systems, while the coupling and coordinating degree can objectively reflect the degree of coordination and development between systems, avoiding the double low coupling trap (Shi Pengfei et al., 2018^[18]; Zhang Baojian et al., 2018^[19]; Wang Guoxia and Liu Ting, 2017^[20]). The mutual promotion and coordinated development between systems is called benign coupling, and vice versa. The coupling and coordinating models are constructed in the following steps:

(1) The entropy weight method is used to determine the weight of each index of each subsystem; the entropy weight method is an objective weighting method, which determines the weight according to the variability of the index and the meaning of the data itself, avoiding the interference of subjective factors, and thus boast with high objectivity and credibility.

Φ Data standardization: indicators are divided into positive and negative effect categories according to formula (1) to eliminate the indicator scale.

$$x'_{ij} = \begin{cases} \frac{\max(x_{ij}) - x_{ij}}{\max(x_{ij}) - \min(x_{ij})} & x_{ij} \text{ has negative effect} \\ \frac{x_{ij} - \min(x_{ij})}{\max(x_{ij}) - \min(x_{ij})} & x_{ij} \text{ has positive effect} \end{cases} \quad (1)$$

⊙ Non negative treatment of indicators: Indicators will become zero after non dimensional treatment, but the calculation formula of information entropy requires that the base number be non-negative. Therefore, in order to ensure the effectiveness and integrity of the indicators, it is necessary to carry out non negative treatment on the indicators

$$y_{ij} = (1 - \alpha) + \alpha x'_{ij}, \quad \text{Set } \alpha = 0.99 \quad (2)$$

⊙ Calculate the entropy value E_j for the j th indicator according to the definition of information entropy,

$$E_j = -k \sum_{i=1}^m P_{ij} \ln(P_{ij}), P_{ij} = \frac{x_{ij}}{\sum_{i=1}^m x_{ij}}, K = 1/\ln m \quad (3)$$

⊙ Calculate the variance factor d_j for indicator j ,

$$d_j = 1 - E_j \quad (4)$$

⊙ Calculate the weight for indicator ω_j ,

$$\omega_j = \frac{d_j}{\sum_{j=1}^n d_j} \quad (5)$$

(2) Based on the integration methodology, the linear weighted method is used to calculate the integrated development degree U_i for each subsystem.

$$U_i = \sum_{j=1}^n \omega_j y_{ij}, \text{ and } \sum_{j=1}^n \omega_j = 1 \quad (6)$$

(3) The multi-system coupling and coordinating degree model is introduced to calculate inter-system

coupling degree C, comprehensive evaluation index T, and system coupling and coordinating degree D, respectively.

$$C = \sqrt[n]{\frac{(U_1 * U_2 * U_3 \cdots U_n)}{\prod_{i \neq j}^n (U_i + U_j)}} \quad (7)$$

When n=2, the coupling of the two systems is calculated as follows:

$$C = \sqrt[2]{\frac{U_1 * U_2}{(U_1 + U_2) * (U_1 + U_2)}} \quad (8)$$

$$T = \sum_{i=1}^m \lambda_i U_i, \text{ and } \sum_{i=1}^m \lambda_i = 1 \quad \lambda_i \text{ indicates the importance of } i \text{ system} \quad (9)$$

$$D = \sqrt{C * T} \quad (10)$$

(4) To determine the type of coupling and coordinating degree, this paper refers to the research results of Liao Zhongbin (1999) and other scholars, using the classification standard of the coupling and coordinating degree in Table 1.

Table 1 Classification standard of coupling and coordinating degree

S/N	Coupling and coordinating degree	Type of the degree	S/N	Coupling and coordinating degree	Type of the degree
1	0~0.1	Serious disorder	2	0.1001~0.2	Serious disorder
3	0.2001~0.3	Moderate disorder	4	0.3001~0.4	Mild disorder
5	0.4001~0.5	On the verge of disorder	6	0.5001~0.6	Barely disorder
7	0.6001~0.7	Primary coordination	8	0.7001~0.8	Moderate coordination
9	0.8001~0.9	Good coordination	10	0.9001~1.0	High-quality coordination

IV. Empirical Analysis

In this paper, we selected the two largest Chinese listed coal enterprises, China Shenhua Energy Company Limited (hereinafter referred to as “CSEC”) and China National Coal Group Corp (hereinafter referred to as “CNCGC”) to conduct empirical and comparative analysis. CSEC is one of the world’s leading integrated coal-based energy companies, specializing in the production and sale of coal and electricity, as well as the construction of the rail and port and fleet transportation of coal. CSEC is the largest coal supplier among listed companies in China and the world, with the largest coal reserves, and its coal business has become a model of clean, efficient and safe production in China’s coal industry. As a promoter, practitioner and leader of clean energy development, as well as a solution provider and service provider of clean energy technology, CSEC is committed to the five development concepts of green development, coordinated development, IDS, open development and shared development, and to promoting low-carbon, green and transformational development of enterprises. CNCGC is a large-scale energy enterprise integrating coal production and trading, coal chemical industry, power generation

and coal mine equipment manufacturing. CNCGC adheres to the core values of scientific development, safety and efficiency, harmony and win-win, and practices the five development concepts of innovation, coordination, green, openness and sharing, aiming to build a clean energy supplier with strong international competitiveness, to become a leader in safe and green production, a demonstrator in clean and efficient utilization, a practitioner in providing quality services, and to maximize the interests of the company, its employees, shareholders and society. This paper measured the system coupling and coordinating degrees of GLCS in CSEC and CNCGC, representative companies of GLCS, from 2010 to 2017, and conducted a longitudinal and horizontal comparative evaluation and analysis of the two companies, to explore the problems and improvement paths of the coupling and coordinating between GLCS and IDS in the two companies. The data presented in this paper is from the Annual Report and the Social Responsibility Report of CSEC and CNCGC in 2010-2017, where the number of talents is replaced by the number of graduate students and above in the company.

4.1 Evaluation Indicator and Weight

According to formula (1)-(5), the weights of indicators of each system can be calculated, and the results are shown in Table 2, from which, it can be seen that for GLCS of enterprises, GLCS and IDS are equally important, and the four sub-systems of resource, environment, innovation and development are also equally important, so the weights of the two major systems and their sub-systems are taken as 0.5 respectively. According to equation (6), the overall evaluation score is calculated for each system.

Table 2: Weights of order parameters and evaluation indicators

Order parameter	Weight	Subsystem	Weight	Evaluation indicator	Weight	Attribute		
GLCS(U_1)	0.5	Environment subsystem(U_{11})	0.5	Investment in environmental protection (X_{11})	0.44	+		
				SO ₂ emission (X_{12})	0.28	-		
				COD emission (X_{13})	0.28	-		
				Comprehensive energy consumption per unit production value (X_{21})	0.48	-		
		Resource subsystem(U_{12})	0.5	Comprehensive utilization rate of wastewater (X_{22})	0.32	+		
				Recovery rate of coal mining area (X_{23})	0.2	+		
				Innovation subsystem(U_{21})	0.5	R&D investment (X_{31})	0.25	+
						Number of talents (X_{32})	0.35	+
IDS (U_2)	0.5					Number of patents granted (X_{33})	0.4	+
						Return on total assets (X_{41})	0.28	+
	Growth subsystem(U_{22})	0.5	Current ratio (X_{42})	0.35	+			
			Turnover of current assets (X_{43})	0.19	+			
			Growth rate of operating income (X_{44})	0.18	+			

4.2 The Dynamic Evolution of the Coupling and Coordinating Degrees of GLCS and IDS

In this paper, we first analyzed the coupling and coordinating of the overall GLCS of CSEC and CNCGC, and divided the GLCS system into two major systems, namely, GLCS and IDS. According to formulas (8)-(10), the coupling and coordinating degree of the GLCS and IDS between CSEC and CNCGC from 2010 to 2017 was calculated, and the coupling and coordinating degree was determined according to Table 1, as shown in Table 3. The comprehensive evaluation scores and system coupling and coordinating degrees of GLCS and IDS between CSEC and CNCGC in 2010-2017 are shown in Figure 2 and Figure 3.

Table 3 The coupling and coordinating degree of the GLCS and IDS between CSEC and CNCGC from 2010 to 2017

Year	CSEC		CNCGC	
	Coupling and coordinating degree	Degree	Coupling and coordinating degree	degree
2010	0.390372	Mild disorder	0.55766	Barely disorder
2011	0.361487	Mild disorder	0.570802	Barely disorder
2012	0.403999	On the verge of disorder	0.506015	Barely disorder
2013	0.498351	On the verge of disorder	0.486554	On the verge of disorder
2014	0.51485	Barely disorder	0.435768	On the verge of disorder
2015	0.470912	On the verge of disorder	0.314156	Mild disorder
2016	0.525887	Barely disorder	0.367895	Mild disorder
2017	0.539136	Barely disorder	0.428091	On the verge of disorder

Figure 2 The evaluation scores and system coupling and coordinating degree of GLCS and IDS in CSEC during 2010-2017

Figure 3 The evaluation scores and system coupling and coordinating degree of GLCS and IDS in CNCGC during 2010-2017

From Table 3, and Figures 2 and 3, it can be found that the coupling and coordinating degree of GLCS and IDS in CSEC and CNCGC is not satisfactory, which ranges from 0.3 to 0.6, and neither of them has reached the degree of coordination. However, the evolution trend of the coupling and coordinating degrees of GLCS and IDS of the two companies over the past eight years is very different. Except for a downward trend in 2015, CSEC showed an overall upward trend in the coupling and coordinating degrees of GLCS and IDS degrees from 2010 to 2017, and the coupling and coordinating situation of its GLCS showed a gradual trend of coordination. The initial coupling and coordinating disorder of CSEC was that its green and low-carbon degrees did not keep pace with IDS degrees, but its progressive coupling and coordinating posture also benefited from the gradual increase in its GLCS. In 2010~ 2017, the coupling and coordinating degree of GLCS and IDS of CNCGC have experienced the development trend of first rising, then declining and then rising. The coupling disorder was basically declining in the first few years, bottomed out in 2015 to reach moderate disorder degrees, and has improved in the last two years, with the coupling disorder lying in low IDS degrees. This is closely related to the impairment of corporate operating performance due to the significant decline in domestic coal prices and the reversal of market supply and demand during the 12th Five-Year Plan period, and CNCGC's insistence on adjusting the industrial layout and structure, expanding the scale of coal conversion, and responding to market risks.

4.3 Dynamic Evolution of Coupling and Coordinating Degree among Subsystems

GLCS in coal enterprises contain two subsystems of ES and RS, and the IDS contains two subsystems of IS and GS. It is important to analyze the coupling and coordinating situation between subsystems to determine the coupling and coordinating degree of GLCS and IDS of an enterprise. The coupling and coordinating evolution between the CSEC and CNCGC subsystems from 2010 to 2017 is shown in Figure 4 and Figure 5. U1U2 indicates the degree of coupling and coordinating between the enterprise's green low-carbon and IDS overall system, U11U21 indicates the degree of coupling and coordinating between the enterprise's environmental subsystem and innovation subsystem, and U11U22 indicates the degree of coupling and coordinating between the enterprise's environmental subsystem and growth subsystem.

From Figure 4, it can be seen that the coupling and coordinating degree of the CSEC's environmental subsystem and innovation subsystem generally showed an upward trend from 2010 to 2017, with a significant increase from moderate disorder in 2011 to moderate coordination degree in 2016, and a good development of the coupling and coordinating situation. The coupling and coordinating degree of the environmental subsystem and enterprise growth subsystem has undergone the evolution and development of first declining, then rising and then declining and then rising again, with the worst being mild disorder in 2011 and the best reaching barely disorder degree in 2017, which is unstable and needs to be further improved to promote the smooth development of the coupling and coordinating of environmental subsystem and enterprise growth subsystem. The coupling and coordinating degree of resource subsystem and innovation subsystem has experienced the development and change of first increasing, then decreasing and then increasing, which is basically at the degree of mild disorder and on the verge of disorder. The coupling and coordinating of resource subsystem and enterprise growth subsystem are consistently at the moderate disorder and serious disorder degrees, while the resource subsystem is still in a poor state and needs further strengthening. What's more, an efficient interaction mechanism has not been formed with the enterprise growth sub-system, and thus there is an urgent need to upgrade and improve it so as to promote the coordinated development of the two sub-systems.

Figure 4 Evolution of the coupling and coordinating degrees among GLCS systems and subsystems in CSEC from 2010-2017

Figure 4 Evolution of the coupling and coordinating degrees among GLCS systems and subsystems in CNCGC from 2010-2017

It can be seen from Figure 5 that the overall evolution of the coupling and coordinating degree between systems fluctuates greatly from 2011 to 2017, and the overall degree of coupling and coordinating between environmental and innovation subsystems is poor and has been in mild disorder and on the verge of disorder degrees, indicating that CNCGC has not formed a positive interaction mechanism between the environmental subsystem and the innovation subsystem, and the degree of enterprise innovation cannot keep up with the degree of environmental green development. Therefore, the degree of scientific research and technological innovation should be further improved and the development of the environmental and innovation subsystems should be better coordinated. The coupling and coordinating between the environmental subsystem and the growth subsystem of the enterprises underwent an evolutionary trend of first decreasing and then increasing, with the best degree of coupling and coordinating between the two subsystems reaching the primary coordination degree in 2010 and turning around after reaching the lowest coordination degree, namely, moderate disorder in 2015. This evolutionary trend mainly lies in the fact that the development degree of the enterprise growth subsystem has declined and failed to keep up with the development degree of the environmental subsystem, which has gradually improved in the past two years thanks to the improvement of the growth subsystem degree of CNCGC. The development of the coupling and coordinating degrees of the resource subsystem and the innovation subsystem has undergone a process of rising and then falling and then falling and then rising again, with large fluctuations and unstable development. The coupling and coordinating degree trends of the resource subsystem and the growth subsystem of the enterprise are basically the same as those of the environmental subsystem and the growth subsystem of the enterprise. However, the overall coupling and coordinating degree is two degrees lower than the coupling and coordinating degree of the environmental subsystem and the enterprise growth subsystem, which mainly lies in the fact that the gap between the development degree of the resource subsystem and the growth subsystem of the enterprise is greater than the gap between the development degree of the environment subsystem and the growth subsystem. On the whole, the CNCGC developed rapidly and steadily in terms of system coupling and coordinating before the 12th Five-Year Plan; during the 12th Five-Year Plan, the development of coordinating was basically on a downward trend and bottomed out in 2015, which was the worst situation. CNCGC actually also posted a loss in 2015 for the first year since its IPO, comparing it to CSEC, which did not bottom out as significantly as CNCGC did in 2015, but also trended downward, showing that 2015 was indeed a tougher year for the domestic coal industry. However, after entering the "13th Five-Year Plan", the domestic coal market was first sluggish and then developed rapidly, and coal prices also increased steadily, in this case, CSEC and CNCGC quickly took measures to improve the coupling and coordinating of GLCS system, leading to obvious upward trend.

4.4 Correlation Analysis of the Coupling and Coordinating Degrees between GLCS System and Sub-systems

The coupling and coordinating degree of the overall GLCS system of coal enterprises may be associated with the development degree of the subsystems and the coupling and coordinating degree between the subsystems, and the development degree of the subsystems and the coupling and coordinating degree between subsystems

has an important impact on the degree of coupling and coordinating of the whole system, thus by improving the development degree of highly correlated subsystems and the degree of coupling and coordinating between subsystems, the overall system's degree of coupling and coordinating can be improved efficiently. Therefore, this paper introduces the grey correlation model to calculate the correlation between the coupling and coordinating degrees of GLCS and IDS, environment, resources and innovation and growth subsystems in CSEC and CNCGC, trying to find out the subsystem with the highest correlation with the coupling and coordinating degrees of GLCS in CSEC and CNCGC.

In this paper, we first calculated the number of correlations between the coupling and coordinating degrees of GLCS and IDS and those of each subsystem in CSEC and CNCGC from 2010 to 2017 according to formula (11), among which, ξ indicates the correlation between the coupling and coordinating degrees of GLCS and IDS and those of each subsystem; $y(k)$ represents the generating sequence, i.e., the coupling and coordinating degrees of GLCS and IDS; and $x_i(k)$ indicates the composite score of each sub-system or the coupling and coordinating degree between sub-systems. Secondly, the mean of the correlations of each type of correlation is obtained, i.e., the correlation γ between the coupling and coordinating degrees of GLCS and IDS and those of each subsystem. As in Table 4, γ_1 represents the correlation degree between the coupling and coordinating degrees of GLCS and the environmental subsystem; γ_2 indicates the correlation degree between the coupling and coordinating degrees of GLCS and resource subsystem; γ_3 shows the correlation degree between the coupling and coordinating degrees of GLCS and innovation system; γ_4 represents the correlation degree between the coupling and coordinating degrees of GLCS and growth system; γ_5 presents the correlation degree between the coupling and coordinating degrees of GLCS and those of environment and innovation subsystems; γ_6 displays the correlation degree between the coupling and coordinating degrees of GLCS and those of environment and growth subsystem; γ_7 shows the correlation degree between the coupling and coordinating degrees of GLCS and those of resources and innovation subsystems; and γ_8 represents the correlation degree between the coupling and coordinating degrees of GLCS and those of resource and growth subsystems.

$$\xi_i(k) = \frac{\min_i \min_k |y(k) - x_i(k)| + \rho \max_i \max_k |y(k) - x_i(k)|}{|y(k) - x_i(k)| + \rho \max_i \max_k |y(k) - x_i(k)|} \quad i = 1, 2 \dots n; k = 1, 2 \dots m \quad (11)$$

Table 4 Correlation degree of the coupling and coordinating degree between GLCS and subsystems, and those of subsystems of CSEC and CNCGC

Enterprise	γ_1	γ_2	γ_3	γ_4	γ_5	γ_6	γ_7	γ_8
CSEC	0.6264	0.7275	0.7897	0.6484	0.6560	0.7202	0.7148	0.7518
CNCGC	0.6632	0.8268	0.6972	0.6854	0.7304	0.5526	0.5624	0.6944

As can be seen from table 4, in terms of the correlation between GLCS and its subsystems, for CSEC, $\gamma_3 > \gamma_2 > \gamma_4 > \gamma_1$, but for CNCGC, $\gamma_2 > \gamma_3 > \gamma_4 > \gamma_1$, which means that the coupling and coordinating degree of GLCS and IDS of CSEC has the highest degree of correlation with the innovation subsystem and the lowest degree of correlation with the environmental subsystem. Therefore, enhancing the degree of innovative subsystems is the key for CSEC to improve the coupling and coordinating system of GLCS and IDS, and CSEC should further strengthen investment in scientific research, and improve innovation capacity to reduce emissions, improve energy efficiency and promote development. In addition, the GLCS and IDS of CNCGC has the highest degree of coupling and coordinating with the resource subsystem, thus raising the degree of resource subsystem is the key for CNCGC to further improve the coupling and coordinating degree of GLCS and IDS, and CNCGC should further strengthen the emphasis on comprehensive utilization of the most resources, improve resource utilization, reduce energy consumption and improve energy efficiency.

When it comes to the correlation degree of coupling and coordinating degree with each subsystem, for CSEC, $\gamma_8 > \gamma_6 > \gamma_7 > \gamma_5$, but for CNCGC, $\gamma_5 > \gamma_8 > \gamma_7 > \gamma_6$, and the coupling and coordinating degree of GLCS and IDS of CSEC had the highest correlation with the resource and growth subsystem, with a correlation of 0.7518, followed by that of the environment and growth subsystem, with a correlation of 0.7202. Moreover, the coupling and coordinating degree of GLCS and IDS of the CNCGC had the highest correlation with that of the environment and innovation subsystem, with a correlation of 0.7304, followed by the coupling and coordinating degree of the

resource and growth subsystem, with a correlation of 0.6944. In conjunction with the previous analysis, the coupling and coordinating degrees of GLCS and IDS of CSEC presented the highest correlation with resource and growth subsystem, while the coupling and coordinating degrees of resource and growth subsystem of CSEC were the worst, consistently at moderate disorder and serious disorder degrees. Therefore, it is of great need for CSEC to improve the coupling and coordinating degree between resource and growth sub-systems, improve the development degree of resource sub-systems, and enhance the interaction mechanism between resource and growth sub-systems to improve resource utilization and increase efficiency for enterprise growth. Secondly, CSEC needs to pay attention to the development of coupling and coordinating between environmental and growth subsystems. Although it has been rapidly improved in the past two years, the degree of coupling and coordinating is still not high and needs to be further strengthened. The coupling and coordinating degree of GLCS and IDS of CNCGC had the highest correlation with that of environment and innovation subsystem, while the coupling and coordinating degree between the environment and the innovative subsystem of CNCGC has developed relatively steadily, but the coupling and coordinating degree was not high, which was mainly due to the fact that the degree of innovative subsystems of the CNCGC has been low. Therefore, CNCGC should increase its investment in research and innovation, improve its innovation capacity, enhance the coupled development mechanism of environment and innovation subsystem, promote energy conservation and emission reduction through innovation, and drive IDS with energy conservation and emission reduction demand. Secondly, CNCGC needs to focus on the development of coupling and coordinating of resources and growing subsystems. Although CNCGC is affected by the downturn of the domestic coal market and the fall of coal prices, the continuous fall of its growth subsystem score is the main reason for the unstable coupling and coordinating development of the resource and growth subsystems, from which we can see that CNCGC has not formed a positive coupling mechanism between the resource and growth subsystems, and has failed to exert the promotion and driving effect of the resource subsystem on the growth subsystem. Therefore, it is urgent for CNCGC to strengthen the establishment of interaction mechanism, explore the method of coordination and development, and promote the development of coupling and coordinating between sub-systems.

V. Conclusion

Based on the connotation of GLCS, this paper deconstructs the GLCS of coal enterprises into the development of coupling and coordinating of ES and RS from the perspective of system, and further deconstructs GLCS into two subsystems of ES and RS. This paper deconstructs IDS into two subsystems of IS and GS, constructs the GLCS evaluation index system and coupling and coordinating evaluation model for coal enterprises, and the correlation model between the coupling and coordinating degree of GLCS and the coupling and coordinating degree of each subsystem and between subsystems, attempting to explore the problems in the GLCS process of coal enterprises from the perspective of the coupling and coordinating development of the system, and to propose the path to facilitate the GLCS of coal enterprises. This paper takes CSEC and CNCGC, two of the largest domestically listed coal enterprises, as examples for empirical analysis, and compares and analyzes their evolution of the coupling and coordinating of GLCS between 2010 and 2017 and the existing problems of these two companies, and draws the following conclusions:

(1) The coupling and coordinating degrees of green low-carbon and IDS in CSEC and CNCGC over the past eight years have been low, at best only at the degree of barely disorder, but the evolutionary trends and causes of the coupling and coordinating of GLCS and IDS in CSEC and CNCGC are very different. CSEC has a low degree of coupling and coordinating of GLCS and IDS because the degree of GLCS cannot keep up with the degree of IDS, while CNCGC has a low degree of IDS. Therefore, the two companies should focus on the establishment of a GLCS and IDS interaction mechanism, with GLCS as the driving force, IDS as the means. To drive GLCS through IDS, to promote IDS with green low-carbon, thus ensuring green low-carbon coupling and coordinating development.

(2) The coupling and coordinating degree between the environment and the innovation subsystems of CSEC is better than the coupling and coordinating degree between other subsystems, which is basically on the rise, and the best state is at the degree of moderate coordination. However, the degree of coupling and coordinating between resources and growing subsystems is the worst, which is always at the moderate disorder and Serious disorder degrees, and is of particular concern to CSEC. The coupling and coordinating between CNCGC subsystems are not always out of balance, but fluctuates greatly, the degree is unstable, and is highly influenced

by fluctuations in business growth performance. However, the coupling and coordinating between CNCGC subsystems has reached a good degree. In the past two years, CNCGC has improved its quality and efficiency, promoted reform and innovation, accelerated transformation and upgrading, enabling the coupling and coordinating degree among its sub-systems to present an obvious tendency to rise, so in the future, CNCGC should further strengthen the coupling and interaction mechanism among sub-systems, so that the coupling and coordinating degree among sub-systems will rise back to the previous best degree and pursue a breakthrough.

(3) The degree of coupling and coordinating of green low-carbon and IDS in CSEC has the highest correlation with the innovation subsystem, thus strengthening research investment and improving innovation capacity is an important direction for CSEC to further improve the coupling and coordinating of green low-carbon and IDS. As CNCGC has the highest association with resource sub-system, improving resource utilization and reducing energy consumption is thus becoming the focus of CNCGC in the future. At the same time, the coupling and coordinating degrees of CSEC's green low-carbon and IDS are highly correlated with the coupling and coordinating degrees of the resource and growth subsystems, and are most influenced by them, followed by the coupling and coordinating degree of resources and growth subsystems, the coupling and coordinating degree of resources and innovation subsystems, and that of environment and innovation subsystems. CNCGC's green low-carbon and IDS coupling and coordinating degrees are most highly correlated with the coupling and coordinating degrees of the environment and innovation subsystem, followed by the coupling and coordinating degrees of the resources and growth subsystems, those of resources and innovation subsystems, and those of the environment and resource subsystems. CSEC and CNCGC can also improve the overall GLCS degree of the enterprise by adjusting the interaction mechanism between the highly related sub-systems to improve their coupling and coordinating degree, thus improving the overall GLCS degree in a targeted and efficient manner.

CSEC and CNCGC, as the two largest listed coal enterprises in China and the practitioners of GLCS, are representative of the issues reflected in the study, which should attract the attention of other coal enterprises and provide them with references, therefore, based on the above conclusions and issues, the following two points of thought and suggestions are given:

(1) Emphasis should be placed on the development of each sub-system and at the same time, the interaction mechanism among sub-systems should be improved to promote the collaborative development of GLCS and IDS. Weak interaction mechanisms between sub-systems will lead to unbalanced development of each sub-system of the coal enterprises, which will weaken the synergistic development of the whole system and make it difficult to resist external risks. Therefore, coal enterprises should really grasp the synergistic relationship between the sub-systems, so that technological innovation can really be applied to the environmental sub-system and resource sub-system to reduce emissions and save energy. At the same time, coal enterprises should balance the input of each system to maximize the input effect, promote the balanced development between systems, maximize the coupling and collaborative effect, give play to the collaborative optimization function of system, and promote the green and low-carbon coupling and coordination development of coal enterprises.

(2) To promote the GLCS of coal enterprises, green innovation drive is the key, technological progress and technological transformation is the breakthrough. coal enterprises should further strengthen their green innovation, through technological innovation to save energy and reduce consumption, improve quality and efficiency, and promote their green low-carbon high quality development. Digital coal mines and intelligent coal mine construction are key development directions for coal enterprises. In "The 13th Five-Year Plan for Coal Industry Development" issued by the National Development and Reform Commission and the National Energy Administration, it is mentioned that by 2020, a modern coal industry system that is intensive, safe, efficient and green will be built, and new progress will be made in the Informaionization and intelligent construction of coal mines, and a number of advanced and efficient intelligent coal mines will be built, which will greatly improve the production efficiency of coal enterprises.

In this paper, the coupling and coordinating model of GLCS is proposed. Two companies, CSEC and CNCGC, are selected as samples for empirical analysis in this paper, exploring the current situation and existing problems of coupling and coordinating of GLCS in CSEC and CNCGC, and suggesting future improvements and direction of development, which cannot cover the situation of all coal enterprises due to limited sample selection, thus in future research, the sample scope can be expanded to explore coupling and coordinating conditions of GLCS in more coal enterprises to further validate the model and explore the universal development

path of green low-carbon coupling and coordinating of coal enterprises. In addition, the evaluation of CSEC and CNCGC in this paper is only an academic analysis and discussion of the relevant data, and is therefore not intended to be relied upon otherwise.

**1. Availability of data and materials

The datasets used and/or analysed during the current study are available from the corresponding author on reasonable request.

All data generated or analysed during this study are included in this published article [and its supplementary information files].

2. Competing interests

No conflict of interest is declared by the authors.

3. Funding

National Natural Science Foundation of China has sponsored this research, grant number 71774105.

4. Authors' contributions, acknowledgements and

Conceptualization, G.Z., and Y.X.; methodology, Y.X.; validation, G.Z. and Y.X.; formal analysis, G.Z., and Y.X.; investigation, G.Z., and Y.X.; writing—original draft preparation, G.Z., and Y.X.

**5. Acknowledgements

Conceptualization, G.Z., and Y.X.; methodology, Y.X.; validation, G.Z. and Y.X.; formal analysis, G.Z., and Y.X.; investigation, G.Z., and Y.X.; writing—original draft preparation, G.Z., and Y.X.

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System Coupling and Coordinating Evaluation of Green Low-carbon Development in coal enterprises

Abstract: Green low-carbon development is the direction for coal enterprises to cope with overcapacity, industrial restructuring and enterprise transformation. Based on the connotation of green low-carbon development, this paper deconstructed the green low-carbon development of coal enterprises into a process of coupling and coordinated development of green low-carbon system (GLCS) and innovation development system (IDS) from a systematic perspective, further deconstructed GLCS into two subsystems of environment (ES) and resources (RS), and deconstructed the innovation development system into two subsystems of innovation (IS) and growth (GS), built the coupling and coordination evaluation model and grey relational degree model of green low-carbon development of coal enterprises, and made an empirical analysis of China Shenhua Energy Company Limited ("*CSEC*") and China National Coal Group Corp ("*CNCGC*") in 2010-2017. The empirical analysis showed that the coupling and coordinating degree of GLCS and IDS of *CSEC* and *CNCGC* is both not high, but there are differences in evolutionary trends and causes, and the coupling and interaction mechanism needs to be strengthened; the coupling coordination degree between ES and IS is good, and between RS and GS is the worst in *CSEC*, and the coupling coordination degree between RS and GS is highly correlated with the coupling coordination degree between GLS and IDS, and improving the degree of IS is an important direction for *CSEC*; But in *CNCGC* the coupling coordination degree between subsystems fluctuates greatly, and there is no persistent good and persistent bad coupling, but in the past two years, the degree of coupling coordination among subsystems has a rising trend, and the degree of RS and the degree of coupling coordination between ES and IS have the highest correlation with the degree of coupling coordination between GLS and IDS. coal enterprises should improve the interaction mechanism among subsystems, strengthen the driving role of green innovation, and promote green low-carbon development.

Key words: green economy; low-carbon development; system coupling; coordination mechanism; innovation.

Figures

Figure 1
The coupling mechanism of the GLCS system of coal enterprises

Figure 2

The evaluation scores and system coupling and coordinating degree of GLCS and IDS in CSEC during 2010-2017

Figure 3

The evaluation scores and system coupling and coordinating degree of GLCS and IDS in CNCGC during 2010-2017

Figure 4

Evolution of the coupling and coordinating degrees among GLCS systems and subsystems in CSEC from 2010-2017

Figure 5

Evolution of the coupling and coordinating degrees among GLCS systems and subsystems in CNCG from 2010-2017