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Evaluation of Electricity Supply Sustainability and Security: A Multi-Criteria Decision Analysis Approach

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Abstract: Electricity supply plays a significantly important role in national economy and society development. Accordingly, the evaluation of electricity supply sustainability and security as an early warning method is beneficial for the decision-makers/policy-makers to take various measures to enhance electricity supply sustainability and security. This study aims at developing a multi-criteria decision analysis framework for electricity supply sustainability and security evaluation, and a total of nine metrics (i.e. Shannon-Weiner index, electricity import dependence, supply adequacy, rural electrification rate, electric power losses ratio, residential consumption ratio, electricity per Gross Domestic Product, electric power consumption per capita, and fossil fuel dependence) in four dimensions including availability and security of supply, affordability and reliability, energy and economic efficiency, and environmental stewardship are employed for electricity supply sustainability and security evaluation. Fuzzy Analytic Hierarchy Process which allows the users to use linguistic terms to express their opinions have been used to determine the weights of the criteria which represent their relative importance in the evaluation of electricity supply sustainability and security. Grey Rational Analysis has been used to prioritize the status of electricity supply sustainability and security of different countries in different years. The electricity supply sustainability and security of the five major emerging national economies (Brazil, Russia, India, China and South Africa) has been studied by the proposed method.

Keywords: Electricity Supply Sustainability and Security Evaluation; Fuzzy Analytic Hierarchy Process; Grey Rational Analysis

1. Introduction

Electricity, as one of the most important energy carriers, plays a significantly important role for sustaining the economic growth (Cowan *et al*., 2014; Tang and Tan, 2013); however, the high dependence on fossil energy sources for electricity generation has leaded to many severe problems, i.e. air pollution, large amount GHG emissions, high reliance on imported energy, and low energy security (Bridges *et al*., 2015; Gracceva and Zeniewski, 2014). Accordingly, the concept of ESSS which is defined as "*the ability of the electrical power system to provide electricity to end-users with a specified level of continuity and quality in a sustainable manner, relating to the existing standards and contractual agreements at the points of delivery*" (Eurelectric, 2004; Eurelectric, 2006) has been widely discussed recently. Many countries have taken various measures for enhancing the security of electricity. For instance, China has launched the renewable energy development plan with the objective of CO_2 mitigation, energy import dependence alleviation, air quality improvement, and water quality improvement (Qi et al., 2014). Brazil has carried out or planned various biofuel projects, i.e. sugarcane bagasse electricity (Silva et al., 2014), hybrid concentrated solar power (CSP)–biomass plants (Soria et al., 2015), and rice husk for electricity generation (Mayer et al., 2015), for mitigating the dependences on fossil fuels for electricity generation and improving environmental performances, and can further enhance the security of electricity supply. All these studies aim at enhancing the security of electricity supply.

The analysis of electricity supply sustainability and security (ESSS) and the changing trend of ESSS is the foundation of proposing effective measures and actions to enhance the ESSS of a country (Portugal-Pereira and Esteban, 2014). However, there are a limited number of studies that focus on developing the methodologies for analyzing the status of ESSS. Therefore, developing the framework for ESSS evaluation is prerequisite and significantly important. The evaluation of ESSS usually considers multiple dimensions. Kjølle and Gjerde (2010) developed an integrated approach for security of electricity supply analysis by integrating the power system reliability analysis and the power market analysis. There are also many studies that have considered more than three indicators for the analysis/evaluation of ESSS, and more information can be found in the works of Zlatar et al. (2014), Gouveia et al. (2014), and Portugal-Pereira and Esteban (2014). Therefore, ESSS evaluation can be recognized as a multi-criteria decision analysis (MCDA) problem. The objective of this study is to evaluate the ESSS of the five major emerging national economies including Brazil, Russia, India, China and South Africa (BRICS) from 1990 to 2010 based on the developed framework for ESSS evaluation, and the proposed framework consists of the criteria system for ESSS evaluation and the multi-criteria decision analysis method to investigate the trend of the ESSS of the BRICS countries. The results obtained by the proposed MCDA method can help the decision-makers/stakeholders to have a good understanding of the ESSS trend of the BRICS countries, and they can draft effective countermeasures and actions for improving the ESSS status of the BRICS.

The remainder of this study is organized as follows: literature reviews were carried out in section 2, and the metrics of ESSS evaluation was also proposed in this section; the multi-criteria decision analysis model by combining Fuzzy Analytic Hierarchy Process and Grey Rational Analysis has been presented in section 3; the results of the ESSS status of the BRICS were presented in section 4; the results were discussed in section 5; and finally this study was concluded in section 6.

2. Literature review

There are many studies focusing on energy concerns (i.e. energy efficiency, energy security, the development of renewable energy, and energy consumption, etc.) of the BRICS (Cowan *et al*., 2014; Zaman *et al*., 2016; Pao and Tsai, 2011). For instance, Song *et al.* (2013) employed the Bootstrap-DEA (Data Envelopment Analysis) to measure and investigate the energy utilization efficiency of the BRICS countries, predict the current status and future trend of energy efficiency, and quantify the relationship between energy efficiency and carbon emissions. Cowan *et al*. (2014) studied the causal nexus between electricity consumption, economic growth and CO_2 emissions in the BRICS countries from 1990 to 2010. Zaman *et al*. (2016) investigated the complex relationship between energy consumption, environment, health and their impacts on BRICS's economic growth. Freitas et al. (2012) analyzed whether or not the Kyoto mechanisms on promoting the development of renewable energy technologies in the BRICS. Pao and Tsai (2011) studied the dynamic relationships between the three factors including pollutant emissions, energy consumption, and the outputs of the Brazil during 1980-2007, and the GM (grey prediction) model was employed to forecast these three factors. Ozturk (2015) explored the sustainability in the food-energy-water nexus of the BRICS countries. However, to the best of our knowledge, there are few studies focusing on the evaluation of electricity supply sustainability or the electricity supply security of the five BRICS countries. For instance, Portugal-Pereira and Esteban (2014) analyzed the electricity generation security of supply under different energy scenarios in Japan by developing a series of indicators. Vivoda (2010) established an energy security assessment instrument to assess the energy security in Asia-Pacific region. Bambawale and Sovacool (2011) investigated China's energy security from the perspective of energy users who work in China's government, university, civil society and business sector. To the best of our knowledge, it is the first time to define use the concept of ESSS which includes the evaluation of both electricity supply security and electricity supply sustainability. Accordingly, the criteria for ESSS evaluation should consists of both the criteria for the evaluation of electricity supply security as well as that for the evaluation of electricity supply sustainability.

With the continuous increase of the awareness and perceptions of human on energy security, there are more and more studies focusing on conceptualizing and defining energy security. For instance, Leiby and Rubin (2013) defined energy security for the U.S. in economic terms as "the protection of the U.S. economy against the risk of significant short-term and long-term increases in energy costs and their attendant macroeconomic consequences". Lesbirel (2004) defined energy security as the availability of sufficient energy resources and services at affordable price.

Sovacool *et al.* (2011) pointed out that energy security refers to equitably providing available, affordable, reliable, efficiency, environmentally benign, proactively governed and socially acceptable energy services to the end-users. It is apparent that measuring energy security should consider multiple dimensions and aspects. One of the most famous examples is the "4A" (availability, affordability, accessibility, and acceptability) criterion system developed by the Asia Pacific Energy Research Centre (APERC, 2007). Electricity is a primary energy carrier, thus, electricity supply security evaluation should also consider multiple dimensions and aspects. For instance, Zlatar et al. (2014) developed six metrics in three dimensions including security of primary energy supply, environmental performances, and power system reliability. Gouveia et al. (2014) developed dozens of metrics in five aspects including resources, infrastructure, electricity production technologies, transport and distribution, and demand for quantifying the security of Portuguese electricity supply. Portugal-Pereira and Esteban (2014) employed the multiple indicators in five dimensions including availability, reliability, technological development, global environmental sustainability, and local environmental protection for measuring Japan's electricity security of supply. There are also some other studies that focus on developing metrics for measuring energy or electricity supply security (Ren and Sovacool, 2014; UEI-EURELECTRIC, 2004). As for the energy supply sustainability assessment, the authors have had comprehensive study in the previous works (Ren et al., 2015c), and there are usually multiple metrics in economic, environmental, social-political, and technological aspects that have been used for sustainability assessment (Ren and Liang, 2017a; Ren et al., 2017b; Ren and Lützen, 2017).

As discussed above, ESSS evaluation has to consider the criteria in multiple dimensions, and it is a MCDA problem. MCDA refers to ranking a finite number of alternatives with the considerations of multiple criteria (Hajkowicz and Higgins, 2008; Ren *et al.*, 2017). MCDA methods have the following characteristics: (a) the ability to handle difficult decision structure; (b) the capacity to account for complex criteria with non-commensurate unit; and (c) support the process of decision-making (Mendoza and Martins, 2006). Moreover, it supports the quantification of multiple objectives with conflicting attributes or subjective aspects (Teixeira de Almeida, 2007). MCDA has been widely used in different multi-criteria decision analysis problems, i.e. water resource management (Garfì et al., 2011; Hajkowicz and Higgins, 2008), fuel cell strategic technologies development solutions in the automotive industry (Sadeghzadeh and Salehi, 2011), sustainability assessment of biogas production (Manzardo et al., 2012; Nzila et al., 2012), concentrated solar thermal technologies assessment (Cavallaro, 2009), natural resource management (Mendoza and Martins, 2006), and supplier evaluation and selection (Ho et al., 2010).

Similar to these problems, the evaluation of ESSS also needs to consider a finite number of alternatives (the ESSS with respect to different years or different countries) and multiple criteria/metrics (i.e. Shannon-Weiner index, rural electrification rate, and electricity per GDP, et al.) (Pan *et al.*, 2017; Narula *et al.*, 2017). Therefore, it is also a multi-criteria decision analysis problem. There are various MCDA methods, i.e. PROMETHEE (Preference Ranking Organization Method for Enrichment

Evaluation) (Brans, 1986; Vincke and Brans, 1985), TOPSIS (Technique for Order Preference by Similarity to an Ideal Solution)(Hwang and Yoon, 1981), ELECTRE (ELimination Et Choix Traduisant la REalité) (Kaya and Kahraman, 2011), GRA (Grey Rational Analysis) (Deng, 1985), and DEA(Data Envelopment Analysis) (Ren et al., 2014), etc. Among these, GRA is the most suitable method for evaluating the ESSS, because it is derived from the grey system theory which has the ability of addressing incomplete information and unclear problems (Deng, 1982). Moreover, it is suitable for solving the complicated interrelationships among multiple factors and variables (Deng, 1985; Morán et al., 2006). The evaluation of ESSS usually involves multiple factors/metrics that have interacted relationships among them, and the interdependent relationships among these affecting factors/metrics on ESSS are unclear. Thus, GRA has the ability to address this kind of problems. Accordingly, GRA has been employed for evaluating the ESSS in this study.

In the applications of GRA, some methods for determining the weights of the criteria/metrics for decision-making are usually combined with GRA. For instance, Xu et al. (2011) used Analytic Hierarchy Process to determine the weights of the criteria for the comprehensive evaluation of co-fired power plants that are prerequisite for the application of GRA. Wang et al. (2008) employed a combined method for determining the weights of the criteria for the integrated evaluation of distributed tripe-generation systems with the improved grey rational analysis. There are also various methods for determining the weights including subjective weighting methods (i.e. Analytic Hierarchy Process (AHP) and Delphi method), objective weighting methods (i.e. entropy method), and the combined weighting methods (i.e. the combination of AHP and Entropy method) (Song *et al.,* 2015; Liu *et al.,* 2015). Among these, AHP developed by Saaty (1980) is the most popular method that has been widely used for weight determination as it can accurately reflect the preferences of the decision-makers and the actual conditions. The traditional AHP does not perform well as it relies on a nine-scale system (1-9) and the reciprocals of these numbers to establish the comparison matrix (Saaty, 1980); however, human judgments usually involve subjectivity, vagueness and ambiguity, thus, it is usually difficult for the decision-makers to use an exact number to compare the relative importance between two factors (Ren et al., 2015a; Ren and Sovacool, 2015). Fuzzy set theory has the ability to handle subjectivity, vagueness and ambiguity existed in human judgments (Zhang *et al*., 2016; An *et al.*, 2016).

As discussed above, fuzzy theory has the ability to address this. Thus, various extensions of AHP by combining with fuzzy theory (Chang, 1996; Durán and Aguilo, 2008; Kaya and Kahraman, 2011; Tan et al., 2014; Wang and Chin, 2008) have been developed. In this study, we employed linear goal programming-method-fuzzy analytic hierarchy process (LGPMFAHP) developed by Wang and Chin (Wang and Chin, 2008) to determine the weights of the metrics for the evaluation of ESSS as it is a method can overcome the existing problems in the most widely used method-extent analysis. Fuzzy AHP can use the thoughts of both fuzzy set theory and hierarchy structure analysis (Ren *et al*., 2013). In other words, it cannot only decompose the complex problem into different hierarchies, but also handle the subjectivity, vagueness and ambiguity existing in human judgments.

Based on the above mentioned literature reviews, a metric system which consists of nine metrics in four dimensions for ESSS evaluation was developed. The four dimensions are availability and security of supply, affordability and reliability, energy and economic efficiency, and environmental stewardship. Shannon-Weiner index, electricity import dependence, and supply adequacy are the three metrics belonging to availability and security of supply (Ren and Sovacool, 2014; Ren and Sovacool, 2015). The 'affordability and reliability' dimension consists of three metrics including rural electrification rate, electric power losses ratio, and residential consumption ratio. There are two metrics in the 'energy and economic efficiency' dimension, namely, electricity per GDP and electric power consumption per capita. Fossil fuel dependence is the metric in the 'environmental stewardship' dimension. The definitions of these nine metrics were specified as follows:

(1) Availability and security of supply (D_1)

● Shannon-Weiner Index (SWI) (D_{11})

The Shannon-Weiner index can be calculated by Eq.1, it can reflect the degree of energy source diversity for electricity generation, and it is a measure of the resilience of the energy system against unquantifiable disturbances (REEK, 2009).

$$D_{11} = -\sum_{k=1}^{n} p_k \ln p_k \tag{1}$$

$p_k \ln p_k = 0$ when $p_k = 0$

where p_k is the share of the k-th energy source for electricity generation, and n is the total number of the energy sources for electricity generation.

● Electricity import dependence (D_{12})

The electricity import dependence is the ratio of the import electricity to the total domestic supply of electricity (see Eq.2), and it is a measure of the ability of self-sufficiency on electricity supply (Lilliestam and Ellenbeck, 2011).

$$D_{12} = \frac{E_{import}}{E_{domestic}} \qquad (2)$$

where E_{import} is the import electricity, and $E_{domestic}$ is the total domestic supply of electricity

● Supply adequacy (D_{13})

The supply adequacy is the ratio of the total electricity production to the domestic supply (see Eq.3), and it can be used to measure the adequacy level of electricity supply (Batlle *et al.*, 2007).

$$D_{12} = \frac{E_{production}}{E_{domestic}} \qquad (3)$$

where $E_{production}$ is the total electricity production, and $E_{domestic}$ is the total domestic supply of electricity

(2) Affordability and reliability (D_2)

●Rural electrification rate (D_{21})

The rural electrification rate represents the percentage of rural population with access to electricity, and it is a measure of power penetration in rural (Zhang and Kumar, 2011).

● Electric power losses ratio (D_{22}) (% of output)

The electric power losses ratio is the ratio of the electric power transmission and distribution losses to the total output, and include losses in transmission between sources of supply and points of distribution and in the distribution to consumers, including pilferage (World-Bank, 2015). It is a measure of the electricity storage and utilization efficiency.

● Residential consumption ratio (D_{23})

The residential consumption ratio is the ratio of the residential consumption of electricity to the final consumption of electricity. It can be used to measure the affordability of electricity to the residents (Zhu *et al*., 2012).

(3) Energy and economic efficiency (D_3)

● Electricity per GDP (D_{31}) (TWh/billion 2005 USD)

The electricity per GDP represents the average consumed electricity for producing per unit of GDP, and it can be calculated by Eq.4, and it is a measure of the electricity utilization efficiency for economy development (Chen *et al*., 2007).

$$D_{31} = \frac{E_{consumption}}{GDP} \tag{4}$$

where $E_{consumption}$ is the total electricity consumption, and GPD represents the Gross Domestic Product.

● Electric power consumption per capita (D_{32})

The electric power consumption per capita is the ratio of the electric power consumption to the total population, as presented in Eq.5, and it can be used to measure the electricity consumption level (Mozumder and Marathe, 2007).

$$D_{32} = \frac{E_{consumption}}{P} \tag{5}$$

where $E_{consumption}$ is the total electricity consumption, and P is the total number of population

(4) Environmental stewardship (D_4)

● Fossil fuel dependence (D_{41})

The fossil fuel dependence is the percentage of the electricity generated by fossil fuels (coal, oil and gas) in the total generated electricity. The high dependence on fossil fuels means high CO_2 emission and high water consumption, thus, this metric can be used to measure the integrated environmental performances of power industry (Bhattacharyya, 2009).

$$D_{13} = \frac{E_{fossil}}{E_{production}} \quad (6)$$

where E_{fossil} is the electricity generated by fossil fuels (coal, oil and gas), and $E_{production}$ is the total generated electricity

It is worth pointing out that the users can select parts of the metrics, and add more dimensions/metrics for measuring the electricity supply security and sustainability according to their requirements and the actual conditions. For instance, some users may also use "consumption ratio by industrial and commercial sectors" as a metric in affordability and reliability (D_2) to measure the performance of electricity supply security and sustainability.

3. Methods

In this section, the linear goal programming-method-fuzzy analytic hierarchy process was firstly presented; then, the grey relational analysis was introduced; finally, the method for the evaluation of ESSS was developed.

3.1 Linear goal programming-method-fuzzy analytic hierarchy process

The linear goal programming-method-fuzzy analytic hierarchy process (LGPMFAHP) is specified in the following four steps based on the work of Wang and Chin (2008):

Step 1: Establishing the pair-wise comparison matrix by using the triangular fuzzy numbers.

Assume that there are a total of n factors (i=1,2,…, n) with the *i*-th criterion denoted C_i. In order to overcome the problems existing in human judgments, i.e. vagueness, ambiguity and subjectivity, the LGP-based FAHP uses the triangular fuzzy numbers, that can express the preferences of the decision-makers more accurately than the 1-9 scale system to compare the relative priority between each pair of criteria that are commonly used in the traditional AHP, to establish the comparison matrix. Accordingly, a pair-wise comparison matrix can be established by the decision-makers by using the fuzzy scales presented in Table 1 (Tseng et al., 2009). Each element in the comparison matrix can be determined by comparing the relative importance/priority of each pair of criteria, as presented in Eqs.1-2.

$$\tilde{A} = \begin{vmatrix} (1,1,1) & \tilde{a}_{12} & \cdots & \tilde{a}_{1n} \\ 1/\tilde{a}_{12} & (1,1,1) & \cdots & \tilde{a}_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ 1/\tilde{a}_{n1} & 1/\tilde{a}_{2n} & \cdots & (1,1,1) \end{vmatrix} \quad (1)$$

$$\tilde{a}_{ji} = \frac{1}{\tilde{a}_{ij}} = \left(\frac{1}{a_{ij}^{u}}, \frac{1}{a_{ij}^{m}}, \frac{1}{a_{ij}^{l}} \right) \quad (2)$$

where $\tilde{A}$ is the comparison matrix comprised by triangular fuzzy numbers, $\tilde{a}_{ij}=\left(a_{ij}^{l},a_{ij}^{m},a_{ij}^{u}\right)$ is a triangular fuzzy number which represents the relative importance of the C_i compared with C_j, and a_{ij}^{l}, a_{ij}^{m} and a_{ij}^{u} are the three elements of the triangular fuzzy number $\tilde{a}_{ij}$.

Step 2: Decomposing the fuzzy comparison matrix into three crisp nonnegative matrices.

The fuzzy comparison matrix in Eq.1 can be decomposed into three crisp nonnegative matrices, as presented in Eqs. 3-5. The elements of cell (i, j) in these three matrices are the three elements of $\tilde{a}_{ij}$ that is the element of cell (i ,j) in the fuzzy comparison matrix $\tilde{A}$, respectively.

$$A_L=\begin{vmatrix} 1 & a_{12}^{l} & \cdots & a_{1n}^{l} \\ 1/a_{12}^{u} & 1 & \cdots & a_{2n}^{l} \\ \vdots & \vdots & \ddots & \vdots \\ 1/a_{n1}^{u} & 1/a_{2n}^{u} & \cdots & 1 \end{vmatrix} \quad (3)$$

$$A_M=\begin{vmatrix} 1 & a_{12}^{m} & \cdots & a_{1n}^{m} \\ 1/a_{12}^{m} & 1 & \cdots & a_{2n}^{m} \\ \vdots & \vdots & \ddots & \vdots \\ 1/a_{n1}^{m} & 1/a_{2n}^{m} & \cdots & 1 \end{vmatrix} \quad (4)$$

$$A_U=\begin{vmatrix} 1 & a_{12}^{u} & \cdots & a_{1n}^{u} \\ 1/a_{12}^{l} & 1 & \cdots & a_{2n}^{u} \\ \vdots & \vdots & \ddots & \vdots \\ 1/a_{n1}^{l} & 1/a_{2n}^{l} & \cdots & 1 \end{vmatrix} \quad (5)$$

Step 3: Determining the fuzzy weights of the criteria by solving linear programming.

The weights of the criteria can be obtained by solving linear programming which aims at minimizing the degree of inconsistency of the fuzzy comparison matrix, as presented in the model (Eqs.6–15). Denotes the fuzzy weight of the *i*-th criterion by $\tilde{\omega}^i = \left(\omega_i^L, \omega_i^M, \omega_i^U\right)$, and ω_i^L, ω_i^M, and ω_i^U are the three elements of $\tilde{\omega}^i$ respectively, and they can be determined by obtaining the optimum solutions of the linear goal model (Eqs.6–15).

$$Minimize \quad D = e^T(E^+ + E^- + \Gamma^+ + \Gamma^- + \Delta) \tag{6}$$

$$(A_L - I)W_U - (n-1)W_L - E^+ + E^- = 0 \tag{7}$$

$$(A_U - I)W_L - (n-1)W_U - \Gamma^+ + \Gamma = 0 \tag{8}$$

$$(A_M - nI)W_M - \Delta = 0 \tag{9}$$

$$\omega_i^L + \sum_{j=1, j\neq ?}^{n} \omega_j^U \geq 1, i = 1, 2, \cdots, n \tag{10}$$

$$\omega_i^U + \sum_{j=1, j\neq ?}^{n} \omega_j^L \leq 1, i = 1, 2, \cdots, n \tag{11}$$

$$\sum_{i=1,}^{n} \omega_i^M = 1 \tag{12}$$

$$W_U - W_M \geq 0 \tag{13}$$

$$W_M - W_L \geq 0 \tag{14}$$

$$W_L, E^+, E^-, \Gamma^+, \Gamma^-, \Delta \geq 0 \tag{15}$$

where D represents the total deviations to reflect the degree of inconsistency of the fuzzy comparison matrix $\tilde{A}, W_L = \left(\omega_1^L, \omega_2^L, \cdots, \omega_n^L\right)^T$, $W_M = \left(\omega_1^M, \omega_2^M, \cdots, \omega_n^M\right)^T$, and $W_U = \left(\omega_1^U, \omega_2^U, \cdots, \omega_n^U\right)^T$ are the matrices in which the element of cell (i,1) are the three elements of $\tilde{\omega}^i$, respectively.

$e^T = (1, 1, \cdots, 1)$, $E^+ = \left(\varepsilon_1^+, \varepsilon_2^+, \cdots, \varepsilon_n^+\right)^T$, $E^- = \left(\varepsilon_1^-, \varepsilon_2^-, \cdots, \varepsilon_n^-\right)^T$, $\Gamma^+ = \left(\gamma_1^+, \gamma_2^+, \cdots, \gamma_n^+\right)^T$, $\Gamma^- = \left(\gamma_1^-, \gamma_2^-, \cdots, \gamma_n^-\right)^T$, and $\Delta = \left(\delta_1, \delta_2, \cdots, \delta_n\right)^T$ are all nonnegative deviation vectors.

Step 4: Defuzzification and normalization.

The fuzzy weight of the i-th criterion by $\tilde{\omega}^i = \left(\omega_i^L, \omega_i^M, \omega_i^U\right)$ can be defuzzified into crisp weights according to the Mean Area (MA) method according to Li (2003) and Ren *et al*. (2015b), as presented in Eq.16. Finally, the crisp weights can be normalized according to Eq.17.

$$\omega_i^{'} = \frac{\omega_i^L + 2\omega_i^M + \omega_i^U}{4} \tag{16}$$

$$\omega_i = \omega_i^{'} \Big/ \sum_{i=1}^{n} \omega_i^{'} \tag{17}$$

where $\omega_i^{'}$ is the defuzzified weight of the i-th criterion, and ω_i is the normalized weight of the i-th criterion.

3.2 Grey Rational Analysis

Grey Rational Analysis as part of grey theory developed by Deng (1985) has been specified in the following six steps (Deng, 2002; Zhai et al., 2009; Manzardo *et al*., 2012):

Step 1: Establishing the decision analysis matrix (X).

Assuming that there are m alternatives characterized by n criteria, as presented in Eq.18

$$X = \begin{vmatrix} x_{11} & x_{12} & \cdots & x_{1n} \\ x_{21} & x_{22} & \cdots & x_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ x_{m1} & x_{m2} & & x_{mn} \end{vmatrix} \tag{18}$$

where x_{ij} represents the value of the *j*-th criterion with respect to the *i*-th alternative

Step 2: Normalize the data in the decision analysis matrix, the methods for data processing should be chosen according to the types of the criteria. The larger the criteria, the better the alternative, the criteria can be called benefit-criteria, on the contrary, the larger the criteria, the worse the alternative, the criteria can be called cost-criteria.

Benefit-criteria:

$$y_{ij}^{k} = \frac{x_{ij}^{k}}{\max_{i=1}^{m}\left\{x_{ij}^{k,+}\right\}}, i=1,2,\cdots,m; j=1,2,\cdots,n \tag{19}$$

Cost-criteria:

$$y_{ij}^{k} = \frac{\min_{i=1}^{m}\left\{x_{ij}^{k,-}\right\}}{x_{ij}^{k}}, i=1,2,\cdots,m; j=1,2,\cdots,n \tag{20}$$

Step 3: Generate the reference alternative, the normalized matrix has been shown in Eq.21, and the reference alternative can be determined by Eq.22 and Eq.23. Reference alternative is the ideal best one.

$$Y = \begin{vmatrix} y_{11} & y_{12} & \cdots & y_{1n} \\ y_{21} & y_{22} & \cdots & y_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ y_{m1} & y_{m2} & \cdots & y_{mn} \end{vmatrix} \tag{21}$$

$$y^{0} = \left\{y_{1}^{0}, y_{2}^{0}, \cdots, y_{n}^{0}\right\} \tag{22}$$

$$y_{j}^{0} = \max_{i=1}^{m} y_{ij}, j=1,2,\cdots,n \tag{23}$$

where y_{j}^{0} is the reference value in relation to the *j*-th criterion

Step 4: Calculate the difference between the alternatives and the reference alternative, and construct the difference matrix by Eqs.24–25.

$$\Delta = \begin{vmatrix} \Delta_{11} & \Delta_{12} & \cdots & \Delta_{1n} \\ \Delta_{21} & \Delta_{22} & \cdots & \Delta_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ \Delta_{m1} & \Delta_{m2} & & \Delta_{mn} \end{vmatrix} \quad (24)$$

$$\Delta_{ij} = \left| y_j^0 - y_{ij} \right|, i = 1, 2, \cdots, m; j = 1, 2, \cdots, n \quad (25)$$

Step 5: Calculate the grey relational coefficient for each alternative by Eq. 26.

$$\varepsilon_{ij} = \frac{\min_{i=1}^{m} \min_{j=1}^{n} \Delta_{ij} + \rho \times \max_{i=1}^{m} \max_{j=1}^{n} \Delta_{ij}}{\Delta_{ij} + \rho \times \max_{i=1}^{m} \max_{j=1}^{n} \Delta_{ij}} \quad (26)$$

where ε_{ij} is the grey relational coefficient, ρ represents the distinguishing coefficient, it takes the value of 0,5 in this paper.

Step 6: Calculate the grey relational degree. A grey relational degree is a weighted sum of the grey relational coefficients, as shown in Eq.27.

$$\gamma_i = \sum_{j=1}^{n} \varepsilon_{ij} \times \omega_j \quad (27)$$

where ω_j represents the weight of the *j*-th criterion

3.3 Evaluation of ESSS

The evaluation of ESSS is based on the combination of LGPMFAHP and GRA, and it consists of three stages, namely, data collection, weights determination, and alternatives prioritization.

Stage 1: Data collection.

In this first stage, all the data of the metrics with respect to the countries in each year will be collected from National Statistical Yearbook, World Bank, International Energy Agency, reports, papers, books, and some other published works..

Stage 2: Weights determination.

In the second stage, the weights of the metrics for the evaluation of ESSS which reflect the relative importance of the metrics can be determined by LGPMFAHP. LGPMFAHP will be firstly used to calculate the weights of the four dimensions of ESSS, then to calculate the local weights of the metrics in each dimension, and finally the global weight of each metric can be determined by calculating the product of the local weight and the weight of the dimension to which the metric belongs to.

Stage 3: Alternatives prioritization.

In the third stage, GRA will be used to prioritize the alternatives based on the weights of the metrics for the evaluation of ESSS which were determined by LGPMFAHP in Stage 1.

4. Results

The linear goal programming-method-fuzzy analytic hierarchy process and grey rational analysis were combined to analyze the ESSS of the BRICS from 1990 to 2010, and there are two objectives: one is to determine the trend of the ESSS of the BRICS from 1990 to 2010, and another is to prioritize the BRICS in terms of their average ESSS in the 21 years.

Stage 1: Data collection.

The data of the nine metrics for ESSS evaluation with respect to the BRICS from 1990 to 2010 were derived from IEA (International Energy Agency) (IEA, 2015) and World Bank (World-Bank, 2015). The results were presented in Figures 1–9.

According to the Shannon-Weiner index which can reflect the degree of energy source diversity for electricity generation presented in Figure 1, Russia has the best holistic performances in terms of the resilience against unquantifiable disturbances to secure electricity supply, India was ranked at the second place, China performed better than Brazil on the resilience against unquantifiable disturbances to secure electricity generation before the new Millennium; while, Brazil exceeded China on this aspect after the new Millennium. The resilience of South Africa against unquantifiable disturbances to secure electricity supply is the worst.

As to the electricity import dependence, Brazil and South Africa has the highest dependence on the imported electricity, Russia was ranked in this middle, and India and China has the lowest dependence.

The supply adequacy of the BRICS from 1990 to 2010 in Figure 3 shows that Russia and China had generated adequate electricity for domestic supply in most of the years from 1990 to 2010. South Africa could achieve self-supply adequacy except the years from 1996 to 2001. India and Brazil had not generated adequate electricity for domestic supply from 1990 to 2010.

The distinctions of the rural electrification rate among the BRCIS from 1990 to 2010 are clear according to Figure 4, Russia and China were the best on this aspect, followed by Brazil, India, and South Africa. The rural electrification rate of Russia had achieved 100% since 1990, and that of China had increased slightly since 1990. The rural electrification rate of Brazil, India, and South Africa had a gradual increase year by year since 1990.

The electric power losses ratio in Figure 5 can reflect the energy storage and utilization efficiency of the BRICS from 1990 to 2010, and it is apparent that China and South Africa had the least electric power loess during 1990 to 2010, followed by Russia, Brazil, and India. Thus, the energy storage and utilization efficiency of China is the highest, and that of India is the lowest.

The residential consumption ratio of Brazil is the highest, that of China is the lowest, and that of the other three countries were ranked in the middle. To some extent, it means that the electricity in Brazil has the highest acceptability in terms of the electricity affordability (mainly refers to the rice of the electricity).

The electricity per GDP of the BRICS from 1990 to 2010 was presented in Figure 7, and Russia required the most amount of electricity and Brazil required the least amount of electricity for sustaining per GDP in a holistic view, it means that the energy utilization efficiency of Brazil is the highest, and that of Russia is the lowest.

The electric power consumption per capita of the BRICS from 1990 to 2010 was presented in Figure 8, it is apparent that the electric power consumption per capita of Russia and South Africa are the highest, followed by Brazil, China, and India.

The electricity production from the fossil fuels (oil, gas and coal sources) was presented in Figure 9, and South Africa had the highest dependence on fossil fuels for electricity generation, followed by India, China, and Brazil. Brazil had the lowest dependence. It means that the development of low-carbon energy sources for electricity generation in Brazil was the best during 1990 to 2010, while that in South Africa was worst.

Stage 2: Weights determination.

LGPMFAHP was used to determine the weights of the metrics which reflect the relative importance of these metrics in ESSS. In order to obtain the comparison matrices for determining the weights of the four dimensions of ESSS and that of the metrics in each dimension, a focus group meeting was held in Chongqing University, and eight experts including two professors of energy strategy management, two administrators, two engineers of power engineering, and two managers from electricity supply companies were invited to participate in the determination of each comparison matrix. In order to eliminate the inconsistency existed in the judgments of these experts, a coordinator was nominated, and he was responsible for coordinating these experts for achieving consensus.

We firstly determined the weights of the four dimensions of ESSS including availability and security of supply (D_1), affordability and reliability (D_2), energy and economic efficiency (D_3), and environmental stewardship (D_4). Then, we calculated the local weights of the metrics in each of the four dimensions. Finally, the global weights of each metric of ESSS were determined by calculating the product of the local weight of the metric and the weight of the dimension to which the metric belongs to.

In order to illustrate how to use LGPMFAHP for determining the weights of the metrics, the weights of the four dimensions have been taken as an example. The decision-makers can firstly use the linguistic terms presented in Table 1 to compare each pair of dimensions. For instance, 'availability and security of supply (D_1)' is regard as 'moderate importance (M)' when comparing with 'energy and economic efficiency (D_3), and the corresponding fuzzy scale is '(1,3/2,2)', thus, (1,3/2,2) was put in cell (1,3) of the fuzzy comparison matrix with respect to the four dimensions. In a similar way, all the other elements could also be determined, as presented in Table 2.

According to Eqs.3–5, the fuzzy comparison matrix with respect to the four dimensions can be divided into three matrices, namely, A_L, A_M, and A_U.

According to Eqs.6–15, the linear goal programming model for determining the weights of the four dimensions can be obtained (see the Appendix).

The weights of the four dimensions can be determined by solving this linear goal programming, the results are presented in Table 3, and the minimum objective value is $D = 0.0204$, thus, the fuzzy comparison matrix with respect to the four dimensions is not absolutely consistent. While the minimum objective value is very near 0, thus, it could be recognized as acceptable in terms of its consistency. Then, the fuzzy weights of the four dimensions can be defuzzified into the crisp weights according to Eq. 16. For instance, the weight of 'availability and security of supply (D_1)': $\left(\omega_1^L, \omega_1^M, \omega_1^U\right) = \left(0.2578, 0.3279, 0.3621\right)$ can be defuzzified into $\frac{0.2578 + 2 \times 0.3279 + 0.3621}{4} = 0.3189$. Similarly, the crisp weights of the other three dimensions can also be determined. Finally, the normalized weights of the four dimensions can be obtained according to Eq.17 (see Table 3).

LGPMFAHP was also used to determine the fuzzy weights of the metrics in each of the four dimensions of ESSS, and the results were presented in Tables 4. After the defuzzification and normalization, the local weights of the metrics in each dimension can be obtained. Accordingly, the global weights of these metrics can be determined.

Taking the global weight of the Shannon-Weiner index as an example, it can be determined by calculating the product of the local weight of Shannon-Weiner index in 'availability and security of supply (D_1)' dimension and the weight of 'availability and security of supply (D_1)', namely, 0.3257×0.3944=0.1285. Similarly, the global weights of the other metrics can also be determined, as presented in Table 5. Note that there is only one metrics in the dimension 'environmental stewardship (D_4)', namely, 'fossil fuel dependence (D_{41})'. Therefore, the local weight of fossil fuel dependence is 1, and the global weight of fossil fuel dependence is equal to that of environmental stewardship.

Stage 3: Alternatives prioritization (ESSS evaluation).

After determining the global weights of the metrics of ESSS, GRA was employed to analyze the ESSS of the BRICS from 19990 to 2010, and the results were presented in Figure 10. The score represents the grey relational degrees which varies from 0 to 1, and the greater the value, the more secure the electricity supply will be. The average score of ESSS of the BRICS from 1990 to 2010 could also be obtained, as shown in Figure 11.

5. Discussions

The following insights can be obtained according to the dynamic ESSS degrees presented in Figure 10 and the average score of electricity supply security of the BRICS from 1990 to 2010. Firstly, the holistic trend of ESSS with respect to Brazil and Russia was continuing deteriorating from 1990 to 2010, while the status of Brazil has slightly becomes better since 2004. The main reason of this phenomenon is that the electricity per GDP of Russia decrease year by year, while that of Brazil is also the lowest among these five nations. Meanwhile, the holistic trend of the electric power consumption per capita of these two countries increases year by year. Therefore, the improvement of energy utilization efficiency is the key for improving the ESSS of these two countries.

Secondly, the holistic trend of ESSS with respect to China, India and South Africa was gradually getting more and more secure from 1990 to 2010, while the ESSS of the three countries had a sharp increase then sharply decrease in 1998, 2002, and 1995, respectively. China's electricity supply sustainability and security is the best among these three nations, and there are several reasons leading to this including the rapid development of low-carbon and renewable energy sources for electricity generation to reduce energy importing ratio, the adoption of various energy-saving measures and energy-efficiency-improvement technologies, and the strategies and measures of mitigating energy poverty to increase rural electrification rate (Zhang *et al.*, 2017; Yao and Chang, 2014; Leung, 2011).

Thirdly, the priority sequence of the BRICS in terms of their average ESSS is Russia, Brazil, China, India, and South Africa in the descending order. In other words, the electricity supply sustainability and security of five major emerging national economies from the most secure to the least is Russia, followed by Brazil, China, India, and South Africa. The result of recognizing Russia as the most secure nation on electricity supply sustainability and security is consistent to the results of some other studies, because Russian cannot only achieve self-sufficiency, but also significantly influence the energy security of some other countries (Bahgat, 2006). For instance, Bahgat (2006) pointed out that Russia cannot only satisfy its own energy demand, but also supplies a large portion of Europe's energy need. Van de Graaf and Colgan (2017) found that Russian gas pricing played a crucial role as a context factor in igniting the Ukrainian crisis. The most significant advantage of Russia's ESSS is the sufficient energy sources (i.e. natural gas, coal, and petroleum, etc.).

Comparing with the previous studies for energy security evaluation or the evaluation of electricity supply sustainability and security, this study has the following innovations: (1) a generic framework for measuring the ESSS in national level was presented, and a generic evaluation criteria system which can be popularized has been developed. In other words, the developed framework can also be employed for the evaluation of the ESSS of some other countries; (2) the linear goal programming-method-fuzzy analytic hierarchy process (LGPMFAHP) which allows the users to use linguistic terms to establish the comparison matrix was firstly used in this filed, this method can accurately help the decision-makers to make correct decision, because it can accurately reflect the opinions and willingness of the decision-makers; and (3) the trend of electricity supply security and sustainability can be obtained, and the results can help the stakeholders (i.e. decision-makers, policy-makers and administrators) to draft appropriate policies and take effective measures to improve the status of electricity supply security and sustainability.

6. Conclusion

In order to help the stakeholders/decision-makers to have a good understanding of the ESSS of a nation, as well as its changing trend ESSS with time for taking effective measures/actions and drafting effective policies/regulations to enhance ESSS, an evaluation criterion system consisting of four dimensions including availability and security of supply, affordability and reliability, energy and economic efficiency, and environmental stewardship and nine metrics was developed for ESSS evaluation. The nice metrics are Shannon-Weiner index, electricity import dependence, supply adequacy, rural electrification rate, electric power losses ratio, residential consumption ratio, electricity per GDP, electric power consumption per capita, and fossil fuel dependence.

The multi-criteria decision analysis method for ESSS evaluation has been proposed by combining fuzzy AHP and GRA. The users are allowed to use linguistic terms to express their opinions for determining the weights of the criteria which represent their relative importance in ESSS evaluation when using this method. Moreover, a generic index, namely grey relational degree, represents the score of ESSS can be obtained. Accordingly, the status of ESSS of different countries in different years can be determined. The status of ESSS of the BRICS from 1990 to 2010 has been investigated by the proposed methods in this study, and some useful insights for the decision-makers were proposed according to the obtained results.

Appendix A The goal programming for determining the weights of the four dimensions

$$\begin{aligned} &Minimize \quad D=\varepsilon_1^+ +\varepsilon_2^+ +\varepsilon_3^+ +\varepsilon_4^+ +\varepsilon_1^- +\varepsilon_2^- +\varepsilon_3^- +\varepsilon_4^- + \\ &\gamma_1^+ +\gamma_2^+ +\gamma_3^+ +\gamma_4^+ +\gamma_1^- +\gamma_2^- +\gamma_3^- +\gamma_4^- +\delta_1+\delta_2+\delta_3+\delta_4 \end{aligned} \tag{A1}$$

$$\begin{aligned} &\frac{2}{3}\omega_2^U+\omega_3^U+2\omega_4^U-3\omega_1^L-\varepsilon_1^+ +\varepsilon_1^- =0 \\ &\frac{2}{3}\omega_1^U+\omega_3^U+\frac{3}{2}\omega_4^U-3\omega_2^L-\varepsilon_2^+ +\varepsilon_2^- =0 \\ &\frac{1}{2}\omega_1^U+\frac{1}{2}\omega_2^U+\frac{3}{2}\omega_4^U-3\omega_3^L-\varepsilon_3^+ +\varepsilon_3^- =0 \\ &\frac{1}{3}\omega_1^U+\frac{2}{5}\omega_2^U+\frac{2}{5}\omega_3^U-3\omega_4^L-\varepsilon_4^+ +\varepsilon_4^- =0 \end{aligned} \tag{A2}$$

$$\begin{aligned} &\frac{3}{2}\omega_2^L+2\omega_3^L+3\omega_4^L-3\omega_1^U-\gamma_1^+ +\gamma_1^- =0 \\ &\frac{3}{2}\omega_1^L+2\omega_3^L+\frac{5}{2}\omega_4^L-3\omega_2^U-\gamma_2^+ +\gamma_2^- =0 \\ &\omega_1^L+\omega_2^L+\frac{5}{2}\omega_4^L-3\omega_3^U-\gamma_3^+ +\gamma_3^- =0 \\ &\frac{1}{2}\omega_1^L+\frac{2}{3}\omega_2^L+\frac{2}{3}\omega_3^L-3\omega_4^U-\gamma_4^+ +\gamma_4^- =0 \end{aligned} \tag{A3}$$

$$\begin{aligned} &-3\omega_1^M+\omega_2^M+\frac{3}{2}\omega_3^M+\frac{5}{2}\omega_4^M-\delta_1=0 \\ &\omega_1^M-3\omega_2^M+\frac{3}{2}\omega_3^M+2\omega_4^M-\delta_2=0 \\ &\frac{2}{3}\omega_1^M+\frac{2}{3}\omega_2^M-3\omega_3^M+2\omega_4^M-\delta_3=0 \\ &\frac{2}{5}\omega_1^M+\frac{1}{2}\omega_2^M+\frac{1}{2}\omega_3^M-3\omega_4^M-\delta_4=0 \end{aligned} \tag{A4}$$

$$\begin{aligned} &\omega_1^L+\omega_2^U+\omega_3^U+\omega_4^U\geq 1 \\ &\omega_2^L+\omega_1^U+\omega_3^U+\omega_4^U\geq 1 \\ &\omega_3^L+\omega_1^U+\omega_2^U+\omega_4^U\geq 1 \\ &\omega_4^L+\omega_1^U+\omega_2^U+\omega_3^U\geq 1 \end{aligned} \tag{A5}$$

$$\begin{aligned}
&\omega_1^U + \omega_2^L + \omega_3^L + \omega_4^L \le 1 \\
&\omega_2^U + \omega_1^L + \omega_3^L + \omega_4^L \le 1 \\
&\omega_3^U + \omega_1^L + \omega_2^L + \omega_4^L \le 1 \\
&\omega_4^U + \omega_1^L + \omega_2^L + \omega_3^L \le 1
\end{aligned} \tag{A6}$$

$$\omega_1^M + \omega_2^M + \omega_3^M + \omega_4^M = 1 \tag{A7}$$

$$\begin{aligned}
&\omega_1^U - \omega_1^M \ge 0 \\
&\omega_2^U - \omega_2^M \ge 0 \\
&\omega_3^U - \omega_3^M \ge 0 \\
&\omega_4^U - \omega_4^M \ge 0
\end{aligned} \tag{A8}$$

$$\begin{aligned}
&\omega_1^M - \omega_1^L \ge 0 \\
&\omega_2^M - \omega_2^L \ge 0 \\
&\omega_3^M - \omega_3^L \ge 0 \\
&\omega_4^M - \omega_4^L \ge 0
\end{aligned} \tag{A9}$$

$$\begin{aligned}
&\left(\omega_1^L, \omega_2^L, \omega_3^L, \omega_4^L\right)^T \ge 0 \\
&\left(\varepsilon_1^+, \varepsilon_2^+, \varepsilon_3^+, \varepsilon_4^+\right)^T \ge 0 \\
&\left(\varepsilon_1^-, \varepsilon_2^-, \varepsilon_3^-, \varepsilon_4^-\right)^T \ge 0 \\
&\left(\gamma_1^+, \gamma_2^+, \gamma_3^+, \gamma_4^+\right)^T \ge 0 \\
&\left(\gamma_1^-, \gamma_2^-, \gamma_3^-, \gamma_4^-\right)^T \ge 0 \\
&\left(\delta_1, \delta_2, \delta_3, \delta_4\right)^T \ge 0
\end{aligned} \tag{A10}$$

where $\left(\omega_i^L, \omega_i^M, \omega_i^U\right), i = 1,2,3,4$ represents the fuzzy weight of the i-th dimension.

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Figures

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Figure 10: Score of electricity supply security of the BRICS from 1990 to 2010

Figure 11: Average score of electricity supply security of the BRICS from 1990 to 2010

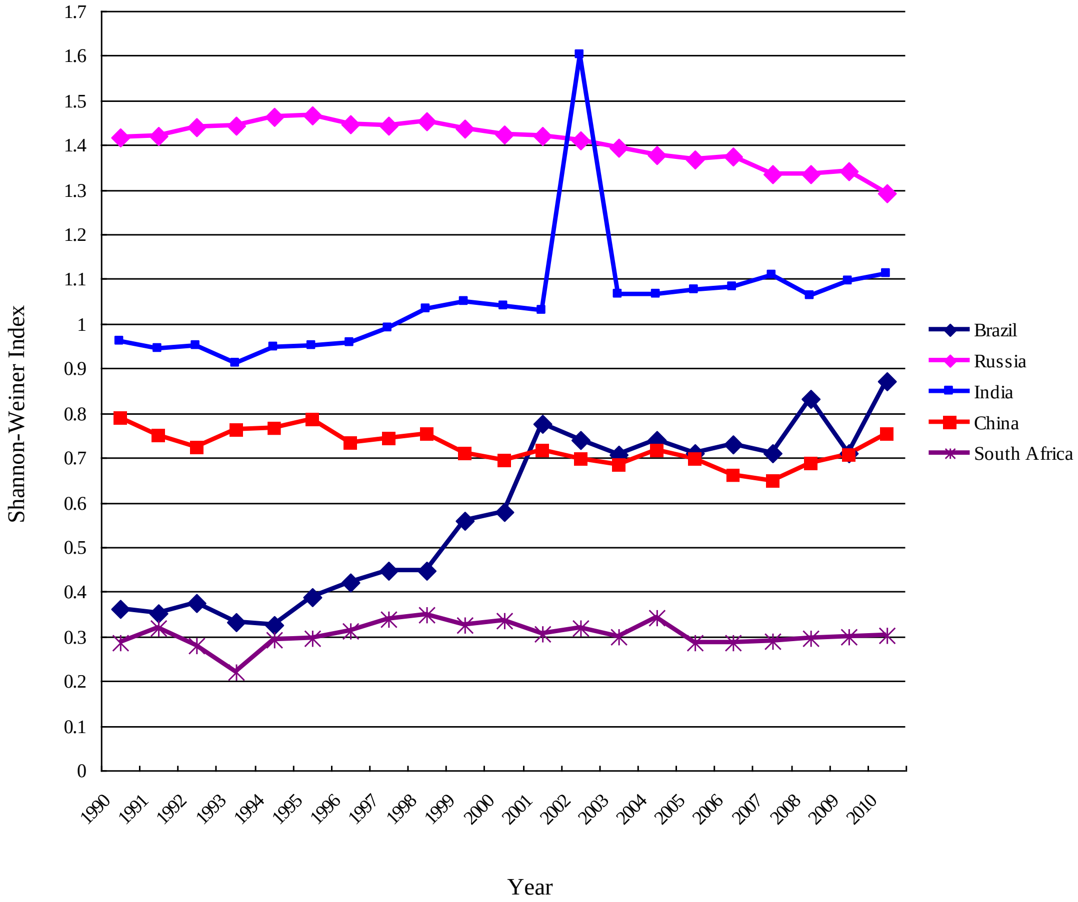

Figure 1: The Shannon-Weiner Index of the BRICS from 1990 to 2010

Sources: IEA (International Energy Agency) [50].

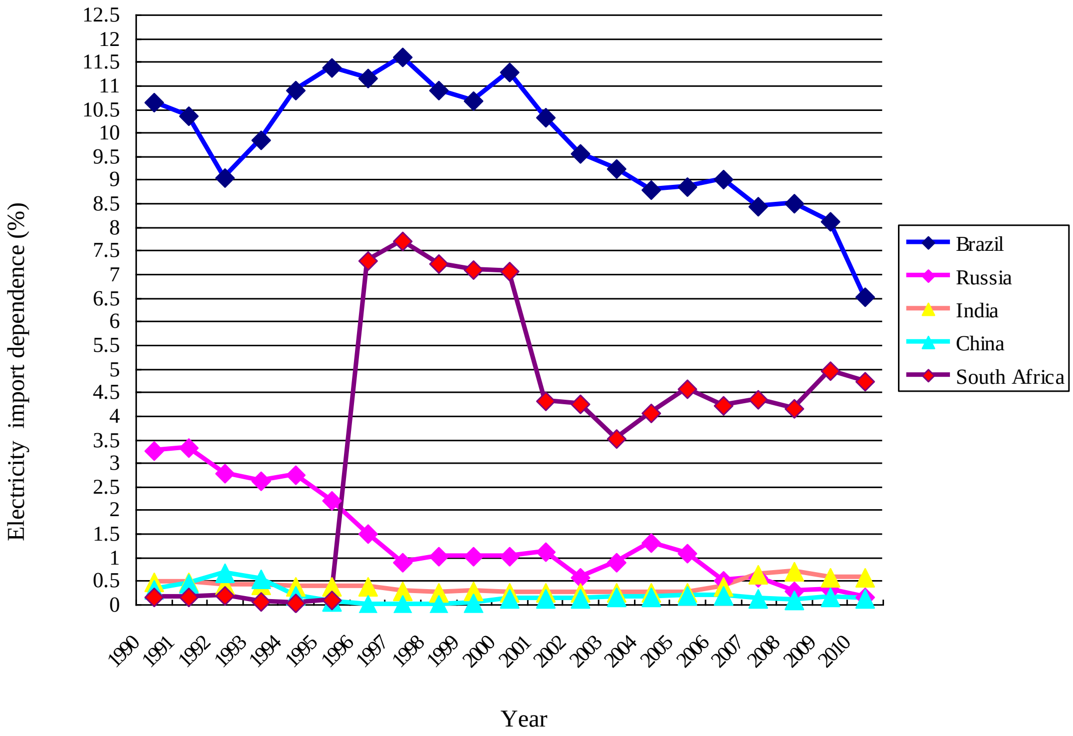

Figure 2: The electricity import dependence of the BRICS from 1990 to 2010

Sources: IEA (International Energy Agency) [50].

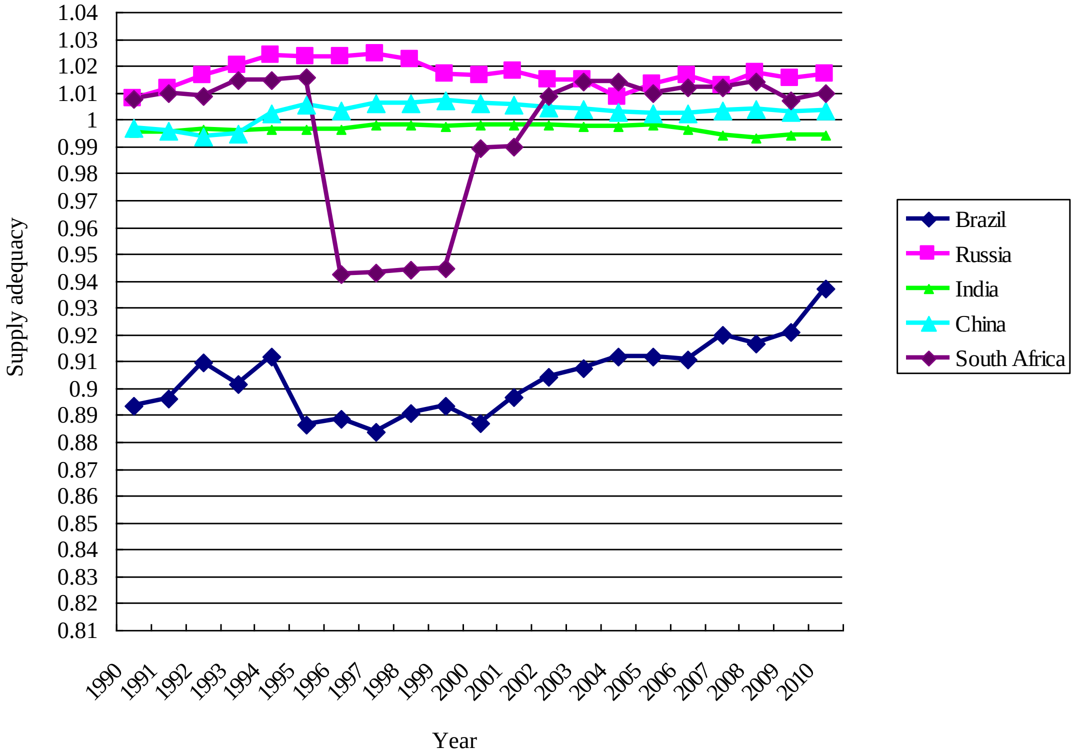

Figure 3: The supply adequacy of the BRICS from 1990 to 2010

Sources: IEA (International Energy Agency) [50].

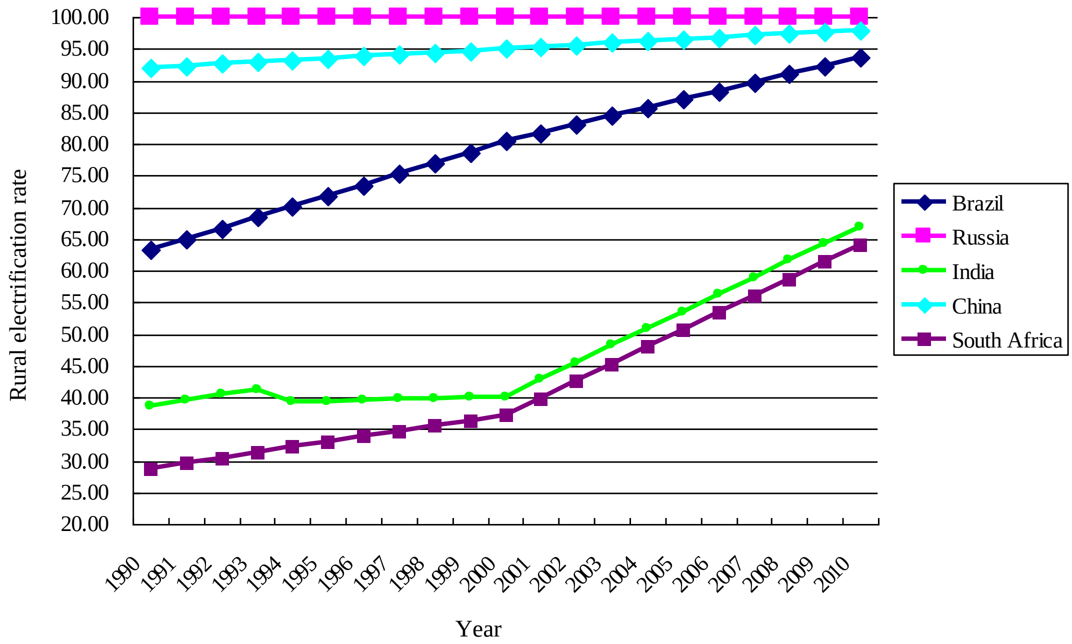

Figure 4: Rural electrification rate of the BRCIS from 1990 to 2010

Source: World Bank[19].

Note: *the access to electricity in rural of the BRICS in 1990, 2000, and 2010 are available, and this metric in other years were estimated by assuming that the metric with respect to each country increases in linear approach.*

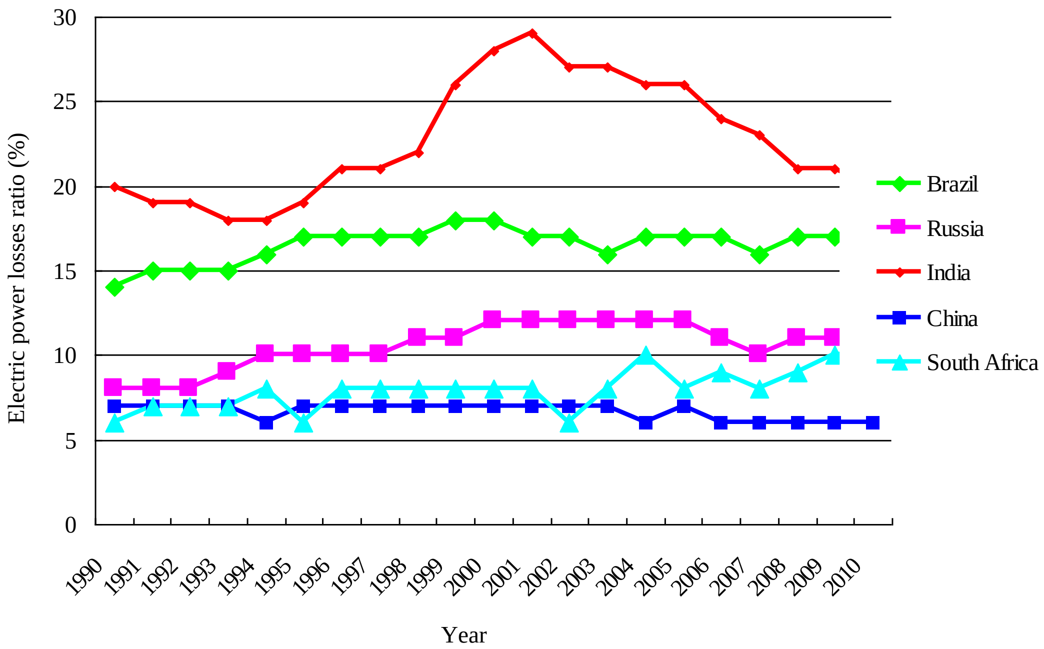

Figure 5: The electric power losses ratio of the BRICS from 1990 to 2010

Source: World Bank [19].

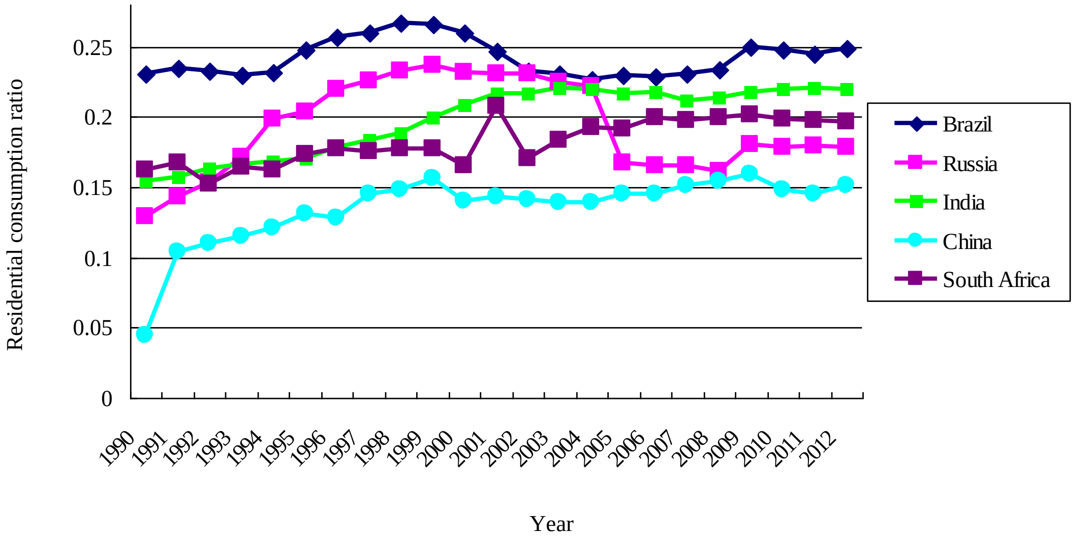

Figure 6: The residential consumption ratio of the BRICS from 1990 to 2010

Sources: IEA(International Energy Agency) [50].

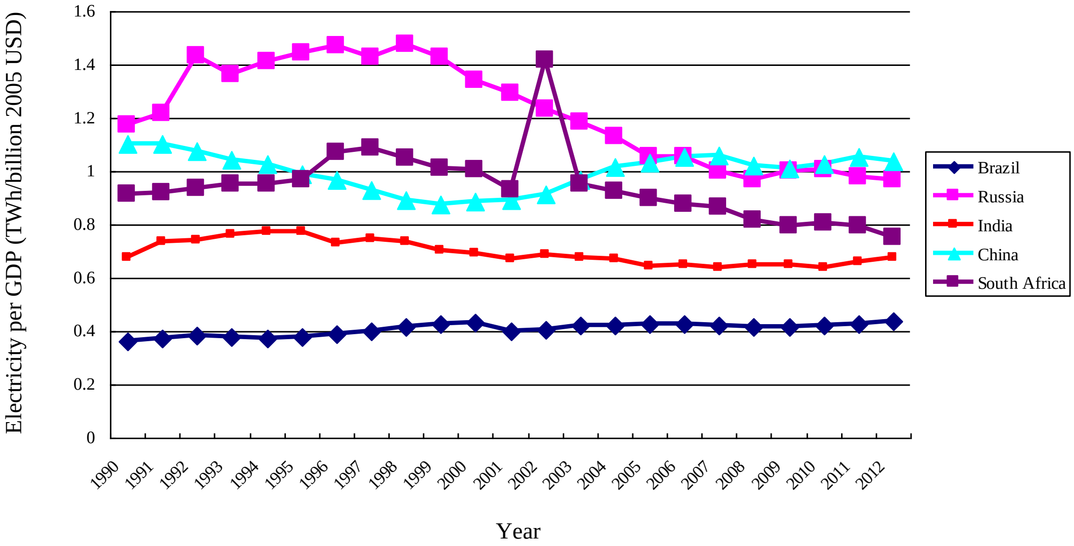

Figure 7: The electricity per GDP of the BRICS from 1990 to 2010

Source: World Bank [19].

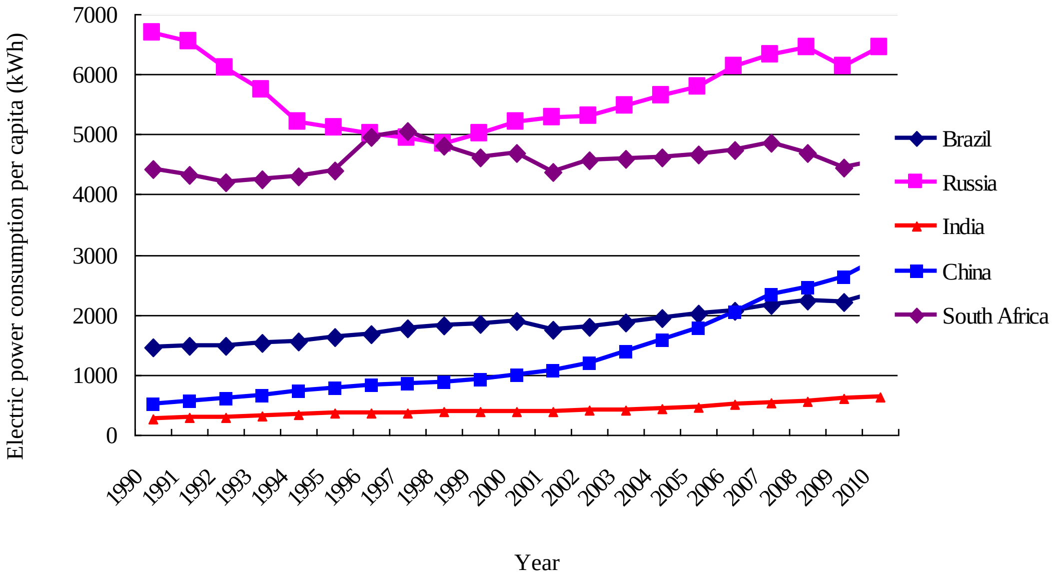

Figure 8: Electric power consumption per capita of the BRICS from 1990 to 2010

Source: World Bank [19].

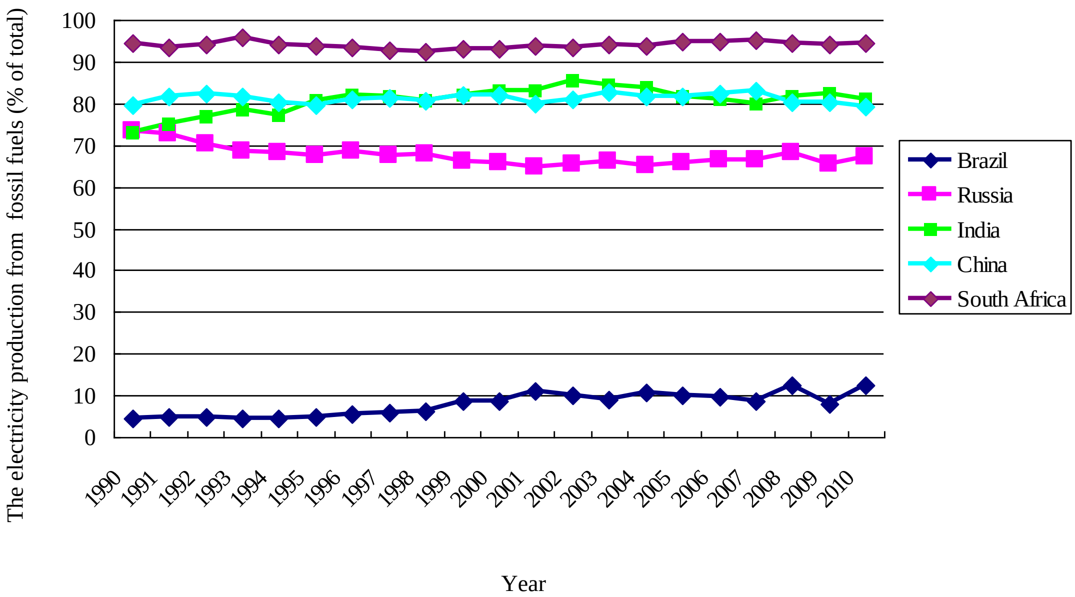

Figure 9: The electricity production from oil, gas and coal sources (% of total)

Sources: World Bank [19].

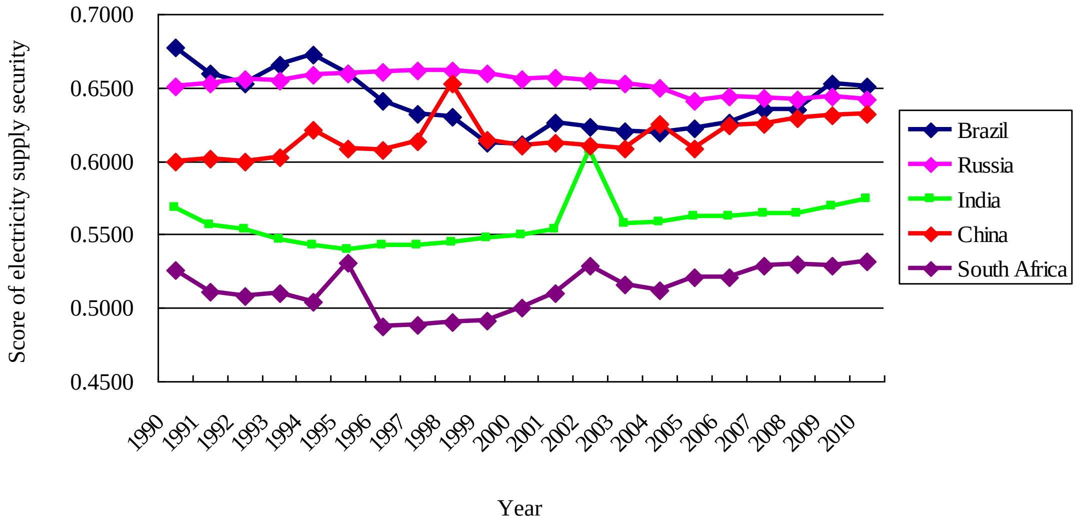

Figure 10: Score of electricity supply security of the BRICS from 1990 to 2010

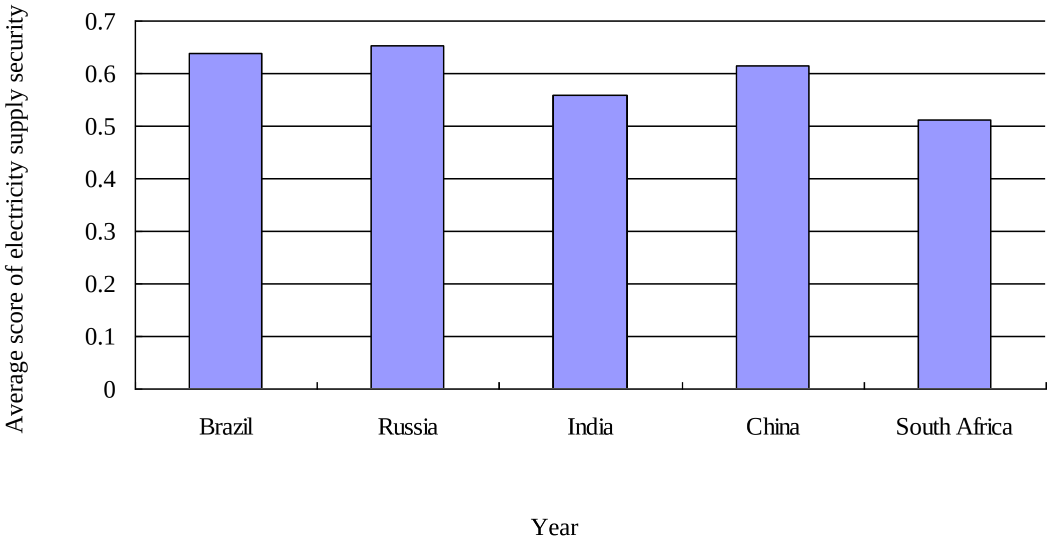

Figure 11: Average score of electricity supply security of the BRICS from 1990 to 2010

Tables

Table 1: The linguistic terms and corresponding fuzzy numbers for pairwise comparison

Linguistic scales	Abbreviations	Fuzzy scales
Equal importance	E	(1,1,1)
Weak importance	W	(2/3,1,3/2)
Moderate importance	M	(1,3/2,2)
Fairly strong importance	FS	(3/2,2,5/2)
Very strong importance	VS	(2,5/2,3)
Absolute importance	A	(5/2,3,7/2)
Reciprocals of these	RW, RM, RFS, RVS, RA	The reciprocals of these fuzzy number

Sources: adapted from Tseng *et al*. (2009)

Table 2: Fuzzy comparison matrix with respect to the four dimensions

	D_1	D_2	D_3	D_4
Availability and security of supply (D_1)	(1,1,1)	(2/3,1,3/2)	(1,3/2,2)	(2,5/2,3)
Affordability and reliability (D_2)	(2/3,1,3/2)	(1,1,1)	(1,3/2,2)	(3/2,2,5/2)
Energy and economic efficiency (D_3)	(1/2,2/3,1)	(1/2,2/3,1)	(1,1,1)	(3/2,2,5/2)
Environmental stewardship (D_4)	(1/3,2/5,1/2)	(2/5,1/2,2/3)	(2/5,1/2,2/3)	(1,1,1)

Table 3: Results of the linear goal programming for determining the weights of the four dimensions

ω_1^L	ω_1^M	ω_1^U	ω_2^L	ω_2^M	ω_2^U	ω_3^L	ω_3^M
0.2578	0.3279	0.3621	0.2370	0.3115	0.3527	0.1878	0.2295
ω_3^U	ω_4^L	ω_4^M	ω_4^U	ε_1^+	ε_2^+	ε_3^+	ε_4^+
0.2636	0.1183	0.1311	0.1374	0	0	0	0.0122
ε_1^-	ε_2^-	ε_3^-	ε_4^-	γ_1^+	γ_2^+	γ_3^+	γ_4^+
0	0	0	0	0	0	0	0
γ_1^-	γ_2^-	γ_3^-	γ_4^-	δ_1	δ_2	δ_3	δ_4
0	0	0	0	0	0	0	0.0082

	D_1	D_2	D_3	D_4
Crisp weights	0.3189	0.3032	0.2276	0.1295
Normalized weights	0.3257	0.3096	0.2324	0.1323

Table 4: Fuzzy comparison matrix with respect to the three metrics in the dimensions of availability and security of supply (D1), availability and security of supply (D_2), and energy and economic efficiency (D_3)

D_1	D_{11}	D_{12}	D_{13}	Fuzzy weight
Shannon-Weiner index	(1,1,1)	(3/2,2,5/2)	(2/3,1,3/2)	(0.3098,0.3939,0.4799)
Electricity import dependence	(2/5,1/2,2/3)	(1,1,1)	(1/3,2/5,1/2)	(0.1796,0.1818,0.1884)
Supply adequacy	(2/3,1,3/2)	(2,5/2,3)	(1,1,1)	(0.3405,0.4242,0.5018)
D_2	D21	D22	D23	Fuzzy weight
Rural electrification rate	(1,1,1)	(2,5/2,3)	(5/2,3,7/2)	(0.5564,0.5752,0.5800)
Electric power losses ratio	(1/3,2/5,1/2)	(1,1,1)	(1,3/2,2)	(0.2058,0.2478,0.2886)
Residential consumption ratio	(2/7,1/3,2/5)	(1/2,2/3,1)	(1,1,1)	(0.1550,0.1770,0.2142)
D_3		D_{31}	D_{32}	Fuzzy weight
Electricity per GDP		(1,1,1)	(3/2,2,5/2)	(0.6000,0.6667,0.7143)
Electric power consumption per capita		(2/5,1/2,2/3)	(1,1,1)	(0.2857,0.3333,0.4000)

Table 5: The local and global weights of the metrics

		Local weights	Global weights
	D_{11}	0.3944	0.1285
D_1: 0.3257	D_{12}	0.1829	0.0596
	D_{13}	0.4227	0.1377
	D_{21}	0.5717	0.1770
D_2: 0.3096	D_{22}	0.2475	0.0766
	D_{23}	0.1808	0.0560
D_3: 0.2324	D_{32}	0.6619	0.1538
	D_{33}	0.3381	0.0786
D_4: 0.1323	D_{41}	1	0.1323