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Article

Assessment of the Sustainable Development Capacity with the Entropy Weight Coefficient Method

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Abstract: Sustainable development is widely accepted in the world. How to reflect the sustainable development capacity of a region is an important issue for enacting policies and plans. An index system for capacity assessment is established by employing the Entropy Weight Coefficient method. The results indicate that the sustainable development capacity of Shandong Province is improving in terms of its economy subsystem, resource subsystem, and society subsystem whilst degrading in its environment subsystem. Shandong Province has shown the general trend towards sustainable development. However, the sustainable development capacity can be constrained by the resources such as energy, land, water, as well as environmental protection. These issues are induced by the economy development model, the security of energy supply, the level of new energy development, the end-of-pipe control of pollution, and the level of science and technology commercialization. Efforts are required to accelerate the development of the tertiary industry, the commercialization of high technology, the development of new energy and renewable energy, and the structure optimization of energy mix. Long-term measures need to be established for the ecosystem and environment protection.

Keywords: sustainable development capacity; environmental system; economy system; society system

1. Introduction

Sustainable development is one of the most important subjects worldwide in the 21st century. Since it was introduced in 1987, the sustainable development theory has been developed continuously. China has achieved rapid economy growth in last decades. However, the non-sustainable problems of the rapid economy growth are increasingly reflected by the conflicts with natural resources, ecosystem, and environment. Ecological crises, such as smog and severe water pollution, occur more frequently. China has become one of the world's most polluted countries that have severe impacts on the ecological system [1–3]. It is not sustainable to maintain a rapid economy growth on the cost of environment and excessive consumption of natural resources. The mode of economy development has to be transformed. As a result, the Chinese government has introduced the concept of ecological civilization to the national development strategy and is actively transforming the economy development mode to promote the sustainable social and economy development. Shandong province plays a crucial role in the national economy of China. In the past two decades, Shandong has maintained a high GDP growth rate and ranked third nationwide. However, Shandong is also a large energy consumer, which discharged a large amount of major pollutants. Shandong is one of the provinces that have the most national strategic economic development zones such as the Yellow River Delta High-Efficiency Eco-Economic Zone. Therefore, it is representative to evaluate China's sustainable development capacity (SDC) with Shandong province as the case study.

Since 1980s, the sustainable development theory has been studied extensively by a large number of international organizations, governments, and research institutes. Significant progress has been made in terms of index system and assessment methodology. Common index systems include system decomposition method [4], goal decomposition method [5], and integrated deductive method [6]. For example, the typical press-state-response (PSR) model was developed by the Organization for Economic Cooperation and Development (OCED) in 1993 [7–10]. The PSR model was subsequently extended to the driving force-state-response (DSR) model by the United Nations Commission on Sustainable Development (UNCSD) and United Nations Policy and Sustainable Development (DPCSD) in 1996 [11,12]. Later, in 1999, the PSR model was extended to driving-force-pressure-state-impact-response (DPSIR) frame and employed by the European Environment Agency [8,13].

In addition, the United Nations Statistics Division developed an index framework which covers economy, climate, solid wastes, and organization [14]. United Nations Environment Programme (UNEP) issued the Global Reporting Initiative (GRI) framework which includes three categories: society, economy, and environment [15]. To evaluate the targets and progress of every nation's government on promoting the sustainable development, UNCSD developed an index framework that consists of four systems of society, economy, environment, and governance. Different than the GRI framework, sustainable development policy and governance is emphasized in this framework [5]. In recent decades, China gradually initiated the research on environmental indexes and made some progress at different levels and different regions. China State Environmental Protection Administration has developed a comprehensive framework for environmental indicators which adopted the PSR model to describe the relationship between economy, environment, and resources [16]. Chinese Academy of Sciences Sustainable Development Research Group developed an index system of five support systems including living support, development support, environmental support, social support, and intelligence support. It includes 16 states, 48 variables, and 208 indictors [17]. Wang *et al*. [18] developed an evaluation index system to assess the impact of urbanization on air environment. It was developed by integrating Balanced Scorecard with PSR and was validated in the Shandong Province. Shi *et al*. [19] proposed a new "EcoDP" indicator, which consists of five sub-indicators to assess the regional sustainable development level. Zhan *et al.* [20] developed a multiple indicator model composed of society system, economic system, and environmental system, which studied the ecological and economic sustainability for a rapidly-urbanizing region in China. These previous studies provide a sound foundation for the development of sustainable development index of the regional system.

With the progress of research on the index system, more index evaluation methods are emerging. Listing technique is the most commonly used method for the sustainability evaluation. It mainly includes a typical framework and typical index. This method is featured with forming the sustainable index by means of standardizing, weight, and integrated processing [21]. The sustainable development evaluation index developed by various international bodies has provided useful references for the continuous studies on the sustainable development evaluation. These include systems developed by UNCSD [22], UNEP [23], Scientific Committee on Problems of the Environment (SCOPE) [24], Word Bank [25], European Commission [26], and the United States [27]. For comparison purpose, it is necessary to standardize the indexes due to different units and order of magnitude. Considering the various contributions of each index to sustainability, weighting is necessary for the standardized indexes. There are two index weighting methods, *i.e.*, objective weighting and subjective weighting. Objective weighting is to calculate the weight coefficients of indexes by means of statistics, such as factor analysis [7], regression analysis [28], and entropy methods [12] without considering the relative importance of the indexes. Subjective weighting methods are used to determine the relative importance of an index by using functions according to value judgments of experts or decision-makers. The major subjective weight methods include the analytic hierarchy process (AHP) [29] and Delphi method [30]. To date, different methods can be used for index standardizing, weighting, and integrating due to the lack of commonly-accepted criteria [21]. Therefore, the absolute values, and even the relative ranking of the sustainability assessment, may vary according to different methods of standardizing, weighting, and integrating.

Entropy theory belongs to the area of thermodynamics. However, it has been employed in many specific areas since the middle of the last century [31,32]. These specific areas include: information entropy [33], administration entropy [34], economy entropy [35,36], and environment entropy [12]. It provides the guides for the research on the nonlinear theory. Entropy increase theory is the fundamental principle in nature. The value of entropy reflects the state of order of a system. To develop a system orderly, a mechanism of negative entropy flow must be introduced. This theory provides useful research perspectives and development approaches for improving the SDC of a system. Currently, this theory has been successfully applied to the research field of sustainable development. For example, Peng and Zhao [37] proposed the Hopfield neural network energy function model. Similarly, the negative entropy flow theory should be optimized by using the objective functions and controlling the security risk of resources industry. Gao and Hu [38] argued that negative entropy flow approaches help to predict the economic downturns. Entropy Weight Coefficient Method (EWCM) is one of the methods which applies entropy theory to solve sustainable development problems. Cheng *et al.* [39] used a method of the coupled principal component analysis and entropy weight coefficient to evaluate the different environmental protection plans. Wang [40] made a comparison between this method and the traditional factor analysis method, which reflect the same evaluation result in the research of a city's comprehensive competitiveness. Compared with other evaluation methods, EWCM overcomes the subjectivity of the evaluation and the problems of the internal factors that affect the sustainable development system. The integrity of evaluation results was also taken into consideration. Therefore, the successful application of EWCM in this research enriched the evaluation methodology system for sustainable development, which is also an innovation of the study.

In summary, the investigation of the SDC of a region should focus on the operational mechanism of systems. Objective quantitative assessment methods should be adopted to allow the profound analysis of crucial factors to the sustainable development, consequently developing a proper index evaluation system. Therefore, the evaluation of SDC is performed in this paper by using EWCM to overcome the shortcomings of the subjective qualitative assessment. A quantitative comparison method is adopted to seek measures for sustainable development through profound analysis on the mechanism of drivers and barriers to the system's sustainable development. These findings provide a good reference for the policy making process.

2. Models

2.1. Construction of the Index System

According to the literature survey findings, the fundamental factors affecting the regional sustainable development include social factors, economic factors, and environmental factors [5,17,38,41]. China's economic development with high energy consumption and severe pollution has led to substantial pressures on natural resources and the environment [42]. In order to highlight the importance of resource conservation and environment protection, the model is constructed considering the society sub-system, economy sub-system, environment sub-system, and resource sub-system as the first-order indicators. The economy sub-system reflects not only the speed but also the quality of regional economic development [41].The economic development considers mainly economic returns and economic scale. The economic development quality includes the proportion of various industries and the contribution of the tertiary industry [18]. This sub-system includes 11 second-order indicators. The society sub-system includes mainly population quality, living conditions, living quality, and the level of science-technology. It includes 14 second-order indicators [18]. The resource sub-system provides crucial support for the sustainable development of a regional system. It reflects not only the carrying capacity of energy resources, land resources, and water resources, but also the relevant information about the development of new energy resources and the transformation of the energy mix. It is well recognized that the new energies are the important resources that can ensure the sustainable development of the energy industry [43,44]. It includes eight second-order indicators. Environmental capacity and environmental carrying capacity have become major barriers to the sustainable development of China. The environmental sub-system mainly includes environmental governance, pollutant discharge, and investment on environmental protection. It includes 10 second-order indicators [42,45]. Data of these 43 indicators are retrieved from the Statistical Yearbook and Environmental Protection Yearbook of Shandong Province. The evaluation index systems of SDC from 2000 to 2013 are shown in Tables 1 and 2.

2.2. Model Development of EWCM

2.2.1. Data Standardization

Entropy is a measure of system uncertainty. It can be used to determine the entropy by measuring and assessing the amount of information included in the data of an index system. If a comprehensive evaluation system is made up of m samples and n indicators, the mathematical model is as follows:

$$S = \{s_1, s_2, \ldots s_i, \ldots s_m\} \quad i = (1,2,\ldots,m)$$

Every sample (object of evaluation) $u_1$has n indicators:

$$u_i = \{X_{i1}, X_{i2}, \ldots X_{ij}, \ldots X_{in}\} \quad j = (1,2,\ldots,n) \tag{1}$$

Hence, the initial data matrix of the evaluation system X is expressed by Equation (2):

$$X = \begin{bmatrix} x_{11} & x_{12} & \cdots & x_{1n} \\ x_{21} & x_{22} & \cdots & x_{2n} \\ \cdots & \cdots & \cdots & \cdots \\ x_{m1} & x_{m2} & \cdots & x_{mn} \end{bmatrix} \quad i = (1,2,\ldots,m), \quad j = (1,2,\ldots,n) \tag{2}$$

x_{ij} is the value of the j^{th} indicator of the i^{th} sample. The dimension, magnitude, and positive or negative ordination vary from indicator to indicator. Therefore, the initial data have to be standardized. Assuming the ideal value of the evaluation indictor j is x_j^*, its value depends on the property of the evaluation indictor. All indicators are classified as a positive or negative index; a positive index indicates an upward development trend and growth, whereas a negative index indicates a downward development trend. For a positive index, the larger x_j^*, the better. For negative index, the smaller x_j^*, the better.

Define d_{ij} as the proximity of x_{ij} to its ideal value x_j^*, and $d_{ij} \in [i=1,2,\ldots,m; j=1,2,\ldots,n]$. For index x_j, the large variation to x_{ij} is indicates this index plays a more significant role in the overall evaluation, and vice versa. If the index values of an indicator are all equal, it will not be counted in the overall evaluation. Using this method, all factors that promote or impede the sustainable development of a system can be identified. Measures promoting the sustainable development of a system can be developed accurately by analyzing these factors.

Table 1. Evaluation index system for SDC of Shandong Province (2000–2013).

First order	Second order	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013
Economy sub-system	EC1	9326	10,195	11,340	13,268	16,413	19,934	23,603	27,604	32,936	35,894	41,106	47,335	51,768	56,323
	EC2	254.27	280.78	350.93	532.84	762.90	1054.29	1113.61	1253.70	1543.59	1903.10	2327.67	2676.97	3125.60	3678.91
	EC3	14.64	23.62	6.46	16.97	16.05	29.55	26.38	23.53	16.81	12.34	25.05	25.70	17.46	12.33
	EC4	654.48	683.99	795.81	1084.21	1491.23	2226.33	2826.14	3541.65	4164.33	4701.36	5668.96	6848.58	7802.45	8914.02
	EC5	6.05	6.94	6.86	6.95	6.82	8.05	10.83	12.16	12.69	13.44	13.21	13.67	15.76	16.36
	EC6	14.8	14.4	13.2	11.9	11.8	10.6	9.7	9.7	9.6	9.5	9.2	8.8	8.6	8.7
	EC7	49.7	49.3	50.3	53.5	56.5	57.4	57.7	56.9	57	55.8	54.2	52.9	51.4	50.1
	EC8	35.5	36.3	36.5	34.6	31.7	32.0	32.6	33.4	33.4	34.7	36.6	38.3	40.0	41.2
	EC9	256.2	258.2	259.8	257.3	251.7	253.4	255.5	257.1	257.2	259.9	264	267.8	271.4	273.7
	EC10	49.95	49.98	49.99	49.80	49.55	48.30	47.89	47.67	47.32	47.36	46.80	46.32	46.64	46.40
	EC11	33.4	38.9	32.7	29.6	29.2	32.1	31.9	33	37.5	30.2	35.8	38.2	37.1	35.3
Resource sub-system	RE1	56.245	52.10	49.25	48.97	34.95	41.59	19.98	38.71	32.87	28.50	30.91	34.76	27.41	29.17
	RE2	96.49	115.50	132.42	143.84	143.95	139.96	140.83	146.17	146.15	146.00	160.56	163.52	172.62	151.88
	RE3	7.60	10.80	11.40	2.2.	4.90	16.00	18.20	9.50	27.40	156.60	334.80	533.50	791.90	1161.90
	RE4	0.58	0.98	1.14	0.86	1.15	1.11	1.04	1.00	0.32	0.33	0.5	0.24	0.43	0.92
	RE5	835.4	1033.4	910.7	983.6	1118.4	1230.3	1034.6	992.2	1130.5	1199.7	1290.1	691.60	798.00	679.30
	RE6	99.77	116.50	131.21	159.75	196.06	256.88	287.86	311.94	321.16	345.36	362.99	385.07	400.36	408.37
	RE7	74.09	76.87	81.84	79.47	75.98	80.76	79.8	80.47	77.98	77.13	76.17	76.47	75.21	73.82
	RE8	312.23	363.51	413.5	472.6	537.52	603.00	643.66	690.73	733.55	734.44	775.69	801.1	819.5	807.9
Environment sub-system	EN1	77.18	84.05	86.96	89.21	90.77	91.64	92.42	93.32	93.72	94.79	95.40	95.68	96.08	96.29
	EN2	82.3	85.5	84.6	87.7	90.5	89.9	92.2	91.5	88.7	92.3	92.8	93.2	95.1	94.2
	EN3	92.6	94.4	93.7	92.2	95.5	97.5	96.6	95.9	97.7	98	98.2	97.9	98.4	98.1
	EN4	1.05	1.13	1.22	1.58	1.75	1.99	2.22	2.37	2.59	2.86	3.15	3.68	3.87	4.63
	EN5	54.07	62.15	65.59	67.86	79.22	91.75	110.11	119.35	129.88	141.38	160.38	195.33	183.43	181.72
	EN6	2290.00	2352.71	2307.09	2457.82	2640.14	2830.38	3026.37	3342.55	3589.10	3867.31	4363.71	4433.31	4791.00	4945.70
	EN7	1.80	1.72	1.69	1.84	1.82	2.00	1.96	1.82	1.69	1.59	1.54	1.86	1.75	1.64
	EN8	670	650	620	620	520	620	580	460	440	420	390	780	700	700
	EN9	951.2	921.9	859.4	829.5	778.9	770.3	758.1	719.9	678.6	647.0	620.5	1982.5	1921.2	1845.7
	EN10	86,017	84,415	83,668	77,456	80,884	84,259	83,235	76,697	70,375	67,305	66,484	172,945	168,583	161,517

Table 1. *Cont.*

First order	Second order	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013
Society sub-system	SO1	33.77	49.70	64.26	83.44	103.06	126.65	143.75	153.77	162.90	168.21	170.31	170.76	171.24	174.51
	SO2	26.78	27.84	29.00	31.05	32.15	34.03	34.68	36.68	37.51	37.47	40.08	40.93	41.51	53.75
	SO3	6490	7101	7615	8400	9437.8	10,744.8	12,192	14,265	16,305	17,811	19,946	22,792	25,755	28,264
	SO4	33.86	35.15	34.59	34.38	34.76	35.48	35.12	37.81	38.06	36.64	37.54	38.26	36.59	38.27
	SO5	1.9	1.8	2.0	1.9	2.1	2.2	2.0	2.1	2.1	1.9	2.0	2.2	2.1	2.2
	SO6	18.0	17.9	18.3	17.1	17.8	18.2	19.5	20	20.4	18.8	18.6	20.9	22.2	20.9
	SO7	3.19	3.31	3.22	3.55	3.47	3.51	3.20	3.38	3.44	3.25	3.43	3.63	3.86	3.97
	SO8	13.14	12.79	12.69	12.79	13.05	13.20	13.25	13.40	13.97	14.29	14.55	14.88	15.41	16.56
	SO9	17.87	18.67	18.87	20.21	21.28	22.30	22.95	23.94	25.31	26.40	27.69	29.41	31.48	34.34
	SO10	4.695	8.953	11.32	12.30	13.48	14.75	16.71	18.35	20.46	40.36	43.28	45.45	47.32	55.44
	SO11	0.48	0.53	0.57	0.65	0.76	0.81	0.85	0.94	1.02	1.29	1.38	1.47	1.53	1.56
	SO12	15.62	13.12	16.89	16.75	17.93	17.64	19.28	20.97	23.16	24.97	26.70	27.53	31.29	33.42
	SO13	6.258	6.696	7.445	8.806	10.102	11.387	12.272	13.396	14.371	15.522	16.489	17.181	18.208	19.063
	SO14	6962	6724	7293	9067	9733	10,743	15,937	22,821	26,688	34,513	51,490	58,843	75,522	76,976

Table 2. Evaluation index referred system for SDC of Shandong Province (2000–2013).

Second order	Indicators referred	Unit
GDP per Capita	EC1	RMB
Total investment in fixed Assets	EC2	Billion RMB
Growth rate of government revenue	EC3	%
Gross heavy industrial output value	EC4	Billion RMB
Proportion of high-tech industry output value in GDP	EC5	%
Proportion of primary industry in GDP	EC6	%
Proportion of secondary industry in GDP	EC7	%
Proportion of tertiary industry in GDP	EC8	%
Index of industrial structure supererogation	EC9	/
Industrial structure coefficient	EC10	/
Tertiary industry contribution rate	EC11	%
Total amount of water resource	RE1	Billion M^3
Primary energy production	RE2	Million tons

Table 2. *Cont.*

Second order	Indicators referred	Unit
Hydropower and wind power production	RE3	Thousand tons
Electricity production elastic coefficient	RE4	/
Natural gas production	RE5	Thousand tons
primary energy consumption	RE6	Million tons
Proportion of coal in primary energy consumption	RE7	%
Industrial land	RE8	Km^2
Industrial solid waste disposal rate	EN1	%
Treatment of industrial waste water compliance rate	EN2	%
Soot standard discharge rate	EN3	%
Ratio of budget for environmental protection in financial expenditure	EN4	%
Discharge of industrial solid wastes	EN5	Million tons
Waste water discharge	EN6	Million tons
Sulfur dioxide emissions	EN7	Million tons
Soot emissions	EN8	Thousand tons
COD discharge	EN9	Thousand tons
NH_3-N discharge	EN10	Tons
Number of ten thousand people in college students	SO1	Number
Proportion of urban population in total population	SO2	%
Urban residents disposable income	SO3	RMB
Engel coefficient	SO4	/
Proportion of fiscal expenditure for science-technology	SO5	%
Proportion of fiscal expenditure for education	SO6	%
Proportion of fiscal expenditure for health	SO7	%
Unemployment insurance rate	SO8	%
Pension insurance rate	SO9	%
Medical insurance rate	SO10	%
Road density	SO11	Km/Km^2
Number of hospital beds for ten thousand people	SO12	Number
Green space area per capita park	SO13	Hectare/ten thousand people
Number of patent ownership	SO14	Number

The proximity of positive indicators is defined as Equation (3):

$$d_{ij} = \frac{x_{ij}}{\max\{x_{i1}, x_{i2}, ..., x_{in}\}} \tag{3}$$

The proximity of negative indicators is defined as Equation (4):

$$d_{ij} = \frac{\min\{x_{i1}, x_{i2}, ..., x_{in}\}}{x_{ij}} \tag{4}$$

The standardized value of d_{ij} is defined as Equation (5):

$$y_{ij} = \frac{d_{ij}}{\sum_{i=1}^{m} d_{ij}} \tag{5}$$

Equation (6) is the standardized matrix:

$$\mathrm{Y}=\begin{bmatrix} y_{11} & y_{12} & \cdots & y_{1n} \\ y_{21} & y_{22} & \cdots & y_{2n} \\ \cdots & \cdots & \cdots & \cdots \\ y_{m1} & y_{m2} & \cdots & y_{mn} \end{bmatrix} \mathrm{i}=(1,2,...,\mathrm{m}), \quad \mathrm{j}=(1,2,...,\mathrm{n}) \tag{6}$$

2.2.2. Information Entropy Model

Information entropy theory was introduced by Shannon in 1948, which is a measure of the average information value of a stochastic system. Based on the definition of information entropy, information entropy of the j^{th} indicator of the evaluation matrix Y is defined by Equation (7):

$$E_j = -k\sum_{i=1}^{m} y_{ij} \ln y_{ij} \tag{7}$$

where, $E_j \geq 0; k \geq 0$. Constant K is only affected by the number of system samples m. For a system with total disordered information, the amount of order is zero with maximum entropy, $E = 1$. Consequently, $0 \leq E \leq 1$. Equation (8) can be derived:

$$k = \frac{1}{\ln m} \tag{8}$$

The information value of an indicator depends on the difference of its information entropy E_j and 1. It is expressed by σ_j:

$$\sigma_j = 1 - E_j \tag{9}$$

The weight is to be calculated by the utility value of the index information determined by EWCM. The utility value is largest, the greatest importance of evaluation. The weight of j^{th} index is defined by Equation (10):

$$w_j = \frac{\sigma_j}{\sum_{j=1}^{n} \sigma_j} \tag{10}$$

Entropy is additive. If the sustainable development evaluation system has multiple levels, the entropy weight w_j of the upper level structure can be determined proportionally according to the effective value of indictor information of the lower level structure. It is to obtain the sum of effective value of every class of indicators by utilizing the effective value of every indicator σ_j to calculate the effective value of every class of indicators in the lower level structure, expressed by $\lambda_k (K = 1,2,...,k)$. Eventually, the sum of all indicators can be obtained:

$$\lambda = \sum_{k=1}^{n} \lambda_k \tag{11}$$

According Equations (10) and (11), Equation (12) is obtained:

$$w_j = \frac{\sigma_j}{\lambda} \tag{12}$$

f_{ij} is the sustainable development evaluation value of x_{ij} expressed by Equation (13):

$$f_{ij} = w_j \times d_{ij} \tag{13}$$

The sustainable development evaluation value of the i^{th} index is expressed by f_i with Equation (14):

$$f_i = \sum_{j=1}^{n} f_{ij} \tag{14}$$

According to Equations (1)–(12), SDC of each sub-system can be calculated. The weight (w_j) and SDC (f_i) of the entire system can be obtained by integrating all sub-systems.

3. Results and Discussion

3.1. SDC of Sub-Systems

The standardization matrix for the evaluation index system of SDC can be developed according to Equations (1)–(4). Consequently, Equations (6)–(12) were used to calculate the information entropy, weight, and the value of SDC of each sub-system (see Tables 3 and 4 and Figure 1).

Table 3. SDC of each subsystem based on EWCM of Shandong Province (2000–2013).

First order	Second order	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	Weight
Economy sub-system	EC1	3.06	3.34	3.72	4.35	5.38	6.53	7.74	9.05	10.79	11.76	13.47	15.51	16.97	18.46	18.46
	EC2	2.17	2.39	2.99	4.54	6.50	8.98	9.48	10.68	13.15	16.21	19.82	22.80	26.62	31.33	31.33
	EC3	3.63	5.85	1.60	4.20	3.97	7.32	6.53	5.83	4.16	3.06	6.20	6.36	4.32	3.05	7.32
	EC4	2.44	2.55	2.97	4.04	5.56	8.30	10.54	13.21	15.53	17.53	21.14	25.54	29.10	33.24	33.24
	EC5	2.47	2.84	2.80	2.84	2.79	3.29	4.43	4.97	5.19	5.49	5.40	5.59	6.44	6.68	6.68
	EC6	1.05	1.08	1.17	1.30	1.31	1.46	1.60	1.60	1.61	1.63	1.68	1.76	1.80	1.78	1.80
	EC7	0.20	0.20	0.19	0.18	0.17	0.17	0.17	0.17	0.17	0.18	0.18	0.19	0.19	0.20	0.20
	EC8	0.32	0.33	0.33	0.31	0.29	0.29	0.29	0.30	0.30	0.31	0.33	0.34	0.36	0.37	0.37
	EC9	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.04	0.04	0.04	0.04
	EC10	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05
	EC11	0.44	0.51	0.43	0.39	0.39	0.42	0.42	0.44	0.50	0.40	0.47	0.50	0.49	0.47	0.51
	Sustainable development capacity	**15.84**	**19.16**	**16.28**	**22.24**	**26.43**	**36.84**	**41.28**	**46.31**	**51.48**	**56.65**	**68.78**	**78.68**	**86.37**	**95.67**	
Resource sub-system	RE1	2.72	2.52	2.38	2.37	1.69	2.01	0.97	1.87	1.59	1.38	1.50	1.68	1.33	1.41	2.72
	RE2	0.35	0.42	0.49	0.53	0.53	0.51	0.52	0.54	0.54	0.53	0.59	0.60	0.63	0.56	0.63
	RE3	0.49	0.70	0.74	0.14	0.32	1.03	1.17	0.61	1.77	10.10	21.60	34.41	51.08	74.94	74.94
	RE4	0.84	1.04	0.91	0.99	1.12	1.23	1.04	1.00	1.13	1.20	1.29	0.69	0.80	0.68	1.29
	RE5	4.81	5.95	5.24	5.66	6.44	7.08	5.96	5.71	6.51	6.91	7.43	3.98	4.59	3.91	7.43
	RE6	9.06	7.75	6.88	5.66	4.61	3.52	3.14	2.90	2.81	2.62	2.49	2.35	2.26	2.21	9.06
	RE7	0.04	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.04	0.04
	RE8	3.89	3.34	2.94	2.57	2.26	2.01	1.89	1.76	1.66	1.65	1.57	1.52	1.48	1.50	3.89
	Sustainable development capacity	**22.19**	**21.76**	**19.61**	**17.95**	**17.00**	**17.44**	**14.71**	**14.42**	**16.04**	**24.43**	**36.49**	**45.26**	**62.21**	**85.26**	

Table 3. *Cont.*

First order	Second order	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	Weight
Environment sub-system	EN1	0.40	0.43	0.45	0.46	0.47	0.47	0.48	0.48	0.48	0.49	0.49	0.49	0.49	0.50	0.50
	EN2	0.21	0.22	0.22	0.23	0.24	0.23	0.24	0.24	0.23	0.24	0.24	0.24	0.25	0.25	0.25
	EN3	0.07	0.07	0.07	0.07	0.07	0.07	0.07	0.07	0.07	0.07	0.07	0.07	0.07	0.07	0.07
	EN4	6.23	6.71	7.24	9.38	10.38	11.81	13.17	14.06	15.37	16.97	18.69	21.84	22.96	27.47	27.47
	EN5	25.93	22.56	21.37	20.66	17.70	15.28	12.73	11.75	10.79	9.92	8.74	7.18	7.64	7.71	25.93
	EN6	10.33	10.05	10.25	9.62	8.96	8.36	7.82	7.08	6.59	6.12	5.42	5.34	4.94	4.78	10.33
	EN7	0.65	0.68	0.70	0.64	0.65	0.59	0.60	0.65	0.70	0.74	0.76	0.63	0.67	0.72	0.76
	EN8	3.89	4.01	4.20	4.20	5.01	4.20	4.49	5.67	5.92	6.21	6.68	3.34	3.72	3.72	6.68
	EN9	10.67	11.01	11.81	12.24	13.03	13.18	13.39	14.10	14.96	15.69	16.36	5.12	5.28	5.50	16.36
	EN10	9.00	9.18	9.26	10.00	9.58	9.19	9.31	10.10	11.01	11.51	11.65	4.48	4.59	4.80	11.65
	Sustainable development capacity	**67.38**	**64.92**	**65.57**	**67.49**	**66.08**	**63.38**	**62.29**	**64.18**	**66.12**	**67.94**	**69.11**	**48.73**	**50.63**	**55.52**	
Society sub-system	SO1	1.74	2.56	3.31	4.29	5.30	6.52	7.40	7.91	8.38	8.66	8.76	8.79	8.81	8.98	8.98
	SO2	0.88	0.92	0.95	1.02	1.06	1.12	1.14	1.21	1.24	1.23	1.32	1.35	1.37	1.77	1.77
	SO3	2.60	2.85	3.06	3.37	3.79	4.31	4.89	5.72	6.54	7.15	8.00	9.14	10.33	11.34	11.34
	SO4	0.08	0.08	0.08	0.08	0.08	0.08	0.08	0.09	0.09	0.09	0.09	0.09	0.09	0.09	0.09
	SO5	0.16	0.16	0.17	0.16	0.18	0.19	0.17	0.18	0.18	0.16	0.17	0.19	0.18	0.19	0.19
	SO6	0.24	0.23	0.24	0.22	0.23	0.24	0.25	0.26	0.27	0.25	0.24	0.27	0.29	0.27	0.29
	SO7	0.73	0.76	0.74	0.82	0.80	0.81	0.74	0.78	0.79	0.75	0.79	0.83	0.89	0.91	0.23
	SO8	0.26	0.25	0.25	0.25	0.26	0.26	0.26	0.27	0.28	0.28	0.29	0.30	0.31	0.33	0.33
	SO9	1.07	1.11	1.13	1.21	1.27	1.33	1.37	1.43	1.51	1.58	1.65	1.76	1.88	2.05	2.05
	SO10	1.87	3.58	4.52	4.91	5.38	5.89	6.67	7.33	8.17	16.12	17.28	18.15	18.90	22.14	22.14
	SO11	2.33	2.58	2.77	3.16	3.69	3.94	4.13	4.57	4.96	6.27	6.71	7.14	7.43	7.58	7.58
	SO12	1.79	1.50	1.94	1.92	2.05	2.02	2.21	2.40	2.65	2.86	3.06	3.15	3.59	3.83	3.83
	SO13	1.97	2.11	2.34	2.77	3.18	3.58	3.86	4.22	4.52	4.89	5.19	5.41	5.73	6.00	6.00
	SO14	3.18	3.07	3.33	4.14	4.45	4.91	7.28	10.43	12.20	15.77	23.53	26.89	34.52	35.18	35.18
	Sustainable development capacity	**18.91**	**21.76**	**24.83**	**28.34**	**31.73**	**35.20**	**40.47**	**46.79**	**51.78**	**66.05**	**77.09**	**83.47**	**94.31**	**100.67**	

Table 4. SDC of the entire system based on EWCM of Shandong Province (2000–2013).

First order	Second order	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	Weight
Economy sub-system	EC1	0.72	0.79	0.87	1.02	1.26	1.54	1.82	2.13	2.54	2.77	3.17	3.65	3.99	4.34	4.34
	EC2	0.51	0.56	0.70	1.07	1.53	2.11	2.23	2.51	3.09	3.81	4.66	5.36	6.26	7.36	7.36
	EC3	0.85	1.37	0.38	0.99	0.93	1.72	1.54	1.37	0.98	0.72	1.46	1.50	1.02	0.72	1.72
	EC4	0.57	0.60	0.70	0.95	1.31	1.95	2.48	3.10	3.65	4.12	4.97	6.00	6.84	7.81	7.81
	EC5	0.58	0.67	0.66	0.67	0.65	0.77	1.04	1.17	1.22	1.29	1.27	1.31	1.51	1.57	1.57
	EC6	0.25	0.25	0.28	0.31	0.31	0.34	0.38	0.38	0.38	0.38	0.40	0.41	0.42	0.42	0.42
	EC7	0.05	0.05	0.05	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.05	0.05
	EC8	0.08	0.08	0.08	0.07	0.07	0.07	0.07	0.07	0.07	0.07	0.08	0.08	0.08	0.09	0.09
	EC9	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01
	EC10	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01
	EC11	0.10	0.12	0.10	0.09	0.09	0.10	0.10	0.10	0.11	0.09	0.11	0.12	0.11	0.11	0.12
Resource sub-system	RE1	1.08	1.00	0.94	0.94	0.67	0.80	0.38	0.74	0.63	0.55	0.59	0.67	0.53	0.56	1.08
	RE2	0.14	0.17	0.19	0.21	0.21	0.20	0.20	0.21	0.21	0.21	0.23	0.24	0.25	0.22	0.25
	RE3	0.19	0.28	0.29	0.06	0.13	0.41	0.46	0.24	0.70	4.00	8.55	13.62	20.22	29.66	29.66
	RE4	0.33	0.41	0.36	0.39	0.44	0.49	0.41	0.39	0.45	0.48	0.51	0.27	0.32	0.27	0.51
	RE5	1.48	2.50	2.91	2.20	2.94	2.84	2.66	2.56	0.82	0.84	1.28	0.61	1.10	2.35	2.94
	RE6	3.58	3.07	2.73	2.24	1.82	1.39	1.24	1.15	1.11	1.04	0.99	0.93	0.89	0.88	3.58
	RE7	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01
	RE8	1.54	1.32	1.16	1.02	0.89	0.80	0.75	0.70	0.66	0.65	0.62	0.60	0.59	0.60	1.54
Environment sub-system	EN1	0.04	0.04	0.04	0.04	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05
	EN2	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02
	EN3	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01
	EN4	0.61	0.65	0.70	0.91	1.01	1.15	1.28	1.37	1.50	1.65	1.82	2.13	2.24	2.67	2.67
	EN5	2.52	2.20	2.08	2.01	1.72	1.49	1.24	1.14	1.05	0.97	0.85	0.70	0.74	0.75	2.52
	EN6	1.01	0.98	1.00	0.94	0.87	0.81	0.76	0.69	0.64	0.60	0.53	0.52	0.48	0.47	1.01
	EN7	0.06	0.07	0.07	0.06	0.06	0.06	0.06	0.06	0.07	0.07	0.07	0.06	0.07	0.07	0.07
	EN8	0.38	0.39	0.41	0.41	0.49	0.41	0.44	0.55	0.58	0.60	0.65	0.33	0.36	0.36	0.65
	EN9	1.04	1.07	1.15	1.19	1.27	1.28	1.30	1.37	1.46	1.53	1.59	0.50	0.51	0.54	1.59
	EN10	0.88	0.89	0.90	0.97	0.93	0.89	0.91	0.98	1.07	1.12	1.13	0.44	0.45	0.47	1.13

Table 4. *cont.*

First order	Second order	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	Weight
	EN10	0.88	0.89	0.90	0.97	0.93	0.89	0.91	0.98	1.07	1.12	1.13	0.44	0.45	0.47	1.13
Society sub-system	SO1	0.47	0.70	0.90	1.17	1.44	1.77	2.01	2.15	2.28	2.35	2.38	2.39	2.40	2.44	2.44
	SO2	0.24	0.25	0.26	0.28	0.29	0.30	0.31	0.33	0.34	0.34	0.36	0.37	0.37	0.48	0.48
	SO3	0.71	0.77	0.83	0.92	1.03	1.17	1.33	1.56	1.78	1.94	2.17	2.48	2.81	3.08	3.08
	SO4	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.03	0.03	0.02	0.03	0.03	0.02	0.03	0.03
	SO5	0.05	0.04	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05
	SO6	0.06	0.06	0.06	0.06	0.06	0.06	0.07	0.07	0.07	0.07	0.07	0.07	0.08	0.07	0.08
	SO7	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.06	0.06	0.06	0.06
	SO8	0.07	0.07	0.07	0.07	0.07	0.07	0.07	0.07	0.08	0.08	0.08	0.08	0.08	0.09	0.09
	SO9	0.29	0.30	0.31	0.33	0.34	0.36	0.37	0.39	0.41	0.43	0.45	0.48	0.51	0.56	0.56
	SO10	0.51	0.97	1.23	1.34	1.46	1.60	1.81	1.99	2.22	4.38	4.70	4.93	5.14	6.02	6.02
	SO11	0.63	0.70	0.75	0.86	1.00	1.07	1.12	1.24	1.35	1.70	1.82	1.94	2.02	2.06	2.06
	SO12	0.49	0.41	0.53	0.52	0.56	0.55	0.60	0.65	0.72	0.78	0.83	0.86	0.98	1.04	1.04
	SO13	0.54	0.57	0.64	0.75	0.86	0.97	1.05	1.15	1.23	1.33	1.41	1.47	1.56	1.63	1.63
	SO14	0.86	0.84	0.91	1.13	1.21	1.33	1.98	2.83	3.31	4.29	6.39	7.31	9.38	9.56	9.56
Sustainable development capacity of whole system		**23.64**	**25.34**	**25.41**	**26.39**	**28.23**	**31.17**	**32.74**	**35.69**	**37.04**	**45.51**	**56.47**	**62.70**	**74.58**	**89.61**	

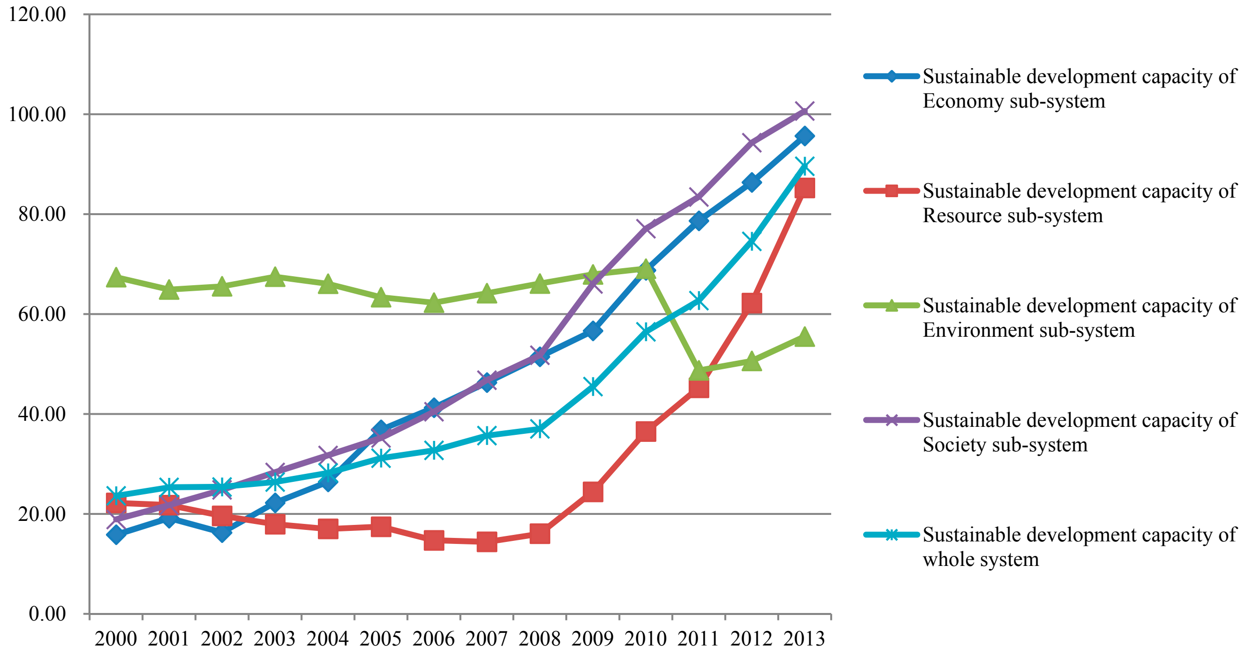

Figure 1. Sustainable development capacity of Shandong Province (2000–2013).

As shown in Table 3 and Figure 1, SDC of the economic sub-system in Shandong Province increases continuously from 15.84 in 2000 to 95.67 in 2013, with an annual growth rate of 15% on average. Urbanization grows continuously with the acceleration of industrialization in Shandong. The urbanization rate in Shandong was 53.75% in 2013, which is 26.97% higher than that in 2000. Fast urbanization processes accelerate the continuous optimization of the industrial structure. The proportion of the tertiary industry to all industries increased from 35.5% in 2000 to 41.2% in 2013. The contribution of the tertiary industry reached 35.3%. Similarly, the index of industrial structure supererogation increased from 256.2 in 2000 to 273.7 in 2013. The coefficient of industrial structure decreased continuously from 49.95 in 2000 to 46.40 in 2013. The continuous optimization of industry structure promoted the economic development. GDP per capita reached to 56,323 RMB in 2013 with an annual growth rate of 14.84%. However, the proportion of secondary industry to all industries is still around for 50%. This indicates the secondary industry remains the major driver of the economy development. The gross output of the heavy industry increases continuously with an annual growth rate of 22.25%. This suggested that the heavy industry is the most significant driving factor of the economic system. By contrast, the proportion of high and new technology industry to all industries is as low as 16.36% in 2013 despite a rapid growth. Such an imbalanced industrial development model is detrimental to the resources, energy, and environment and, consequently, the sustainable development in Shandong.

SDC of the resource sub-system increased continuously from 22.19 in 2000 to 85.26 in 2013 with an annual growth rate of 10.9% on average. The growth rate is lower than that of the economic system. However, the resource system can, in turn, affect SDC of the economic system. As shown in Table 1, the total water resource in Shandong declined from 56.25 billion cubic meters in 2000 to 29.17 billion cubic meters in 2013 with an average decreasing rate of 4.93%. The reduction of water supply affected not only the industry development but also the living of local residents [46]. Although the total primary energy output of Shandong increased continuously to 151.88 million tons in 2013, the primary energy consumption was 408.37 million tons. The energy supply of Shandong is not able to fulfill the energy demand of economic development. With the acceleration of industry development in Shandong, the demand of industrial land increased continuously from 312.23 square kilometers in 2000 to 807.9 square kilometers in 2013 with an annual growth rate of 7.59%. This has drawn great concerns of local governments with the carrying capacity of land resources to meet such high industrial land demand in Shandong [47]. In addition, the issue of energy mix is prominent with over 70% being coal. China is rich in coal but with low petroleum and scarce gas resources. China's energy consumption is coal dominated. It is well reflected in China's economy development. The security of energy supply, the guarantee of water resources, and the carrying capacity of land have become the significant barriers to the sustainable economy development [48]. Therefore, a series of policies regarding energy, water, and land conservation have been developed and adopted. These include a comprehensive work plan for energy conservation and emission reduction, State Council air pollution prevention and control action plan, State Council water pollution prevention and control action plan, *etc*. Similarly, Shandong has been actively developing new energy resources to ease the pressures of energy supply and environmental pollution. The output of wind energy and hydroelectric energy reached 1.16 million tons of standard coal equivalent (SCE) in 2013. The annual average growth rate is 47.24% in comparison with the 7600 tons of SCE in 2000. However, it is far behind the targets of the newly-developed energy and renewable energy development program. It is especially important to speed up the development of the other new and renewable energy resources such as solar energy, bio-energy, nuclear energy, *etc*.

SDC of the environment sub-system decreased continuously from 67.38 in 2000 to 55.52 in 2013 with an annual growth rate of −1.48%. The conflicts between economy development and environment protection become increasingly urgent. The discharge of industrial solid waste and waste water, the emission of soot, COD, and ammonia-nitrogen continued to increase with an annual growth rate of 9.77%, 6.10%, 0.34%, 5.23%, and 4.97%, respectively. The last decades have witnessed some improvements in the treatment rate of industrial solid waste, the qualified rate of waste water treatment, and the qualified rate of exhaust control. However, environmental pollution issues, such as haze and water contamination, have drawn a growing public concern in recent years. Indeed, environmental pollution has become one of top agenda items for the Chinese Government. Efforts have been made accordingly such as more financial expenditure in environmental protection. The proportion of the financial expenditure on the environmental protection to the total national budget increased from 1.05% in 2000 to 4.63% in 2013, with an annual growth rate of 12.09% on average. Sulfur dioxide discharge was well-controlled with an annual reduction rate of 0.71%, on average. However, the measures based on end-of-pipe control cannot fulfill the demand of environmental protection. The environmental protection should be based on prevention with process controls. Meanwhile, other factors must be taken into consideration as well, such as economy development models, energy consumption structure, and urban construction.

SDC of the society sub-system increased continuously from 18.91 in 2000 to 100.67 in 2013 with an annual growth rate of 13.73% on average. With the rapid economic development, the population quality, living conditions, living quality, and science-technology level all developed rapidly. Since 2000, population quality in terms of the number of university students and urban population ratio increased significantly with annual growth rates of 13.47% and 5.5% on average, respectively. Living conditions in terms of the unemployment insurance rate, pension insurance rate, medical insurance rate, proportion of fiscal expenditure for health increased 3.4%, 16.47%, 50.745%, and 0.78%, respectively, since 2000. Living quality in terms of disposable income per capita, Engel coefficient, hospital beds per ten thousand people, and green space area per capita all increased with average annual growth rates of 11.98%, 0.95%, 6.03%, and 8.95%. With the rapid economy development and the improvement of living conditions per capita, Shandong has paid an increasingly level of attention to the development of science and technology and education. The proportion of fiscal expenditure for science-technology and education increased 0.3% and 2.9% in comparison with 2000. The amount of patents owned increased 20.30% annually since 2000. This indicates that with the increasing investment in science-technology and education, the scientific technology level improves continuously. Science and technology are the primary production forces. Social civilization level will improve continuously and the social factor system will develop continuously with the increasing investment in education, and science and technology.

3.2. SDC of the Entire System

SDC of the entire system is shown in Table 4 and Figure 1. SDC increased from 23.64 in 2000 to 89.61 in 2013, with an annual growth rate of 10.80% on average. The critical factors that affect SDC of Shandong includes resource factor, social factor, economy factor, and environmental factor with the weight of 39.58%, 27.18%, 23.50%, and 9.73%, respectively. It indicates that environmental issues are still the major impeding factor for the sustainable development in Shandong. From the perspective of each sub-system, the major driving factors that can promote the sustainable development in Shandong, including hydroelectric and wind energy with the weight of 29.66%. Other major factors include the number of patents owned (9.56%), total output of heavy industry (7.81%), fixed asset investment (7.36%), medical insurance rate (6.02%), GDP per capita (4.34%), primary energy consumption (3.58%), dispensable income per urban capita (3.08%), production of natural gas (2.94%), and the ratio of the budget for environmental protection (2.67%). These 10 factors have the total weight of 77.02%. Therefore, the major driving factors promoting SDC are related to new energy, science-technology development, industrialization, resident living, and environmental protection investment.

It is Shandong's strategic policy of promoting sustainable development by actively developing new and renewable energy. According to the national guideline for new energy and renewable development, the consumption of new energy and renewable energy will account for 15% of the primary energy consumption by 2020. Wind energy, hydro energy, solar energy, and nuclear energy will exceed 100 million kWh by 2030 [49]. Therefore, there is great potential for new energy and renewable energy development in Shandong Province. This is crucial to further optimize the energy mix and ease the pressure of energy supply shortage.

The science and technology factor is another major driving factor for the sustainable development in Shandong. The weight of patents owned reached 9.56%. However, the total output of new high-technology industry accounts for as low as 1.57% of the GDP. The low commercialization rate of patents has been one of most significant barriers to the technological innovation in China. Therefore, reforms are required from the perspectives of governance and regulations to facilitate the commercialization of research outcomes apart from more investment on education and science-technology.

The environmental system is another constraint to the sustainable development in Shandong. The Chinese government has recognized the conflicts derived from the imbalance of environmental, social, and economic development. It is widely acknowledged that the economy development should not be on the cost of degrading of environmental quality [45]. As a result, the ecological civilization construction has been set as an important target for social economic development. It places more focus on the quality and benefits instead of the growth rate of economic development, indicating the low carbon transformation of the economy development in China [50–52]. Therefore, environmental protection investment factor will be one of the major driving forces for the sustainable development in Shandong. However, the current expenditure on environmental protection accounts for as low as 2.67% of the annual budget in Shandong. Therefore, Shandong must increase the expenditure on environmental protection and pollution prevention so that its sustainable development capacity is improved. Apart from the end-of-pipe control, prevention and process controls should be adopted, as well.

4. Conclusions

China is facing a series of challenges such as resource shortages, environmental pollution, and low energy efficiency. As one of the developed provinces, Shandong plays a crucial role in the national economy. The improvement of SDC in Shandong contributes to the improvement of SDC at the national level. In order to overcome the shortcomings of subjectivity evaluation, EWCM is used in this study for the assessment of SDC. The proposed evaluation index system of SDC includes four first-order indictors of economy sub-system, resource sub-system, environment sub-system, and society sub-system. This is followed by 43 second-order indicators.

SDC of the economy system, resource system, and society system in Shandong continues to improve with an annual growth rate of 15%, 10.9%, and 13.73%, respectively. However, SDC of the environment system continues to drop with an annual growth rate of −1.48%. This indicates that the imbalanced development between society, economy, and environment remains unchanged. In order to mitigate these issues, Shandong has actively implement the measures such as industrial restructure, energy structure optimization, new energy development, scientific development, and investment in environmental protection. The entire system shows a positive trend towards sustainable development. Therefore, SDC of Shandong increased continuously from 23.64 in 2000 to 89.61 in 2023, with an average annual growth rate of 10.80%. However, environment remains the major impeding factor for the sustainable development in Shandong.

It is imperative to conduct profound analysis on the critical factors of each subsystem to avoid the backlash and amplification of impeding factors to the sustainable development. Currently, the economic growth model in Shandong is still dominated by the secondary industry. Heavy industry remains the top driving factor for the development of the local economy. The associated issues of energy, land, and water conservation have to be solved properly in order to ensure sustainable growth of the economy. Secondly, environmental problems occur regularly despite increasing investment on environmental protection and the improvement of end-of-pipe control. Further classification and investigation are required in order to solve these issues from a system's perspective. Thirdly, more efforts are required for the new and renewable energy developments in addition to improving energy efficiency. This is due to the facts of energy supply shortage and energy backlash effects. Fourthly, the weight of high-tech industry to the entire system is as low as 1.57%. On the contrary, the weight of patent amount is 9.56%. This discrepancy reflects the imbalance between the research and development and its commercialization. Efforts are required to facilitate the commercialization of research outcomes.

Shandong should transform the economic growth model dominated by the secondary industry by accelerating the development of the tertiary industry and high-tech industry. The energy mix should be optimized by means of reducing consumption intensity and developing new and renewable energy resources. Ecosystem conservation and environmental governance should be conducted from a system perspective. Apart from the end–of-pipe control, mechanism of prevention and long term control should be established. Commercialization of research and development should be strengthened to provide necessary support for the sustainable development in Shandong.

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Author Contributions

The study was designed by Qingsong Wang, Xueliang Yuan and Jian Zhang. The data from yearbooks and professional websites are retrieved by Jinglan Hong, Yun Gao and Wei Liu. The results were analyzed by Qingsong Wang. The policies related to the research are reviewed by Xueliang Yuan. Model design and English corrections were completed by Jian Zuo.

Conflicts of Interest

The authors declare no conflict of interest.

References

1. Xiao, S.E.; Lei, J.S. Calculation and causes of environmental pollution loss in China. *China Popul. Resour. Environ.***2011**, *21*, 70–74. (In Chinese)
2. Wang, C.J.; Wang, F.; Zhang, H.G.; Ye, Y.Y.; Wu, Q.T.; Su, Y.X. Carbon Emissions Decomposition and Environmental Mitigation Policy Recommendations for Sustainable Development in Shandong Province. *Sustainability* **2014**, *6*, 8164–8179.
3. Wang, Q.S.; Liu, P.; Yuan, X.L.; Cheng, X.X.; Ma, R.J.; Mu, R.M.; Zuo, J. Structural Evolution of Household Energy Consumption: A China Study. *Sustainability* **2015**, *7*, 3919–3932.
4. Ang, B.W.; Zhang, F.Q. A survey of index decomposition analysis in energy and environmental studies. *Energy* **2000**, *25*, 1149–1176.
5. United Nations (UN). *Indicators of Sustainable Development: Guidelines and Methodologies*; United Nations: New York, NY, USA, 2007.
6. Cao, B.; Lin, J.Y.; Cui, S.H. Review on Assessment Index of Sustainable Development. *Environ. Sci. Technol.***2010**, *33*, 99–105. (In Chinese)

7. Organisation for Economic Co-operation and Development (OECD). *Towards Sustainable Development: Environmental Indicators*; OECD: Paris, France, 1998.
8. Organisation for Economic Co-operation and Development (OECD). *OECD Environmental Indicators: Towards Sustainable Development*; OECD: Paris, France, 2001.
9. Zhang, X.; Chen, W.; Ma, C.; Zhang, G.; Ju, M. Assessment method for regional environmental risk based on Pressure-State-Response model. *China Environ. Sci.* **2012**, *32*, 84–87. (In Chinese)
10. Zhang, X.; Ma, C.; Zhan, S.; Chen, W. Evaluation and simulation for ecological risk based on emergy analysis and pressure-state-response model in a coastal city, China. *Procedia Environ. Sci.* **2012**, *13*, 221–231.
11. Organisation for Economic Co-operation and Development (OECD). *Environmental Indicators for Agriculture: Volume1Concepts and Frameworks*; OECD: Paris, France, 1999.
12. Wang, Q.S.; Yuan, X.L.; Ma, C.Y.; Zhang, Z.; Zuo, J. Research on the Impact Assessment of Urbanization on Air Environment with Urban Environmental Entropy Model: A Case Study. *Stoch. Environ. Res Risk Assess.* **2012**, *26*, 443–450.
13. Ma, C.; Zhang, X.; Zhang, G.; Ju, M.; Zhou, B.; Li, X. Application of DPSIR framework in environmental impact assessment for port planning. *China Environ. Sci.* **2012**, *32*, 107–111.
14. Zhe, L.P. *Sustainable Development Theory and China's Agenda 21*; China Meteorological Press: Beijing, China, 2001.
15. Kittiya, Y.; James, G. An extended performance reporting framework for social and environmental accounting. *Bus. Strategy Environ.* **2006**, *15*, 309–321.
16. Zhang, K.M.; He, X.Y.; Wen, Z.G. Research on the urban environment sustainable development index system of China. China. *Popul. Resour. Environ.* **2000**, *7*, 4–9. (In Chinese)
17. Reach Group of Strategy of Sustainable Development. *China Sustainable Development Strategy Report—Building a Resource-Efficient and Environment-Friendly Society*; Science Press: Beijing, China, 2006.
18. Wang, Q.S.; Yuan, X.L.; Zhang, J.; Mu, R.M.; Yang, H.C.; Ma, C.Y. Key evaluation framework for the impacts of urbanization on air environment—A case study. *Ecol. Indic.* **2013**, *24*, 266–272.
19. Shi, Y.; Zhou, C.B.; Wang, R.S.; Xu, W.Y. Measuring China's regional ecological development through "EcoDP". *Ecol. Indic.* **2012**, *15*, 253–262.
20. Zhan, S.; Zhang, X.; Ma, C.; Chen, W. Dynamic modelling for ecological and economic sustainability in a rapid urbanizing region. *Procedia Environ. Sci.* **2012**, *13*, 242–251.
21. Huang, J.L. An Overview and Trend of Sustainability Assessment Methodologies. *Ecol. Econ.* **2015**, *31*, 18–23.
22. Commission on Sustainable Development. *Indicators of Sustainable Development: Guidelines and Methodologies*; United Nations Department of Economic and Social Affairs: New York, NY, USA, 2001.
23. Global Reporting Initiative (GRI). *Sustainability Reporting Guidelines*; Global Reporting Initiative: Amsterdam, The Netherlands, 2002.
24. Ye, W.H.; Tong, C. Review of Review of the United Nations Sustainable Development Indicators. China. *Popul. Resour. Environ.* **1997**, *7*, 83–87. (In Chinese)
25. Wang, H.Y. The latest index system to measure sustainable development. *China. Popul. Resour. Environ.* **1996**, *6*, 39–43. (In Chinese)

26. European Commission. *Towards Environmental Pressure Indicators for the EU*; Office for Official Publications of the European Communities: Luxembourg, 1999.
27. Cao, F.Z. American sustainable development indicators. *Environ. Sci. Trends* **1996**, *2*, 5–8. (In Chinese)
28. Sui, Y.; Zhang, L. Visual Tracking via Locally Structured Gaussian Process Regression. *IEEE Signal Process. Lett.* **2015**, *22*, 1331–1335.
29. Azarnivand, A.; Chitsaz, N. Adaptive policy responses to water shortage mitigation in the arid regions—A systematic approach based on eDPSIR, DEMATEL and MCDA. *Environ. Monit. Assess.***2015**, *187*, doi:10.1007/s10661-014-4225-4.
30. Anna, T.D.; Palomeque, F.L. Measuring sustainable tourism at the municipal level. *Ann. Tour. Res.* **2014**, *49*, 22–137.
31. Larry, L.S.; James, K.W. Application of steady state maximum entropy methods to high kinetic energy impacts on ceramic targets. *Int. J. Impact Eng.* **1999**, *23*, 869–882.
32. Allan, J. Entropy and the cost of complexity in industrial production. *Exergy* **2002**, *2*, 295–299.
33. Tan, Y.Z.; Wu, C.F. The laws of the information entropy values of land use composition. *J. Nat. Resour.***2003**, *18*, 112–117. (In Chinese)
34. Durowoju, O.A.; Chan, K.H.; Wang, X.J. Entropy assessment of supply chain disruption. *J. Manuf. Technol. Manag.* **2012**, *23*, 998–1014.
35. Tomas, K.; Bengt, M. Entropy and economic processes-physics perspectives. *Ecol. Econ.* **2001**, *36*, 165–179.
36. Jowsey, E. Economic aspects of natural resource exploitation. *Int. J. Sustain. Dev. World Ecol.* **2009**, *16*, 303–307.
37. Peng, H.; Zhao, G.H. Resource industry operation study: Cooperation, constraint and sustainability. *Adv. Mater. Res.***2012**, *524–527*, 2971–2976.
38. Gao, J.; Hu, J. Financial crisis, Omori's law, and negative entropy flow. *Int. Rev. Financ. Anal.* **2014**, *33*, 79–86.
39. Cheng, X.L.; Zhang, Y.Z. Sediment Treatment Scheme Optimization of Southern Route in the Yellow River Diversion of Xinsanyizhai Based on Principle Component Analysis and Entropy Weight Coefficient Method. *Water Resour. Power* **2013**, *31*, 133–135. (In Chinese)
40. Wan, Q.C. Comprehensive evaluation of urban competitiveness based on entropy weight coefficient method. *Stat. Decis.* **2009**, *11*, 59–61. (In Chinese)
41. Frugoli, P.A.; Almeida, C.M.V.B.; Agostinho, F.; Giannetti, B.F.; Huisingh, D. Can measures of well-being and progress help societies to achieve sustainable development? *J. Clean. Prod.* **2015**, *90*, 370–380.
42. Wang, T.X.; Xu, S.G. Dynamic successive assessment method of water environment carrying capacity and its application. *Ecol. Indic.***2015**, *52*, 134–146.
43. Shortall, R.; Davidsdottir, B.; Axelsson, G. Geothermal energy for sustainable development: A review of sustainability impacts and assessment frameworks. *Renew. Sustain. Energy Rev*. **2015**, *44*, 391–406.
44. Zhao, H.R.; Guo, S. External Benefit Evaluation of Renewable Energy Power in China for Sustainability. *Sustainability* **2015**, *7*, 4783–4805.

45. Wang, Q.S.; Yuan, X.L.; Chen, X.X.; Mu, R.M.; Zuo, J. Coordinated development of energy, economy and environment subsystems-a case study. *Ecol. Indic.* **2014**, *46*, 514–523.
46. Liu, J.J.; Dong, S.C.; Li, Z.H. Comprehensive Evaluation of China's Water Resources Carrying Capacity. *J. Nat. Resour.* **2011**, *26*, 258–269. (In Chinese)
47. Liu, J.S.; Liu, Y.; Yu, Q.Z.; Sun, J.J. Research on Water Resources Carrying Capacity and Spatial Differences in Shandong Province. *Water Resour. Power* **2010**, *28*, 19–21. (In Chinese)
48. Zhang, J.S.; Qi, Q. Reviews on supply security of China's vital energy under uncertainties. *Resour. Ind.* **2013**, *15*, 11–18. (In Chinese)
49. He, J.K. The strategic choice of Chinese energy revolution and low carbon development. *Wuhan Univ. J.* **2015**, *68*, 5–12. (In Chinese)
50. Mao, X.Q.; Wen, Y.Y.; Li, D.; Liu, Q. Significance, Ideas and Framework of index system for ecological civilization. *China Stat.* **2013**, *5*, 43–45. (In Chinese)
51. Yuan, X.L.; Mu, R.M.; Zuo, J.; Wang, Q.S. Economic Development, Energy Consumption and Air Pollution—A Critical Assessment in China. *Hum. Ecol. Risk Assess.* **2015**, *21*, 781–798.
52. Mu, R.M.; Zuo, J.; Yuan, X.L. China's approach to nuclear safety—From the perspective of policy and institutional system. *Energy Policy* **2015**, *76*, 161–172.