Research on the Coupling Coordination of Energy-Economy-Environment System in Zhejiang Province

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Abstract: Driven by the "dual-carbon" strategy, the coupling and coordination of energy-economy-environment systems (referred to as 3E systems) has become a key issue in promoting coordinated regional development. Taking Zhejiang Province as an example, based on the long time-series panel data from 2008 to 2022, the entropy value method is used to construct a coupling coordination degree model, and the evolution law and driving mechanism of the coupling coordination degree between systems are analyzed in multiple dimensions. The results show that the degree of coordination of the 3E system in Zhejiang Province is generally on the rise, but there are fluctuations in some years, and the degree of coupling coordination of subsystems still needs to be improved. Based on this, strategies to optimize the coupling coordination degree of 3E systems in Zhejiang Province are proposed to provide theoretical and practical references for exploring its sustainable development path.

Keywords: energy-economy-environment; coupling coordination; entropy method; Zhejiang Province

1. Introduction

Energy, economy and environment is a complex system, energy sustainability is the foundation, environmental sustainability is the condition, economic sustainability is the ultimate goal 1, the interaction between the three and the role of determining the sustainable development of the interregional economy. Energy supply drives economic growth, while energy consumption will have a serious negative impact on the environment, and environmental pressure prompts the transformation of the energy structure, which in turn adjusts the economic growth model. Therefore, the study of the coupling and coordination between the three is reflected in how to maintain sustained economic growth while keeping the balance of energy supply and avoiding excessive damage to the environment.

In 2020, China has clearly put forward the goals of "carbon peaking" and "carbon neutrality". The concepts and policies of "low carbon economy", "carbon trading" and other types of production and lifestyle that reduce carbon emissions have emerged2. With the introduction of a series of policies and the state in the "dual-carbon" goal of energy and environmental issues, Zhejiang Province, to promote green development, energy saving and emission reduction and low-carbon transformation and other aspects of the corresponding policy measures. 2022, the People's Government of Zhejiang Province, Zhejiang Province, issued the "Zhejiang Province, energy development" Fourteenth Five-Year Plan ", which clearly proposes to promote the use of clean energy in order to realize green, low-carbon sustainable development. By studying the coupled energy-economy-environment synergistic path in Zhejiang Province, it not only responds to China's strategic needs and promotes the green economic transformation of Zhejiang Province, but also has a demonstrative role for other provinces in energy and environmental governance.

In recent years, scholars at home and abroad have carried out a large number of studies centered on the measurement and enhancement of the coupling synergy between energy, economy and environment. In international studies, two-way causality between economic growth, energy consumption and environmental pollution is common in developing countries[3-5] (e.g., India, Ghana); CO_2 emissions in the Middle East are strongly correlated with economic growth and need to be decoupled through renewable energy substitution 6. In domestic studies, at the national level, the coupling and coordination of China's 3E system is generally on an upward trend, but regional differentiation is significant, with the coupling advantage prominent in the eastern region, but the coupling in the central and western regions is still in a state of dysfunction[7-9]; at the provincial level, there are related to the resource-based regions, such as Xinjiang 10 and Shanxi 11, and ecologically fragile zones, such as Qinghai 12 and Gansu 13. In terms of research methods, the entropy method [14-15], entropy weight TOPSIS method 16, and principal component analysis method 17 are used to measure the degree of coordination. However, the existing literature mostly focuses on cross-sectional data or short-cycle analysis. This study covers a total of 15 years of panel data from 2008 to 2022, and based on the traditional entropy value method, conducts a dynamic analysis of the time series to explore the key stages of Zhejiang Province's transition from traditional industry to digital economy, and the key stages of Zhejiang Province's transition from the 11th Five-Year Plan to the 14th Five-Year Plan, and the key stages of Zhejiang Province's transition from traditional industry to digital economy. After the policy cycle from the "11th Five-Year Plan" to the "14th Five-Year Plan" and the impact of the epidemic, the unique economic structure and geographic environment of Zhejiang Province, which is in the critical period of economic transformation and energy restructuring, provide new scenarios for empirical research.

Therefore, this paper selects the panel data of Zhejiang Province from 2008 to 2022, and adopts the entropy value method to analyze the dynamics of the coupling coordination degree of Zhejiang Province, to explore the challenges faced by Zhejiang Province, and to dig out the development mode suitable for the local area.

2. Selection and Analysis of Indicators for Energy-Economy-Environment System

2.1 Selection of Indicators

In the coupled synergistic study of 3E system in Zhejiang Province, the selection of indicators should take into account whether it can reflect the characteristics of energy, economy and environment, but also in line with the actual situation in Zhejiang Province, to ensure that the model is scientific and accurate. Combined with the basis of existing scholars' research [10] and the current situation in Zhejiang Province, 21 indicators were finally selected, including 17 positive indicators and 4 negative indicators, and the specific indicators were selected as shown in Table 1.

Table 1. Energy, economic and environmental indicators

System level	Indicator layer	Unit	Causality
Energy	Total Energy Production	Million tons of standard coal	+
	Total energy consumption in the province	Million tons of standard coal	-
	Elasticity coefficient of energy consumption	-	+
	Coefficient of Elasticity of Electricity Consumption	-	+
	Total Electricity Consumption	billion kilowatt-hours	+
	Growth rate of energy consumption over the previous year	%	+
	Power Generation	billion kilowatt-hours	+
Economy	GDP	billions of dollars	+
	GDP per capita	Yuan	+
	Per capita disposable income of urban and rural residents	Yuan	+
	Total retail sales of consumer goods	billion	+
	Primary Industry as % of GDP	%	+
	Share of secondary industry in GDP	%	+
	Tertiary Industry in GDP	%	+
Environment	Water resources per capita	Cubic meters/person	+

Water consumption per capita	Cubic meters per person	-
Total Industrial Exhaust Emissions	billion standard cubic meters	-
Total Wastewater Discharge	million tons	-
Comprehensive utilization rate of industrial solid waste	%	+

Data source: Zhejiang Provincial Bureau of Statistics, National Bureau of Statistics, Zhejiang Statistical Yearbook, etc.

2.2 System coupling analysis

In the first step, the entropy method was used to calculate indicator weights and evaluation indexes
(1) Data standardization
Standardize the raw data, X_{ij} (i = 1,2, ..., n; j = 1,2, ..., m) denotes the initial data of the jth indicator in the ith year.
Forward normalization process:

$$x'_{ij} = \frac{x_{ij}-min(x_j)}{max(x_j)-min(x_j)} \quad (1)$$

Reverse normalization processing:

$$x'_{ij} = \frac{max(x_j)-x_{ij}}{max(x_j)-min(x_j)} \quad (2)$$

(2) Calculating the weight
Calculate the weight of year i under the jth indicator:

$$p_{ij} = \frac{x'_{ij}}{\sum_{i=1}^{n} x'_{ij}} \quad (3)$$

(3) Calculate the entropy value
Calculate the entropy value of the jth indicator:

$$e_j = -\frac{1}{ln(n)}\sum_{i=1}^{n} p_{ij} ln(p_{ij}),\quad 0\le e_j\le 1 \quad (4)$$

(4) Calculating redundancy

$$d_j = 1 - e_j \quad (5)$$

(5) Calculation of weights
Calculate the weight of the jth indicator:

$$w_j = \frac{d_j}{\sum_{j=1}^{m} d_j} \quad (6)$$

(6) Calculation of the evaluation index
Calculate the evaluation index of the subsystem using the weights of the indicators:

$$S_i = \sum_{j=1}^{m} w_j \cdot x'_{ij} \quad (7)$$

The second step is to establish the coupling coordination degree model for coupling analysis
The evaluation indexes of the three subsystems of energy, economy and environment are denoted as U_1,U_2,U_3, and the coupling degree C of energy-economy-environment system is constructed:

$$C = 3 \times \sqrt[3]{\frac{U_1 \cdot U_2 \cdot U_3}{(U_1+U_2+U_3)^3}} \quad (8)$$

System coupling for two subsystems, e.g. energy-economy system:

$$C = 2 \times \sqrt{\frac{U_1 \cdot U_2}{(U_1+U_2)^2}} \quad (9)$$

However, the coupling degree cannot reflect the good or bad degree of coordination between the subsystems, so the coupling coordination degree D value is constructed to analyze the coordination and consistency between the systems:

$$D = \sqrt{U \times C} \quad (10)$$

The value of D is in the range of [0,1], where $U = \alpha U_1 + \beta U_2 + \gamma U_3$, so that $\alpha = \beta = \gamma = 1/3$, i.e., energy, economy and environment are equally important. The larger the value, the higher the degree of coordination between the systems. The coupling coordination degree standard and the degree of coordination is shown in Table 2.

Table 2. Coupling coordination criteria and degree of coordination

Criteria for grading coupling coordination	
Interval of D-values for coupling coordination	**Degree of coupling coordination**
[0.0~0.1)	Extreme Dissonance
[0.1~0.2)	Severe Dissonance
[0.2~0.3)	Moderate Dissonance
[0.3~0.4)	Mildly dysfunctional
[0.4~0.5)	Nearly dysfunctional
[0.5~0.6)	Barely coordinated
[0.6~0.7)	Elementary coordination
[0.7~0.8)	Intermediate coordination
[0.8~0.9)	Good coordination
[0.9~1.0]	Quality coordination

3. Evaluation analysis of energy-economy-environment system in Zhejiang Province

3.1 System coupling analysis

3.1.1 Energy-economy-environment indicator assignment

The weights of the indicators obtained by applying equations (1)-(6) are shown in Table 3.

Table 3. Weights of energy, economic and environmental indicators in Zhejiang Province

Systems	Indicators	Weights
Energy	Total Energy Production	0.2125
	Total energy consumption in the province	0.0656
	Elasticity coefficient of energy consumption	0.2731
	Coefficient of Elasticity of Electricity Consumption	0.1203
	Total Electricity Consumption	0.1210
	Growth rate of energy consumption over the previous year	0.1291
	Electricity Generation	0.0784
Economy	GDP	0.1591
	GDP per capita	0.1476
	Per capita disposable income of urban and rural residents	0.1603
	Total retail sales of consumer goods	0.1388
	Primary Industry as % of GDP	0.1211
	Share of secondary industry in GDP	0.1508
	Tertiary Industry in GDP	0.1222
Environment	Water resources per capita	0.2016
	Water consumption per capita	0.1091
	Total Industrial Exhaust Emissions	0.0930
	Total Wastewater Discharge	0.1265
	Comprehensive utilization rate of industrial solid waste	0.0713

Completed Investment in Industrial Pollution Control	0.2097
Total afforestation area	0.1889

3.1.2 Energy-economic-environmental subsystem evaluation indexes

According to the formula (7) to find the evaluation index of each subsystem, based on the results of Table 4 and Figure 1, the energy, economic and environmental evaluation index of Zhejiang Province was analyzed dynamically. Among them, the environmental subsystem and the energy subsystem fluctuate sharply, while the economic subsystem shows a clear upward trend, and the overall performance is continuous growth. In order to deeply explore the interaction between the subsystems, the coupling degree and coupling coordination degree will be calculated and analyzed next.

Table 4. Energy, economic and environmental evaluation index of Zhejiang Province

particular year	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022
Energy	0.1785	0.1832	0.3635	0.3214	0.1791	0.2932	0.1564	0.2799	0.3692	0.3658	0.3887	0.3934	0.7266	0.6931	0.9294
Economy	0.2819	0.2930	0.3328	0.3801	0.4030	0.4332	0.4568	0.4766	0.5114	0.5476	0.5888	0.6322	0.6432	0.7166	0.7473
Environment	0.3315	0.4065	0.3741	0.2897	0.5376	0.5084	0.5971	0.6871	0.6506	0.3740	0.4068	0.5354	0.6506	0.3987	0.3105

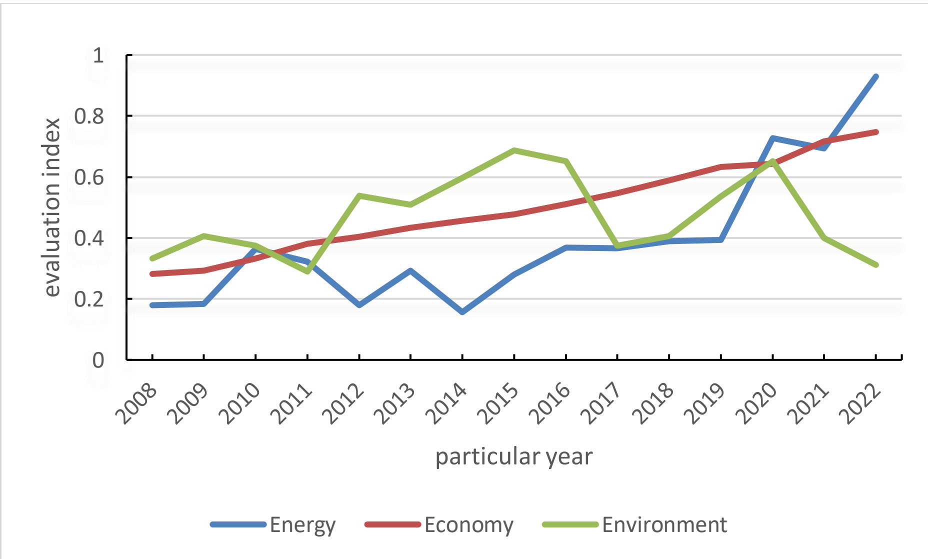

Fig. 1 Evaluation index of energy, economy and environment in Zhejiang Province

3.1.3 Analysis of energy-economy-environment system coupling

The coupling degree of the 3E system is obtained by applying Eq. (8) is shown in Table 5, and a line graph is produced as in Figure. 2 to observe the trend.

Table 5. Energy-Economy-Environment System Coupling

particular year	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022

coupling	0.653	0.608	0.943	0.525	0.602	0.908	0.37	0.781	0.895	0.916	0.931	0.937	0.996	0.891	0.575

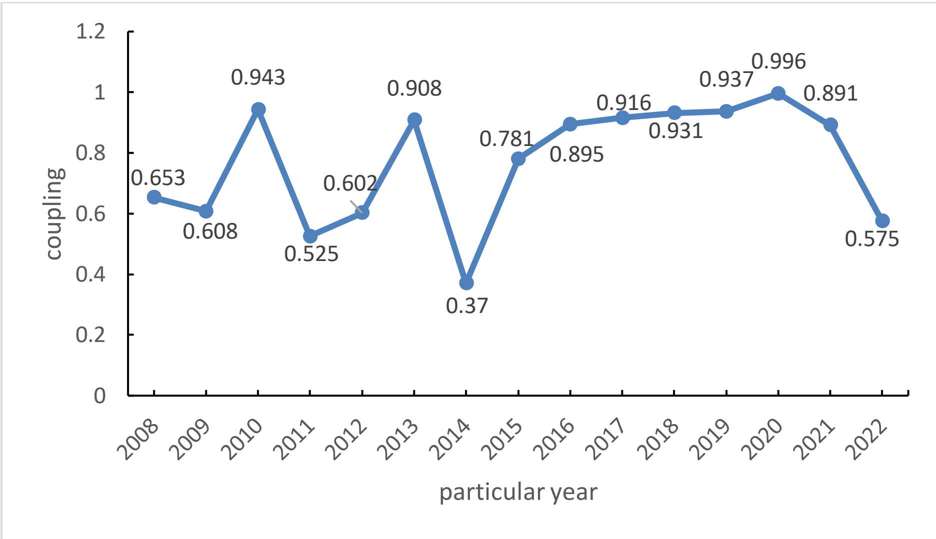

Fig. 2 Energy-economy-environment system coupling degree

According to the results of Table 6 and Figure 2, the 3E system coupling of Zhejiang Province shows a high level of development as a whole. 2008-2014 coupling fluctuation is larger, mainly due to the fact that Zhejiang Province is in the middle stage of industrialization, the private economy is active, the scale of manufacturing industry is expanding, and the promotion of the "Tengcheng and Bird" industrial upgrading, reducing the production of high energy consumption and high pollution industries, resulting in a short-term imbalance of the 3E system. From 2015 to 2021, the coupling degree of the 3E system in Zhejiang Province fluctuates and rises, thanks to the importance of the digital economy and green economy in Zhejiang Province, and the implementation of the concept of "green water and green mountains are golden silver mountains", which promotes the synergy of economic development, energy transformation and environmental protection, and the coupling degree of the system effectively increases. The coupling degree of the system is effectively improved. However, in 2022, the 3E system coupling degree of Zhejiang Province declines to 0.575, which is mainly affected by the external environment and the internal transformation of the two layers, the fluctuation of the international energy price, increasing the pressure of energy consumption, the world economic downward pressure is increasing, the economic subsystem of Zhejiang Province is also subject to a certain degree of impact, which further weakens the coordination with the energy and environmental subsystems, and the decline in the short-term coupling degree reflects the transformation of Zhejiang Province. Pressure intensifies.

3.2 Analysis of the degree of coordination of coupled systems

3.2.1 Energy-economy-environment system coupling coordination degree

The coupling coordination degree of the 3E system is calculated according to Eq. (10) is shown in Table 6, and a line graph is made as shown in Figure. 3.

Table 6. 3E system coupling coordination degree

particular year	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022
D-value of coupling harmonizat	0.187	0.276	0.437	0.279	0.431	0.567	0.378	0.641	0.706	0.57	0.625	0.723	0.893	0.75	0.626

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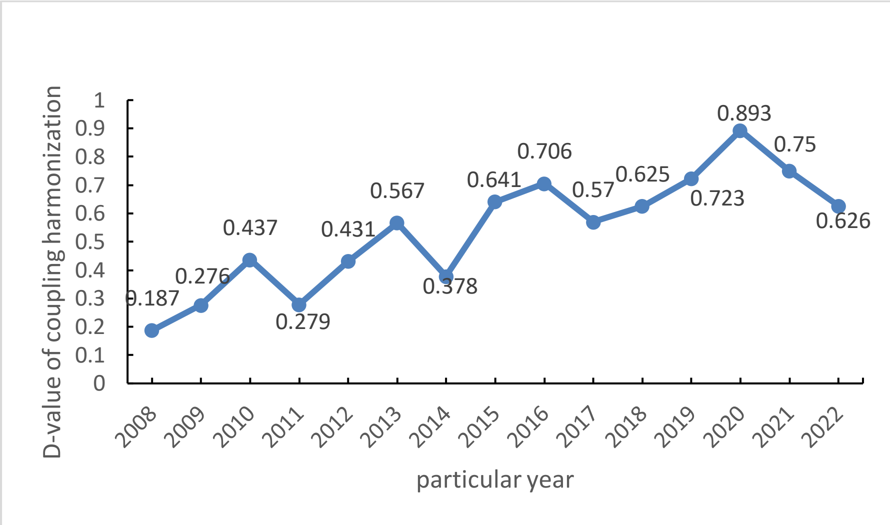

Fig. 3 Degree of coordination of 3E system coupling

As shown in Table 6 and Figure 3, the degree of coupling coordination in Zhejiang Province fluctuates greatly. In the initial exploration of the adjustment stage in 2008-2013, the coupling coordination degree was low in 2008, in the state of "serious dissonance", reflecting the early economic development of Zhejiang Province relies on high-energy-consuming industries, and in 2013 to the state of "barely coordinated", thanks to the implementation of the "Twelfth Five-Year" energy-saving and emission reduction policies. Thanks to the implementation of the "Twelfth Five-Year Plan" energy-saving and emission reduction policies. But in 2014, it dropped to 0.378, at this time, Zhejiang Province is facing the pressure of economic transformation, industrial upgrading is not perfect, the proportion of traditional energy is still high, this stage, Zhejiang Province, the economy and the environment have made gradual adjustments, but due to the lack of coordination between the various elements of the coupling degree of coordination has not been able to reach a higher level, and is still in the coordination of the state is not complete. In the optimization and enhancement stage from 2015 to 2020, the coupling coordination degree is greatly improved, and reaches the highest point of 0.893 in 2020, which is in the "good coordination", on the one hand, Zhejiang province corresponds to the national "13th Five-Year Plan" policy to implement the requirements to accelerate the development of energy saving and environmental protection and other strategic emerging industries. On the one hand, Zhejiang Province, according to the national "13th Five-Year Plan" policy implementation requirements, accelerate the development of energy saving and environmental protection and other strategic emerging industries, and promote the green and sustainable development; on the other hand, Zhejiang Province, actively promote the adjustment of energy structure, promote the use of photovoltaic, natural gas and other clean energy, and deepen the Zhejiang Province, "Five Waters", and resolutely fight the "battle of the blue sky" The coupling coordination has been improved continuously by deepening the "Five Water Control" in Zhejiang Province and resolutely fighting the "Battle of Blue Sky Defense" and other environmental governance actions. However, in the 2021-2022 external impact and adjustment phase, the coupling degree of coordination in 2022 declined to the "primary coordination" state, from the external environment, by the Russian-Ukrainian conflict, the new crown epidemic and the compound impact of extreme weather, the global energy supply and demand imbalance, Zhejiang Province, energy reliance on imports, the increase in the cost of energy, which restricts the coupling synergy of the economy and the environment; from the internal environment; the coupling degree of coordination. From the external environment, the imbalance between global energy supply and demand, Zhejiang Province's dependence on energy imports, and the increase in energy costs have constrained the coupling and synergy between the economy and the environment; from the internal level, the pressure of economic growth is great, and some of the high-consumption industries have been restored, but the substitution of clean energy has not reached the expected effect, and the cost of environmental management has been on the rise, so that the degree of coupling and synergy has been fluctuating, and the degree of short-term decline.

3.2.2 Degree of coordination of subsystem coupling

According to equations (9) and (10), the coupling coordination degree between subsystems is calculated in Table 7, and a line graph is made as shown in Figure. 4 to analyze the dynamic changes between subsystems.

Table 7. Subsystem coupling coordination degree

particular year	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022
Energy - Economy	0.14	0.196	0.423	0.467	0.318	0.495	0.248	0.514	0.609	0.629	0.669	0.694	0.867	0.894	0.995
Energy - Environment	0.256	0.338	0.494	0.216	0.394	0.563	0.296	0.637	0.708	0.495	0.549	0.661	0.901	0.662	0.496
Economy - Environment	0.183	0.316	0.4	0.216	0.637	0.652	0.734	0.803	0.816	0.593	0.665	0.824	0.913	0.713	0.496

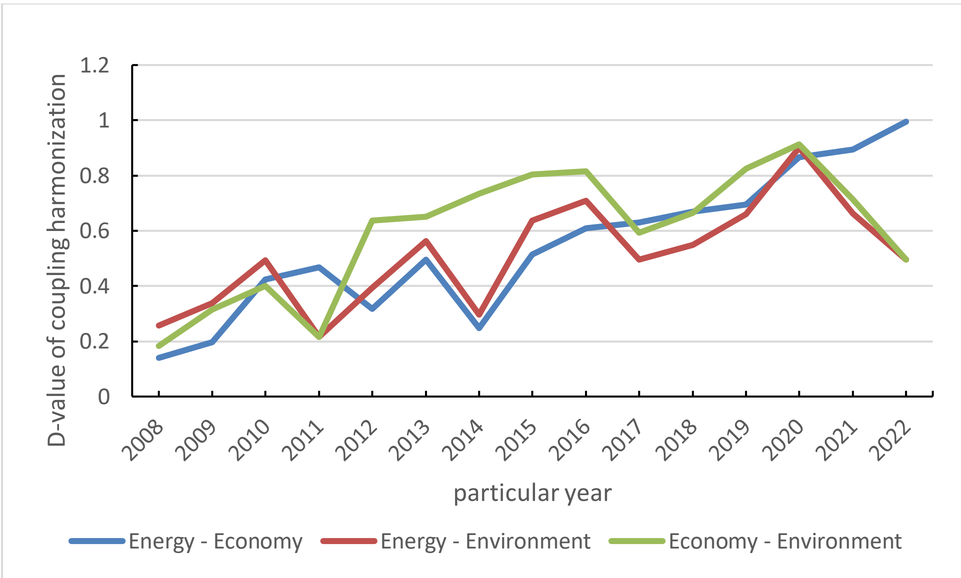

Fig. 4 Degree of coordination of subsystem coupling

For the energy-economy system, the coupling coordination degree of its subsystems shows obvious volatility. in 2008, the coupling coordination degree of the energy-economy subsystem was only 0.14, when Zhejiang Province relied on textile, chemical and other high-energy-consumption industries, and the efficiency of energy utilization was low. However, there is a significant growth after 2014, and the coupling degree of coordination rises to 0.995 in 2022, thanks to the efforts to deepen the digital reform, strengthen the energy operation and scheduling, promote resource saving and intensive recycling, reduce the dependence on traditional energy, and promote the high-quality development of the economy. The degree of coordinated development between energy and economy in Zhejiang Province has gradually strengthened, and there is great potential for synergistic development between the two.

For the energy-environment system, before 2017, its subsystem coupling and coordination degree fluctuates greatly, and from 2017 to 2020, the coupling and coordination degree has a significant increase, but after 2020 there is a short-term decline, and the coupling and coordination degree of the energy-environment system in 2022 falls to 0.496, indicating that Zhejiang Province in the previous period of the "five waters" and other actions have been effective, although they have been effective. This indicates that although Zhejiang Province has achieved some results in the previous “Five Water Controls” and other actions, deep-rooted conflicts still exist, and some high-energy-consuming industries have not been completely transformed, so even though the economy continues to develop, it fails to achieve an effective balance between energy consumption and environmental protection in the short term.

For the economic-environmental system, it fluctuates and rises from 2008 to 2020, but declines to 0.496 in 2022.The rise in the early period is mainly due to the emphasis on environmental governance in the early stage of economic development and the rise of environmental protection industries. However, as China's urbanization process accelerates, the idea of “development before governance” still exists in some areas of Zhejiang Province, and the environmental benefits of emerging industries are offset by the pollution of traditional industries, leading to prominent contradictions between economic development and ecological protection.

4. Conclusions and policy recommendations

4.1 Main conclusions

In this paper, the entropy value method is used to construct the coupled coordination degree model and analyze the 3E system index data of Zhejiang Province from 2008 to 2022, and the following conclusions are drawn:

(1) During the period of 2008-2022, the coupled coordination degree of energy-economy-environment system in Zhejiang Province shows stage changes. In the early stage, it is mostly in the state of disorder or barely coordinated, but with the passage of time, it gradually develops to primary coordination, intermediate coordination and good coordination, but still there are fluctuations in some years, for example, there is a decline in the coupling coordination degree to the state of primary coordination in 2022.

(2) During the period of 2008-2022, the overall coupled coordination degree of energy-economic subsystems in Zhejiang Province was good, and showed a steady upward trend after 2014, with the optimal synergistic development of energy-economic subsystems. The energy-environmental subsystem and economic-environmental subsystem's coupled coordination degree fluctuates greatly, and its degree of coordination needs to be further improved. The current problems faced by the environment in Zhejiang Province are large, which is the main factor hindering the coordinated development of Zhejiang Province.

4.2 Policy recommendations

According to the results of empirical analysis, combined with the actual situation in Zhejiang Province, the following policy recommendations are put forward:

(1) Optimize the energy structure and build a low-carbon energy system. Based on digital technology, integrate renewable energy production, transmission, consumption and dynamic optimal allocation, and build a “smart energy brain”. Strengthen regional energy cooperation, relying on the Yangtze River Delta integration, Zhejiang Province can strengthen energy collaboration with Anhui, Fujian and other neighboring provinces to ease the pressure on local energy supply.

(2) Green upgrading of industries and promoting synergistic development of economy and environment. Build a green industrial ecological chain and a green development model of “leading industries leading + small and medium-sized enterprise clusters”. For example, Shaoxing textile industry promotes low-carbon printing and dyeing technology, and the government encourages and guides enterprises to actively participate in the process, and innovate the “eco+” business model. The government encourages and guides enterprises to actively participate in the innovation of “ecology plus” business model, such as Lishui, Quzhou and other advantageous areas to explore the new path of ecological value transformation, transforming environmental advantages into economic advantages, and breaking the economic-environmental imbalance.

(3) Innovative governance mechanisms to strengthen the synergistic development of the 3E system. Establish a dynamic coupling control mechanism, regularly assess the risk of 3E system disorder in Zhejiang Province, and

formulate differentiated policies. Improve market synergistic tools, explore the synergistic development mode of “emission right” and “carbon emission right” trading, and realize the precision of governance.

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