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Measurement of Regional Green Economy Sustainable Development Ability Based on Entropy Weight-Topsis-Coupling Coordination Degree—A Case Study in Shandong Province, China

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Abstract: Traditional development models are being slowly replaced by green economic development models. This paper views regional green economic development as a large complex system and develops a conceptual DPSIR (drivers, pressures, state, impact, response model of intervention) to construct a regional green economy development measurement index system, after which an entropy weight-TOPSIS-coupling coordination degree evaluation model is developed to quantitatively horizontally and vertically analyze regional green economy sustainable development trends and the coupled coordination status of each subsystem. The evaluation model is then employed to analyze the sustainable development of the green economy in Shandong Province from 2010 to 2016. The analysis results were found to be in line with the actual green economy development situation in Shandong Province, indicating that the measurement model had strong practicability for regional green economy development. Meanwhile, this model can demonstrate clearly how those indicators impact on the regional green economy sustainable development and fill the absence of existing studies on regional green economy sustainable development.

Keywords: green economy; sustainable development; DPSIR; entropy weight-TOPSIS-coupling coordination

1. Introduction

Green development is a necessary condition for sustainable development, which is essential for a better life in the future. Green development takes account of both development quality and development efficiency, as it is focuses on the efficient use of resources and comprehensive environmental protection. However, green development requires the harmonious and unified development of the economy, the ecology, and the society, of which green economy development is particularly important. In 1989, Pearce's "Green Economy Blueprint" first mentioned the "green economy" and claimed that the establishment of an "affordable economy" required that economic development be related to resource and environmental carrying capacities and that national economic balance should include the costs related to the polluted environment and resource waste [1]. In 2011, the UNEP pointed out that green economies needed to be low-carbon, resource-saving, and socially inclusive, should promote social equality for the benefit of mankind, and reduce environmental risks and ecological scarcities [2]. In 2012, the World Bank pointed out that green economies required environmentally friendly and highly socially inclusive economic growth so as to both protect and improve the ecological environment and make full use of natural resources to ensure the coordinated development of the society, the economy, and the environment, with economic growth being focused on sustainable development [3]. However, the traditional 'black' development concepts of unilaterally pursuing the maximization of economic benefits is deeply rooted in society, which highlights the current contradictions between economic growth, social construction, and ecological protection, such as severe haze, sandstorms, greenhouse benefits, and El Niño disasters [4]. To develop green economies further while maintaining economic development, it is necessary to first measure current economic development, explore the impacts of green economy developments, and develop methods to ensure sustainable green economy development.

To measure the current state of green economy development, this paper constructs a green economy development evaluation index system based on the drivers, pressures, state, impact, response model of intervention (DPSIR) that is combined with an entropy weight-TOPSIS-coupling coordination degree model.

In recent years, green economy development evaluation research has mainly focused on the construction of green economy development evaluation index systems and associated measurement methods. Many international authorities have developed green economy development evaluation index systems. For example, the United Nations Environment Program (UNEP) [5] established a green economy evaluation index system, The Global Green Growth Institute (GGGI) [6] built a green economy indicator evaluation system from the perspective of national development, social status, resource consumption and environmental status, , the World Commission for Environment and Development (WCED) [7] established an urban green development evaluation index system that included urban green coverage and tertiary industry, the OECD (OECD) [8] constructed a green growth indicator system to reflect sustainable economic development indicators, and the EU [9] conducted comparative selection indicator analysis. As these economic evaluation index systems mainly involved the integration of green economy development capabilities from different countries, it is not possible to specifically evaluate the regional economic development status in each region. However, research scholars have evaluated green economy development by selecting green GDP [10–12] green economy efficiency [13–15], green economy indexes [16,17], and other indicators. While these green economy evaluation index systems were able to better measure the development of green economies in certain areas, they were only able to describe green economy development levels on a macro level, and were unable to deeply analyze the impact of the economic, resource, environmental, social, and technological factor interactions on green economy development. To overcome these problems, in this paper, a DPSIR is used to construct a green economy development evaluation index system that accounts for the internal mechanisms and allows for in-depth evaluations of green economy development in a certain region or multiple regions.

Green economy evaluations need to have objective, practical, and scientific measurement methods. To date, several research methods have been developed. For example, Beijing Normal University adopted a Delphi method to determine indicator entropy so as to assess the green economy differences in different provinces and cities in China [4], Zeng, and Bi used principal component, clustering, and multiple linear regression analyses to analyze the horizontal and vertical dimensional development of the green economy in 30 provinces in China, from which it was found that the overall development was good, but the inter-regional two-level differentiation was serious [18], and Yi and Zhang used an entropy weight method and a difference coefficient to study the green economy level in 30 provinces in China in 2015, and found significant regional differences [19]. While these methods were able to comprehensively elucidate the regional green economy developments, they were unable to fully reveal the internal development restrictions. Na used an SBM model to measure provincial-level green economy efficiency in China from 1995 to 2012 and found that the regional green economy efficiency differences were large, and that the energy and carbon dioxide emissions were the key factors restricting the green economy efficiency [14], and Xiaoyun W used DEA-BCC and DEA-Malmquist models to analyze the green economy efficiency of 285 cities in China from 2004 to 2012, and found that technological progress was the main driver restricting urban green economy development efficiencies [15]. The above methods were able to identify the objective factors restricting the development of the green economy to some extent by analyzing the multi-input and output efficiencies of the complex green economy development system. However, there has been little research on green economy development trends and the degrees to which the various factors affect green economy development. Therefore, this paper adopted an entropy-TOPSIS-coupling coordination model that first vertically measures the green economy development trends and then horizontally analyzes the coordination between the various internal factors to determine the factors that are restricting green economy development.

2. Construction of the Green Economy Development Evaluation Index System

Green economy development systems are complex systems as they are influenced by economic, social, energy, environmental, and technological factors. Therefore, when constructing measurement indicators, it is necessary to ensure that each evaluation index truly reflects the state of the regional green economy development, takes account of the rationality of each evaluation index, and has sufficient applicability over a considerable period of time.

The DPSIR conceptual model, which evolved from the PSR conceptual model, was first proposed by the European Environmental Agency (EEA) in 1999 [20] to provide a basic and effective model for research into the resource environment, the social economy, and other issues. As shown in Figure 1, the DPSIR model is a complex circulatory system [21] that divided into the resource, environmental, societal, economic, and technological indicators that affect green economy development, which are then assessed into five categories; drivers (D), pressures (P), state (S), impact (I), and response (R); to take account of the indicator interactions. The model mainly emphasizes the causal relationship between human economic activities and environmental changes: human production and life drive economic development, but also bring pressure to the local ecological environment, changing the original state and nature of resources and environment; changes in the environment will also affect human life and urban development. In order to maintain the sustainable development of society, humans will take measures to respond to these changes. This model has been used to analyze regional green economy development [22], regional adaptations to climate change [23], economic development and environmental warnings [24], and economic development and carbon emissions [25], and has achieved good results.

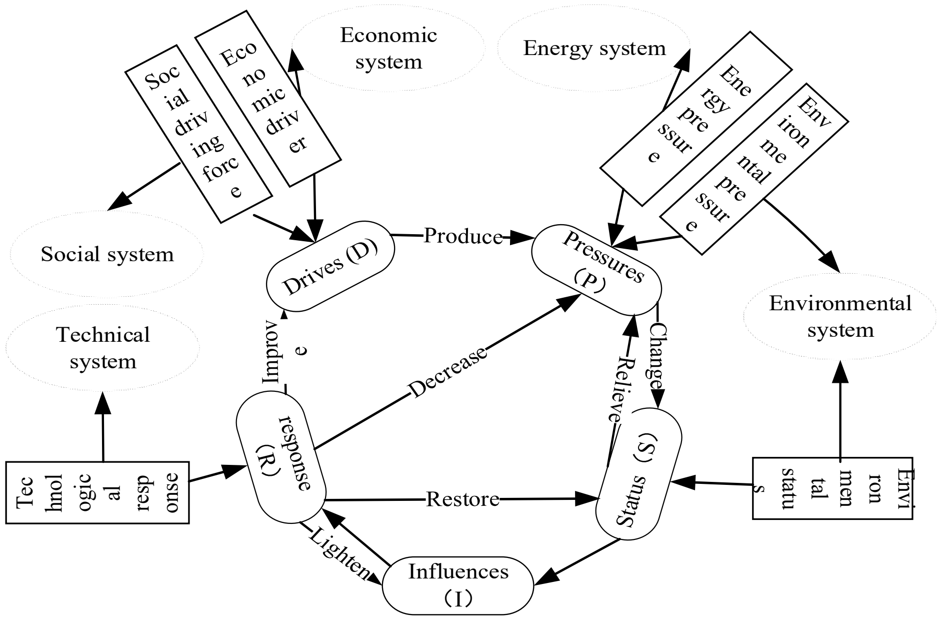

Figure 1. DPSIR green economy development evaluation system framework.

Natural resources, population, science and technology, culture, and education determine the level of regional economic development from the aspects of regional resource richness, production and consumption capacity, productivity development level, and human resource quality. The development of green economy is an inevitable choice for the sustainable development of economy, society, and ecological environment [26,27]. Green economy development is needed to improve the conflict among economic development and energy consumption, resource utilization, and environmental protection [28,29].

Shi, B. and Yang, H [16] selected 85 indicators to evaluate the urban green economy from the perspectives of economy, society, and resources. Shi, L and Xiang, X [25] from the driving force-pressure-state-impact-response selected 19 indicators including regional GDP, unit GDP energy, carbon emissions per unit of GDP, public perception of low-carbon cities, and forest coverage to evaluate urban low-carbon economy. Shen Juqin and Sun Yue [30] combined with the DPSIR model to select 28 indicators for evaluation of fixed asset investment, energy consumption, green coverage, per capita disposable income, and sewage treatment rate from the factors affecting regional green GDP development.

This paper selects 26 indicators that affect regional green economy development from five aspects: economy, society, environment, energy and technology. Because the impact is difficult to measure, to avoid uncertainty in the "I-impact" factor index in the DPSIR model criterion layer construction, a criterion layer based on the DPSR, namely the drivers-pressures-state-response, is established. Therefore, the 26 indicators are divided into economic driving force D1, social driving force D2, energy pressure P1, environmental pressure P2, environmental state S1, and science and technology response R1, total of six blocks, to measure regional green economy development.

The choice of economic driving indicators selected fixed asset investment, foreign trade volume GDP growth rate, per capita GDP, per capita disposable income of urban residents, and household consumption level from the perspectives of internal and external, national individual and income expenditure as the basis for measuring the standard economic driving force.

The choice of social driving force indicators selected the family size, per capita water use, per capita urban road area, and 10,000-person bus ownership of the household registration population from the population problem and infrastructure security level that have significant impact on social development.

Energy pressure indicators were selected by analyzing the relationship between economic development and energy consumption. The energy consumption and power consumption of the two major factors that constrain economic development are selected for measurement.

Environmental pressures reveal the industrial production that is the most vulnerable to the environment during the economic development process. Therefore, industrial wastewater discharge, industrial smoke (powder) dust emissions, industrial solid waste comprehensive utilization, SO_2 emissions per unit of GDP, and chemical oxygen demand emissions are selected as the basis for measurement.

The choice of environmental status indicators is mainly based on the perspective of green life. The pollution-free treatment rate of living garbage, the per capita park green area, the forest coverage rate, and the green area coverage of the built-up area were selected as the basis for measurement.

As an important part of promoting green development of science and technology, science, and technology response indicators should be selected from the process of investment in science and technology innovation, output, and application. Therefore, R&D expenditures accounted for the proportion of GDP, the proportion of R&D personnel with high education (master's degree or above), the number of patents granted by 10,000 people, the proportion of secondary industry to GDP, and the proportion of tertiary industry to GDP as the basis for measuring scientific and technological response. The specific indicator system is shown in Table 1.

Table 1. Evaluation index system for the green economy development based on the DPSIR.

Target Layer	Standard Layer	Factor Layer	Indicator Layer	Indicator Direction	Unit	Selection Basis
Evaluation index system for green economy development	D Drivers	D1 Economic drivers	Per capita GDP (D11)	+	CNY	Measures the state of regional economic development
			Household consumption level (D12)	+	CNY	Measures the extent to which economic development meets all aspects of human needs
			Foreign trade (D13)	+	100 million dollars	Reflects the scale of regional foreign trade
			GDP growth rate (D14)	+	%	Measures the speed of the regional economic development
			Fixed asset investment (D15)	+	100 million CNY	Reflects the comprehensive fixed investment indicators
			Disposable income of urban residents (D16)	+	CNY per person	Measures the proportion of daily income to total income
		D2 Social drivers	Household registration family size (D21)	–	Persons per household	Reflects the size of the family
			The 10,000-person bus ownership (D22)	+	Vehicles per 10,000 people	Reflects regional traffic convenience
			Per capita urban road area (D23)	+	Square meters per person	Reflects the congestion level in the area
			Per capita water consumption (D24)	–	Tonnes per person	Reflects the level of the sustainable use of water resources in regional cities
	P Pressures	P1 Energy pressures	Unit GDP energy consumption (P11)	–	Tonnes of standard coal per 10,000 CNY	Reflects the level of energy conservation in the region
			Unit GDP power consumption (P12)	–	kWh per 10,000 CNY	Reflects the level of energy conservation in the region
		P2 Environmental pressures	Industrial wastewater discharge (P21)	–	10,000 tonnes	Measures the amount of wastewater generated during industrial development
			Industrial smoke (powder) dust emissions (P22)	–	10,000 tonnes	Measures the total amount of particulate matter emitted by a company during production
			Industrial solid waste comprehensive utilization (P23)	–	%	Comprehensively reflects the extraction efficiency of industrial solid waste
			SO2 emissions per unit of GDP (P24)	–	Tons/100 million CNY	National binding emissions reduction indicator
			Chemical oxygen demand emissions (P25)	–	Tonnes	Measures water pollution
	S State	S1 Environmental state	Per capita park green area (S11)	+	Square meter	An important green space indicator
			Forest coverage rate (S12)	+	%	Reflects regional forest resources
			Pollution-free treatment rate of living garbage (S13)	+	%	Effective garbage disposal rate

Table 1. *Cont.*

Target Layer	Standard Layer	Factor Layer	Indicator Layer	Indicator Direction	Unit	Selection Basis
			Green area coverage in the built-up area (S14)	+	%	Measures regional vegetation coverage
	R Response	R1 Tech response	R&D expenditure as a proportion of GDP (R11)	+	%	Measures investment in scientific research
			Number of patents granted per 10,000 people, (R12)	+	Items per 10,000 people	Reflects scientific and technological achievements
			Proportion of R&D personnel with high education (master's degree or above) (R13)	+	%	Measures talent support for science and technology
			Proportion of tertiary industry to GDP (R14)	+	%	Measures the development of the tertiary industry sector
			Proportion of secondary industry to GDP (R15)	−	%	Measures the development of the secondary industry sector

The standard economic driving force indicators are fixed asset investments, foreign trade, GDP growth rate, per capita GDP, urban resident per capita disposable income, and household consumption level. The basic household scale and infrastructure security levels are assessed by the social driver indicators; household registration family size, per capita water consumption, per capita urban road area, and buses per 10,000-people. The current economic development stage is assessed using the energy pressure indicators, which include energy consumption and power consumption constraints, with GDP energy consumption and unit GDP power consumption being the pressure measures. The environmental pressure indicators are; industrial wastewater discharge, industrial smoke (powder) dust emissions, comprehensive industrial solid waste utilization, SO_2 emissions per unit of GDP, and chemical oxygen demand emissions. The environmental state indicators that measure the environmental green status are: the pollution-free treatment rate for living garbage, the per capita park green area, the forest coverage rate, and the green area coverage in built-up areas. As scientific and technological innovation can promote green economic development, the indicators are: R&D expenditures as a proportion of GDP, the proportion of R&D personnel with higher education (master's degree or above), the number of patents granted per 10,000 people, the proportion of secondary industry to GDP, and the proportion of tertiary industry to GDP.

3. Regional Green Economy Development System Research Model

3.1. Model Summary

The entropy-TOPSIS-coupling coordination degree model is constructed to horizontally and vertically measure the regional green economy development, the specific model for which is shown in Figure 2. First, Index weight reflects the different importance of indicators in the evaluation process, and it is a comprehensive measure of subjective and objective responses to the relative importance of indicators in decision-making (or evaluation) issues. Decancq, K. and Lugo, A. [31] summarized eight methods for setting indicator weights and highlight their strengths and weaknesses. The entropy method employs the inherent information in the evaluation indicators to discriminate the utility value of the indicators, which avoids any subjective factors, and therefore has higher credibility than subjective weighting methods such as Delphi and AHP [32,33]. TOPSIS (technique for order preference by similarity to an ideal solution), is simple to calculate and produces reasonable results as it is able to obtain the relative proximity between each evaluation object and the optimal solution by calculating the distance between each evaluation object and the optimal solution and the worst solution, after which the evaluation objects are ranked based on relative proximity [34]. The combination of these two methods (entropy weight-TOPIS) is able to more objectively and accurately reflect the evolutionary regional green economy development trends using a simple and practical calculation method.

Second, coupling is a physics concept that refers to a phenomenon whereby two or more systems or forms of motion interact [35]. The coordination degree is the degree to which the internal system factors are in harmony during the development process and reflects the system trends as it moves from disorder to order [36,37]. A coupling coordination degree is introduced to quantitatively analyze the degree of internal system coupling in regional green economy development, determine whether the coordination status of each subsystem is good or bad, clarify the role of each subsystem in the green economy development, and determine a lateral regional green economy development measurement.

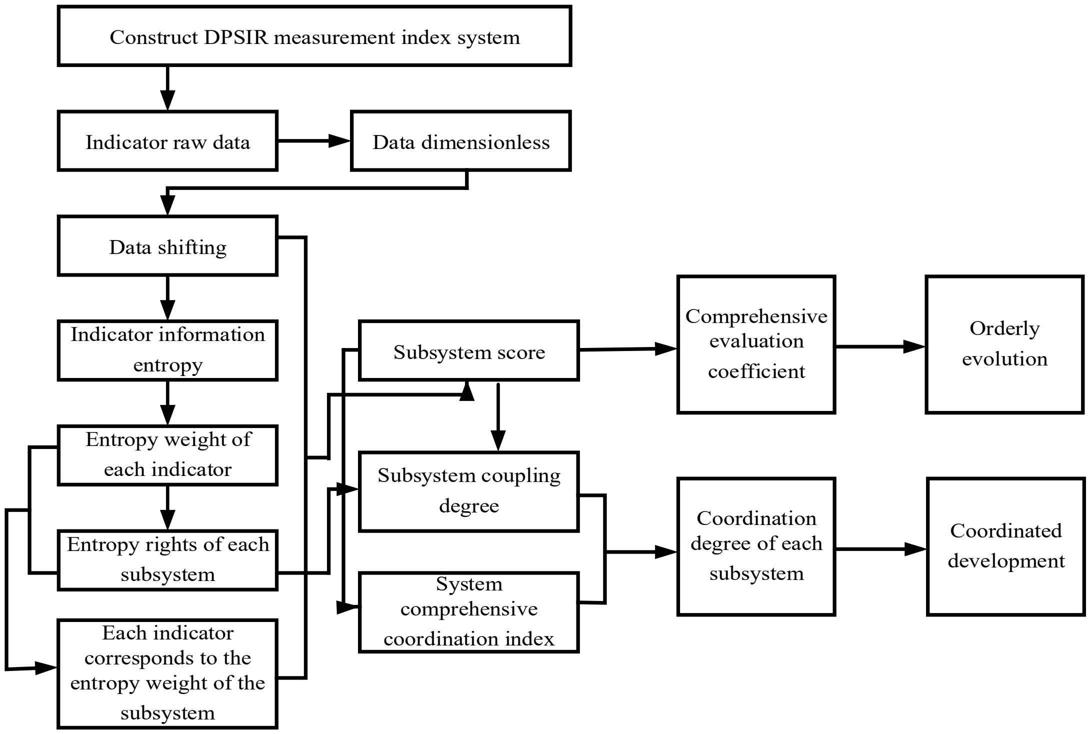

Figure 2. Research framework for the sustainable development of the green economy.

3.2. Model Solution

Step 1. Calculate the normalized measurement matrix.

With n indicators to measure the regional green economy development over m years, the initial measurement matrix can be expressed as

$$A = \begin{bmatrix} a_{11} & a_{12} & \cdots & a_{1n} \\ a_{21} & a_{22} & \cdots & a_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ a_{m1} & a_{m2} & \cdots & a_{mn} \end{bmatrix}$$

where a_{ij} represents the measurement value of the j-th measurement indicator in the i-th year.

To eliminate the different dimensions and orders of magnitude in the original variable sequences and guarantee the reliability of the measurement analysis results, a linear dimensionless processing method is applied to the initial measurement matrix. Where a_{ij} is the benefit criteria set,

$$a_{ij}{}' = \frac{a_{ij} - \min\limits_{1 \le i \le m} a_{ij}}{\max\limits_{1 \le i \le m} a_{ij} - \min\limits_{1 \le i \le m} a_{ij}} \tag{1}$$

and where a_{ij} is the cost criteria set,

$$a_{ij}{}' = \frac{\max\limits_{1 \le i \le m} a_{ij} - a_{ij}}{\max\limits_{1 \le i \le m} a_{ij} - \min\limits_{1 \le i \le m} a_{ij}} \tag{2}$$

To eliminate the impact of the index value normalized logarithmic calculations, it is necessary to coordinate the a_{ij} translation, which is expressed as

$$\mathrm{f}_{ij} = a_{ij}{}' + \theta \tag{3}$$

where θ is the translational amplitude for the relevant reference, $\theta > \min\left(a_{ij}'\right)$; when the value for θ is closer to $\min\left(a_{ij}'\right)$, the measurement result is more significant [38]; therefore, this study uses θ = 0.001; and the measured matrix $\mathrm{F} = [f_{ij}]_{m\times n}$ is then obtained.

Step 2. Determine the entropy weight for each indicator.

From basic information theory principles, information is a measure of the degree of order in a system and entropy is a measure of the degree of disorder in a system; therefore, the smaller the indicator information entropy, the greater the information provided by the indicator, the greater the effect in the comprehensive evaluation, and the higher the weight. The entropy weight rule is an objective weighting method that makes weight judgments based on the size of the data information load. Here, the objective weight for each index is determined by the degree of dispersion in the measurement index, as this reduces the influence of human subjectivity on the evaluation result and makes the evaluation results more realistic.

From the information entropy definition, the entropy value and entropy weight for the *j*-th measure index are calculated as

$$E_j = -\frac{1}{\ln m}\sum_{i=1}^{m}\frac{\mathrm{f}_{ij}}{f_j}\ln\frac{\mathrm{f}_{ij}}{\mathrm{f}_j}\ (j = 1,\ 2,\ \ldots,\ n) \quad (4)$$

$$w_j = \frac{1-E_j}{n-\sum_{j=1}^{n}E_j}(j = 1,\ 2,\ \ldots,\ n) \quad (5)$$

$$\text{where } f_j = \sum_{i=1}^{m} f_{ij} \quad (6)$$

Step 3. Determine the entropy weight for each subsystem.

For the multi-layered structural measurement system, based on the addition of the information entropy weight, the entropy weight W_k for each subsystem in the corresponding criterion layer is calculated using the entropy weight w_j of each index layer. The entropy weight P_j in the subsystems corresponding to each index is then obtained, after which the development scores in each subsystem Z_{ik} are calculated. It is assumed that there are s measure indicators under the *k*-th subsystem.

Calculate the entropy weight of each subsystem in the corresponding criterion layer W_k

$$W_k = \sum_{j=s(k-1)+1}^{s} w_j\ (k = 1,\ 2,\ 3,\ 4) \quad (7)$$

Calculate the entropy weight in the subsystem corresponding to each index P_j

$$p_j = \frac{w_j}{W_k}\ (j = 1,\ 2,\ \ldots,\ n) \quad (8)$$

Calculate the development scores for each subsystem in the *i*-th year Z_{ik}

$$Z_{ik} = \sum_{j=\mathrm{s(k-1)+1}}^{s} f_{ij}p_j\ (k = 1,\ 2,\ 3,\ 4) \quad (9)$$

Step 4. Calculate the comprehensive evaluation coefficient C_j for the sustainable development of the green economy system based on TOPSIS.

A larger $\boldsymbol{C_j}$ value indicates that the green economy is more sustainable; therefore, $\boldsymbol{C_j}$ indicates the overall development of the regional green economy at the macro level. The specific steps are

(1) Determine the positive ideal solution Z_{ik}^{+} and the negative ideal solution Z_{ik} for each subsystem

$$Z_{ik}^{+} = \{\max Z_{ik}|i = 1,2,3,\ldots,m\} = \left\{Z_{i1}^{+}, Z_{i2}^{+}, Z_{i3}^{+}, Z_{i4}^{+}\right\} \quad (10)$$

$$Z_{ik} = \{\min Z_{ik} | i = 1, 2, 3, \ldots, m\} = \{Z_{i1}^-, Z_{i2}^-, Z_{i3}^-, Z_{i4}^-\} \tag{11}$$

(2) The distance from the i-th year weighted value to the positive Z_{ik}^+ and the negative ideal solution Z_{ik} can be calculated as

$$D_i^+ = \sqrt{\sum_{k=1}^{4} (Z_{ik} - Z_{ik}^+)^2} \tag{12}$$

$$D_i^- = \sqrt{\sum_{k=1}^{4} (Z_{ik} - Z_{ik})^2} \tag{13}$$

(3) Calculate the relative closeness to the ideal solution and rank the performance order. The comprehensive evaluation coefficient C_i for the sustainable development of the regional green economy development system in the i-th year is expressed as

$$C_i = \frac{D_i^-}{D_i^+ + D_i^-}, \ (0 \le C_i \le 1) \tag{14}$$

Step 5. Calculate the coupling coordination degree in the regional green economy.

Calculate the coupling coordination degree $\boldsymbol{K_i}$ of the regional sustainable green economy in the i-th year to account for the coupling degree and the coordination degree correlation characteristics, which can then be used to assess the intensity and orderly development of the annual coupling between the internal subsystems in the regional sustainable green economy. The specific steps are as follows:

(1) $\boldsymbol{M_i}$ is the sustainable green economy multi-factor coupling degree in the i-th year; the larger the value, the better the state of the sustainable regional green economy, the calculation formula for which is

$$M_i = \left| \prod_{k=1}^{k} Z_{ik} / \left(\frac{\sum_{k=1}^{k} Z_{ik}}{k} \right)^k \right|^{\frac{1}{k}} \tag{15}$$

where k is the number of coupled subsystems needed to calculate the sustainable green economy development; that is, $2 \le k \le 4, k \in \mathrm{N}^+$.

(2) $\boldsymbol{Q_i}$ is the sustainable green economy comprehensive coordination index in the i-th year, which reflects the orderly and/or disorderly development; the more orderly the system, the better the development of the sustainable green economy; the calculation formula for which is

$$Q_i = \sum_{k=1}^{4} Z_{ik} \times W_k \tag{16}$$

(3) The coupling degree and comprehensive coordination index are combined to determine the coupling coordination degree, which is expressed as

$$K_i = \left| \sqrt{M_i \times Q_i} \right| \tag{17}$$

The larger the $\boldsymbol{K_i}$, the more cooperative the subsystems in that year, and the higher the coordination. The coordination degree is divided into 8 levels [39], as shown in Table 2.

Table 2. Coordination levels.

K_i	0~0.09	0.10~0.29	0.30~0.39	0.40~0.49
Levels	High imbalance	Moderate imbalance	Slight imbalance	Approaching imbalance
K_i	**0.50~0.59**	**0.60~0.69**	**0.70~0.89**	**0.90~1**
Levels	Reluctant coordination	Primary coordination	Intermediate coordination	High coordination

4. Case Study

4.1. Data Sources

Shandong Province has the third largest provincial economy in China, the third highest provincial GDP at 1/11 of total Chinese GDP, and is the second most populous province in China. Shandong Province is therefore, one the most economically developed and economically strong provinces, and is one of the fastest growing. While the overall economic development in Shandong Province is rising, there are still deficiencies in its green economy development. Therefore, this paper analyzes the green economy development in Shandong Province to demonstrate the validity of the proposed methods and provide guidance for future evaluations.

The index data for this study were taken from the National Statistical Yearbooks (2011–2017) [40] and the Shandong Statistical Yearbooks (2011–2017) [41], with some original data being converted using the relevant calculation formulas.

4.2. Results Analysis

As previously described, the sustainable green economy system was both vertically and horizontally analyzed. First, the overall development trends of the green economy development system were vertically analyzed, after which the coordination between the various internal green economy development subsystems were laterally measured and the restricting development factors explored.

Using Formulas (1)–(8), the entropy and entropy weights for the regional green economy development indicators in Shandong Province were calculated, the results for which are shown in Table 3.

Table 3. Entropy and entropy weights for the regional green economic development system indicators in Shandong Province.

Target Layer	Standard Layer		Indicator Layer			
	Code	W_k	Code	E_j	w_j	P_j
Sustainable Green economic development system	D	0.3666	D11	0.8716	0.0333	0.0908
			D12	0.8489	0.0392	0.1069
			D13	0.9038	0.0249	0.0680
			D15	0.8090	0.0495	0.1351
			D15	0.8321	0.0435	0.1188
			D16	0.8707	0.0335	0.0915
			D21	0.8228	0.0340	0.0929
			D22	0.7128	0.0274	0.0748
			D23	0.8530	0.0261	0.0712
			D24	0.8088	0.0550	0.1501
	P	0.2216	P11	0.8769	0.0339	0.1531
			P12	0.8539	0.0389	0.1758
			P21	0.8085	0.0277	0.1252
			P22	0.8486	0.0301	0.1360
			P23	0.8265	0.0215	0.0969
			P24	0.8687	0.0309	0.1395
			P25	0.8943	0.0385	0.1736
	I	0.2081	I11	0.8994	0.0459	0.2208
			I12	0.7878	0.0745	0.3579
			I13	0.8692	0.0381	0.1831
			I14	0.8499	0.0496	0.2382
	R	0.2037	R11	0.8930	0.0319	0.1568
			R12	0.8839	0.0379	0.1860
			R13	0.9172	0.0497	0.2438
			R14	0.8808	0.0393	0.1927
			R15	0.8517	0.0450	0.2208

As can be seen from the calculation results, the economic and social drivers in each subsystem accounted for a large proportion of the green economy development, followed by energy and environmental pressure, with the environmental state and technological response accounting for a relatively small proportion.

4.2.1. Comprehensive Evaluation Results from the Vertical Analysis

Based on the entropy weights for each layer, the green economy development level scores in Shandong Province were calculated using Formulas (9) and (10), the results for which are shown in Table 4.

Table 4. Development level scores in each subsystem of Shandong Province's sustainable green economy development system from 2010 to 2016.

Year	D	P	S	R
2010	0.3967	0.6920	0.0001	0.2209
2011	0.4290	0.7806	0.0307	0.3176
2012	0.4983	0.6315	0.3067	0.4181
2013	0.5064	0.5394	0.8348	0.4646
2014	0.5249	0.5446	0.9137	0.6052
2015	0.5467	0.5877	0.8498	0.7451
2016	0.6111	0.1883	0.9085	0.7792

Equations (11)–(15) were then applied to calculate the distance between the green economy subsystems and the ideal values from 2010–2016 and determine the closeness coefficients, the results for which are shown in Table 5.

Table 5. D_i^+, D_i^- and C_i. for the development of the green economy in Shandong Province from 2010 to 2016.

Year	D_i^+	D_i^-	C_i	RANK
2010	1.0955	0.5037	0.3149	7
2011	1.0129	0.6018	0.3727	6
2012	0.7306	0.5828	0.4437	5
2013	0.4175	0.9442	0.6934	3
2014	0.3057	1.0610	0.7763	2
2015	0.2158	1.0857	0.8342	1
2016	0.5923	1.0876	0.6474	4

For further analysis, the green economy development trends were transformed from the tables into graphs, as shown in Figures 3 and 4.

As can be seen from Figures 3 and 4, the sustainability of the green economy in Shandong Province from 2010–2016 was generally rising and had good momentum. D_i^+ decreased from 1.10 to 0.59, D_i^-. increased from 0.50 to 1.09, and the comprehensive closeness C_i gradually increased from 0.31 to 0.83, indicating that the sustainable green economy was gradually developing towards an ideal state. The sustainable green economy system development comprehensive score from 2010 to 2015 increased from 0.34 to 0.66, indicating that Shandong's economy was continuing to develop at high speed. Although the comprehensive score in 2016 slightly decreased, it was still in a rapid development period. The progress made in recent years by Shandong Province was mainly due to the active implementation of the green economy development concept. Since 2010, the drivers and pressures and the state and response systems have been rapidly rising, the driving system has been slowly changing, and the state subsystem had the fastest rising speed, all of which was mainly due to the continuous economic and social development; however, the development speed was more moderate. Environmental protection has been gradually receiving attention, with environmental protection investment having increased substantially, which has led to a continuous improvement in the environment. At the same time, science and technology has strengthened to support economic development. However, the continuing economic growth has resulted in increased energy and environmental pressure, with the pressure on the green economy development being at a relatively high level from 2010–2015. The limited energy sources have restricted green economy development and has also caused harm to the environment.

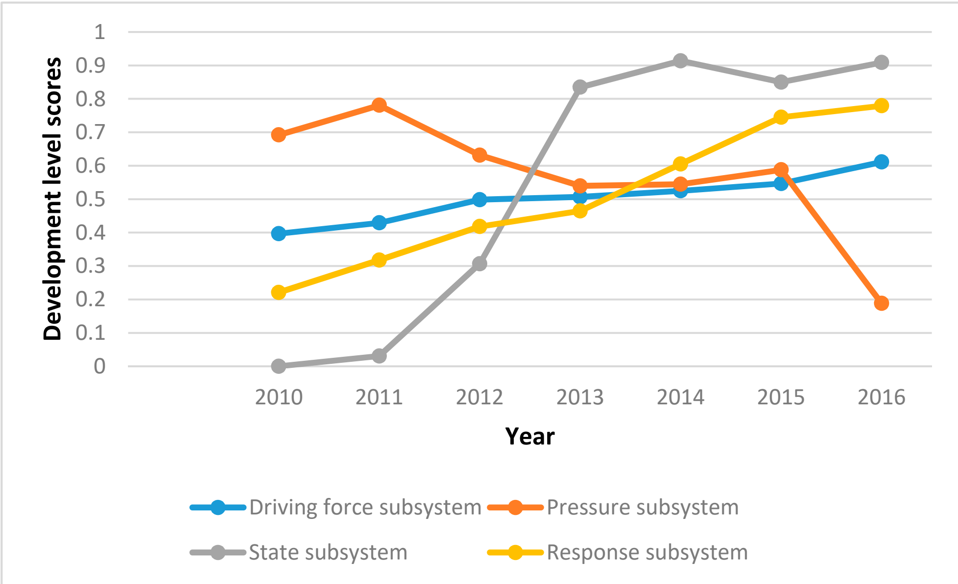

Figure 3. Development level scores for each subsystem in Shandong Province's sustainable green economy.

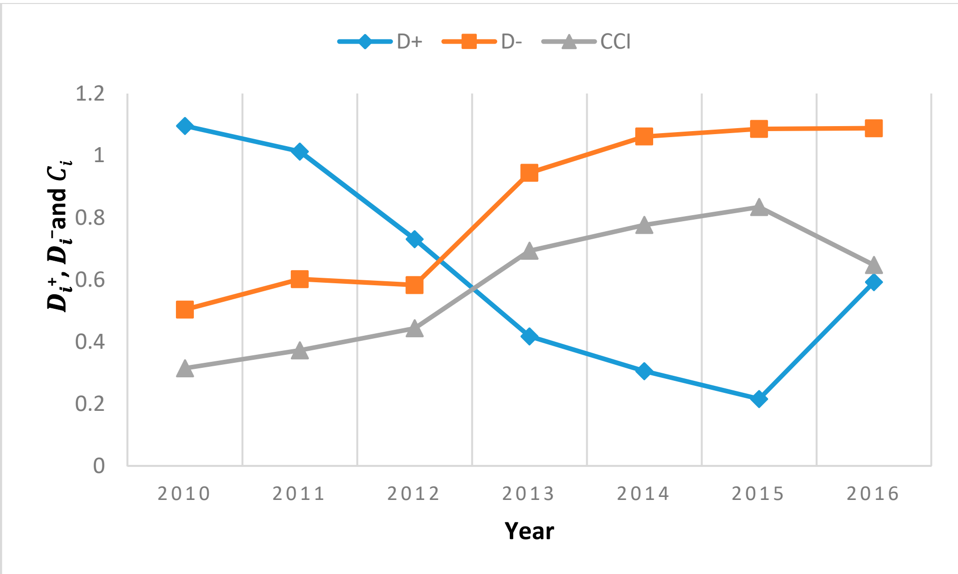

Figure 4. D_i^+, D_i^-, and C_i for the green economy system in Shandong Province from 2010 to 2016.

In short, Shandong Province faces challenges and it is necessary to continuously coordinate the relationship between green economy development and the economic, social, energy, environmental, and technological subsystems.

4.2.2. Coordinated Development Results from the Horizontal Analysis

Using Equations (16)–(18), the coupling coordination degrees between the two subsystems and the four subsystems in Shandong Province were calculated from 2010 to 2016, the results for which are shown in Table 6.

Table 6. Coupling coordination degrees between the two subsystems and the four subsystems in Shandong Province from 2010 to 2016.

Year	D-P	Coordination Level	P-S	Coordination Level	R-D	Coordination Level
2010	0.5362	Reluctant coordination	0.0607	High imbalance	0.4273	Approaching imbalance
2011	0.5621	Reluctant coordination	0.2617	Moderate imbalance	0.4685	Approaching imbalance
2012	0.5660	Reluctant coordination	0.4372	Approaching imbalance	0.5165	Reluctant coordination
2013	0.5523	Reluctant coordination	0.5352	Reluctant coordination	0.5292	Reluctant coordination
2014	0.5595	Reluctant coordination	0.5483	Reluctant coordination	0.5612	Reluctant coordination
2015	0.5748	Reluctant coordination	0.5495	Reluctant coordination	0.5900	Reluctant coordination
2016	0.4749	Approaching imbalance	0.4172	Approaching imbalance	0.6164	Primary coordination
Year	**R-P**	**Coordination Level**	**R-S**	**Coordination Level**	**D-P-S-R**	**Coordination Level**
2010	0.4122	Approaching imbalance e	0.0438	High imbalance	0.2283	Moderate imbalance
2011	0.4642	Approaching imbalance	0.2008	Moderate imbalance	0.4963	Approaching imbalance
2012	0.4694	Approaching imbalance	0.3837	Slight imbalance	0.6752	Primary coordination
2013	0.4621	Approaching imbalance	0.5072	Reluctant coordination	0.7471	Intermediate coordination
2014	0.4935	Approaching imbalance	0.5540	Reluctant coordination	0.7813	Intermediate coordination
2015	0.5292	Reluctant coordination	0.5727	Reluctant coordination	0.8056	Intermediate coordination
2016	0.3984	Reluctant coordination	0.5889	Reluctant coordination	0.7261	Intermediate coordination

For further analysis, the green economy development trends were transformed into a graph, as shown in Figure 5:

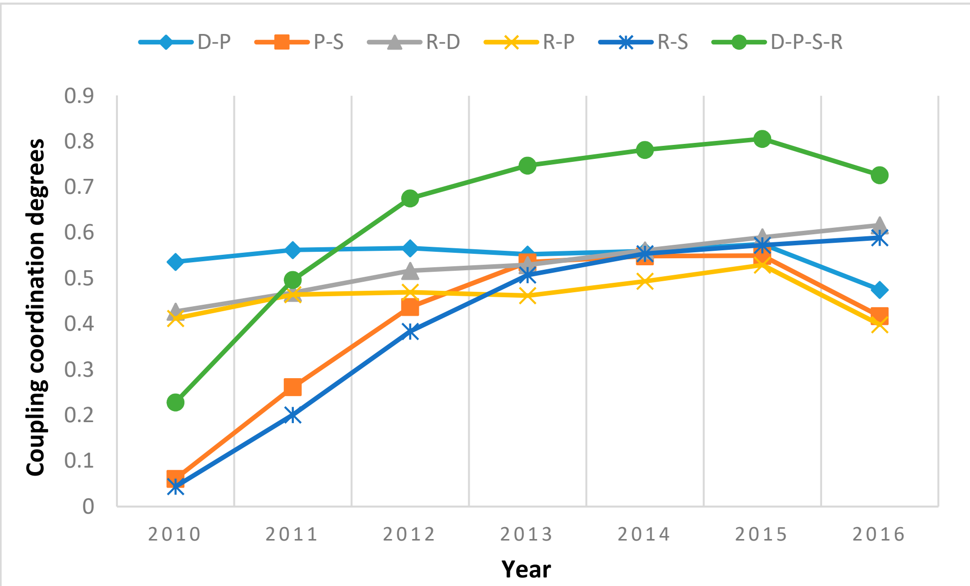

Figure 5. Coordination degrees between the subsystems in Shandong Province.

As can be seen from Figure 5, the coordination between the internal sustainable developmental subsystems in Shandong Province were steadily developing from 2010 to 2016, with the coupling coordination index rising from a moderate imbalance of 0.23 to an intermediate coordination of 0.81. The overall system coordination degree was generally higher than the coordination degree between the two subsystems. These results clearly demonstrated that the coordinated development of the complex sustainable green economy is due to the interactions of the various internal subsystems.

The coupling-coordination degree index for the response-state subsystems changed the most rapidly, with the coupling coordination degree index increasing from a high imbalance of 0.04

to reluctant coordination at 0.59, which also clearly indicated that the response-state subsystem coordination had a significant impact on green economy development. This was mainly because the scientific and technological support was generating more environmental compensation mechanisms, which were slowly encouraging scientific and technological innovation.

The coupling-coordination degree index of the pressure-state subsystems changed in an inverted U shape. From 2014–2015, the subsystem coupling coordination index attained the maximum at 0.55, which was the reluctant coordination level, which put pressure on the energy and environmental subsystems. Therefore, to promote continual positive change in the environment, continuous coordination between the energy and environmental subsystems is needed.

The coupling-coordination degree index for the response-pressure subsystem fluctuated between 0.4 and 0.5, and was therefore approaching coordination. This was because the scientific and technological responses were beginning to alleviate the energy and environmental pressures; however, there is significant room for improvement as the scientific and technological progress needs to be transformed into a driving economic development force to ease the development pressure.

The coupling-coordination degree indexes of the drivers-pressures and response-state subsystem remained at a reconciliation level. Therefore, it is necessary to continuously increase the drivers to promote steady green economy progress and ensure the application of the scientific and technological innovations

In short, Shandong Province needs to pay attention to coordinating the relationship between the science and technology response and the economy, society, energy, and the environment by increasing investment in science and technology innovation, and ensuring the innovations are transformed into economic development drivers. To fully develop the green economy in Shandong Province, its economic dependence on resources needs to be reduced, environmental pollution controls further strengthened, and a resource-conserving and environmentally-friendly society more fully promoted.

5. Conclusions

This paper constructed a sustainable regional green economy development index system from five aspects; economic, social, technological, resources, and environmental; using DPSIR and entropy-TOPSIS-coupling coordination to horizontally and vertically quantitatively analyze the sustainable green economy development. The model was verified by the actual situation of green economy development in Shandong Province from 2010 to 2016, which confirmed the feasibility of the method. The analysis in this study came to the following conclusions:

(1) The DPSIR was used to transform the internal development of each subsystem into a driver, a pressure, a state, or a response. Compared to traditional economic evaluations that tend to only reveal the surface conditions, the DPSIR was shown to more fully reveal the impact of the various factors on economic development and comprehensively analyze the interrelated relationships; therefore, based on the DPSIR theory, this paper established a green economic development evaluation index system, which provides a good theoretical framework for the global green economy development evaluation.

(2) The entropy weight-TOPSIS model established in this paper has important application value for the longitudinal analysis of green economy development. The analysis of the comprehensive green economy development scores each year was shown to determine the distance between the current development status and the ideal status in each year, thus allowing for a clarification of the green economy development trends; therefore, this method was also shown to have a good reference value for the multi-dimensional comprehensive analyses of regional green economic development systems.

(3) Coupling coordination theory was used to analyze the coordinated development of the various subsystems and identify the constraints on sustainable green economy development from economic, social, technological, resource, and environmental perspectives; therefore, as this method provides a valuable reference for the development of the green economy, targeted future development planning recommendations could be proposed based on the actual regional situation.

6. Suggested Countermeasures

The problems existing in Shandong Province during the development of green economy are universal, and the level of green economy development tends to rise as a whole, but the coordination between subsystems is still at a low level, economic growth and excessive resource consumption and weak technological support. coexist. In order to accelerate the transformation of the green economy, active measures still need to be taken. Possible measures include:

(1) Focus on developing its own advantageous industries. A green economy requires the coordinated development of the economy, the society, energy, the environment, and science and technology. As the economy acts as material support for the development process, it should be fully attended to; therefore, choosing industrial developments that suit green economy development can assist in growing the economy and reducing the dependence on environmentally polluting resources.

(2) Improve development efficiency and reduce total energy consumption. The key to successful green economy development is to increase investment in innovation and then apply these innovations to development to improve overall efficiency. Therefore, more focus and more investment need to be put on emerging industries such as green energy and environmental protection, and priority given to the energy conservation and environmental protection project development to ensure stable green economy growth, which means that the bottleneck between economic development, energy, and the environment must be broken.

(3) Focus on the development of green markets. By continuously focusing on the development of a green market, the enthusiasm in micro-subjects can be fully mobilized; however, the sustainable development of a green market requires dedicated policy guidance and constraints at the government level to encourage the development of the green economy.

However, regardless of our positive results, there were still several limitations in this study. The regional green economy development indicator system is a multi-level, multi-directional, multi-structured system. Due to indicator data measurability, this paper only considered economic, social, environmental, and other measurable indicators, and ignored the other factors that affect sustainable development, such as institutional factors and policy factors. Therefore, further research is needed to develop a more robust regional evaluation system.

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