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An Empirical Study on the Coordinated Development of Energy-Economy-Environment-Society System in Sichuan-Chongqing Region Under the "Dual Carbon" Goals

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Abstract **Original Research Article**

From the perspective of regional development, this paper conducts an in-depth research on the coordinated development of four major systems, namely energy, economy, environment and society, in Sichuan-Chongqing Region against the backdrop of the Dual Carbon Goals. Breaking the limitations of the traditional energy-economy-environment analytical framework, this study incorporates the social dimension to establish a 3E+S system framework and analyzes the dynamic correlations and developmental characteristics of various regional subsystems. Meanwhile, a coupling coordination degree model is constructed for empirical analysis to comprehensively evaluate the development levels of the four systems and identify their evolutionary trends of coupling coordination. The results reveal that the coupling coordination degree of the composite system in Sichuan-Chongqing Region maintains a continuous upward trend, yet has not reached the high-quality coupling level. Accordingly, targeted development strategies are proposed to facilitate the high-quality, coordinated and sustainable development of Sichuan-Chongqing Region under the Dual Carbon Goals.

Keywords: Sichuan-Chongqing Region, 3E System, Coupling Coordination.

1 Introduction

Since the 21st century, global climate change governance has grown increasingly critical, with all countries advancing emission reduction and sustainable development initiatives. As a major carbon emitter, China's climate governance actions have attracted extensive international attention. In 2020, China formally put forward the "Dual Carbon" Goals, clarifying the roadmap of peaking carbon dioxide emissions before 2030 and achieving carbon neutrality before 2060. This sets a clear direction for the optimization of domestic energy structure and green economic transformation, and also provides impetus for global climate governance. Subsequently, China has rolled out a series of supporting policies and actions. In 2021, the 14th Five-Year Plan defined core tasks including green low-carbon energy development and energy system reform. Furthermore, China demonstrated its responsibility for global climate governance at the United Nations Climate Change Conference. The Report to the 20th National Congress of the Communist Party of China in 2022 refined the implementation path for the Dual Carbon Goals, establishing core strategies covering green transition, the principle of "establishing new systems before phasing out outdated ones", and energy innovation. Consensus reached at international climate conferences in 2023 further confirms the inevitable trend of global low-carbon development, reflecting China’s firm resolve in environmental governance and its leading role on the international stage.

2 Literature Review

The academic community has witnessed growing research interest in the energy-economy-environment system (abbreviated as the 3E System). For instance, Grossman and Krueger [1] (1995) proposed the Environmental Kuznets Curve (EKC). Bi Hongjie and Feng Yuguang [2] (2013) adopted dissipative structure theory to analyze the 3E System and constructed the Brusselator model to investigate its evolutionary laws. Yang Mengxin and Wu Jie [3] (2020) explored multi-dimensional complex systems beyond the triple framework, and found that the overall coordination degree of such systems remains moderate, while contradictions persist between energy and environmental subsystems. Studies by Ma Shiping et al. [4] (2022), Wang Linyu et al. [5] (2022) and Li Guozhu et al. [6] (2021) illustrated that domestic research on the 3E System has gone through multiple developmental stages, including methodological exploration, construction of evaluation systems, and dynamic analysis of regional 3E coordination degrees.

Wang Junling et al. [7] (2012) built an evaluation indicator system for 3E System coordination based on the development reality of Hebei Province, and adjusted indicators for energy, economy and environment according to the correlation between energy and economic growth. Research by Fan Zhongqi et al. [8] (2006) indicated that China’s overall 3E System maintained basic coordination from 1990 to 2002, following a U-shaped evolutionary trajectory. Zeng Ming and Wang Yajuan [9] (2013) found that China’s 3E System exhibited low coordination levels during 1996–2010, featuring mild incoordination between energy-economy and energy-environment subsystems, as well as severe incoordination between economy and environment. Studies by Zhou Yanfei et al. [10] (2018) and Wang Zhenshuang et al. [11] (2015) further enriched the understanding of 3E coordination degrees. Their results showed that most provincial 3E Systems in China failed to reach sound coordination in 2016; meanwhile, the cement industry’s 3E System in Shandong Province saw year-on-year improvements from 2005 to 2010 but stayed at a mild maladjustment level. Lu Jin et al. [12] (2016) investigated the provincial coupling coordination levels of China’s 3E System, pointing out that the coupling index of economy and environment rose nationwide, yet the overall coupling degree remained low, with eastern provinces outperforming western ones.

Against the backdrop of the national strategy for coordinated regional development, regional units serve as a fundamental carrier of high-quality development, and the interactive effects between social subsystem and energy, economy, environment subsystems cannot be overlooked. On this basis, this paper develops an extended complex system framework labeled "3E+S" derived from the original 3E System. The research verifies that energy, economy, environment and society form an interrelated complex system under the Dual Carbon Goals. Referring to the research framework proposed by Wang Linyu et al. [5] (2022), this paper constructs an influence mechanism for the energy-economy-environment-society system in Sichuan-Chongqing Region.

3 Research Design

3.1 Construction of Energy-Economy-Environment-Society Coupling Coordination Development Model

3.1.1 Evaluation of System Development Quality

Assuming there are i years and j indicators, Xij denotes the original data for the j-th indicator in year i. max(Xij) and min(Xij) represent the maximum and minimum values of the j-th indicator across all systems, respectively. Since the data are not comparable during statistical analysis, the range method is employed to standardize each indicator, yielding Yij as the standardized value, as shown in Equations (1) and (2).

$$Y_{ij} = \frac{X_{ij} - \min(X_{ij})}{\max(X_{ij}) - \min(X_{ij})}$$, Formula (1): For positive indicators（1）

$$Y_{ij} = \frac{\max(X_{ij}) - X_{ij}}{\max(X_{ij}) - \min(X_{ij})}$$,

Formula (2): For negative indicators（2）

Secondly, calculate the proportion P_{ij} of the j-th indicator in system i, and use P_{ij} to compute the entropy value S_j.

$$P_{ij} = \frac{Y_{ij}}{\sum_{i=1}^{n} Y_{ij}} \quad (3)$$

$$S_j = \frac{\sum_{i=1}^{n} P_{ij} \ln P_{ij}}{\ln(n)} \quad (4)$$

Finally, the entropy weighting method is applied to determine the weights of each indicator, yielding the final weight values μ_j as shown in the formula below.

$$\mu_j = \frac{1 - S_j}{\sum_{i=1}^{n} 1 - S_j} \quad (5)$$

3.1.2 Coupling Coordination Degree Model

Drawing on the coupling coordination degree model from physics, this paper measures the coupling coordination level among the energy-economy-environment-society composite system in the Sichuan-Chongqing Region, quantifies the synergy degree of the four subsystems, and judges their coordinated development level. The specific formulas are presented below. In Formula (6), n refers to the number of subsystems, and C represents the coupling degree ranging from 0 to 1; the closer C is to 1, the better the coupling state among subsystems.

$$C = n * \left[\frac{U_1 * U_2 \cdots * U_n}{(U_1 + U_2 + \cdots U_n)^n}\right]^{\frac{1}{n}} \quad (6)$$

Un denotes the comprehensive evaluation index of each subsystem, including the comprehensive evaluation index of energy, economy, environment and society in this research. T is the comprehensive coordination index of the composite system. α1、α2…αn are corresponding weights reflecting the contribution of each subsystem to coupling coordination degree, satisfying α1+ α2+…+αn=1. This study assigns equal weights to the four subsystems, meaning energy, economy, environment and society contribute equally to coupling coordination, i.e., α1=α2=α3=α4=1/4.where D is the coupling coordination degree of the composite system.

$$T = \alpha_1 * U_1 + \alpha_2 * U_2 + \cdots \alpha_n U_n \quad (7)$$

$$D = \sqrt{C * T} \quad (8)$$

3.2 Selection of Evaluation Indicators and Classification of Coupling Coordination Grades

3.2.1 Construction of Evaluation Indicator System

Combining existing research results and the policy background of carbon peaking and carbon neutrality, this paper constructs an evaluation indicator system covering the energy-economy-environment-society system, containing 20 single indicators (14 positive indicators and 6 negative indicators). Detailed indicators are listed in Table 1.

Table 1 Evaluation Indicator System of the Coupling System

Coupling System	Secondary Indicators	Unit	Attribute
Energy Subsystem	Total energy consumption	10,000 tons of standard coal	Negative

Coupling System	Secondary Indicators	Unit	Attribute
	Energy consumption per unit of GDP	10,000 tons of standard coal / 100 million CNY	Negative
	Total annual electricity consumption	100 million kWh	Positive
	Industrial electricity consumption	100 million kWh	Positive
	Proportion of coal in total energy consumption	%	Negative
	Proportion of oil & natural gas in energy consumption	%	Negative
Economic Subsystem	Total retail sales of consumer goods	100 million CNY	Positive
	Total import and export volume	100 million USD	Positive
	Total freight volume	10,000 tons	Positive
	Proportion of tertiary industry	%	Positive
	Per capita GDP	CNY per capita	Positive
Environmental Subsystem	Comprehensive utilization rate of industrial solid waste	%	Positive
	Total industrial waste gas emissions	100 million cubic meters	Negative
	Investment in industrial pollution governance	10,000 CNY	Positive
	Forest coverage rate	%	Positive
	Per capita public green space area	Square meters per capita	Positive
Social Subsystem	Engel coefficient	%	Negative
	Urbanization rate	%	Positive
	Per capita disposable income	CNY per capita	Positive
	Natural population growth rate	‰	Positive

3.2.2 Classification Standard of Coupling Coordination Grades

The coupling coordination degree is divided into four development stages with twelve coordination subtypes, as shown in Table 2.

Table 2 Classification Standard of Coupling Coordination Degree

Coordination Stage	Coupling Coordination Degree Interval	Sub-interval	Coordination Subtype
Low-level Coupling Stage	(0,0.3]	(0,0.1]	Extreme Disorder
		(0.1,0.2]	Severe Disorder
		(0.2,0.3]	Moderate Disorder
Antagonistic Stage	(0.3,0.5]	(0.3,0.4]	Mild Disorder
		(0.4,0.5]	Endangered Disorder
Run-in Adaptation Stage	(0.5,0.8]	(0.5,0.6]	Forced Coordination
		(0.6,0.7]	Primary Coordination
		(0.7,0.8]	Intermediate Coordination
High-level Coupling Stage	(0.8,1]	(0.8,0.9]	Sound Coordination
		(0.9,1]	High-quality Coordination

4 Empirical Analysis

4.1 Data Sources

This paper selects the Sichuan-Chongqing Region as the research object, with the sample period covering 2014–2023. Raw data are mainly derived from Sichuan Statistical Yearbook, Chongqing Statistical Yearbook (2014–2023) and municipal/district statistical communiqués on national economic and social development. The interpolation method is adopted to supplement partial missing data.

4.2 Comprehensive Development Evaluation Index

The entropy weight method and linear weighting method are used to calculate the comprehensive development evaluation indices of the four subsystems (energy, economy, environment and society). The results are displayed in Table 3.

Table 3 Comprehensive Development Evaluation Indices of Energy-Economy-Environment-Society System

Subsystem	Region	2014	2015	2016	2017	2018	2019	2020	2021	2022	2023
Energy	Sichuan	0.162	0.089	0.074	0.142	0.170	0.182	0.216	0.265	0.241	0.358
	Chongqing	0.202	0.205	0.199	0.228	0.209	0.222	0.226	0.242	0.261	0.262
Economy	Sichuan	0.045	0.052	0.079	0.136	0.198	0.203	0.215	0.281	0.291	0.317
	Chongqing	0.075	0.109	0.148	0.199	0.252	0.262	0.279	0.335	0.345	0.379
Environment	Sichuan	0.091	0.074	0.077	0.092	0.106	0.175	0.205	0.185	0.189	0.220
	Chongqing	0.164	0.132	0.087	0.184	0.145	0.113	0.129	0.119	0.235	0.252
Society	Sichuan	0.080	0.090	0.102	0.118	0.130	0.138	0.115	0.119	0.121	0.128
	Chongqing	0.132	0.150	0.174	0.187	0.200	0.156	0.184	0.187	0.187	0.190
Composite Index	Sichuan	0.095	0.076	0.083	0.122	0.151	0.175	0.188	0.212	0.210	0.256
	Chongqing	0.143	0.149	0.152	0.199	0.202	0.188	0.205	0.221	0.257	0.271

From the perspective of the energy subsystem's comprehensive evaluation index, Sichuan Province achieves the optimal energy system performance, with an index of 0.358 in 2023. Chongqing's energy system operates at an unsatisfactory level, with only 0.262 in 2023. The core constraint lies in severe energy shortage in Chongqing: conventional hydropower resources have been fully exploited, wind and solar reserves are limited, and coal resources suffer from difficult mining and poor storage conditions, jointly restricting local energy development.

In contrast, Chongqing ranks first in the economic subsystem's development quality. The underlying reason is its diversified industrial layout covering manufacturing, finance, foreign trade & logistics, service industry, innovation & entrepreneurship, cross-border cooperation, big data & artificial intelligence, cultural tourism and other sectors. The municipal government has successively issued targeted policies to stimulate corporate innovation, attract enterprises and investment, and drive sustained economic growth as well as industrial structure upgrading.

4.3 Analysis of Coupling Coordination Degree

To accurately evaluate the quality of coupling coordinated development of the energy-economy-environment-society system in Sichuan-Chongqing Region, this paper calculates the composite system's coupling coordination degree via Formula (6)–(8) and conducts quantitative assessment.

Table 4 Coupling Coordination Degree of Energy-Economy-Environment-Society System

Region	2014	2015	2016	2017	2018	2019	2020	2021	2022	2023
Sichuan	0.293	0.273	0.287	0.347	0.383	0.416	0.426	0.449	0.447	0.488
Chongqing	0.367	0.381	0.382	0.446	0.445	0.423	0.443	0.454	0.501	0.512

Table 5 Coupling Coordination Grades of Energy-Economy-Environment-Society System

Year	Sichuan	Chongqing
2014	Moderate Disorder	Mild Disorder
2015	Moderate Disorder	Mild Disorder
2016	Moderate Disorder	Mild Disorder
2017	Mild Disorder	Endangered Disorder
2018	Mild Disorder	Endangered Disorder
2019	Endangered Disorder	Endangered Disorder
2020	Endangered Disorder	Endangered Disorder
2021	Endangered Disorder	Endangered Disorder
2022	Endangered Disorder	Forced Coordination
2023	Endangered Disorder	Forced Coordination

According to Table 4 and Table 5, Chongqing's coupling coordination degree fluctuates slightly overall and reaches the coordinated threshold in 2022. Comparatively, Sichuan faces prominent problems including subsystem imbalance and inadequate development, leading to inferior coupling coordination performance. Governments at all levels should attach great importance to this issue, strengthen forward-looking planning and strategic arrangements, and promote high-quality coupling coordinated development of the energy-economy-environment-society composite system.

5 Prediction Analysis

Based on the SPSSAU platform, this paper adopts the Grey Prediction Model GM(1,1) to forecast the coupling coordination degree of the energy-economy-environment-society system in Sichuan and Chongqing from 2024 to 2028. The predicted results are presented in Table 6.

Table 6 Forecast of Coupling Coordination Degree (2024–2028)

Year	Sichuan		Chongqing	
	D Value	Coordination Grade	D Value	Coordination Grade
2024	0.524	Forced Coordination	0.532	Forced Coordination
2025	0.556	Forced Coordination	0.553	Forced Coordination
2026	0.590	Forced Coordination	0.575	Forced Coordination
2027	0.626	Primary Coordination	0.597	Forced Coordination
2028	0.664	Primary Coordination	0.621	Primary Coordination

Table 6 reveals that the coupling coordination level of the Sichuan-Chongqing composite system will rise to varying degrees during 2024–2028, and both regions will enter the primary coordination stage. Nevertheless, joint efforts from government authorities and the whole society are required to realize the predicted coordination level and boost high-quality development of the composite system.

6 Conclusions and Policy Suggestions

6.1 Research Conclusions

The results indicate that Chongqing encounters prominent constraints in its energy subsystem due to insufficient conventional hydropower and coal reserves, resulting in a low comprehensive evaluation score for energy development. Meanwhile, Chongqing's environmental subsystem exhibits volatile performance with an overall declining trend. However, Chongqing's economic subsystem maintains robust growth momentum, supported by diversified industrial layout and proactive policy incentives. In comparison, Sichuan achieves better performance in the energy subsystem but faces bottlenecks in environmental and social subsystems.

In the process of advancing the Dual Carbon Goals, energy development has entered an era of low growth rate and low incremental demand. Reducing coal consumption, stabilizing oil supply, expanding natural gas utilization and developing diversified power sources have become core development priorities. Regional development strategies and priorities should be differentiated in accordance with local resource endowments and practical demands.

6.2 Policy Suggestions

Targeting the unique energy mix of the Sichuan-Chongqing Region, a regional energy coordination mechanism should be established to improve energy utilization efficiency and sustainability. Sichuan is endowed with abundant hydropower resources while Chongqing possesses rich natural gas reserves; both provinces/municipalities should leverage their respective energy advantages to realize resource complementarity and regional synergy. It is necessary to build a flexible and efficient regional energy trading market to facilitate cross-regional energy flow and optimized resource allocation.

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