Energy Sustainability Evaluation Model Based on the Matter-Element Extension Method: A Case Study of Shandong Province, China

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Abstract: Energy sustainability is of vital importance to regional sustainability, because energy sustainability is closely related to both regional economic growth and social stability. The existing energy sustainability evaluation methods lack a unified system to determine the relevant influencing factors, are relatively weak in quantitative analysis, and do not fully describe the ‘paradoxical’ characteristics of energy sustainability. To solve those problems and to reasonably and objectively evaluate energy sustainability, we propose an energy sustainability evaluation model based on the matter-element extension method. We first select energy sustainability evaluation indexes based on previous research and experience. Then, a variation coefficient method is used to determine the weights of these indexes. Finally, the study establishes the classical domain, joint domain, and the matter-element relationship to evaluate energy sustainability through matter-element extension. Data from Shandong Province is used as a case study to evaluate the region’s energy sustainability. The case study shows that the proposed energy sustainability evaluation model, based on the matter-element extension method, can effectively evaluate regional energy sustainability.

Keywords: matter-element extension; energy sustainability; variation coefficient; model

1. Introduction

Energy is the lifeblood of economic development and the pillar of social development for a region. It is indispensable for people’s daily life. In this sense, energy sustainability is of vital significance in shaping a region’s destiny. Energy sustainability can be described on different scales, and different regions have specific particularities based on energy use over time and different energy sources [1–11]. Based on previous studies, Lynne Chester developed the concept of “energy sustainability” [1]. Christian Winzer defined energy sustainability as the continuity of energy supply relative to energy demand [2]. Kruyt et al. proposed four major elements of energy sustainability: energy usability of an economic entity, energy availability, economic cost of supply sustainability, and environmental sustainability [3]. Maull defined energy sustainability as embodying the eco-environmental sustainability of energy and the economic sustainability of energy. Eco-environmental sustainability involves sustainable development and represents the higher goal of energy sustainability [4]. Douglas R. Bohi et al. proposed that energy sustainability can be improved by introducing energy consumption reduction policies [5]. Benjamin K. Sovacool et al. conducted an analysis that concluded that energy sustainability consists of usability, affordability, efficiency, and environmental management [6]. Energy sustainability mainly centers on the threat posed by a sudden interruption in supply, so efficient investment portfolios can lower power generation cost, bring in more renewable energy sources, and improve energy sustainability [7]. Anil Markandya et al.
proposed that tax policies can be used when there is a threat to energy sustainability, which highlights the importance of the energy tax [8]. Larry Hughes proposed the concept of “4Rs” including review, reduce, replace, and restrict. All have a bearing on energy sustainability [9]. Purchasing energy from abroad does not translate to a guaranteed energy supply to China. Furthermore, the effect of guaranteeing cross-border pipeline transport is not very clearly defined [10,11].

Shandong Province is a major energy consumer in China; in 2015, the energy consumption of Shandong Province accounted for 8.55% of the total energy consumption of the country (data derived from Shandong Statistical Yearbook [12]). Shandong also faces problems with energy sustainability. Currently, its total energy consumption, dominated by coal consumption, continues to rise and its clean coal technologies need further improvement. There are also problems with the energy system, including a natural monopoly and imperfect market competition. The energy industry needs to be further transformed and upgraded.

These factors all influence regional energy sustainability. As such, scientifically evaluating the status of energy sustainability directs attention to that topic, and promotes regional sustainable development. At its heart, the sustainability of any activity refers to the balancing of social, environmental, and economic aspects and impacts. Therefore, these three aspects can inform energy sustainability. To support this work, this paper applies the matter-element extension method to establish an energy sustainability evaluation model; the corresponding indicators are selected from three domains: social, environmental, and economic. The study calculates the appropriate balance of the three aspects (that is, a multi-index correlation), and then evaluates the status of energy sustainability in Shandong Province. In addition, this model provides reference value for other regions and countries facing the same energy-related challenges.

2. Literature Review

When evaluating and studying the status of energy sustainability, some scholars have applied the perspectives of energy use efficiency, energy consumption, energy demand forecast, and others [11,13–19]. Blyth and Lefevre adopted the Herfindahl-Hirschman Index (HHI) to investigate the energy sustainability of energy suppliers [13]. Cail Cohen proposed an energy sustainability strategy, that is, energy diversification [14]. Mamdouh posited that the energy sustainability guarantee of America in the 21st century cannot be realized by focusing on energy alone, and that four measures should be introduced: development of blended fuels, improvement of energy efficiency, supervision and management of petroleum import dependence, and diversification of energy import sources [15]. Jansen et al. applied the property stack method to design a long-term energy sustainability index based on the Shannon-Wiener Index (SWI) [16]. Willrich proposed that the exporting country seeks investment and market sustainability, while the importing country seeks adequate energy supply to maintain the steady growth of the national economy. Energy sustainability results from direct interactions between the exporting country and the importing country [17]. Jonathan E. Sinton et al. analyzed the relationship between total energy consumption and energy use efficiency, and the relationship between economic development and industrial structure and other factors in China. As a result, they argued that energy consumption can be reduced by improving energy use efficiency and optimizing industrial structure [19].

The energy index system for sustainable development established by the International Atomic Energy Agency (IAEA) selected 41 evaluation indexes from energy-related fields, including gross domestic product (GDP), population, land, waste, and environment. These indexes provide references for member states in evaluating their environmental, economic, energy, and social policies [20]. Domestically, scholars establish related evaluation index systems mainly by analyzing different grades of factors influencing energy sustainability. These researchers then introduce different analytical methods to evaluate the status of energy sustainability. For example, Liu et al. adopted factor analysis, scenario analysis, and an ArcGIS spatial analysis technique to construct an energy sustainability evaluation model for China. They probed the spatial–temporal evolution characteristics of energy sustainability.
in China from two aspects: energy supply stability and energy use sustainability [11,21]. Hu et al. constructed three aspects and nine indexes to evaluate China’s status of energy sustainability based on the pressure-state-response (PSR) model. They suggested that the country’s energy sustainability can be enhanced in the future in four ways: strengthening energy exploitation and development, improving energy use efficiency, optimizing energy structure, and constructing diversified energy supply channels [22]. Many other scholars have completed related studies [23,24].

As mentioned above, there are many unresolved issues in evaluating energy sustainability. Those unsolved questions include the following. First, many scholars start from their own perspectives to determine relevant influencing factors, resulting in the absence of a unified system to evaluate the status of energy sustainability. Second, quantitative studies are relatively weak, and need improvements in spatial scale, evaluation, and other aspects. Third, a subjective weighting approach is used to assign weights to influencing factors, resulting in a lack of objectivity. Fourth, there is no clear understanding of the ‘paradoxical’ characteristics of energy sustainability, making it impossible to reflect the essence of dynamic change and development. Finally, studies have not reached a consensus on the criteria used for quantitative studies on energy sustainability.

Based on this literature review, this paper constructs and defines related evaluation indexes based on experience and previous studies. The study then uses the variation coefficient method to assign weights, and uses the matter-element extension model to analyze data about Shandong Province and evaluate its energy sustainability status. This method can correctly evaluate the status of energy sustainability, and achieve more objective results by eliminating the influence of human factors as much as possible. The approach also provides a new way to evaluate energy sustainability.

3. Materials and Methods

3.1. Energy Sustainability Evaluation Index System

This paper uses the energy sustainability evaluation index system established by Chen et al. with the Driving Force, Pressure, State, Impact, Response (DPSIR) model, which comprehensively analyzes and describes environmental problems and their relationships with social development. As a general framework derived from sociological studies and used to organize environmental status information, the DPSIR provides a system-level structure for index organization to support studies on environmental and sustainable development. The model applies the perspective of systematic analysis to assess interactions between mankind and environmental systems [11,25].

To establish an evaluation system, this paper selects some indexes from the indexes of DPSIR, including natural population growth rate, economic growth rate, energy consumption per capita, and others, listed in Table 1. The natural population growth rate is defined as the ratio of the natural population increase (results from deducting the number of deaths from the number of births) in a set period (usually a year) to the average population (or mid-term population) of this period, expressed in the form of permillage. The GDP growth rate represents the economic growth rate. Energy consumption per capita is expressed by each person’s average annual energy consumption. The energy consumption elasticity coefficient reflects the proportional relationship between the growth rate of energy consumption and that of the national economy. Both energy consumption per unit of GDP and energy consumption per 10,000 RMB industrial growth value can be used to reflect the relationship between economic growth and energy consumption.

3.2. Weight Determination by the Variation Coefficient Method

The objective weighting method is an effective way to reduce the intervention of human factors. It extracts valuable information by analyzing original data. Usually, the weights of each index in this method are determined using mathematical calculations [26,27]. Therefore, it can reflect the importance of indexes’ authenticity better in the comprehensive evaluation [28]. As an objective weighting approach, the variation coefficient method calculates index weights based on index data,
and reflects objective information about changes in that index data [29]. This paper uses the index data on Shandong Province during 2011–2014, derived from the Shandong Statistical Yearbook [12]. Table 1 provides the detailed data.

Process of weight determination:

Normalize original data to eliminate dimensional influence;

For “the smaller, the more optimal”-type indexes

\[ x'_{ij} = \frac{\max_i [x_{ij}] - x_{ij}}{\max_i [x_{ij}] - \min_i [x_{ij}]} \]  

(1)

For “the greater, the more optimal”-type indexes

\[ x'_{ij} = \frac{x_{ij} - \min_i [x_{ij}]}{\max_i [x_{ij}] - \min_i [x_{ij}]} \]  

(2)

In these expressions, \( x'_{ij} \) represents the data on the \( j \)th index in the \( i \)th year after processing; \( x_{ij} \) represents the measured data before processing. Table 2 presents the processed data.

Solve the mean \( c_j \) and standard deviation \( s_j \) of each index

\[ c_j = \frac{1}{n} \sum_{i=1}^{n} c_{ij} \]  

(3)

\[ s_j = \sqrt{\frac{\sum_{i=1}^{n} (c_{ij} - c_j)^2}{n-1}} \]  

(4)

Calculate the variation coefficient \( v_j \) of each index

\[ v_j = \frac{s_j}{c_j} \]  

(5)

Determine the weight \( w_j \) of each index

\[ w_j = \frac{v_j}{\sum_{i=1}^{n} v_j} \]  

(6)

3.3. Matter-Element Extension Model

In the 1980s, the Chinese scholar Cai proposed the matter-element extension method, and used a formalized model to study and analyze the possibility and law of matter extension. This approach mainly solves incompatible complex issues, and is also suitable for the evaluation of multi-factor issues [18,30]. Since it was proposed, the matter-element extension model has been applied in many ways. Zhou et al. used the matter-element extension model to evaluate pension services for urban communities [31]. Zhao B et al. analyzed a multi-grade evaluation system and rock slope stability based on extension methods and system engineering theories [32]. Based on the extension-based theoretical analysis on matter-element models, Jia et al. proposed an extension portioning method for the vulnerable ground depression areas of Dezhou on the North China Plain [33]. Energy sustainability evaluations are a complex process; therefore, we use the matter element extension method to analyze it. This allows the full use of the matter element extension method and results in more scientific and reasonable evaluation results.

3.3.1. Determination of Classical Domain, Joint Domain, and the Matter-Element to Be Evaluated

(i) Determination of classical domain
\[ R_j = (N_j, C_i, V_j') = \begin{bmatrix} N_j & C_1 & V_{j1} \\ \vdots & \vdots & \vdots \\ C_n & V_{jn} \end{bmatrix} = \begin{bmatrix} N_j & C_1 & (a_{ij}, b_{ij}) \\ \vdots & \vdots & \vdots \\ C_n & C_n & (a_{nj}, b_{nj}) \end{bmatrix} \]  

(7)

In this expression, \( N_j \) represents the \( j \) energy sustainability grades (For example, \( N_1 \) represents the level I); \( C_i \) represents the characteristic of each sustainability grade (For example, \( C_1 \) represents the Natural population growth rate); \( V_{j'} \) represents the quantitative range determined by \( N_j \) regarding \( C_i \); and \( (a_{ij}, b_{ij}) \) represents the classical domain.

(ii) Determination of joint domain

\[ R_p = (P, C, V_p) = \begin{bmatrix} P & C_1 & V_{p1} \\ \vdots & \vdots & \vdots \\ C_n & V_{pn} \end{bmatrix} = \begin{bmatrix} P & C_1 & (a_{pi}, b_{pi}) \\ \vdots & \vdots & \vdots \\ C_n & C_n & (a_{pi}, b_{pi}) \end{bmatrix} \]  

(8)

In this expression, \( P \) represents the entirety of energy sustainability grades; \( V_p \) represents the extended quantitative range of characteristic \( C_i \); (The range is from the minimum value to the maximum value); and \( (a_{pi}, b_{pi}) \) represents the joint domain.

(iii) Determination of the matter-element to be evaluated

\[ R_0 = (N_0, C, V) = \begin{bmatrix} N_0 & C_1 & V_1 \\ \vdots & \vdots & \vdots \\ C_n & V_n \end{bmatrix} \]  

(9)

In this expression, \( R_0 \) represents the matter-element to be evaluated; \( C_i \) represents the characteristics of the matter-element to be evaluated; and \( V_i \) represents the measured data on \( C_i \).

3.3.2. Determination of the Critical Values of Joint Domain Matter-Element and Classical Domain Matter-Element

Based on the literature [34] and indexes selected for this paper, the method of determining the classical domain in literature [35] was used to determine the critical value in combination with actual conditions, as shown in Table 3. In Table 3, \( N_i \) represents the grading of energy sustainability degree; \( N_1 \) represents grade I (extremely secure); \( N_2 \) represents grade II (secure); \( N_3 \) represents grade III (critical sustainability); \( N_4 \) represents grade IV (insecure); \( N_5 \) represents grade V (extremely insecure); and \( N_p \) represents the range of the joint domain.

3.3.3. Data Correlation Calculation and Grade Judgment

\[ \rho(v_i, V_j') = \left| v_i - \frac{1}{2}(a_{ij} + b_{ij}) \right| - \frac{1}{2}(b_{ij} - a_{ij}) \]  

(10)

\[ \rho(v_i, V_{pi}) = \left| v_i - \frac{1}{2}(a_{pi} + b_{pi}) \right| - \frac{1}{2}(b_{pi} - a_{pi}) \]  

\( i \in \{1, 2, 3, 4, 5, 6\}, \ j \in \{1, 2, 3, 4, 5\} \)  

(11)

Formulas (10) and (11) represent the distance between point \( v_i \) and interval \( V_j' \), and the distance between point \( v_i \) and interval \( V_{pi} \), respectively.

Based on the given distance formulas, the single index correlation function \( K_j(v_1) \) is used to calculate the matter-element to be evaluated, \( N_0 \), and to evaluate the single index correlation of grade \( N_j \).
\[ K_j(V_i) = \begin{cases} 
-\frac{\rho(v_i, V'_j)}{|V'_j|}, & v_i \in V'_j \\
\frac{\rho(v_i, V_p)}{\rho(v_i, V'_j)} - \rho(v_i, V'_j), & v_i \not\in V'_j 
\end{cases} \quad (12) \]

When \( K_m(v_i) = \max K_j(v_i) \), the index \( v_i \) in the matter-element to be evaluated, \( N_0 \), belongs to the evaluation grade of \( N_m \).

After obtaining the matter-element to be evaluated and the single index correlation of each evaluation grade, Formula (13) is used to calculate the matter-element to be evaluated: \( K_j(V) \), i.e., using a multi-index correlation.

\[ K_j(V) = \sum_i W_i K_j(v_i) \quad (13) \]

After obtaining a multi-index correlation of the matter-element to be evaluated, we arranged the specific values by size. The level of the maximum value represents the evaluation results for Shandong province energy sustainability.

4. Results

4.1. Application Example

Based on the selected evaluation indexes, this paper collects relevant data, and establishes the index system shown in Table 1.

| Index | \( C_1 \) | \( C_2 \) | \( C_3 \) | \( C_4 \) | \( C_5 \) | \( C_6 \) |
|-------|---------|---------|---------|---------|---------|---------|
| 2011  | 5.40    | 10.9    | 0.1994  | 0.62    | 0.86    | 1.26    |
| 2012  | 4.95    | 9.8     | 0.2106  | 0.48    | 0.82    | 1.16    |
| 2013  | 5.01    | 9.6     | 0.2255  | 0.50    | 0.78    | 1.07    |
| 2014  | 7.39    | 8.7     | 0.2342  | 0.38    | 0.74    | 0.99    |
| 2015 (evaluating year) | 5.88 | 8.0 | 0.2424 | 0.50 | 0.71 | 0.91 |

Notes: \( C_1 \)-Population growth rate (‰); \( C_2 \)-Economic growth rate (%); \( C_3 \)-Per capita energy consumption (ton coal equivalent/people); \( C_4 \)-Energy consumption elasticity; \( C_5 \)-Energy intensity (tone coal equivalent/ten-thousand yuan); \( C_6 \)-Energy consumption per unit of added value (tone coal equivalent/ten-thousand yuan); Data sources: Shandong Statistical Yearbook [12].

The variation coefficient method is used to determine the weights of indexes, shown in Table 2.

| Index | \( W_1 \) | \( W_2 \) | \( W_3 \) | \( W_4 \) | \( W_5 \) | \( W_6 \) |
|-------|---------|---------|---------|---------|---------|---------|
| 2011  | 0.1370  | 0.1742  | 0.1867  | 0.1595  | 0.1742  | 0.1682  |
| 2012  | 0.1370  | 0.1742  | 0.1867  | 0.1595  | 0.1742  | 0.1682  |
| 2013  | 0.1370  | 0.1742  | 0.1867  | 0.1595  | 0.1742  | 0.1682  |
| 2014  | 0.1370  | 0.1742  | 0.1867  | 0.1595  | 0.1742  | 0.1682  |

Based on the method of determining the classical domain described above, the critical value is determined based on actual conditions, shown in Table 3.

For Step 4, based on data for 2015 in Shandong Province, the matter-element model established above was used to calculate the correlation between sample data and different evaluation grades. This allowed the determination of evaluation results.
Table 3. Critical values of joint domain matter-element and classical domain matter-element.

|   | \(N_1\) | \(N_2\) | \(N_3\) | \(N_4\) | \(N_5\) | \(N_p\) |
|---|---|---|---|---|---|---|
| \(C_1\) | (0.5064) | (5.064, 5.79) | (5.79, 6.516) | (6.516, 7.242) | (7.242, 7.968) | (0, 7.968) |
| \(C_2\) | (10.9, 10.239) | (10.239, 9.4095) | (9.4095, 8.58) | (8.58, 7.7505) | (7.7505, 6.921) | (6.921, 10.9) |
| \(C_3\) | (0, 0.2091) | (0.2091, 0.2224) | (0.2224, 0.2357) | (0.2357, 0.2491) | (0.2491, 0.2624) | (0, 0.2624) |
| \(C_4\) | (0, 0.738) | (0.738, 0.783) | (0.783, 0.828) | (0.828, 0.873) | (0.873, 0.918) | (0, 0.918) |
| \(C_5\) | (0, 0.974) | (0.974, 1.08) | (1.08, 1.186) | (1.186, 1.292) | (1.292, 1.398) | (0, 1.398) |

Notes: \(N_1, N_2, \ldots N_p\) indicates the grade; \(C_1, C_2, \ldots C_6\) indicate the index.

4.2. Evaluation Process

Step 1 Establish classical domain

\[
R_1 = (N_1, C_1, V_1) = \begin{bmatrix} N_1 & C_1 & \text{(0, 5.064)} \\ C_2 & \text{(10.9, 10.239)} \\ C_3 & \text{(0, 0.2091)} \\ C_4 & \text{(0, 0.424)} \\ C_5 & \text{(0, 0.738)} \\ C_6 & \text{(0, 0.974)} \end{bmatrix}
\]

\(R_2, R_3, R_4,\) and \(R_5\) can be obtained using the same approach.

Step 2 Establish joint domain

\[
R_p = (P, C, V_p) = \begin{bmatrix} N_p & C_1 & \text{(0, 7.968)} \\ C_2 & \text{(6.921, 10.9)} \\ C_3 & \text{(0, 0.2624)} \\ C_4 & \text{(0, 0.712)} \\ C_5 & \text{(0, 0.918)} \\ C_6 & \text{(0, 1.398)} \end{bmatrix}
\]

Step 3 Establish the matter-element to be evaluated

\[
R_0 = (N_0, C, V) = \begin{bmatrix} N_0 & C_1 & 5.88 \\ C_2 & 8.0 \\ C_3 & 0.2424 \\ C_4 & 0.5 \\ C_5 & 0.71 \\ C_6 & 0.91 \end{bmatrix}
\]

Step 4 Calculate the correlation and evaluation results

Table 4 provides the results of the correlation analysis and evaluation.

| Index | \(K_1(V_1)\) | \(K_2(V_1)\) | \(K_3(V_1)\) | \(K_4(V_1)\) | \(K_5(V_1)\) | Evaluation Results |
|---|---|---|---|---|---|---|
| \(C_1\) | -0.2810 | -0.0413 | 0.1240 | -0.2335 | -0.3948 | III |
| \(C_2\) | -0.7288 | -0.6748 | -0.5664 | -0.6992 | -0.5000 | V |
| \(C_3\) | -0.6251 | -0.5001 | -0.2501 | 0.4997 | -0.2499 | IV |
| \(C_4\) | -0.2639 | -0.0185 | 0.0556 | -0.2429 | -0.3977 | III |
| \(C_5\) | 0.2818 | -0.1186 | -0.2598 | -0.3620 | -0.4394 | I |
| \(C_6\) | 0.0657 | -0.1159 | -0.2584 | -0.3613 | -0.4391 | I |
| \(K(V)\) | -0.2641 | -0.2597 | -0.2082 | -0.2231 | -0.4017 | III |
4.3. Analysis on Evaluation Results

Table 4 provides the single index correlations of different indexes: C₁ and C₄ have a sustainability grade of III; C₅ and C₆ have a sustainability grade of I; C₃ has a sustainability grade of IV; and C₂ has a sustainability grade of V. Of the six indexes, two have a critical sustainability grade; two have an extremely secure grade; one has an insecure grade; and one has a significantly insecure grade. By calculating the comprehensive correlation using Formula (13), we generate: max K_j(V) = −0.2082 and K_4(V) = −0.2231. This outcome indicates that Shandong Province had a critical sustainability grade in 2015; since then, it has shifted towards unsustainability. This is consistent with actual conditions, embodies the status of energy sustainability faced by Shandong Province, and provides a valuable reference for other regions.

5. Conclusions

The energy sustainability evaluation model established in this paper resulted from combining the variation coefficient method for weight assignment and the matter-element extension method. This approach provides a new perspective to quantitatively evaluate the status of energy sustainability, and has significant benefits. First, adopting the variation coefficient method for weight assignment achieves more scientific and reasonable index weights, and reduces the influence of subjective factors. Second, based on an established energy security index system [34], this paper satisfactorily embodies the relationship between energy sustainability and socio-economic development, and strengthens the comprehensive analysis and evaluation of the status of energy sustainability. Finally, applying the matter-element extension method reflects the characteristics associated with the dynamic development of energy sustainability, and shows the ‘paradoxical’ characteristics inherent in that sustainability.

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