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Evaluation of electricity supply sustainability and security: 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 were employed for electricity supply sustainability and security evaluation. Fuzzy Analytic Hierarchy Process which allows the users to use linguistic terms to express their opinions was 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 was 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) was studied in Chinese perspective by the proposed method.

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, 2006) was widely discussed recently. Many countries took various measures for enhancing the security of electricity. For instance, China 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 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 aimed 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

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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 from Chinese perspective 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 a limited number of 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 and Liang, 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