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Measuring and improving regional energy security: A methodological framework based on both quantitative and qualitative analysis

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Abstract: As energy security has been an increasingly hot topic in research, a reliable and sound framework for allaying energy security is necessary. In this paper, it establishes a methodological framework based on quantitative and qualitative approaches for measuring and improving energy security from a broad sense. Firstly, it interprets the conceptual framework of energy security composed by seven dimensions, and 28 indicators are designed for its assessment. Then, Fuzzy AHP is used to indicate the importance of the dimensions and indicators, and the hybrid model of GRA-TOPSIS is introduced to evaluate energy security performance. Further, a qualitative root cause analysis is conducted with Why-Why Diagram to identify the possible causes affecting energy security. After that, a case study is conducted to investigate energy security of Henan province in China within the period of 2005-2017. The results indicate that, energy security is no longer a single-dimensional concept, but a synthetic term, and the technological, environmental, social, even political aspects can be improved to enhance energy security. The methodological framework with quantitative and qualitative techniques can help achieve an all-around understanding of energy security.

Keywords: Energy security, conceptual framework, Fuzzy AHP, GRA-TOPSIS; Why-Why Diagram

Nomenclature

Abbreviations and acronyms

AHP	Analytic Hierarchy Process
GRA	Grey Relation Analysis
MCDM	Multi-criteria decision making
NIS	Negative ideal solution
PIS	Positive ideal solution
SCE	Standard coal equivalent
SO_2	Sulfur dioxide
SWI	Shannon Wiener Index
TOPSIS	Technique for Order Preference by Similarity to Ideal Solution

Parameters and variables

$\tilde{m}_{ij}$	Triangular fuzzy number
m_{ij}^{L}	The lowest possible value of the triangular fuzzy number
m_{ij}^{M}	The most possible value of the triangular fuzzy number
m_{ij}^{U}	The highest possible value of the triangular fuzzy number
S_i	Fuzzy synthetic extent of the *i*-th criterion
S_i^{L}	The lowest possible value of the fuzzy synthetic extent for the *i*-th criterion
S_i^{M}	The most possible value of the fuzzy synthetic extent for the *i*-th criterion
S_i^{U}	The highest possible value of the fuzzy synthetic extent for the *i*-th criterion
$\tilde{P}$	Possibility matrix
$\tilde{p}_{ij}$	Degree of possibility of $S_i \geq S_j$
$d'(C_i)$	Degree of possibility for the i_{th} criterion greater than that with respect to all the others

W'	Weight vector for all criteria
W	Normalized weight vectors
x_{ij}	Positive attribute value for the i-th alternative with respect to the j-th indicator
x'_{ij}	Negative attribute value for the i-th alternative with respect to the j-th indicator
a_0	A positive number
a_{ij}	Standardized attribute value for the i-th alternative with respect to the j-th indicator
Z	Weighted normalized decision matrix
z_{ij}	Weighted normalized value the i-th alternative with respect to the j-th indicator
Z_j^+	Weighted normalized value for all indicators in PIS
z_j^+	The maximum weighted normalized value of the j-th indicator among all alternatives
Z_j^-	Weighted normalized value for all indicators in NIS
z_j^-	The minimum weighted normalized value of the j-th indicator among all alternatives
r_{ij}^+	Grey correlation coefficient between the i-th alternative and the PIS for the j-th indicator
r_{ij}^-	Grey correlation coefficient between the i-th alternative and the NIS for the j-th indicator
ρ	Resolution ratio
R^+	Grey correlation coefficient matrix between all alternatives and PIS
R^-	Grey correlation coefficient matrix between all alternatives and NIS
r_i^+	Grey correlation degree between the i-th alternative and PIS
r_i^-	Grey correlation degree between the i-th alternative and NIS
R_i^+	Standardized grey correlation degree between the i-th alternative and PIS
R_i^-	Standardized grey correlation degree between the i-th alternative and NIS

d_i^+	Euclid distance between the *i*-th alternative and PIS
d_i^-	Euclid distance between the *i*-th alternative and NIS
D_i^+	Standardized Euclid distance between the *i*-th alternative and PIS
D_i^-	Standardized Euclid distance between the *i*-th alternative and NIS
S_i^+	proximity to PIS for the *i*-th alternative
S_i^-	Proximity to NIS for the *i*-th alternative
C_i	Grey proximity for the *i*-th alternative

1. Introduction

China has been leading global energy consumption for a decade since it replaced the United States as the world's largest energy consumer in 2009 [1]. Flourishing Chinese economy has pushed the rapid increase of demand for energy, resulting in expanding gap between domestic energy supply and demand, and increasingly rising dependence on energy imports [2]. In 2009, the Chinese government promised to reduce its intensity of carbon emissions by 40 to 45 percent on 2005 level by 2020 [3], and even pledged to peak carbon emissions, reduce carbon intensity by 60 to 65 percent on 2005 level, and increase the share of non-fossil fuels in primary energy consumption to approximately 20 percent around 2030 [4]. To achieve these targets and ensure energy security without cumbering economic development, China confronts unprecedented pressure. Although renewable energy are thought as promising solutions for enhancing energy security and environmental sustainability [5,6], their development in China has shown great regional disparity, and it needs a really long period to improve China's energy security [7].

In fact, plentiful studies on energy security have been undertaken, and the early ones are conducted mainly based on segmentary definitions of energy security, focusing on energy supply and demand, while ignoring the environmental, social and political aspects. It’s most common to define energy security as reliable and affordable energy supply to support economy development [8]. From the perspective of supply security, some researches use simple or aggregated indexes to measure energy security [9-11], and Kruyt et al. summarized 24 simple and aggregated energy security indicators in their study [12]. International Energy Agency developed the Energy Security Index which integrated diversity of importing sources with political stability and energy prices [13]. With the extending dimensions of energy security, more indices have been developed, such as risky external energy supply index [14], energy security price index and energy security physical availability index [15], ex-post and ex-ante index of energy security [16], gas supply security index [17], sustainable energy security index [18-20], energy security and environmental sustainability index [21], and some other indices with multiple dimensions [22-24], which were widely used to assess energy security.

Energy security is a complex system not only involving geological or economic elements, while, the traditional understanding is incomplete and must be expanded to include many social, environmental and political factors and challenges [25], which makes it more difficult to be conceptualized and measured than ever before [26]. APERC proposed the 4As framework of energy security composed of availability, accessibility, acceptability and affordability [27], which has been used by many scholars [11,28,29]. Based on that, some further explorations were made from a more synthesized prospective. A most prominent research is conducted by Sovacool and his team [30-34], who developed five dimensions of energy security composed of 20 components by conducting 64 semi-structured research interviews. Some other dimensions and indicators of energy security have also been devised [22,35-37]. In addition, a plenty of energy security evaluation and analysis were conducted for US [38,39], France, UK and Italy [15,40,41], Finland [42], Morocco [43], Russia [23,44], Poland [45], Sri Lanka, Thailand and Vietnam [46,47], Philippines [48], India [19,20,49], Chinese Taiwan [50], and

China mainland [2,51-53]. Some international energy security assessments have even been undertook, such as countries in Eastern Mediterranean [54], Asia-Pacific region [35], East Asia[55], Northeast Asia [36], ASEAN [32,56], South Asia [21], Baltic States [57], European Union [24,58-64], Eastern Europe [65], members in the Group of Seven [66], OECD countries [67,68], 28 countries in Africa [69], even international and global comparisons and assessments [22,34,70-72]. Some studies also discussed energy security in rural areas [29], resource-poor island economics [73,74], small island developing countries [75], while very few qualitative energy security analysis was conducted [39,48,76-78].

In sum, scholars have proposed various indicators containing aspects such as energy supply and demand, environment and climate change, social and cultural factors, technology and efficiency, geopolitical risks, and political, military, and diplomatic factors. Some trends or characteristics can be summarized on the definition, conceptual framework, and even techniques for analyzing energy security. Firstly, the contents of energy security gradually extended from energy related dimensions such as energy supply and demand to multiple dimensions included economic, technological, environmental, social, and even political and cultural aspects [22,24,79-81]. Secondly, more attentions have been paid on quantitative assessment of energy security, while, the reasons or factors leading to the specific energy security performance have barely been analyzed with efficient techniques, and comprehensive and comparative analysis from both quantitative and qualitative perspectives are increasingly importing for policy makers [56,82]. Thirdly, there are many dimensions and indicators for measuring energy security, but how to weight and aggregate them to represent energy security is still in controversy [16,83]. So, the main objective of this study is to develop a practical framework to evaluate and analyze energy security from both quantitative and qualitative perspectives. With quantitative approaches, it can establish a sophisticated conceptual framework of energy security and make an effective assessment of energy security performance. The qualitative technique can facilitate the analysis and identification of possible factors and root causes to improve energy security performance.

The main contribution of this study lies in three aspects:

- A conceptual framework for assessing energy security with 7 dimensions and 23 criteria was proposed from a comprehensive and all-around perspective.
- A methodology integrated both quantitative and qualitative techniques was developed to analyze energy security performance.
- A cased study of energy security analysis in Henan province of China was conducted to demonstrate the effectiveness of the conceptual and methodological framework.

The remaining part of this paper is organized as follows: Section 2 describes the conceptual framework and indicators for measuring energy security. Section 3 presents the quantitative and qualitative methodological framework consisting of Fuzzy AHP-GRA-TOPSIS and Why-Why Diagram. In Section 4, a case study of energy security assessment and analysis is conducted for Henan province, China, within the period of 2005-2017. Section 5 and 6 make some further discussions and draws conclusions for this study, respectively.

2. Conceptual framework

To get an in-depth and comprehensive understanding of energy security, it’s necessary to deliberate a conceptual framework, design dimensions and indicators for energy security assessment. To define the dimensions and indicators, this paper has reviewed and synthesized the approaches and indices from the literature [2,22,26,27,30,35,36,58,67,68]. Finally, it identifies the following seven dimensions of energy security: availability and diversity, affordability, sociality and equality, energy infrastructure, technology and efficiency, environmental sustainability, and governance. Based on that, it further decomposes them into 23 components, which are measured by 28 indicators, as shown in Table A1 of the Supplementary Material.

2.1 Availability and diversity

The dimension of availability and diversity refers to the geophysical existence of energy resources as well as its potential ability to satisfy regional demands for energy resources [26,27,35,68]. It can be decomposed into four components: energy production, energy potential, energy independence, and energy diversification. All these components deal with the relationships between energy supply and demand. To understand the contents of this dimension, primary energy production, fossil fuel reserves, self-sufficiency and Shannon Wiener Index (SWI) are selected as indicators for measurement.

2.2 Affordability

Since energy products and service are provided to consumers by following market pricing systems, it’s essential to consider consumers’ ability to afford them [2,27]. The dimension of affordability exactly deals with factors regarding energy prices and expenditures on energy products and service. It decomposes this dimension into three components: energy price, electricity cost, and energy expenditure. To be detailed, average selling price of electricity is used to measure energy price, coal-fired power tariff is used to measure electricity cost, and percentage of expenditure on water, electricity and fuels in total household expenditure is used to measure energy expenditure.

2.3 Sociality and equality

This dimension relates to the social factors of energy security and sustainability [22,26,67]. Here it can be decomposed into two components: Residents' living conditions and equality. Residents' living conditions reflect the impact of energy supply on daily life, which is measured by two indicators: average energy consumption per household and average indoor heating area. While equality refers to residents’ access to clean and modern energy products and service. Therefore, two indicators are selected to measure it: percentage of electricity in total energy consumption and percentage of population with access to gas.

2.4 Energy infrastructure

The dimension of energy infrastructure measures the construction and usage of energy infrastructure [2,22,48], which can be decomposed into two components: reliability and construction of energy infrastructure. The component of reliability reflects the reliability of energy production and consumption, and two indicators are selected to measure them: reliability of power supply and average blackout hours per household. The component of energy infrastructure construction reflects the stock of energy infrastructure, and is measured with three indicators, length and capacity of power transmission lines, as well as natural gas pipelines.

2.5 Technology and efficiency

Since technology development can help improve efficiency of energy production, conversion, transmission and consumption [22,58], six components are selected to depict this dimension: energy conversion, capacity factor, auxiliary power consumption rate, energy transmission and distribution efficiency, energy consumption efficiency, and innovation & research, which are measured by six indicators: efficiency of energy conversion, utilization of power plants, ratio of power plants' electricity consumption to generation, electricity transmission and distribution losses, energy intensity, and research intensity.

2.6 Environmental sustainability

This dimension relates to the effect of energy consumption on environment, because energy consumption is thought to be the major source of various air pollutants [22,36]. Therefore, it mainly investigates emissions of air pollutants in this study, and three components are used to measure it: air quality, acidification potential, and photochemical potential. Among them, air quality is measured by the emissions of smoke and dust emissions, acidification potential is measured by the emissions of sulfur dioxide, and photochemical potential is measured by the emissions of nitrogen dioxide.

2.7 Governance

Energy governance has been an increasingly important dimension of energy security in recent years, here this dimension reflects the role of government in energy security[22,26,32,34]. So, this dimension can be decomposed into three components: market potential, government efficiency, and energy & environment management, and three indicators are selected for their measurement: investment in energy industry, government efficiency, and percentage of government expenditure on energy conservation & environment protection in total expenditures.

3. Methodological framework

Energy security assessment involves factors relating to the above seven dimensions, and multi-criteria decision making (MCDM) methods are thought to be efficient tools for solving this multidimensional problem [84,85]. To do this, Fuzzy Analytic Hierarchy Process (AHP) and the hybrid model of Grey Relation Analysis (GRA) and Technique for Order Preference by Similarity to Ideal Solution (TOPSIS) are selected as quantitative techniques for assessing energy security performance. In addition, Why-Why Diagram is introduced to reveal the underlying reasons and factors that lead to the good or bad energy security performance. To be specific, it firstly evaluates energy security with the proposed quantitative methods by deriving performance scores, which determines the state of national or regional energy security performance. To further probe the reasons or factors that lead to the good or poor energy security performance, the qualitative technique of Why-Why Diagram is employed to approach the root causes by keeping asking why for several rounds, and solutions for the root causes are given finally. From a proper point, these two techniques answer different questions on energy security, one focusing on how, and the other on why. The whole methodological framework is as presented in Figure 1.

3.1 Fuzzy AHP

AHP is an effective method for solving MCDM problems [86], and usually combined with fuzzy logic to improve robustness and flexibility in processing nonlinear variables and dealing with the uncertainty and ambiguity in decision making [87]. In fact, various variants of Fuzzy AHP have been developed [88-92], among which the variant of Fuzzy Extent Analysis is usually used to determine criteria weights [87,93-97], and this variant is employed to allocate weights to the dimensions and indicators, and the procedure is as follows [88,89]:

Step 1: Defining and analyzing the decision problem.

Usually, it needs to establish a hierarchy structure model at first, which consists of three levels: the top level describes the overall goal of the decision problem, the middle level lists the criteria, and the bottom level demonstrates the alternatives. The overall goal of this study is energy security performance. To conduct this evaluation, seven criteria or dimensions are proposed, and each of them can be decomposed into several components, even indicators, as shown in Table A1 of the Supplementary Material.

Step 2: Obtaining the decision matrix.

Based on pairwise comparisons of the criteria and alternatives according to their relative importance with respect to the overall goal or criteria with triangular fuzzy numbers, as presented in Table 1, the decision matrix for each decision unit can be obtained as Eq. (1).

$$\tilde{M} = \begin{vmatrix} \tilde{1} & \tilde{m}_{12} & \cdots & \tilde{m}_{1n} \\ \tilde{m}_{21} & \tilde{1} & \cdots & \tilde{m}_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ \tilde{m}_{n1} & \tilde{m}_{n2} & \cdots & \tilde{1} \end{vmatrix} = \begin{vmatrix} \tilde{1} & \tilde{m}_{12} & \cdots & \tilde{m}_{1n} \\ 1/\tilde{m}_{12} & \tilde{1} & \cdots & \tilde{m}_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ 1/\tilde{m}_{1n} & 1/\tilde{m}_{2n} & \cdots & \tilde{1} \end{vmatrix} \qquad (1)$$

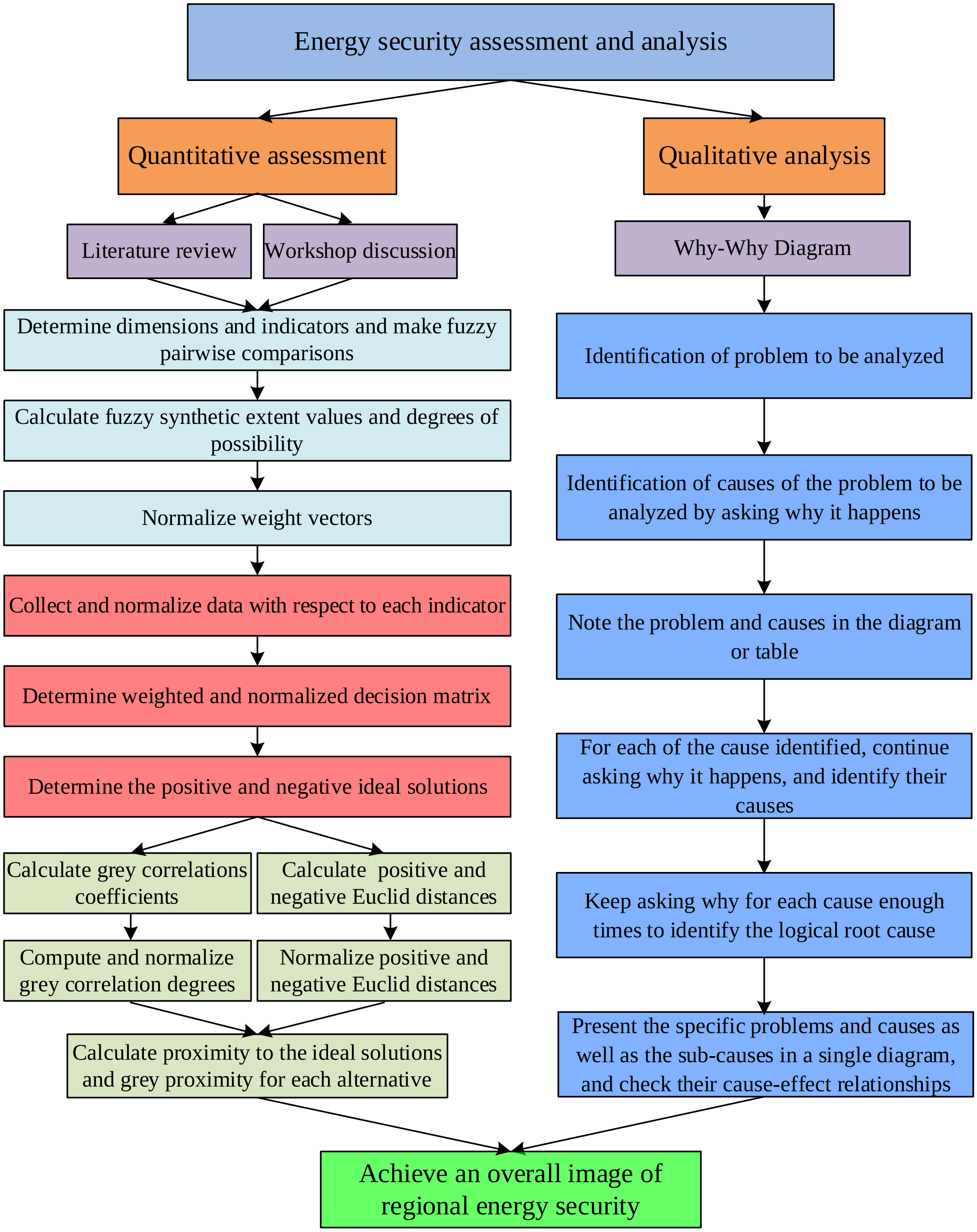

Figure 1. Quantitative and qualitative methodological framework for analyzing energy security.

Step 3: Calculating the value of fuzzy synthetic extent for each criterion by Eqs. (2)–(4).

$$S_i = \sum_{j=1}^{n} \tilde{m}_{ij} \otimes \left[\sum_{i=1}^{n} \sum_{j=1}^{n} \tilde{m}_{ij} \right]^{-1} \tag{2}$$

where

$$\sum_{j=1}^{n} \tilde{m}_{ij} = \left(\sum_{j=1}^{n} m_{ij}^{L}, \sum_{j=1}^{n} m_{ij}^{M}, \sum_{j=1}^{n} m_{ij}^{U} \right) \quad i, j = 1, 2, \cdots, n \tag{3}$$

$$\left[\sum_{i=1}^{n} \sum_{j=1}^{n} \tilde{m}_{ij} \right]^{-1} = \left(\frac{1}{\sum_{i=1}^{n} \sum_{j=1}^{n} m_{ij}^{L}}, \frac{1}{\sum_{i=1}^{n} \sum_{j=1}^{n} m_{ij}^{M}}, \frac{1}{\sum_{i=1}^{n} \sum_{j=1}^{n} m_{ij}^{U}} \right) \tag{4}$$

Table 1. Triangular fuzzy numbers translated from linguistic terms [98]

Linguistic scales	Triangular fuzzy scales
Equally important (E)	(1, 1, 1)
Slightly important (S)	(1/2, 1, 3/2)
Moderately important (M)	(1, 3/2, 2)
Fairly strongly important (F)	(3/2, 2, 5/2)
Very strongly important (V)	(2, 5/2, 3)
Absolutely important (A)	(5/2, 3, 7/2)
Reciprocals of these	Reciprocals of these fuzzy numbers

Step 4: Computing the degree of possibility of $S_i = \left(S_i^L, S_i^M, S_i^U \right) \geqslant S_j = \left(S_j^L, S_j^M, S_j^U \right)$ by Eq. (5), and the possibility matrix can be derived as shown in Eq. (6).

$$\tilde{p}_{ij} = V(S_i \geq S_j) = \begin{cases} 1 & S_i^M \geq S_j^M \\ 0 & S_i^U \leq S_j^L \\ \dfrac{S_j^L - S_i^U}{(S_i^M - S_i^U) - (S_j^M - S_j^L)} & otherwise \end{cases} \tag{5}$$

$$\tilde{P} = \begin{vmatrix} / & \tilde{p}_{12} & \cdots & \tilde{p}_{1n} \\ \tilde{p}_{21} & / & \cdots & \tilde{p}_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ \tilde{p}_{n1} & \tilde{p}_{n2} & \cdots & / \end{vmatrix} \tag{6}$$

Step 5: Obtaining the degree of possibility for each criterion to be greater than that for all the others.

For instance, the degree of possibility for the *i*-th criterion greater than that with respect to all the others is specified by Eq. (7).

$$
\begin{aligned}
d'(C_i) &= V(S_i \geq S_1, S_2, \cdots, S_k, \cdots, S_n) \\
&= V(S_i \geq S_1) \text{ and } V(S_i \geq S_2) \text{ and } \ldots \text{ and } V(S_i \geq S_n) = \min V(S_i \geq S_k)
\end{aligned} \tag{7}
$$

where $k = 1, 2, \cdots, n$ and $k \neq i$.

Then the weight vector for these criteria can be derived by Eq. (8).

$$W' = \left(d'(C_1), d'(C_2), \cdots, d'(C_n)\right)^T \tag{8}$$

Step 6: Achieving the normalized weight vectors by Eqs. (9)–(10).

$$W = \left(d(C_1), d(C_2), \cdots, d(C_n)\right)^T = \left(w_1, w_2, \cdots, w_n\right) \tag{9}$$

where

$$d(C_i) = \frac{d'(C_i)}{\sum_{i=1}^{n} d'(C_i)} \tag{10}$$

3.2 GRA-TOPSIS

GRA, developed by Deng (1989), is a technique that can analyze the relationship between different data series [99], and prioritize alternatives by comparing the similarity of their geometrical shape [100,101]. Several studies have employed this technique to assess and rank various alternatives. By using GRA, Lee and Lin (2011) evaluated energy performance of office buildings [102], Malekpoor et al. (2018) ranked the conflicting criteria in sustainable energy generation [103], Huang et al. (2019) analyzed factors strongly corelated with China’s carbon emissions [104], Wang et al. (2020) prioritized blocks of shale gas exploitation [105], and Zuo et al. (2020) determined the factors affecting performance of a hydrogen-fueled micro-cylindrical combustor [106]. However, GRA is also criticized for three drawbacks: (1) It’s rather difficult to choose the positive ideal solution (PIS) and negative ideal solution (NIS) as references; (2) The ranking results of some grey relational degree procedures may change when altering sample order because only adjacent samples are considered; (3) it may not preserve certain mathematical characteristics of the original data observations by relying on the similarity of the geometrical shape of data series to rank alternatives [101].

TOPSIS, proposed by Hwang and Yoon (1981) [107], is a MCDM technique that prioritizes alternatives by considering the shortest and greatest distances between each alternative and the PIS and NIS simultaneously [108], and usually chosen as the technique for alternatives ranking and prioritizing because of its stability and ease of use with cardinal information [108]. By using this method, Nazari et al. (2018) identified the most suitable solar farm site [109], Wang et al. (2017) evaluated building energy performance [110], Vavreka and Chovancová (2019) measured energy economic and environmental performance for 28 EU states [111], Solangi et al. (2019) and Ervural et al. (2018) prioritized energy strategies [112,113], and Alao et al. (2020) prioritized the waste-to-energy technological options in Nigeria [114]. However, there are some major problems for this method: (1) The normalization processes compress different types of data series into a unified range, which is not good for ranking and can't reflect the true dominance of alternatives [115]; (2) TOPSIS focuses on distances between each alternative and the ideal solutions, which can't reflect the situation or posture changes among data sequences, and fails to analyze correlations within data series of different alternatives [116]; (3) It doesn't consider the relative importance of the distances between each alternative and the ideal solutions from these points [117].

In fact, GRA and TOPSIS do have some similarities in inputs and operations [118]. The drawbacks of TOPSIS can be avoided by introducing grey relation coefficient of GRA [119], which can measure correlations among elements or alternatives with degree of similarity or differences in their development trends [120]. To objectively and rationally rank and prioritize alternatives, some studies combined these two methods. For example, Tian et al. (2017) constructed an integrated closeness index by establishing a nonlinear programming based on the grey correlations closeness of GRA and distance closeness index of TOPSIS [116]. More researchers used a GRA-TOPSIS model by introducing PIS and NIS for TOPSIS into GRA to get both positive and negative grey relations [119,121-126]. Based on that, Liu et al. (2019) and Quan et al. (2019) combined grey relational coefficients in GRA and Euclidean distances in TOPSIS to compose a new index for ranking alternatives [127,128].

Here it introduced a hybrid model of GRA-TOPSIS which combined GRA and the TOPSIS together and avoided their defects. The steps are as follows [128,129]:

Step 1: Standardizing data series. Since the attribute values of some indicators are negative ones, they need to be transformed to positive ones by Eq. (11).

$$x_{ij} = x'_{ij} + a_0 \tag{11}$$

where x'_{ij} is the negative attribute value with respect to the *j*-th indicator, a_0 is a positive number to make sure x_{ij} ≥0.

The benefit-type and cost-type indicators can be standardized by Eqs. (12)-(13), respectively.

$$a_{ij} = 1 / x_{ij} \tag{12}$$

$$a_{ij} = x_{ij} / \min x_j \tag{13}$$

Step 2: Determining the weighted normalized decision matrix by Eq. (14).

$$Z = [z_{ij}]_{i \times j} \tag{14}$$

where $z_{ij} = w_j \times a_{ij}$.

Step 3: Selecting the maximum and minimum values with respect to each indicator in matrix Z , then the PIS and NIS can be determined by Eqs. (15)–(16).

$$Z_j^+ = \left(z_1^+, z_2^+, \cdots, z_j^+, \cdots, z_n^+ \right) \tag{15}$$

$$Z_j^- = \left(z_1^-, z_2^-, \cdots, z_j^-, \cdots, z_n^- \right) \tag{16}$$

where $Z_j^+ = \max_i \left(z_{ij} \right)$, $Z_j^- = \min_i \left(z_{ij} \right)$.

Step 4: Calculating r_{ij}^{+} and r_{ij}^{-}, the grey correlation coefficients between the *i*-th alternative and the PIS and NIS with respect to the *j*-th indicator, then composing the grey correlation coefficient matrixes R^{+} and R^{-} by Eqs. (17)–(18) [128,129].

$$R^{+}=\left(r_{ij}^{+}\right)_{m\times n},r_{ij}^{+}=\frac{\min_{i}\min_{j}\left|z_{j}^{+}-z_{ij}\right|+\rho\max_{i}\max_{j}\left|z_{j}^{+}-z_{ij}\right|}{\left|z_{j}^{+}-z_{ij}\right|+\rho\max_{i}\max_{j}\left|z_{j}^{+}-z_{ij}\right|} \tag{17}$$

$$R^{-}=\left(r_{ij}^{-}\right)_{m\times n},r_{ij}^{-}=\frac{\min_{i}\min_{j}\left|z_{j}^{-}-z_{ij}\right|+\rho\max_{i}\max_{j}\left|z_{j}^{-}-z_{ij}\right|}{\left|z_{j}^{-}-z_{ij}\right|+\rho\max_{i}\max_{j}\left|z_{j}^{-}-z_{ij}\right|} \tag{18}$$

where $\rho\in[0,1]$, is the resolution ratio, and it shows the best resolution when ρ is no bigger than 0.5463. Generally, it takes 0.5 [128,129].

Step 5: Computing r_{i}^{+} and r_{i}^{-}, the grey correlation degrees between the *i*-th alternative and the PIS and NIS by Eqs. (19)–(20), and standardizing them by Eqs. (21)–(22) [128,129].

$$r_{i}^{+}=\frac{1}{n}\sum_{j=1}^{n}r_{ij}^{+} \tag{19}$$

$$r_{i}^{-}=\frac{1}{n}\sum_{j=1}^{n}r_{ij}^{-} \tag{20}$$

$$R_{i}^{+}=\frac{r_{i}^{+}}{\sum_{i=1}^{m}r_{i}^{+}} \tag{21}$$

$$R_{i}^{-}=\frac{r_{i}^{-}}{\sum_{i=1}^{m}r_{i}^{-}} \tag{22}$$

Step 6: Calculate d_{i}^{+} and d_{i}^{-}, the Euclid distances between the *i*-th alternative and the PIS and NIS by Eqs. (23)–(24), and standardizing by Eqs. (25)–(26) [128,129].

$$d_{i}^{+}=\sqrt{\sum_{j=1}^{n}\left(z_{ij}-z_{j}^{+}\right)^{2}} \tag{23}$$

$$d_i^- = \sqrt{\sum_{j=1}^{n}\left(z_{ij} - z_j^-\right)^2} \tag{24}$$

$$D_i^+ = \frac{d_i^+}{\sum_{i=1}^{m} d_i^+} \tag{25}$$

$$D_i^- = \frac{d_i^-}{\sum_{i=1}^{m} d_i^-} \tag{26}$$

Step 7: Combining R_i^+, R_i^-, D_i^+ and D_i^- to achieve the proximity to the ideal solutions by Eqs. (27)–(28). In this paper it takes $\varsigma = \tau = 0.5$ [128,129].

$$S_i^+ = \varsigma R_i^+ + \tau D_i^- \tag{27}$$

$$S_i^- = \varsigma R_i^- + \tau D_i^+ \tag{28}$$

Step 8: Obtaining the grey proximity for each alternative by Eq (29), and the final priority for all the alternatives can be derived [128,129].

$$C_i = S_i^+ / (S_i^+ + S_i^-) \tag{29}$$

3.3 Why-Why Diagram

Why-Why Diagram, also known as Why-Why Analysis, firstly developed by Sakichi Toyoda in 1930s, is an iterative interrogative technique to investigate the root causes leading to a particular problem by asking why iteratively [130]. To derive the root causes, the decision makers need to keep asking why, and the identified causes for the specific question form the basis of the following questions [130,131]. In most cases, with five iterations of this ask-answer procedure at most, the root causes can be identified [132]. The procedure of Why-Why Diagram is as following [132,133]:

Step 1: Identifying the specific problem need to be analyzed. The root cause analysis is started with the identification of the observed problem [132], and once the specific problem to be analyzed has been identified, it can be put at the root of the why-why diagram or table.

Step 2: Analyzing the causes by asking why it happened for the identified problem. The decision makers need to ask why the identified problem happened, and list all possible causes or reasons [132].

Step 3: Putting all the causes leading to this problem at the second level of the diagram. With the determination of causes for the specific problem, the decision makers should place them at the second level of the diagram just exactly under the problem just identified [132].

Step 4: Taking each of the cause identified as a new problem and continue to explore their causes. The policy makers should take every cause for the problem as a new problem, and once again ask why it happened to explore the causes for each newly generated problem. In addition, the newly explored causes should be placed at the third level [133].

Step 5: Keeping taking the causes as new problems and asking why enough times to identify the logical root causes. The decision makers need to keep taking the causes as new problems, identify the possible causes, and try this procedure for enough times until no further causes can be developed [132].

Step 6: Finding solutions to each root cause. As the root causes for the initially identified problem have been determined, the solutions to the root causes need to be proposed, and then the initial problem can easily and properly be solved [133].

What need to be noticed is that this analysis usually focuses on processes or improvements, and there may be more than one cause for each problem. When doing the ask-answer procedure, it needs to describe as many reasons as possible to find the actual root causes rather than describe symptoms [132].

4. Case study: Energy security in Henan province of China

This study takes Henan province in China as an example, and adopts the methodologic framework based on quantitative and qualitative approaches, to measure and analyze its energy security performance within the period of 2005-2017.

4.1 Study area

Located in middle China (see Figure 2), Henan is a large province with huge economy and energy consumption, as well as the largest population in China, making it a major energy consumer of this country. With 18 provincial cities and great disparity in economy and resources, Henan province is a miniature of China. As an energy giant province, Henan is also a critical pivot for implementing the strategy of Rising Central China [134]. Therefore, the understanding of energy security in Henan province is of great significance for improving its energy security, and can also provide insights for the decision making of provincial even national energy policy in China. Therefore, it takes Henan province as an example and investigates its energy security performance by adopting the conceptual and methodological framework proposed in this study.

Henan province is home to approximately 9 billion tons of coal reserves, however, is also the fifth largest energy consumer in China, which makes it a major energy importer [135]. In fact, Henan used to be a net energy supplier for a long history, and its energy production and consumption experienced a very slow but steady increasing trend before 1999, as shown in Figure 3. After that, its energy consumption showed a sharp increase, in line with China's economy development, which ushered the decade of historically fastest economic growth in early 2000s. However, its energy production can hardly catch up with the expansion of energy consumption, and even showed some decrease during this period, which may be caused by government's efforts on shutting down small coalmines. From 2010, the energy production and consumption in Henan province went two completely different directions: energy consumption continued a slowing down growth to 231 million tons of standard coal equivalent (SCE), while energy production suffered a cliff fall to 97 million tons of SCE. By 2016, its dependence on external energy supply came to a historical record of 60 percent [136]. Besides, its energy intensity was still at a relatively high level, ranking lower than most Chinese provinces, although a continuing declining was witnessed in recent years. In addition, environmental problems caused by fossil fuel consumption pose extra pressure on local government, although soot and dust emissions have been decreasing year by year, as shown in Figure 4. In 2015, Henan produced 1144 thousand tons of sulfur dioxide (SO_2) and 846 thousand tons of soot and dust, ranking the third and sixth among all provinces of the country, respectively [137].

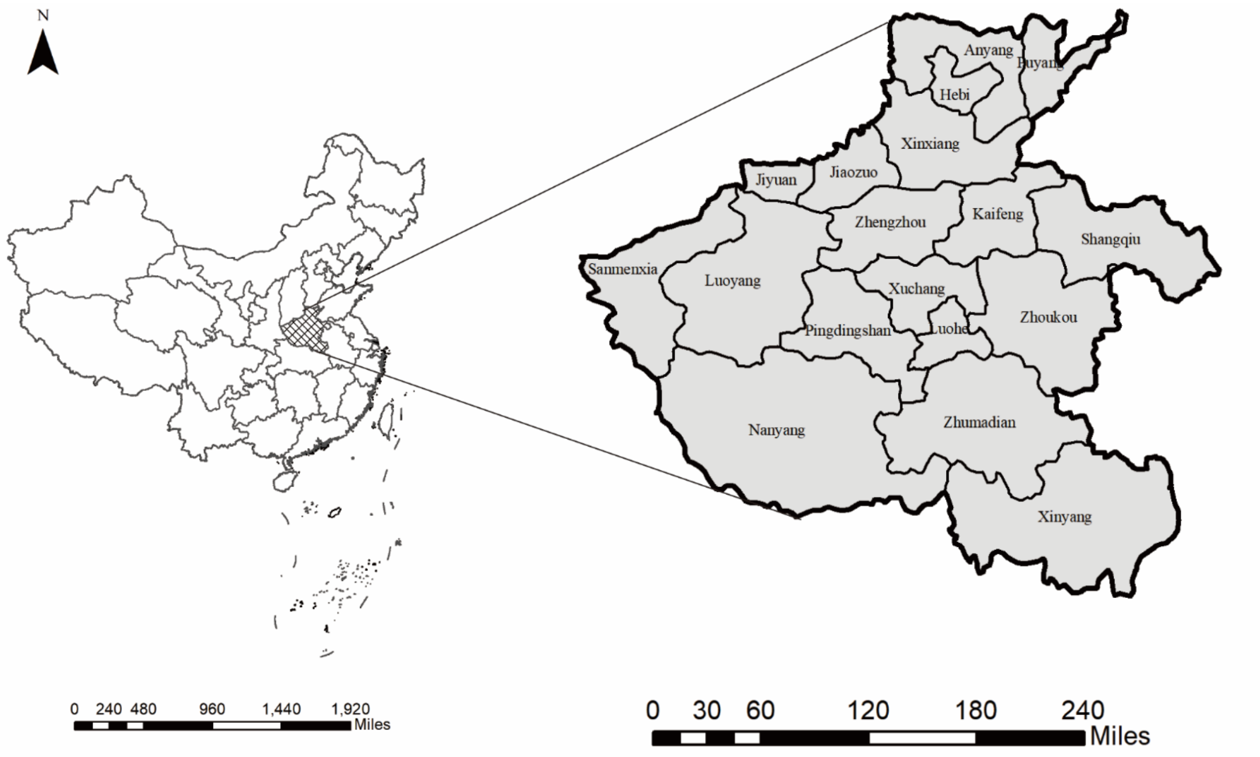

Figure 2. Location of Henan province in China.

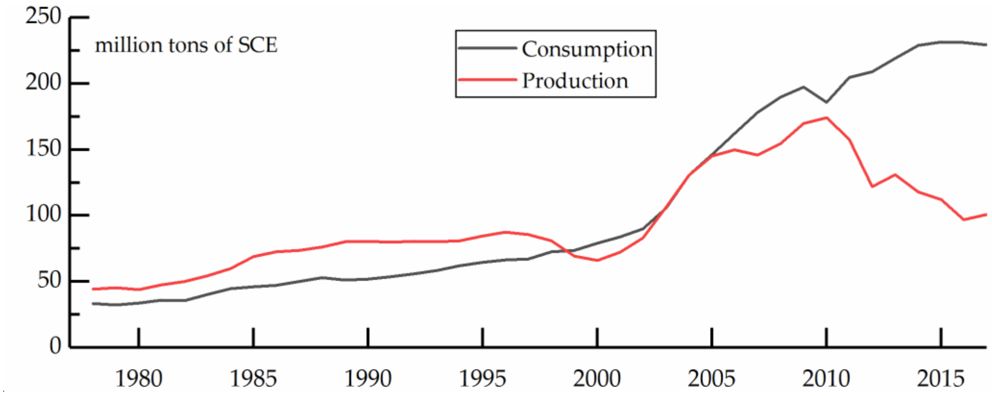

Figure 3. Energy production and consumption of Henan, China, 1978-2017.

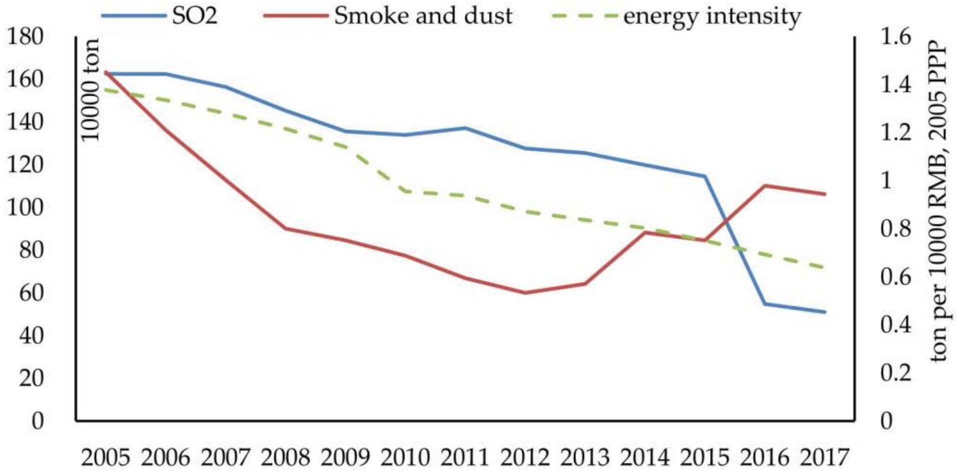

Figure 4. Energy intensity, SO_2 emissions, smoke and dust emission of Henan, China, 2005-2017.

4.2 Weight determination

Fuzzy AHP is designed to achieve weights for all dimensions, components, and indicators. With the hierarchy structure model in Table A1 of the Supplementary Material, the pairwise comparisons of the seven dimensions with respect to the overall goal and the pairwise comparisons of indicators with respect to their corresponding dimensions can be derived by inviting experts in this field to make judgments according to their relative importance, and the linguistic judgment matrices are shown in Tables A2–A9 of the Supplementary Material. To help understand the procedure of Fuzzy AHP, the weight determination of the seven dimensions are demonstrated as an example, which are provided in S1 of the Supplementary Material. With similar procedures, the local weights for indicators within each dimension can be calculated, and the global weights for all indicators are shown in Table A10 of the Supplementary Material.

4.3 Results of hybrid model of GRA-TOPSIS

Data with respect to these 28 indicators within the period of 2005-2017 for measurement of energy security performance in Henan province, China are collected from Henan Statistics Yearbook, China Electric Power Yearbook, and some research achievements [138]. Due to the adjustment of environment statistic caliber in Henan Statistics Yearbook, data on volume of air pollutant emissions in 2016 and 2017 is not comparable with previous years. Therefore, it relied on Grey Model to estimate the data on air pollutant emissions for 2016 and 2017.

After that, energy security performance of Henan province can be calculated by employing the hybrid model of GRA-TOPSIS. The results of the main parameters for the calculation have been presented in Table A11 of the Supplementary Material, and the results of energy security performance in Henan province with respect to the period of 2005 to 2017 are presented in Figure 5.

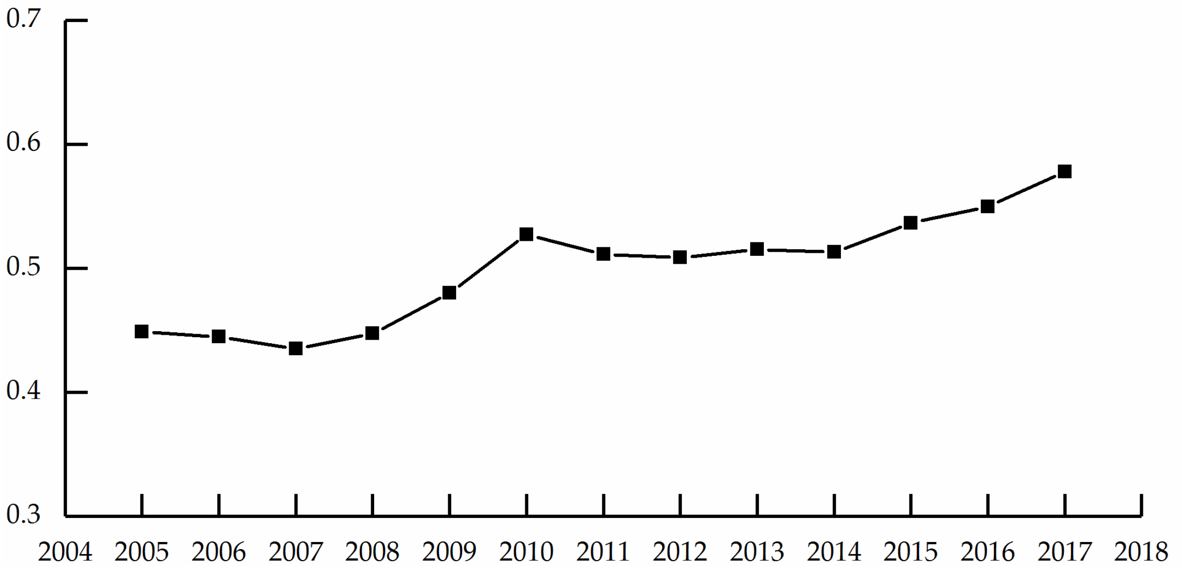

Figure 5. Energy security performance of Henan province, 2005-2017.

4.4 Energy security performance analysis

Following the procedure of GRA-TOPSIS, the final scores of grey proximity representing energy security performance of Henan province can be derived, which is in the interval of [0,1], and the greater value indicates better energy security performance. Figure 5 demonstrated the overall trend of the energy security performance in Henan province during 2005-2017, and indicated that Henan province showed an upward curve for its energy security performance. Specifically, this period can be divided into three stages. From 2005 to 2010, the energy security performance presented an upward trend. Afterwards, it has been stuck at the level of 0.5 from 2010 to 2014. Then, from 2015 to 2017, a slow but steady increasing trend was witnessed, climbing up from 0.5 to 0.6. By tracing the evolution of energy security performance in Henan province during the period of 2005-2017, it is believed that an obvious improvement has been achieved in Henan province, especially in recent years.

To better understand the evolution process and probe the factors that enhance energy security in Henan province, a dimensional analysis was conducted, as shown in Figure 6.

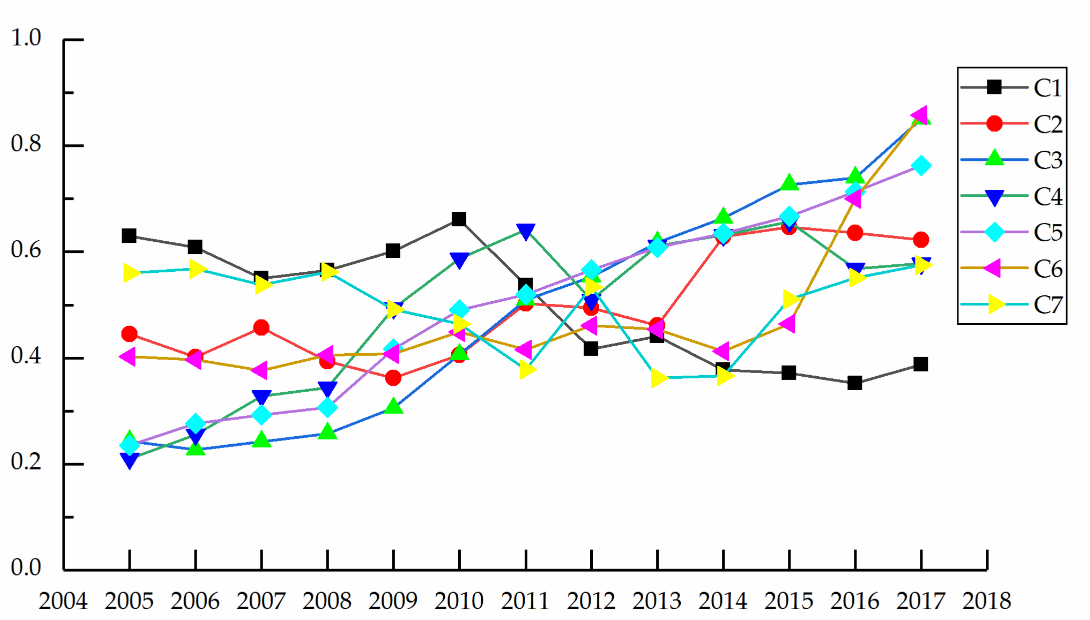

Figure 6. Dimensional analysis of energy security performance in Henan province, 2005-2017.

By analysing the trajectory of availability and diversity in Henan province over this period, a deteriorate trend can be witnessed (C1 in Figure 6). To be specific, energy reserve and production in Henan province kept declining, while its energy consumption went an opposite direction with an annual growth rate of 3.8 percent. Therefore, a continuously rising dependence on energy imports can be noticed, from total self-reliance to a dependence rate of 56 percent. However, the increasingly diversified energy mix helped improve its energy security.

With respect to the dimension of affordability, an overall slightly improved performance was displayed (C2 in Figure 6). Although energy costs and prices increased during these years, the share of households' expenditure on energy in total expenditure experienced a dropping trend, especially after 2011, less than 5 percent of households' expenditure was spent on energy products and service. These changing numbers indicated that although people spent more money on energy products and service, the much faster-growing residents' income improved their affordability for energy products and service.

By spending more money on energy products and service, residents improved their life quality. An obvious symbol is that increasing people are enjoying modernized energy products and service, e.g., electricity, natural gas, and heating services. During this period, the average energy consumption per household has doubled, and the average heated area per capita even increased by 550 percent. At the same time, the percentage of urban population with access to coal gas, petroleum gas, or natural gas grew from less than 70 percent to nearly 95 percent, indicating improved living standard and fair energy supply patterns (C3 in Figure 6).

The dimension of energy infrastructure also showed a dramatic change during this period (C4 in Figure 6). The China Electric Power Yearbook reported a reliability indicator of power grid over 99.8 percent during this period, and the other indicator, average blackout hours per household, also presented a V-shape change. From 2005 to 2010, the average blackout hours showed a rapid decline, while the downward trend reversed and the value started to creep up again from 2011. The main reason maybe that the extreme weather leads to overload of power grid. In addition, the energy infrastructures, including gas pipelines, power transmission line and substation capacity, have kept continuous improvements.

Energy technology and efficiency are increasingly important in improving energy security. Fortunately, Henan province was keeping an ongoing and steady upward trend in this dimension (C5 in Figure 6). This study selected six indicators to represent it, and five of them involved to better performance, except the indicator of capacity factor. This indicator reflects the utilization of power plants, which seems to have experienced an ongoing decline, and this is very possible leaded by the excess capacity in electricity industry.

Environment quality has been a significant part of energy security. Although Henan province has made some progress in improving air quality, it was mainly achieved in recent years. From 2005 to 2015, Henan province were suffering poor air environment. After that, the central and local governments has paid great efforts in improving air quality, and air pollutant emissions were strictly controlled and restricted. Therefore, a great improvement in environmental sustainability after 2016 can be noticed (C6 in Figure 6).

Governance is an essential element in energy security. However, it seems to be ignored in Henan province, and the performance with respect to this dimension failed to achieve any improvement, even showed some decline (C7 in Figure 6). Although the provincial government efficiency has improved during this decade, its efforts on energy industry, energy conservation & environment protection were decreasing. The deterioration of energy governance has affected the further improvement of energy security performance of Henan province.

4.5 Root cause analysis by Why-Why Diagram

According to the results of energy security measurement, it can be noticed that Henan province have achieved a moderate level of energy security. Then the root causes for this moderate energy security performance can be analyzed by employing Why-Why Diagram, and the results of root cause analysis are presented in Figure 7.

The first Why:

Why did Henan province failed to achieve a high level of energy security performance (see the first level in Figure 7)?

Answer: (1) There is a great gap between energy supply and demand, and this gap has kept expanding in recent years; (2) Environmental sustainability are facing great challenges, and the energy related pollutants have significantly affected environmental quality (as shown in the second level of Figure 7).

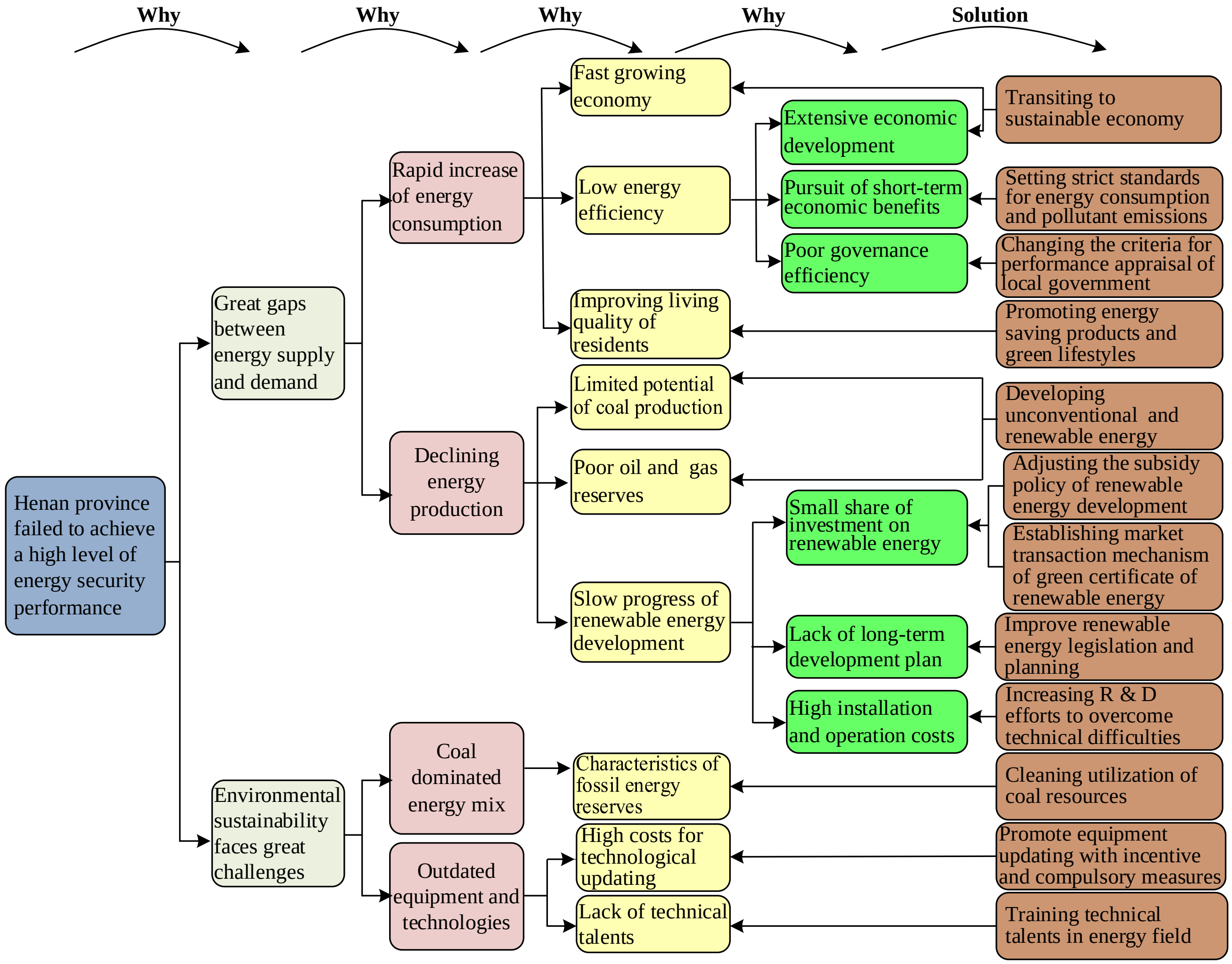

Figure 7. Why-Why Diagram for moderate energy security performance in Henan province.

The second why:

(1) Why did the gap between energy supply and demand keep expanding (see the second level in Figure 7)?

Answer: (1) Energy consumption in Henan province has being increasing rapidly; (2) Energy production can’t catch up with the increase of energy consumption, and even decreased since 2010 (as shown in the third level of Figure 7).

(2) Why did environmental sustainability be affected (see the second level in Figure 7)?

Answer: (1) Coal is a relatively low efficient energy source and emits various air pollutants in combustion, however, has provided most sources of energy supply; (2) The equipment and processing technologies in the coal industry are relatively backward (as shown in the third level of Figure 7).

The third why:

(1) Why did energy consumption in Henan province increase so fast (see the third level in Figure 7)?

Answer: (1) Henan province is a large economy in China, and the rapid growing economy around the country has also leaded to the fast growth of economy in Henan province, which pushed the sharp increase of energy consumption; (2) Energy efficiency in Henan province is relatively lower than other provinces, and this leaded to extra energy consumption; (3) With the increase of household income, home heaters and various appliances have been popularly used, which contribute greatly to energy consumption (as shown in the fourth level of Figure 7).

(2) Why did energy production decline in Henan province (see the third level in Figure 7)?

Answer: (1) Although Henan province has rich coal reserves, it can hardly increase coal production due to the limited demand for coal products; (2) Oil and gas are scarce resources in Henan province, so it can hardly increase its production in short time; (3) Renewable energy is considered as a promising source for increasing energy supply, however, failed to make any progress in Henan province (as shown in the fourth level of Figure 7).

(3) Why was energy mix in Henan province dominated by coal (see the third level in Figure 7)?

Answer: Henan province has a very similar characteristic of fossil energy reserves with China, which is rich in coal, while scarce in oil and gas. This special characteristic of energy endowment determined a coal-dominated energy mix, as shown in the fourth level of Figure 7.

(4) Why were the equipment and processing technologies in the coal industry relatively backward (see the third level in Figure 7)?

Answer: (1) Updating of equipment and processing technologies in the coal industry needs a quite large number of financial costs, and this may bring extra burden to coal enterprises; (2) There isn't sufficient supply of specialized talents and technicians, and it can hardly promote the technological and equipment upgradation (as shown in the fourth level of Figure 7).

The fourth why:

(1) Why was energy efficiency in Henan province lagging behind other provinces (see the fourth level in Figure 7)?

Answer: (1) Henan province adopted an extensive economic development model during the past decades, which leaded to massive energy wastes in energy production and consumption; (2) The local government efficiency has also been criticized, which brought inefficient governance on local energy production and consumption; (3) In order to acquire as much economic profits as possible in short term, enterprises didn't care energy efficiency (as shown in the fifth level of Figure 7).

(2) Why did renewable energy develop with a relatively slow progress in Henan province (see the fourth level in Figure 7)?

Answer: (1) The development of renewable energy needs a detailed and long-term plan, but Henan province hasn't formed a solid and scientific plan that can be used to guide the research, investment, and operations of renewable energy projects; (2) There is a lack of desire to supply capital to renewable energy industry, so there shows a very weak growth of renewable energy industry in Henan province; (3) Henan province do have some potential for developing wind power, solar power and biofuels , but the high installation and operation costs prevented them from achieving further progresses.

Solutions to the root causes:

With respect to the 13 root causes identified for the moderate energy security performance in Henan province, this study gave 12 pieces of solutions, as presented in Figure 7. It can be noticed that these solutions have involved mostly renewable energy development and technological innovation, with 4 pieces of solutions on both aspects. The others relate to economic development, social participation, energy governance, and environmental policy. In fact, renewable energy and technological innovation have been taken as the most important countermeasures for enhancing energy security around the world. The main threats to energy security in Henan province are the short supply of energy resources and relatively low energy efficiency. Various renewable energy sources can provide additional and clean energy supply, and technological innovation can accelerate renewable energy development and improve energy efficiency and environmental sustainability.

5. Discussions

Energy security is a complicated system, and various dimensions, indicators, indices, and multiple techniques have been introduced to achieve an all-around understanding of energy security. However, there is no single method that is the best for analyzing energy security, because each method can only describe one-sided impression. So, it can only consider as much details related to energy security as possible, and try best to depict it from multiple perspectives. In fact, there is always a debating between the qualitative and quantitative approaches on assessing energy security, and the qualitative techniques are usually criticized due to their subjectivity with great prejudice and arbitrariness. As a complicated system, energy security not just related to physical energy resources, but also closely linked with many dimensions in social sciences, which is mainly conducted through induction and deductive analysis [139,140]. An analysis totally relying on quantitative assessment is also not an option, because it only considers the information derived from quantitative data and ignores the needs of different societies as well as their changing trends.

This paper provided a hybrid model of GRA-TOPSIS to assess energy security performance in

Henan province of China. To prove the effectiveness of this hybrid model, it was compared with the two separate techniques of GRA and TOPSIS, and the results are displayed in Table A12 of the Suppletory Material. It shows that the hybrid GRA-TOPSIS model has achieved a different priority from that obtained by GRA and TOPSIS. Despite that, the positions of the alternatives derived by these three techniques doesn't show too much varieties, and most of the difference in positions for each alternative is within two places. The most obvious difference is the position in the case of 2014, where GRA ranked this alternative at the fourth place and TOPSIS ranked it at the eighth, while the hybrid model ranked it at the sixth. In fact, the hybrid GRA-TOPSIS model is more like a reconciliation or compromise between GRA and TOPSIS. Because the grey proximity for each alternative derived by the hybrid model is a combination of grey correlation degrees obtained by GRA and the Euclid distances obtained by TOPSIS. By doing this, it can integrate the advantages of those two methods in ranking priorities by considering degree of similarity or differences and distances between the alternatives and PIS and NIS simultaneously. This integration is actually a combination of the parameters derived from the two separate techniques, and further studies can be conducted to explore the deep integration between them or other MCDM techniques.

A qualitative tool, Why-Why Analysis, was used to approach the possible reasons that lead to the specific energy security performance in this study, and it is capable of identifying the root causes as many as possible to derive the solutions for solving the problem. Despite that, there also exist complex interactions among the reasons and factors that affect energy security performance, so the analysis of correlations or effects between different factors is also necessary. Several methods are available for analyzing these mutual effects, e.g., Decision Making Trial and Evaluation Laboratory and Cognitive Map, which will be investigated in the following studies. In addition, the root causes for energy security in other provinces also need to be analyzed for comparisons, and this could be one of the further studies that can be conducted.

6. Conclusions

To assess and analyze energy security from a comprehensive and all-around perspective, a conceptual and methodological framework has been provided in this study. In addition, it also conducted a case study to investigate energy security performance in Henan province, China, within the period of 2005 to 2017. Some conclusions can be drawn for this study.

Firstly, energy security is a conception with increasingly multidimensional meanings. Although the geographical existence of energy resources reflects the foundation of energy security in a traditional way, the economic globalization and technological improvement provide additional and broad sense to it. In an open and globalized world, energy demand can be met by importing energy products and services from other areas or countries, which provides additional access to energy availability. With the progress of science and technology, the resilience of energy security has been greatly enhanced. On the one hand, the development of renewable and unconventional energy was becoming technologically and economically feasible, which expanded energy sources. On the other hand, more advanced technology and equipment can help to improve energy efficiency and create more value. Besides, energy security not only means additional energy availability and accessibility, but also better living environment and life quality. Economy, environment and society are the three pillars of sustainable development. Standing on this point, energy security should also include the social, environmental, even political factors related to energy.

Secondly, it provided a comprehensive and all around conceptual and methodological framework for analyzing energy security with both quantitative and qualitative techniques. From the conceptual perspective, it depicted energy security from seven dimensions: availability and diversity, affordability, sociality and equality, energy infrastructure, technology and efficiency, environmental sustainability, and governance, and further decomposed them into 23 components and measured with 28 indicators. From the methodological perspective, a semi-mathematical approach, Fuzzy AHP, is used to allocate weights to the dimensions and indicators, and then the hybrid model of GRA-TOPSIS is introduced to evaluate performance of the alternatives. In addition, a qualitative analyzing technique, Why-Why Diagram, is employed to explore the root causes that lead to a specific energy security performance. Thus, this framework can analyze energy security from multiple perspectives.

Additionally, it conducted a case study by investigating energy security in Henan province, China, within the period of 2005 to 2017. It indicated that this province has experienced an upward energy security trajectory during this period. At the beginning years, energy security performance in this province remained at a low level, mainly due to its simple energy mix, obsolete equipment and infrastructures, straggling energy efficiency and technology, inadequate energy products and services, and ignorance of energy governance and environmental sustainability. With the growth of national and local economy, and the advancement of science and technology, energy efficiency has been improved, which helped enhance energy security. When stepping into the 2010s, its energy consumption gradually rise to a historically high level of more than 200 million tons SCE, stunting the further enhancement of energy security, even leading to some degree of decrease. After 2015, as China's economy slowed down, and the central government initiated industrial structural adjustment, reduction of excess capacity and economy transition. These explained the slow and steady turnaround of energy security performance after the hesitation and slight decline between 2010 and 2015. What can be foreseen is that energy security performance in Henan province will continue growing upward when China's economy steps into the phase of "New Normal", a crucial rebalancing strategy in which economic diversity and sustainable economic growth are embraced [141]. However, there is still a long way to go for this province to push its energy situation to a “secure” level, and energy security in Henan province is in a unadvantageous situation with a great possibility, although continuous improvement has been achieved throughout these years.

Acknowledgments

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