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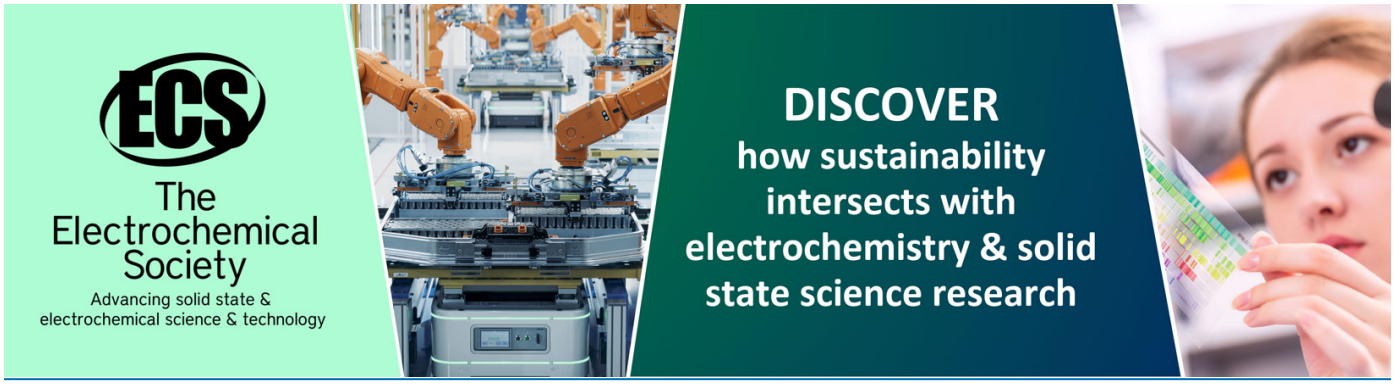

The Evolutionary Characteristics of the Coupling Relationship of Energy, Economy and Environment in Hebei Province, China

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Abstract. Based on the system coupling mechanism, a three-system coupling model of energy, economy and environment is constructed. Based on the panel data of Hebei Province from 2010 to 2019, the empirical analysis of the development status of the three systems of energy, economy and environment in Hebei Province. The results show that the coupling degree of the three systems of energy, economy and environment in Hebei Province generally shows an upward trend, and the coupling degree is consistent with the coordination degree of energy-economy, energy-environment and economy-environment. The coordinated development of each binary system is the basic guarantee for the increase in the coupling of the ternary system.

1. Introduction

Hebei Province's economic development is dominated by heavy industry, and there are problems with irrational consumption economy and low utilization rate in energy consumption. At the moment of economic transformation and upgrading, the relationship between energy, economy and environment has become a research Hotspot. Existing research studies the logical relationship between 3E systems from the perspectives of cointegration analysis, causality test, and calculation and evaluation of 3E coordination degree. Due to the difference between long-time data and data processing methods, scholars have different conclusions on the research of the relationship between energy-economy, energy-environment and economy-environment, and lack of analysis of the internal mechanism of 3E. Based on the establishment of a comprehensive system evaluation index system and the preliminary establishment of a three-system coupling model of energy, economy and environment, this paper estimates the coupling degree of the 3E system in Hebei Province from 2008 to 2019, and analyzes and explains the coupling relationship between the three.

2. Overview of 3E System in Hebei Province

Hebei is an important energy base in my country. From the perspective of total energy consumption, the development of total energy consumption in Hebei Province from 2011 to 2019 can be divided into two stages. The first stage is from 2011 to 2013, and the total energy consumption in this stage has maintained an upward trend. By 2013, it reached 30159.38 tons of standard coal, and its growth rate has also been at a relatively high level. The second phase is from 2014 to 2019. The total energy consumption of Hebei Province has declined to a certain extent. Compared with 2013, the amount of

standard coal in 2014 decreased by 356.18 million tons. Since then, it has continued to rise, reaching 33953.82 million tons of standard coal in 2019.

From the perspective of various energy consumption varieties, coal accounts for the largest proportion, accounting for more than 80%, followed by oil, accounting for 6%-9%. In contrast, natural gas and other energy resources account for a smaller proportion. Energy consumption is mainly coal. Judging from the development trend, the proportion of coal consumption is basically in a downward trend, natural gas and other energy sources are in contrast, and the situation in Hebei where coal is the absolute proportion is gradually improving.

In the exhaust gas pollutant emissions of Hebei Province in 2019, the emissions of sulfur dioxide, nitrogen oxides and soot were 600,000 tons, 1.046 million tons and 804,000 tons; the main pollutants of rivers were chemical oxygen demand, biochemical oxygen demand and total Phosphorus, the excess rate is 46.3%, 38.9% and 36.4% respectively; the province's general industrial solid waste is 330 million tons, the disposal volume is 120 million tons, and the comprehensive utilization is 187 million tons. Hebei Province, China's major heavy industry province, and Hebei's pollution situation are closely related to its steel-based industrial structure and the energy consumption structure of "one coal alone".

At the end of 2019, the GDP of Hebei Province reached 35594.5 billion yuan, an increase of 6.8% over the previous year. The overall situation is stable and positive. However, Sichuan, Hubei, Fujian and other provinces with similar volumes showed strong performances. Hebei's GDP ranking slipped from 6th to 13th in the country.

3. Model construction and data sources

3.1. Theoretical analysis of system coupling mechanism

Coupling is a physical concept, a process in which the interaction between two or more elements affects each other. Coordination and development are two key levels of coupling. Coordination is the degree of close interaction between systems, and development is the process of continuous improvement of the level of interaction between systems. This paper introduces the analytical coordination of the dispersion model and combines the two to solve the coupling level.

3.1.1. Binary system coupling. There are two systems X and Y, the dispersion coefficient of the two is

$$C_v = \frac{\sqrt{\frac{(X-Y)^2}{2}}}{\frac{(X+Y)}{2}} \tag{1}$$

Simplified by deduction:

$$C_V = \sqrt{2\left[1 - XY \Big/ \left(\frac{X+Y}{2}\right)^2\right]} = \sqrt{2(1-C)} \tag{2}$$

It is the standard measurement model of coordination, in which:

$$C = XY \Big/ \left(\frac{X+Y}{2}\right)^2 \tag{3}$$

When the deviation is0, X = Y, forming a ray with a slope of 1 at the origin, each point on the ray reaches the optimal coordination degree 1, and this ray is the optimal coordination line. When the dispersion is not 0, the ray deviates from the origin, and the intercept is generated on the horizontal and vertical axes. The coordination degree is lower than the optimal value. For example, the coordination degree represented by the P and Q points is lower than the J point.

From the formula (2), we can see that the smaller deviation is, the larger C is, the better. At the same time, because the value of C is between 0 and 1, for the intuitiveness and comparability of empirical results, we use (3) Instead of (2) to calculate the degree of coordination.

Coupling is a comprehensive result of coordination and development. The degree of coupling can be expressed by the intersection of the coordination line and the development line. First, any point on the optimal coordination line is the most superiority of the coordination degree. When the coordination degree is the same, the point on the higher development indifference curve has a higher level of coupling. Second, when there is no difference in the overall development level of the system, the higher the coordination degree, the higher the coupling level. Third, coupling emphasizes coordinated development on the one hand, while pursuing a higher level of development, so the coupling model can be simply summarized as

$$D = C \times T \tag{4}$$

3.1.2. Three-system coupling. The theoretical analysis of the three-system coupling mechanism has not yet formed a generally accepted research framework. This paper builds a three-system coupling theoretical model based on the two-system coupling mechanism. First, when the dispersion of the three systems is 0, with X=Y=Z, then all points that meet this condition will form a ray that coincides with the diagonal of the cube from the origin, that is, the optimal coordination line, which Within X-O-Y, Y-O-Z and X-O-Z, there are countless equal horizontal development lines. Together they form an infinitely extending cube in a three-dimensional coordinate system. Coupling degree is the intersection of coordination degree and development degree. It is the optimal coordination line. Any point on the optimal coordination line represents a corresponding coupling degree. The point farther away from the origin represents the higher coupling degree. From this we set the dispersion coefficients of the three systems X, Y, Z as

$$C'_V = \sqrt{\frac{\frac{1}{2}\left[\left(X-\frac{X+Y+Z}{3}\right)^2+\left(Y-\frac{X+Y+Z}{3}\right)^2+\left(Z-\frac{X+Y+Z}{3}\right)^2\right]}{\left(\frac{X+Y+Z}{3}\right)^2}} \tag{5}$$

Simplified

$$C'_v = \sqrt{1-\frac{3(xy+yz+zx)}{(x+y+z)^2}} = \sqrt{3(1-c)} \tag{6}$$

The coordination degree of the three systems is:

$$C' = \frac{3(XY+YZ+ZX)}{(X+Y+Z)^2} \tag{7}$$

Further, by introducing equal yield curves, the development measurement model of the ternary system can be set as:

$$T' = \alpha X + \beta Y + \gamma z \tag{8}$$

Further, the coupling model can be located:

$$D' = C' \times T' \tag{9}$$

Here, X, Y, and Z represent the three systems of energy, economy, and environment, respectively. This article believes that X, Y, and Z are equally important. Therefore, you can set $\alpha = \beta = \gamma = 1/3$.

3.2. Determine the index system and weight

Constructing a 3E system evaluation index system is an important basis for scientifically reflecting the development level of subsystems and quantifying the coordinated development degree between systems. By separately defining the concepts of energy, economy and environment, comprehensively considering various factors, drawing on existing research results, following the principles of scientifi city, dynamics, operability and hierarchy. This article considers the energy and economic system from the four aspects

of total quantity, structure, benefit and regional proportion, decomposes the environmental system into environmental pollution degree indicators and environmental protection indicators, and comprehensively displays the comprehensive connotation of the 3E system. The index classification is shown in Table 1.

Table 1. Evaluation index system of energy-economy-environment system in Hebei Province

Subsystem	System	elements Index and weight
Energy X	Total index x_1	Total primary energy production X_{11} (0.10); total energy consumption X_{12} (-) (0.12)
	Structural index x_2	The proportion of electricity consumption to energy consumption X_{21} (0.15); energy consumption elasticity coefficient X_{22} (-) (0.12)
	Benefit Index X_3	Energy consumption per unit of GDP X_{31} (-) (0.12); energy consumption per 10,000 yuan output value of industrial enterprises above designated size X_{32} (-) (0.12)
	Regional Energy Relative Index X_4	Total energy consumption accounts for X_{41} (-) (0.13) of the country; total disposable energy production accounts for X_{42} (-) (0.13)
Economy Y	Overall economic strength indicator Y_1	Regional GDP Y_{11} (0.087); Resident Consumption Level Y_{12} (0.089); Total Fixed Asset Investment Y_{13} (0.089); Social Consumer Goods Retail Total Y_{14} (0.092)
	Economic structure indicator Y_2	The output value of primary industry accounts for Y_{21} (0.076) of GDP; the output value of secondary industry accounts for Y_{22} (0.086) of GDP; the output value of primary industry accounts for Y_{23} (0.086) of GDP;
	Economic benefit Y_3	GDP growth rate Y_{31} (0.086); GDP per capital growth rate Y_{32} (0.090)
	Regional economic relative indicator Y_4	GDP accounts for Y_{41} (0.069) of the country; total fixed asset investment accounts for Y_{42} (0.078) of the country; total retail sales of consumer goods account for Y_{43} (0.072) of the country
Environment Z	Environmental pollution index Z_1	Waste water discharge Z_{11} (-) (0.13); soot discharge Z_{12} (-) (0.12); SO2 discharge Z_{13} (-) (0.12); industrial solid waste generation Z_{14} (-) (0.13)
	Environmental protection index Z_2	Comprehensive utilization rate of industrial solid waste Z_{21} (0.11); SO2 removal rate Z_{22} (0.16); industrial soot removal rate Z_{23} (0.12); industrial waste-water discharge compliance rate Z_{24} (0.10)

Note: "-" indicates that the indicator is a negative indicator, the smaller the indicator value, the better, and the remaining indicators are positive indicators, the larger the indicator value, the better.

3.3. Data source

This article limits the research time series to 2010-2019, and the data comes from the idea China Statistical Yearbook and Hebei Statistical Yearbook. Some missing data are estimated by linear fitting method.

3.4. Brief description of the empirical steps

First, the standardization of index values. The standardization method adopted in this paper is to divide the indicators into positive indicators and negative indicators, find the maximum Xij and minimum Xij of each index data, and then use the extreme value between groups for processing.

Second, the determination of indicator weights. After standardizing the data, in order to avoid the deviation caused by subjective factors, this paper uses the entropy method to determine the weight of each index.

Third, comprehensive index calculation and coupling degree calculation. The comprehensive index can measure the development level and status of each subsystem.

Fourth, judge the type of coordinated development. The specific classification types are shown in Table 2.

Table 2. Judgment criteria and classification types of coupling degree

Disorders and recessions		coordinated development	
Coordination	Type	Coordination	Type
0~0.09	Extremely imbalanced recession	0.50~0.59	Barely coordinated development
0.10~0.19	Severe disorders and recession	0.60~0.69	Primary coordinated development
0.20~0.29	Moderate Disorder Recession Class	0.70~0.79	Intermediate Coordinated Development Class
0.30~0.39	Mild disordered recession	0.80~0.89	Good coordinated development
0.40~0.49	Frequent imbalanced recession	0.90~1.00	High quality coordinated development

4. Empirical analysis

4.1. Comprehensive evaluation index analysis

The 3E comprehensive index reflects the development degree of each subsystem. Table 3 shows the calculated 3E comprehensive index of Hebei Province from 2010 to 2019. Figure 3 shows the change trend of the comprehensive index. From Table 3 and Figure 1 we can see:

Table 3. Hebei Province 2010-2019 comprehensive index of energy, economy and environment

Year	Energy Comprehensive Index	Economic Comprehensive Index	Environmental Comprehensive Index
2010	0.47	0.12	0.37
2011	0.48	0.16	0.45
2012	0.50	0.31	0.48
2013	0.45	0.46	0.57
2014	0.34	0.54	0.52
2015	0.39	0.50	0.56
2016	0.42	0.47	0.65
2017	0.44	0.54	0.70
2018	0.50	0.44	0.51
2019	0.53	0.55	0.58

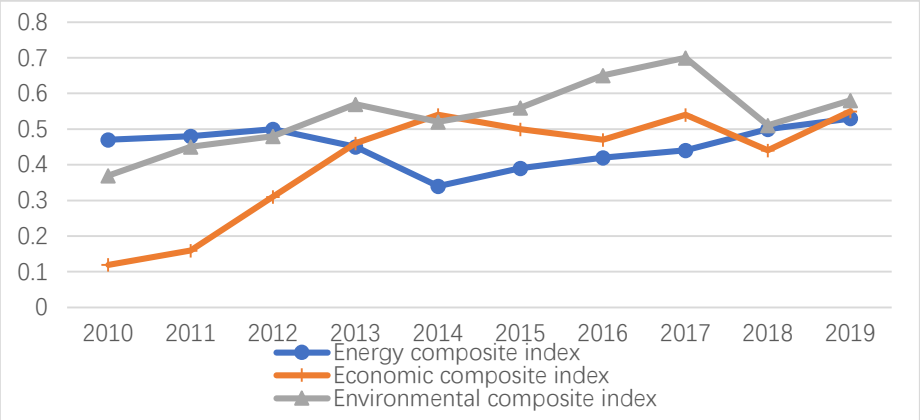

Figure 1. Dynamic evolution trend of the comprehensive index of 3E in Hebei

First, the energy composite index showed a slight upward trend from 2010 to 2012, and a larger decline from 2012 to 2014. From 2015 to 2019, it will rise slowly. It reflects that the comprehensive energy development level has gradually improved in recent years. The comprehensive economic index is divided into two stages. The first stage changes from 0.12 to 0.54, and the second stage is basically stable at 0.55 after a brief decline. This shows that the economy has maintained a rapid development state. The environmental comprehensive index rose from 0.37 to 0.70 and fell to 0.51 in 2010-2019, indicating that environmental pollution and other issues have been contained and showing a gradual improvement.

Second, upon further observation, it can be seen that the comprehensive energy index has shifted from a steady to a downward trend, indicating that large-scale investment in energy has promoted rapid economic growth, but the comprehensive development level of energy with low efficiency and low energy consumption is low and continues to decline. Secondly, the comprehensive environmental index in this period showed an upward trend, indicating that environmental capacity has a strong capacity to accommodate rapid economic development. At the same time, after the economy has stabilized, the comprehensive energy index has changed from falling to rising, which means that economic development helps to use technology to achieve the optimal allocation and efficient use of resources. The extensive development mode of relying on increasing energy input to maintain economic development leads to the deterioration of environmental quality. Since the 13th Five-Year Plan, environmental protection and pollution control measures have been actively taken, and environmental pollution has been effectively contained.

4.2. Coupling analysis

Table 4 shows the calculation results of the four types of coupling degrees of energy and economy, energy and environment, economy and environment, and economy, environment and energy in Hebei Province from 2010 to 2019. Figure 4 depicts the dynamics of energy, economy and environment coupling timing changes Evolutionary trends.

4.2.1. 2E system coupling analysis. It can be seen from Table 4 and Figure 4:

The degree of energy-economy coupling shows a downward, upward, and slowly increasing trend, changing from a severely dysfunctional recession type to a barely coordinated development type. This shows that the energy system and the economic system of Hebei Province generally maintain the same direction of change. From the perspective of change, the coupling between energy and economy has been on the rise for a long time. With the improvement of the quality of economic development, the improvement of energy utilization efficiency and the improvement of energy consumption structure will feed back the reasons for economic development.

The energy-environment coupling degree is fluctuating between 0.4 and 0.6, with an average value of 0.5. Overall, the two have basically maintained a state of primary and coordinated development, and have continued to increase in subsequent years, indicating that Hebei's environmental pollution remediation and ecological construction have continued to strengthen, the energy consumption structure has been continuously adjusted, and energy conservation and emission reduction have been gradually promoted. Certain progress has been made in the sustainable development of the energy system.

The degree of economic-environmental coupling has risen from a severely imbalanced recession to a state of barely coordinated development, indicating that the feedback between the environmental system and the economic system is two-way, and the extensive economic growth mode has a negative effect on the environment, and the deterioration of the environment will in turn Restrict economic development.

Table 4. The coupling degree of energy, economic and environmental systems in Hebei Province from 2010 to 2019

Year	Energy-	Energy-	Economy-	Energy-Economy-
2010	0.19	0.42	0.18	0.29
2011	0.24	0.49	0.24	0.34
2012	0.38	0.50	0.38	0.43
2013	0.45	0.41	0.51	0.49
2014	0.42	0.47	0.53	0.46
2015	0.44	0.54	0.55	0.50
2016	0.44	0.56	0.61	0.55
2017	0.48	0.50	0.56	0.57
2018	0.50	0.54	0.63	0.57
2019	0.43	0.50	0.55	0.60

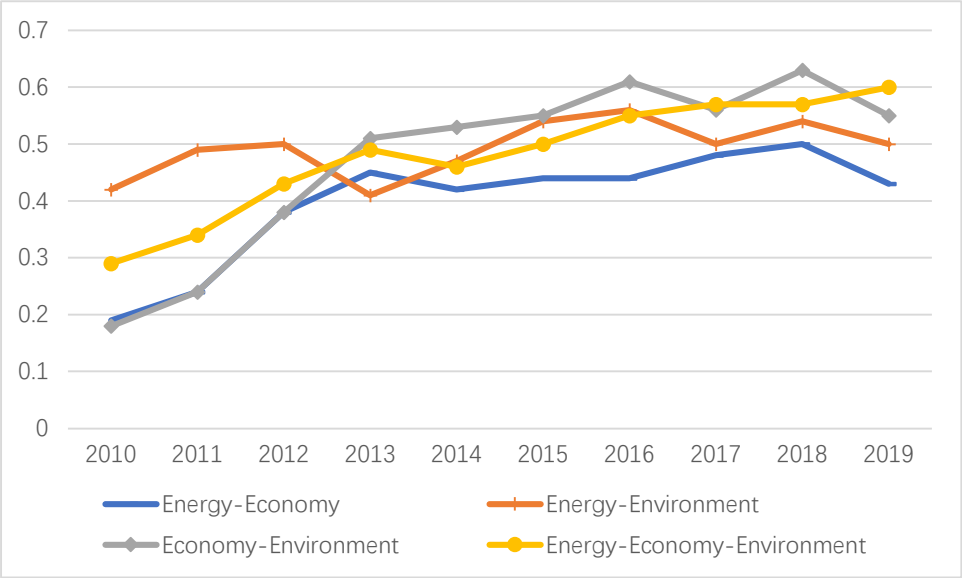

Figure 2. Trend of the coupling situation of energy, economic and environmental systems in Hebei Province

4.2.2. 3E system coupling analysis. Except for a brief decline from 2013 to 2014, the coupling degree in the remaining years showed an upward trend, generally ranging from 0.29 to 0.60, which changed from a moderate imbalance to a barely coordinated development. The change of the coupling level of the 3E system is closely related to the coupling degree of the 2E system, and the dynamic potential is

basically the same. Overall, the coupling level of the three major systems has gradually increased, and a positive feedback mechanism has gradually been formed.

5. Conclusions and recommendations

Using the coupling method, the comprehensive change relationship of energy, economy and environment in Hebei Province is analyzed, and the dynamic characteristics of the coupling evolution of the three subsystems of energy, economy and environment are discussed. The main conclusions and recommendations are as follows: energy as a factor of production is the main driving force for economic development, and economic growth promotes the development of energy; strengthening effective environmental protection, improving the efficiency of energy use, is conducive to improving the structure of energy use, and coordinating energy the relationship with the environment; extensive economic growth has a negative effect on the environment, and the deterioration of environmental quality will in turn restrict economic development; the degree of coordinated development of the 3E system and the 2E system is closely related, and it can be governed from within the 2E system in the future. Promote the benign development of 3E system.

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