Coupled Coordinated Development of Electrification and Carbon Emissions in the Central China Region under the "Dual Carbon" Goal

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Abstract. The essence of "dual carbon" goals is enforcing carbon emission limits. Clean energy supply and energy electrification are irreversible trends. This study evaluates levels in four Central China provinces from 2014 to 2021 through an electrification and carbon emission index system. By employing the entropy method and coupling coordination model, the research explores the relationship between electrification and carbon emissions, uncovering improved coordination and synergies in efforts towards electrification and carbon emission reduction. These findings provide valuable insights for Central China's coordinated development within the "dual carbon" framework.

Keywords: Central China region; Electrification; Carbon emissions; Entropy value method Coupled and coordinated development.

1 Introduction

China's "dual carbon" objectives prioritize clean energy supply and energy electrification to address global climate commitments. According to data from the National Bureau of Statistics, China's total energy consumption for the year 2024 was 5.96 billion tons of standard coal, an increase of 4.3% compared to the previous year. Among this, coal consumption rose by 1.7% and electricity consumption increased by 6.8%. Electrification and carbon emissions have a bidirectional driving effect: on the one hand, electrification replaces traditional fossil energy with electricity to achieve carbon emission reduction; On the other hand, the pressure to reduce carbon emissions can also force the process of electrification. Therefore, exploring the coordinated development relationship between electrification and carbon emissions is significant and can also provide decision-making references for the benign coupling between the two.

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Scholarly research on electrification and carbon emission governance has delved into three key areas. Firstly, Ruan et al. (2022) suggest that electrification can help reduce emissions [1], which depends on the low-carbon transition of electricity generation [2]. Zheng et al. (2015) [3] and Miao et al. (2022) [4] both emphasize the importance of decarbonizing the power supply. Research also shows that the construction [5] and industrial sectors [6] have limited emission reduction potential, while the transportation sector offers the greatest opportunity [7]. Secondly, carbon constraints can accelerate electrification [8] and drive power system adaptation [9], and stricter carbon targets lead to faster electrification progress [10]. Thirdly, existing studies agree that the two are closely linked and can be optimized together. Most research focuses on specific sectors such as construction [11], brewing [12], and transportation [13]. Few studies examine the broader macro-level interaction between electrification and carbon reduction, limiting a full understanding of their dynamic relationship.

Our study analyzed data from the four provinces in Central China (Henan, Hubei, Hunan, and Jiangxi) from 2014 to 2021. The entropy method was used to measure electrification and carbon emissions levels, and the coupling coordination degree model examined their interactive relationship. The goal was to explore the coordination mechanism between electrification and carbon emissions, thus providing a scientific basis for promoting regional green and low-carbon development.

2 Electrification and Carbon Emission Level Measurement and Analysis

2.1 Research Methods

The entropy method is an objective weighting method [14]. To avoid subjective biases, we adopt the entropy method to quantify the levels of electrification and carbon emissions, making the measurement results more objective . The specific calculation steps are as follows.

Firstly, standardize the original data:

$$Y_{ij} = \begin{cases} (X_{ij} - \min\{X_j\})/(\max\{X_j\} - \min\{X_j\}) & \text{, positive effect} \\ (\max\{X_j\} - X_{ij})/(\max\{X_j\} - \min\{X_j\}) & \text{, negtive effect} \end{cases} \tag{1}$$

X_{ij} represents the original data of the j-th index of the i-th sample (i = 1, 2, 3... m, m = 32; j = 1, 2, 3... n, n = 11); Y_{ij} represents the standardized value of the j-th index of the i-th sample.

Secondly, use equation (2) to get the proportion of the j-th index of the i-th sample (P_{ij}) and equation (3) to determine the entropy value (e_j) of the j-th index:

$$P_{ij} = \frac{Y_{ij}}{\sum_{i=1}^{n} Y_{ij}} \tag{2}$$

$$e_j = -\frac{1}{\ln m} * \sum_{j=1}^{m} P_{ij} * \ln P_{ij} \tag{3}$$

Thirdly, equation (4) calculates the index's redundancy (d_j) , and equation (5) calculates the index's weight (w_j) :

$$d_j = 1 - e_j \tag{4}$$

$$w_j = \frac{d_j}{\sum_{j=1}^{n} d_j} \tag{5}$$

Finally, calculate the comprehensive score of each sample as equation (6):

S_i represents the comprehensive electrification score of the i-th sample, which can be obtained by summing the weighted standardized values of all indicators.

$$S_i = \sum_{j=1}^{n} \left(w_j * Y_{ij} \right) \tag{6}$$

2.2 Data Sources

This study covers relevant electrification and carbon emission indicators data in the Central China region from 2014 to 2021. Electrification indicators data mainly come from the *China Statistical Yearbook*, *China Electric Power Statistical Yearbook*, *China Energy Statistical Yearbook*, and provincial statistical year reports for the years 2014 to 2021. Carbon emission indicators data are sourced from the China Emission Accounts and Datasets (CEADs) [1]database.

2.3 Establishment of the Index System

The 2022 electrification report[2] and Zhang (2023) [15] both introduced an index system focusing on power consumption, supply, and energy efficiency. Commonly used metrics for carbon emissions evaluation include total emissions, per capita emissions, emissions per unit GDP [16], and carbon emission density [17]. This paper adheres to the principles of data accuracy, comprehensiveness, and accessibility, selecting 14 indicators for electrification and 4 indicators for carbon emissions. Indicators marked with" + "indicate a positive effect. A higher value in the electrification system signifies increased electrification, while in the carbon emission system, it indicates a more severe emission situation. Conversely, indicators marked with" − " have a negative effect. The specific indicator system and the weights w_j calculated using the entropy method are shown in Tables 1 and 2, respectively.

Table 1. Electrification Index System

Primary Indicator	Secondary Indicator	Unit	Attribute	Weight
Electricity Consumption	Proportion of Electricity in Terminal Energy Consumption	%	+	0.09479

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[1] China Emission Accounts and Datasets(CEADs), https://www.ceads.net.cn/

[2] Reference resource: China Electrification Development Report 2022.

	Per Capita Electricity Consumption	kWh/per	+	0.08803
	Per Capita Residential Electricity Consumption	kWh/per	+	0.09068
	Compound Annual Growth Rate of Electricity Consumption	%	+	0.08461
Electricity Supply	Installed Power Generation Capacity	10,000 kW	+	0.08064
	Proportion of Non-Fossil Energy Power Generation	%	+	0.06123
	Renewable Energy Penetration Rate	%	+	0.11899
	Change Rate of Power Generation Equipment Utilization Hours	%	+	0.06569
	Power Grid Investment Change Rate	%	+	0.07890
Electricity Efficiency	Installed Capacity of Urban and Rural Residential Users	kW	+	0.06640
	Electricity Consumption per Unit GDP	kWh/10,000 Yuan	-	0.04151
	Electricity Consumption Elasticity Coefficient	/	-	0.07051
	Change Rate of Coal Consumption for Power Supply	%	-	0.02911
	Change Rate of Coal Consumption for Power Generation	%	-	0.02892

Table 2. Carbon Emission Index System

Primary Indicator	Secondary Indicator	Unit	Attribute	Weight
Carbon Emission Scale	Total Carbon Emissions	10,000 tons	-	0.26889
	Per Capita Carbon Emissions	tons/per	-	0.31477
Carbon Emission Intensity	Carbon Emissions per Unit GDP	tons/10,000 yuan	-	0.14596
Carbon Emission Density	Carbon Emissions per Unit Area	tons/square kilometer	-	0.27038

2.4 Analysis of Electrification and Carbon Emission Levels

Electrification level.

Table 3 shows that electrification progress in Central China provinces varied from 2014 to 2021. Henan, Jiangxi, and Hunan experienced rapid growth with average annual rates of 14.78%, 13.33%, and 12.67% respectively. Hubei's growth was slower at 5.83% due to its mature infrastructure. Jiangxi excelled later, possibly due to increased investment. Energy efficiency lagged behind supply and consumption improvements, particularly in Jiangxi and Hunan, indicating a need for sustainable electrification focus.

Table 3. Scores of Electrification Levels

		2014	2015	2016	2017	2018	2019	2020	2021
Henan	Consumption	0.1039	0.0924	0.1253	0.1527	0.2236	0.2161	0.2097	0.2659
	Supply	0.0483	0.1101	0.1459	0.1573	0.2269	0.1830	0.2298	0.2923
	Efficiency	0.1059	0.1240	0.1224	0.1264	0.1273	0.1626	0.1458	0.1181
	Comprehensive	0.2581	0.3265	0.3935	0.4364	0.5777	0.5617	0.5853	0.6763
Hubei	Consumption	0.0702	0.0717	0.1051	0.1278	0.1828	0.2130	0.2034	0.2663
	Supply	0.2036	0.1766	0.2312	0.2076	0.2353	0.2133	0.2777	0.2477
	Efficiency	0.1495	0.1330	0.1320	0.1465	0.1106	0.1310	0.1601	0.1221
	Comprehensive	0.4233	0.3813	0.4683	0.4819	0.5287	0.5573	0.6412	0.6361
Hunan	Consumption	0.0376	0.0394	0.0606	0.0730	0.1271	0.1555	0.1764	0.2532
	Supply	0.0966	0.1350	0.1992	0.1649	0.2099	0.2432	0.2051	0.3108
	Efficiency	0.1672	0.1283	0.1533	0.1708	0.1276	0.1656	0.1675	0.1307
	Comprehensive	0.3013	0.3028	0.4131	0.4086	0.4645	0.5643	0.5489	0.6947
Jiangxi	Consumption	0.0894	0.0964	0.1275	0.1543	0.1945	0.2189	0.2523	0.3202
	Supply	0.1172	0.1387	0.1200	0.1697	0.2014	0.2445	0.2248	0.2925
	Efficiency	0.0894	0.1011	0.0950	0.0992	0.1246	0.1049	0.0937	0.1070
	Comprehensive	0.2960	0.3362	0.3425	0.4233	0.5205	0.5683	0.5707	0.7197

Carbon Emission levels.

Table 4. Scores of Carbon Emission Level

	2014	2015	2016	2017	2018	2019	2020	2021
Henan	0.2855	0.3453	0.3793	0.4450	0.4892	0.5667	0.5401	0.5277
Hubei	0.7338	0.7515	0.7629	0.7493	0.7729	0.7209	0.8036	0.7167
Hunan	0.6072	0.5792	0.5438	0.5110	0.5806	0.5783	0.6141	0.5976
Jiangxi	0.8745	0.8610	0.8702	0.8574	0.8546	0.8511	0.8605	0.8700

Table 4 displays the relatively steady carbon emission demands in central China from 2014 to 2021, without notable decreases. Jiangxi consistently records the highest emissions, followed by Hubei, and then closely by Hunan and Henan. The industrial profiles and energy consumption patterns are vital factors: Jiangxi's heavy industries and Hubei's energy-intensive sectors contribute to their higher emissions. Despite mitigation efforts in Hunan and Henan, rising energy needs are leading to increased emissions, emphasizing the ongoing challenge of emission reduction in the future.

3 Analysis of the CCD of the "Electrification - Carbon Emission" System

3.1 Research Methods

The CCD model analyzes interaction and coordinated development among interconnected systems, focusing on the relationship between electrification and carbon emissions to provide insights into their coordination status. Firstly, construct the coupling degree equation:

$$C = \frac{2 * \sqrt{U_1 * U_2}}{U_1 + U_2} \tag{7}$$

C stands for coupling degree, U_1 and U_2 are the comprehensive evaluation scores of electrification and carbon emissions respectively, and $C \in (0,1)$. The closer C is to 1, the greater the coupling degree among the subsystems, indicating a stronger correlation between them. To avoid the situation where the development levels of the two systems are relatively low but the coupling degree is relatively high, a coordination degree equation is constructed:

$$T = \alpha * U_1 + \beta * U_2 \tag{8}$$

T represents the coordination degree, equally weighing electrification and carbon emissions at 0.5 each, as per Zhang et al. (2024) [18]. Considering the intensity and correlation of their interaction, the coupling coordination degree equation is formulated:

$$D = \sqrt{C * T} \tag{9}$$

D stands for the coupling coordination degree, $D \in (0,1)$. D quantifies the correlation and sustained harmonious development within the two systems, showcasing their level of coordination.

3.2 Results and Analysis of CCD

Coupling Degree Analysis.

As shown in Figure 1, the coupling degrees among the provinces have shown increasing trends, reflecting a stronger interaction between electrification and carbon emissions. Henan consistently leads in coupling, possibly due to coal reliance or emission policies. Hubei and Hunan also display growing interaction. Jiangxi notably improved its coupling degree from 2014 to 2021, marking the most significant increase among the provinces.

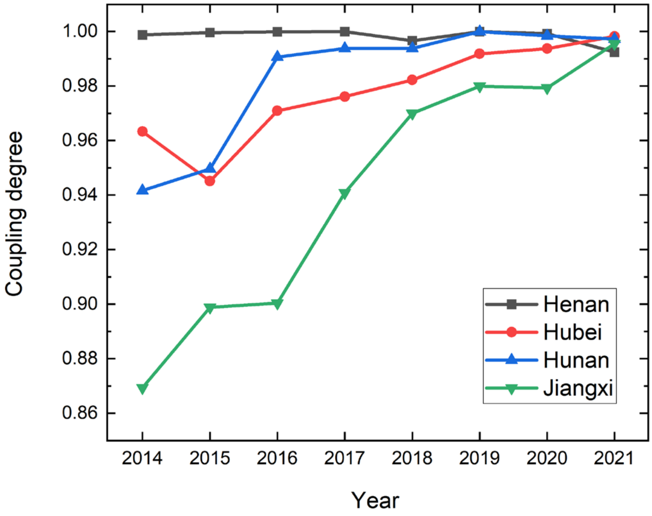

Fig. 1. Carbon Emission Coupling Degree of Electrification

Coordination Degree Analysis.

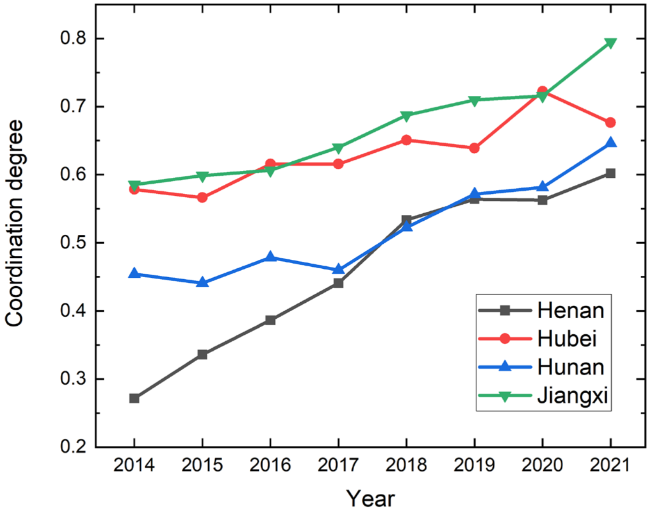

Fig. 2. Carbon Emission Coordination Degree of Electrification

As depicted in Figure 2, the coordination degree indicates positive coupling in interactions, reflecting coordination quality. In Henan, it starts low but improves steadily, showing ongoing optimization. Hubei and Hunan exhibit upward trends with fluctuations, suggesting evolving challenges in their coordination. Jiangxi displays the highest growth rate, likely due to its green development focus, emission reduction efforts, and industrial transformation, enhancing coordination between electrification and carbon emissions.

Analysis of Coupling Coordination Degree.

In practical applications, the degree of coupling coordination is generally classified into extremely disordered($D \in [0.0,0.1]$), severely disordered($D \in [0.1,0.2]$), moderately disordered($D \in [0.2,0.3]$), slightly disordered($D \in [0.3,0.4]$), nearly disordered ($D \in [0.4,0.5]$), barely coordinated ($D \in [0.5,0.6]$), primary coordinated ($D \in [0.6,0.7]$), intermediate coordinated ($D \in [0.7,0.8]$), good coordinated($D \in [0.8,0.9]$), and high-quality coordinated($D \in [0.9,1.0]$)[19].

Table 5. The CCD of the Four Provinces in Central China

	2014	2015	2016	2017	2018	2019	2020	2021
Henan	Barely	Barely	Primary	Primary	Intermediate	Intermediate	Intermediate	Intermediate
Hubei	Intermediate	Intermediate	Intermediate	Intermediate	Intermediate	Intermediate	Good	Good
Hunan	Primary	Primary	Primary	Primary	Intermediate	Intermediate	Intermediate	Good
Jiangxi	Intermediate	Intermediate	Intermediate	Intermediate	Good	Good	Good	Good

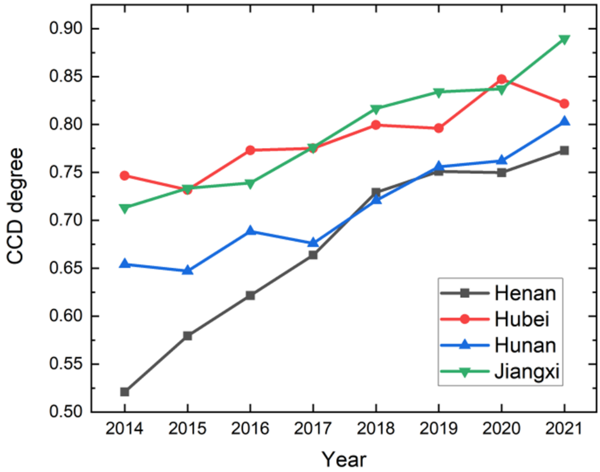

Fig. 3. CCD of Electrification and Carbon Emissions

The CCD analysis of the Central China provinces, as shown in Table 5 and Figure 3, demonstrates continuous improvement in interaction and coordinated development between electrification and carbon emission systems. Henan progressed from low to medium coordination between 2014 and 2021, yet coal reliance and ties to energy-intensive sectors hinder further advancements. Hubei consistently maintained an intermediate or higher coordination level, achieving good coordination in 2020, indicating a positive development trajectory. Hunan transitioned from primary to intermediate coordination by 2018, displaying notable growth potential. Jiangxi excelled in coupling coordination, achieving good coordination in 2018, propelled by proactive green policies, energy conservation, and industrial transformation efforts that have facilitated coordinated progress in electrification and carbon emissions across all provinces.

4 Conclusion

This study, aligned with the "dual carbon" objective, assesses the electrification and carbon emissions systems in four central China provinces from 2014 to 2021 using the entropy method. It examines system interaction and coordination levels using the coupling coordination degree model, highlighting disparities in coupling coordination across provinces. While Henan shows high coupling but lower coordination and coordination degrees, suggesting a need for improved development alignment, Hubei and Hunan exhibit stable and high coordination levels, indicating positive progress. Jiangxi displays notable growth with enhanced system interaction and coordination. Tailored policies are suggested for each province: Henan should focus on industrial optimization and energy structure adjustment, Hubei and Hunan on integrating traditional industries with clean energy, and Jiangxi on leveraging clean energy and industry green transformation. Regional coordination can be enhanced through grid interconnection and diverse clean energy sources for improved efficiency.

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