https://doi.org/10.1016/j.energy.2016.12.030

Measuring energy security performance within China: Toward an inter-provincial prospective

Long Zhang [a,b,c*], Jing Yu[a,b], Benjamin K. Sovacool [c,d], Jingzheng Ren[e]

[a] School of Economics and Management, China University of Geosciences, Wuhan 430074, China

[b] Mineral Resource Strategy and Policy Research Center, China University of Geosciences, Wuhan 430074, China

[c] Center for Energy Technologies, Department of Business and Technology Development, Aarhus University, Birk Centerpark 15, DK-7400 Herning, Denmark

[d] Science Policy Research Unit (SPRU), School of Business, Management, and Economics, University of Sussex, United Kingdom

[e] Department of Technology and Innovation, University of Southern Denmark, Campusvej 55, DK-5230 Odense M, Denmark

[*] Corresponding author: longzhang@btech.au.dk(Long Zhang)

Address: Birk Centerpark 15, DK-7400 Herning, Denmark

Abstract:

China has been the world's largest energy consumer and producer for many years, yet while myriad studies have investigated Chinese performance on energy metrics compared to other countries, few to none have looked internally at Chinese provinces. This paper firstly develops a five-dimensional evaluation system centered on the energy security dimensions of availability and diversity, affordability and equality, technology and efficiency, environmental sustainability, and governance and innovation. It then correlates these dimensions to 20 distinct energy security metrics that are used to assess the energy security performance of 30 Chinese provinces, divided into eight regions. Our results reveal both trends in energy policy and practice as well as provincial status of comparative energy security for the year 2013. We find, for instance, that there is no province which performs well in all five of the energy security dimensions, and that all provinces confronted threats related to energy availability and diversity. We also demonstrate that in comparative terms, the Middle Reaches of Yellow River and the Northwest were the most energy-secure, while the Middle Reaches of Yangtze River and the Northeast were least energy-secure.

Keywords: energy security; Fuzzy AHP; PROMETHEE; sensitivity analysis; China

1. Introduction

Recently, there has been no shortage of scholarly or practitioner interest in energy security. Of particular concern is China, which surpassed the United States as the world's largest energy consumer in 2010, with a share of 20.3 percent of world total energy consumption that year (British Petroleum, 2011) [1]. Energy demand in China is expected to increase 60% further from 2015 to 2035, and by the early 2030s, China could become the world's largest energy importer, overtaking Europe in terms of volume of imports, with its import dependence rising from 15% to 23% (British Petroleum, 2015) [2]. China even became a net coal importer since 2009 (Rong and Victor, 2011) [3], and the country's dependence on foreign oil exceeded 60 percent in 2014 (Ministry of Land and Resources of PRC, 2014) [4]. These resource dependence concerns also do little to address a second serious problem of climate change, which requires less fossil fuel consumption for climate change mitigation (Jacobson, 2002) [5]. What's more, the consumption of fossil fuels causes serious ambient air pollution, leading to urban haze in major cities in eastern China, which has greatly threatened public health (Chen, et al., 2013) [6]. Further complicating matters, discussions about peak oil, price fluctuations, and energy inequality have drawn the attention of policymakers and investors, as energy security is closely related with national goals of sustainable development and economic growth (Sovacool and Brown, 2010) [7].

Indeed, as the third largest entity of the world, China is also the largest energy producer, with a share of 19% of world's energy production (U.S. Energy Information Administration, 2015) [8]. However, China's provinces vary greatly in energy endowment, economy development, industrial structure, technology development, and even social and cultural customs, and there is a great spatial disparity between flows of energy fuels and services within them (Chen et al, 2010; Wang et al., 2011; Bao and Fang, 2013; Zhang et al., 2012; National Bureau of Statistics of China, 2013)

[9-13]. Due to these disparities, energy researchers and policymakers in China are left with at least three puzzling research questions:

(1) How can the spatial energy security trends of Chinese provinces be analyzed?

(2) How can energy security performance be measured at the provincial level?

(3) How can the provincial energy security of China be enhanced?

Interestingly, despite an abundance of research on energy security metrics and performance (Le Coq and Paltseva, 2009; Vivoda, 2010; Cohen et al., 2011; Sovacool et al., 2011; Sovacool, 2011, 2013a and 2013b) [14-20], no studies have as of yet answered these three questions. Admittedly, many studies have investigated China's energy security issues (Bambawale and Sovacool, 2011; Wu et al., 2012; Ren and Sovacool, 2014; Liu, 2014; Geng and Ji, 2014; Yao and Chang, 2014; Yang and Chen, 2014) [21-27]. For instance, Wu et al. (2012) measured China's security of energy supply with 14 indicators [22]. Geng and Ji (2014) [25] developed a multi-dimensional indicator system to evaluate China's national energy security. Yang and Chen (2014) [27] established an evaluation framework to measure Chinese performance on energy security metrics. None, however, have looked at Chinese energy security at the provincial scale.

To do so, this study first reviews the academic literature in energy studies to present five dimensions of energy security: availability and diversity, affordability and equality, technology and efficiency, environmental sustainability, and governance and innovation. It then corresponds these to 20 different metrics and assigns them weights based on Fuzzy Analytical Hierarchy Process (an established method in the energy studies and engineering fields), and investigates the energy security performance of 30 Chinese provinces with another two methods, Preference Ranking Organization Method for Enrichment Evaluations (PROMETHEE), and Sensitivity

Analysis. The final parts of the article present its results and analysis as well as policy implications and conclusions.

2. Dimensions and metrics of energy security

This section firstly reviews the conceptual underpinning of energy security, summarizing recent peer-reviewed research related to energy security dimensions and metrics.

2.1 Literature review

In the existing literature, energy security is most commonly defined as the reliable supply of energy at reasonable prices to support the economy and industry (Yergin, 1988; International Energy Agency, 2001; Bielecki, 2002; Dorian et al., 2006; Asif & Muneer, 2007; Jun et al., 2009) [28-33]. This traditional definition of energy security has been critiqued for being too narrow and for downplaying broader social and environmental factors such as climate change or community acceptance (Yergin, 2006) [34]. The "4A" framework of energy security (availability, accessibility, acceptability and affordability) proposed by APERC (Asia Pacific Energy Research Centre, 2007) [35] is a more representative conception, one utilized by numerous scholars (Hughes, 2012; Winzer, 2012) [36-37].

There is no shortage of simple or aggregated indexes to measure energy security. Kruyt et al. (2009) [38] overviewed 24 simple and aggregated indicators for security of supply found in literature. The most widely used are reserves to production ratios, diversity indices, including Herfindahl-Hirschman index (HHI) and Shannon Wiener index (SWI) (Neff. 1997; Vivoda, 2009; Cohen et al., 2011; Shakya and Shrestha, 2011) [16, 39-41]. A noteworthy energy security index developed by International Energy Agency (2007) [42] integrated HHI with the political stability of importing sources and energy prices. Taking a similar approach, Lefèvre (2010) [43] designed an energy security price index and energy security physical availability index, and used these two indices to project the energy security of France and UK over the period of 2004–2030. Based on IEA's energy security index, Löschel et al. (2010) [44] developed ex-post and ex-ante indicators of energy security, and used them to depict the energy security of Germany, Netherlands, Spain and the United States. To measure the short-term risk of energy supply, Le Coq and Paltseva (2009) [14] developed a Risky External Energy Supply Index, which combined net import dependency, political risks of the supplying country, energy transport risks, energy fungibility and the economic importance of each energy type, and used it to measure the risks of oil, gas and coal for the EU members. By constructing the Gas Supply Security Index, Cabalu (2010) [45] combined gas intensity, net gas import dependency, ratio of domestic gas production to total domestic gas consumption and geopolitical risk, and examined the relative vulnerability to natural gas supply disruptions of seven gas-importing countries in Asia for year 2008. These indexes all make meaningful contributions in examining security of energy supply.

There are also a number of metrics of energy security that have been proposed in the literature from a more synthesized prospective. Vivoda (2010) [15] proposed a set of quantitative and qualitative indicators to evaluate national or regional energy security, supposing that it consists of 11 dimensions and 44 attributes. Von Hippel et al. (2011) [46] devised 29 indicators of energy security including six dimensions. Unfortunately, they failed to conduct any empirical study with their instrument for any country or region. Sovacool and Mukherjee (2011) [47] developed five dimensions consisting of 20 components and 320 simple indicators along with 52 complex indicators to assess energy security. Wu et al. (2012) measured China's energy supply security with 14 indicators [22]. Martchamadol and Kumar (2012) used 19 indicators, which can be categorized into five sets, to analyze the energy security in Thailand for the period 1986-2030 in three energy scenarios presented by APERC [48].

2.2 Dimensions and metrics

To provide a comprehensive, yet capable and parsimonious approach to measuring energy on a provincial level, this paper synthesized such dimensions and indicators from the literature (Vivoda, 2010; Hippel et al., 2011; Sovacool and Mukherjee, 2011; Martchamadol and Kumar, 2012; Liu et al., 2012; Liu, 2014; Ren and Sovacool, 2014; Asdrubali, 2015) [15, 23-24, 46-50]. Thus, we hold that energy security consists of availability and diversity, affordability and equality, technology and efficiency, environmental sustainability, and governance and innovation. As presented in Table 1, these five dimensions can be effectively decomposed into 20 components, and thereby measured with 20 metrics. We must empathize that these five dimensions have been validated by recent quantitative assessments of energy security (Ren and Sovacool, 2014) [23] as well as qualitative research with energy experts (Sovacool et al., 2011) [17], a series of focus groups and workshops (Sovacool, 2013b) [20], and surveys of energy security attitudes both looking internally at China (Bambawale and Sovacool, 2011) *[21]* as well as a comparative sample of eleven countries including China (Sovacool et al., 2012; Sovacool, 2016) *[51-52]*.

2.2.1 Availability and diversity

The dimension of availability and diversity represents security of energy supply and demand, which consists of factors relating to energy resources and endowments, energy production, imports and exports, and energy consumption. We decomposed this dimension into four components in Table 1: security of supply, energy potential, dependency, and diversity.

2.2.2 Affordability and equality

The dimension of affordability and equality refers to the economic aspects of energy security such as the prices of energy carriers, price fluctuations, and energy equality. Four components are included in this dimension in Table 1: stability, electricity generation costs, electricity equality, and affordability of gasoline.

2.2.3 Technology and efficiency

This dimension relates to the development of energy related technologies and overall energy efficiency. It comprises four components in Table 1: energy efficiency, grid efficiency, grid reliability, and capacity factors.

2.2.4 Environmental sustainability

The dimension of environmental sustainability represents the environmental and social aspects of energy production and consumption. We broke this dimension into five components in Table 1: land use, water pollution, climate change, acidification, and photochemical pollution.

2.2.5 Governance and innovation

The dimension of governance and innovation regards political factors related to energy security. We utilized three components in Table 1 to represent this dimension: market potential, innovation and research, and energy and environment management.

3. Data and methodology

With our dimensions and metrics chosen, we proceed to collect data on our metrics and then to weight them using the principles and procedures of Fuzzy AHP. After that, we use PROMETHEE to evaluate the energy security performance for 30 Chinese provinces.

3.1 Data collection and Processing

After establishing the metrics iterated above in Table 1, we proceeded to collect data on them for 30 provinces in China, excluding Hong Kong, Taiwan, Macao and Tibet. All data is for 2013, and is derived from the China Statistics Yearbook and the Statistics Yearbooks of the 30 provinces (2014) [53-83], excepting for the data on carbon emissions, which came from the reference (Bai, 2016) [84].

In order to achieve dimensionless analysis, data of the metrics was normalized by Eq. (1) and (2), respectively.

$$p_{ij} = (x_{ij} - \min x) / (\max x_j - \min x_j) \tag{1}$$

$$p_{ij} = (\max x - x_{ij}) / (\max x_j - \min x_j) \tag{2}$$

where p_{ij} is the normalized value of the i_{th} province with respect to the j_{th} metric, x_{ij} represents the original value of the i_{th} province with respect to the j_{th} metric, and $\max x_j$ and $\min x_j$ are the maximum and minimum value of the 30 provinces with respect to the j_{th} metric.

3.2 Multi-criteria Decision Making Methods

To provide weights to the data and evaluate energy security performance for 30 Chinese provinces, this study chose two types of Multi-criteria Decision Making methods: Fuzzy Analytical Hierarchal Processes (Fuzzy AHP) and Preference Ranking Organization Method for Enrichment Evaluations (PROMETHEE). Fuzzy AHP is frequently used to capture expert knowledge of a preference numerically, and applied to solving hierarchical and complex decision-making problems (Chang, 1996) [85]. Fuzzy AHP uses a membership function to calculate a grade of membership that a given variable belongs to, and triangular and trapezoidal functions are usually used in fuzzy logic because they are simple to use but also accurate (Ocampo-Duque et al., 2006; Güngör et al., 2009; Heo et al., 2010; Lee et al., 2011; Ren and Sovacool, 2014) [86-90]. The PROMETHEE method is one of the most recent MCDA techniques, firstly developed by Brans (1982) [91]. It has witnessed a rapid proliferation throughout academic research, with several hundred articles published in more than 100 scholarly journals since 1985 (Behzadian, 2010) [92].

3.2.1 Fuzzy AHP

Our procedure of fuzzy AHP proceed along the following steps:

Step 1: Determining the comparison matrix by using linguistic terms. This step is to make pairwise comparisons of dimensions and metrics by using linguistic terms in the same level of hierarchy structure. In this study, it relies on the linguistic terms and corresponding fuzzy numbers (as presented in Table 2) to make pairwise comparisons.

Step 2: Transforming the linguistic terms into fuzzy numbers. This step aims at transforming the linguistic terms of the pairwise comparisons in Step 1 into fuzzy numbers according to Table 2. Then, the pairwise comparison matrix could be obtained, as presented in Eq. (3)

$$\tilde{A} = \begin{vmatrix} \tilde{1} & \tilde{a}_{12} & \cdots & \tilde{a}_{1n} \\ \tilde{a}_{21} & \tilde{1} & \cdots & \tilde{a}_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ \tilde{a}_{n1} & \tilde{a}_{n2} & \cdots & \tilde{1} \end{vmatrix} = \begin{vmatrix} \tilde{1} & \tilde{a}_{12} & \cdots & \tilde{a}_{1n} \\ 1/\tilde{a}_{12} & \tilde{1} & \cdots & \tilde{a}_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ 1/\tilde{a}_{1n} & 1/\tilde{a}_{2n} & \cdots & \tilde{1} \end{vmatrix} \tag{3}$$

where $\tilde{a}_{ij} = \left(a_{ij}^{L}, a_{ij}^{M}, a_{ij}^{U}\right)$

Step 3: Calculating the fuzzy geometric mean and determining fuzzy weights. The fuzzy geometric mean and fuzzy weight with respect to each factor could be computed by Eqs. (4) and (5), respectively.

$$\tilde{r}_j = (\tilde{a}_{j1} \times \tilde{a}_{j2} \cdots \times \tilde{a}_{jn})^{1/n} \tag{4}$$

$$\widetilde{\omega}_j = \widetilde{r}_j / \sum_{j=1}^{n} \widetilde{r}_j \tag{5}$$

where $\widetilde{r}_j$ is the geometric mean of the fuzzy comparison values of the j_{th} factor to each of the other criteria, and $\widetilde{\omega}_j$ refers to the fuzzy weight of the j_{th} factor.

Step 4: Transforming the fuzzy weights into crisp numbers. The Center of Gravity method was applied to defuzzify the fuzzy weights into crisp numbers, as shown Eq. (6)

$$\omega_j = \left(\omega_j^L + 2\omega_j^M + \omega_j^U\right)/4 \tag{6}$$

where ω_j is the crisp weight of the j_{th} factor, $\widetilde{\omega}_j = \left(\omega_j^L, \omega_j^M, \omega_j^U\right)$, and $\omega_j^L, \omega_j^M, \omega_j^U$ are the elements of the fuzzy weight.

Our use of PROMETHEE derives from the literature on ranking organization methods for enrichment evaluations (L'Eglise et al., 2001; Macharis and Springael, 2004; Albadvi et al., 2007; Anand and Kodali, 2008) [93-96]. The basic principle of PROMETHEE is based on a pairwise comparison of alternatives along with each recognized criterion, and the alternatives are evaluated according to different criteria, which have been minimized or maximized. More detailed information can be referred from the research of Behzadian (2010) and Brans et al. (1986) [92, 97].

3.2.2 PROMETHEE

The procedure of PROMETHEE is as follows:

Step 1: Computing the deviations based on pairwise comparisons according to Eq. (7)

$$d_j(a,b) = g_j(a) - g_j(b) \tag{7}$$

Step 2: Determining the preference function for the criterion. Usually, there are six types of generalized preference function: (1) usual criterion, (2) U-shape criterion, (3) V-shape criterion, (4) level criterion, (5) V-shape with indifference criterion, and (6) Gaussian criterion, as presented in Eqs. (9)-(14) (Anand and Kodali, 2008) [96]. The more widely used is the linear preference function, which is also known as V-shape criterion.

$$P_j(d) = F_j[d_j(a,b)] \tag{8}$$

$$P(d) = \begin{cases} 1 & d > 0 \\ 0 & d \le 0 \end{cases} \tag{9}$$

$$P(d) = \begin{cases} 1 & d > p \\ 0 & d \le p \end{cases} \tag{10}$$

$$P(d) = \begin{cases} 1 & d > p \\ d/p & d \le p \end{cases} \tag{11}$$

$$P(d) = \begin{cases} 1 & d > p \\ 0.5 & q < d \le p \\ 0 & d \le q \end{cases} \tag{12}$$

$$P(d) = \begin{cases} 1 & d > p \\ (d-q)/(p-q) & q < d \le p \\ 0 & d \le q \end{cases} \tag{13}$$

$$P(d) = \begin{cases} 1 - e^{(-d^2/2\sigma^2)} & d > 0 \\ 0 & d \le 0 \end{cases} \tag{14}$$

where $P(d)$ refers to the preference of alternative a with regard to alternative b on each criteria.

Step 3: Calculating the global preference index according to Eq. (15)

$$\pi\left(a,b\right) = \sum_{j=1}^{k} P_j(d) * \omega_j \tag{15}$$

where $\pi\left(a,b\right)$ donates the weighted sum $P_j(d)$ for each criterion.

Step 4: Computing the positive and negative outranking flows with respect to each alternative according to Eqs. (16) and (17).

$$\phi^{+}(a) = \frac{1}{m-1}\sum_{i=1}^{m}\pi(a,i) \tag{16}$$

$$\phi^{-}(a) = \frac{1}{m-1}\sum_{i=1}^{m}\pi(i,a) \tag{17}$$

Step 5: Calculating the net outranking flow with Eq. (18)

$$\phi(a) = \phi^{+}(a) - \phi^{-}(a) \tag{18}$$

There are various kinds of software that were developed to facilitate the PROMETHEE process, including PROMCALC, DECISION LAB and Visual PROMETHEE. In this paper, the Visual PROMETHEE was used to evaluate the energy security performance of China's 30 provinces.

4. Results and analysis

With the dimensions and components of energy security presented in Table 1, the pairwise comparisons with respect to the five dimensions and the components in each dimension were determined as presented in the Appendix A. In order to illustrate how we employed Fuzzy AHP to determine energy security weights, the pairwise comparison with respect to the five dimensions of energy security was firstly transformed into fuzzy scales, as shown in Table 3.

Then, the fuzzy weights of the five dimensions could be determined according to Eq. (4) and (5), and the results were presented as follows:

W= (0.2964, 0.2964, 0.1588, 0.1588, 0.0896)

In a similar approach, the weight of the metrics in each dimension can also be determined. Then, the global normalized weight of each metric can be obtained, which is the product of the metric's weight in the hierarchy and the weight of its belonging dimension, as presented in Table 4.

Then, we used Visual PROMETHEE to evaluate the energy security of China's 30 provinces for the calendar year 2013.

Table 5 and Figure 1 present our results of provincial energy security performance measurement. The value of Phi is the net outranking flows with respect to the 30 provinces of China, and the Score is the normalized value of Phi according to Eq. (1). The greater the value of Phi or the score, the more secure the energy supply of the corresponding province would be. This data suggests that Shaanxi (0.2413), Shanxi (0.1430), Ningxia (0.1344), Anhui (0.1150), and Qinghai (0.1086) were the five most energy-secure provinces in 2013. All of them are middle and western provinces, rich in energy resources. By contrast, Guangxi (-0.1752), Jilin (-0.1642), Shanghai (-0.1638) Hubei (-0.1601), and Liaoning (-0.1594), performed the worst on energy security metrics for 2013.

According to the varying levels of economic development and geography, the 30 provinces can also be divided into eight regions to provide analysis at a higher scale, namely Northern Coast, Eastern Coast, Southern Coast, Northeast, Middle Reaches of Yellow River, Middle Reaches of Yangtze River, Northwest, and Southwest, regions which are shown in Figure 2. It is apparent that the Middle Reaches of Yellow River performs the best on energy security, since most of China's energy resources locate in this region. This is followed by the Northwest, also a region where energy resources are significant. The Southwest, Southern Coast and Northern Coast are in the third group, and they have achieved moderate energy security performance. However, the Eastern Coast, Middle reaches of Yangtze River, and the Northeast, perform the worst energy security performance.

The next phase of our methodology involved further analyzing the results with PROMETHEE network (see Figure 3). More specifically, the Middle Reaches of Yellow River and the Northwest have the most significant energy reserves and levels of production in China, but these have been compromised by threats to economic development including weakening infrastructure and environmental degradation. The Southwest, Southern Coast and Northern Coast show a moderate energy security performance. The Eastern Coast, the most economically vibrant area of China, performs poorly due to high levels of consumption, growing dependence on imports, and environmental degradation. Similarly, the Middle Reaches of Yangtze River, lacking fossil fuels and lagging behind the coastal provinces in terms of economic development, performs relatively poorly as well. The worst energy security performer is the Northeast region, whose situation is similar to the Middle Reaches of Yangtze River.

Interestingly, our analysis suggests that the provinces in the Middle Reaches of Yellow River, Northwest, and Northern Coast have shown little variance in their energy security performance. Sichuan, Yunnan and Guizhou, where most of energy resources in Southern China reside, demonstrates relatively high performance. Chongqing and Guangxi show extremely poor energy security performance. The same situation has been observed in the Southern and Eastern Coast regions, where both Hainan and Shanghai show much lower scores of energy security compared with their neighbors. On the contrary, Anhui, rich in coal, has a much better energy security performance than the other three provinces in this region, while Heilongjiang, rich in petroleum, performs better with respect to energy security than Liaoning and Jilin.

The performance score of each dimension for the 30 provinces are shown in Table 6. Grouping the 30 provinces into eight regions, the performance score with respect to each region was determined by calculating the average scores presented in Figure 4.

According to Figure 4, it is apparent that the best energy security performance across all provinces relate to the dimension of affordability and equality, with an average score of 70.40. Chinese provinces demonstrate a moderate performance on technology and efficiency (54.89), environmental sustainability (51.18), and governance and innovation (55.37). Chinese provinces perform the worst on the dimension of availability and diversity (31.58). In addition, there is rather great variance among the eight regions across three dimensions, namely, availability and diversity which range from 14.93 to 72.35, affordability and equality which range from 39.36 to 91.08, and technology and efficiency which range from 38.27 to 90.21. The other two dimensions, environmental sustainability (ranges from 34.83 to 72.14), and governance and innovation (ranges from 45.20 to 66.53), show smaller variances. Thus, it could be concluded that energy availability and diversity are the main challenges facing China's energy security at the national level.

Moreover, the Middle Reaches of Yellow River and the Northwest show the best performance on availability and diversity. The Eastern Coast, Southern Coast and Northwest are the three regions who perform best on affordability and equality. The Eastern Coast, at the same time, demonstrates a much higher performance on the dimension of technology and efficiency than any other regions. As to the dimension of environmental sustainability, Southern China, including the Southern Coast and Southwest, do better than other regions. As shown above, the eight regions indicate a small variance with each other on the dimension of governance and innovation, but the coastal provinces do perform better than inland provinces.

Lastly, a Sensitivity Analysis was given to the 30 provinces. Firstly, it distributed equal weight to every metric, in which case, a Phi could be obtained for each province, which can indicate their energy security performance. Then, 20 scenarios were proposed, and in the $i-th$ scenario, the weight of the $i-th$ metric equals 0.24, while the weights of the rest metrics equal 0.04. For each scenario, the energy security performance for each province can be computed. Subsequently, the Sensitivity Analysis Factor (SAF) could be calculated, which measures how much a province's energy security performance has change when the weight of a particular metric change from 0.05

to 0.24. After that, the results of Sensitivity Analysis with respect to the eight regions are calculated, as shown in Figure 5. The positive SAF means that the energy security performance is enhanced, while the negative SAF means the performance is weakened. The greater the absolute SAF, the more sensitive the performance is.

Figure 5 also illustrates that the dimension of availability and diversity causes the greatest sensitivity on energy security performance, with an absolute SAF of 0.32, the technology and efficiency, and environmental sustainability lead to a moderate sensitivity, with the absolute SAFs of 0.20 and 0.23, respectively. Energy security performance is least sensitive to the dimension of affordability and equality (absolute SAF is 0.12), and governance and innovation (absolute SAF is 0.13). Specifically, the energy security performance of the Northwest and the Middle Reaches of Yellow River would be greatly enhanced by the increasing the weight of metrics related to availability and diversity, while that of the Eastern Coast and Southern Coast would be severely weakened. The performance of the Eastern Coast and Northern Coast would be improved if the metrics about technology and efficiency were weighted more, but the performance of the Northwest, Southwest and Northeast would suffer. When the metrics about environmental sustainability increase in weight, the Southern Coast, Middle Reaches of Yangtze River and Southwest would benefit while the Northwest, Middle Reaches of Yellow River, and Northern Coast would see performance decline.

5. Conclusions and policy implications

Our results do suggest some salient policy implications for enhancing China’s energy security and bridging the gap in energy security performance among different provinces and regions.

Firstly, our data strongly implies that developing renewable sources of electricity and alternative fuels for transport (usually called "New Energy Vehicles" in China) would improve energy security performance and diversify the energy mix. Since energy availability and diversity were determined by our analysis to be the most severe threat facing China's energy security as a whole, national and provincial planners need to invest in more reliable energy sources. China has great renewable energy potential, which can not only maintain its security of energy supply and contribute to diversification, it can also create more jobs and reduce environmental pollution. Coastal provinces in particular, substantial consumers and importers, should find ways to increase such local sources of energy supply. With their comparatively more advanced science and technology sectors, offshore wind power and biofuels perhaps have the most appeal. The Middle Reaches of Yangtze River are gifted with great hydropower and biofuel potential. The Southwest is richest in hydropower as well as unconventional fuels such as shale gas. Each of these resources should be developed to diversify China's energy supply mix.

Secondly, improvements in energy efficiency are needed. On the one hand, most of China's energy resources spatially distant from consumers and located far inland, for instance, coal reserves, existing solar PV deployment, and installed onshore wind power remains in the Middle Reaches of Yellow River and the Northwest; oil and gas reserves are situated in the Northeast and Northwest; hydropower resources are utilized primarily in the Southwest and Middle Reaches of Yangtze River; and biofuel sources are concentrated in Southern China. On the other hand, the inland provinces perform much worse than the coastal provinces on technology and efficiency, and have fewer R&D expenditures and less established infrastructure. Improvements in energy efficiency can optimize the whole life cycle the energy industry, including exploitation, production, processing, transmission and consumption. Thus, R&D on energy efficiency systems such as smart meters, improved distribution networks to minimize transmission losses, and enhancements to residential, commercial, and industrial building stock is quite beneficial and urgent.

Thirdly, more attention and investment should be paid to mitigating environmental problems and improving environment quality. Though the government has promised that by 2020 China would reduce its carbon intensity by 40 to 45 percent compared to 2005 levels, people remain embroiled in severe environment problems, especially those associated with the mining, processing, combustion, and waste of coal. The government should enforce the adoption of better pollution controls on coal-fired power plants and increase responsible for public infrastructure projects for energy conservation and environment improvement, such as public green spaces and charging stations for electrical vehicles.

Lastly, national Chinese energy strategy should be adjusted to balance development among different regions and provinces. The coastal provinces have strengthened their economies for several decades since the Reform and Opening, and Western China, including the Northwest, Southwest, and a part of Middle Reaches of Yellow River, is under development with the deployment of the Development of the Western Region in China since 2000. However, the Central region of China, including the Middle reaches of Yangtze River, Northeast, and another part of Middle Reaches of Yellow River, have been neglected by national strategy, and show suboptimal energy security performance, a phenomenon termed “Central Sinking” by some scholars (Yang and Zhu, 2007) [98]. The Northeast, who used to be called as the “Eldest Son of the Republic” for its contribution in the planned economy era (OECD, 2006) [99], now also performs poorly on various economic and demographic metrics. Thus, senior Chinese decision makers should focus more on investing in and improving the energy security of the Central Region.

For those outside of China, the study also reveals the complexity of energy security as both a concept and by location. Energy security performance can vary greatly across geographic space. Many provinces in Western China perform much better than the developed coastal provinces. Western provinces, for instance, perform much better in terms of energy availability. More importantly, their relative advantage has been amplified by a smaller population so they can enjoy more energy endowments and resources per capita. The lesson here is relatively simple: Chinese performance on energy security differs greatly within its regions and provinces. Thus, energy analysts should begin to take a far more nuanced approach when they partake in energy security assessments.

Moreover, our study shows that a traditional view of energy security limited to supply security of fossil fuels ignores other salient dimensions such as energy efficiency, energy equality and governance. In fact, the Fuzzy AHP in this study gave higher weights to the dimension of availability and diversity, and affordability and equality, and the 30 provinces demonstrated the greatest variance in the dimension of availability and diversity. Overall, the evaluative framework proposed in this paper consists of five dimensions associated with current elements about energy security. This instrument can be seen as a significant contribution to existing literature on energy security, and it can help evaluate the energy security performance for different regions or countries.

Acknowledgements

This research is supported by the Humanities and Social Sciences Planning Fund of Ministry of Education (Grant 13YJA790143), Key Research Projects of Philosophy and Social Sciences of Ministry of Education (Grant 12JZD034), Key Projects of Open Fund of Mineral Resource

Strategy and Policy Research Center of China University of Geosciences (WUHAN) (Grant H2014006A, H2015003A), and China Scholarship Council (201506410016).

Appendix A. pairwise comparisons

Appendix A is the pairwise comparisons with respect to the five dimensions and the components in each dimension (see appendix Tables A1-A6).

Appendix B. Supplementary material

Appendix B is associated with the raw energy security data and the process of data analysis.

References

Albadvi, A., Chaharsooghi, S.K., Esfahanipour, A., 2007. Decision making in stock trading: an application of PROMETHEE, Eur. J. Oper. Res. 177, 673-683.

Anand, G., Kodali, R., 2008. Selection of lean manufacturing systems using the PROMETHEE. Journal of Modelling in Management 3(1), 40-70.

Anhui Provincial Bureau of Statistics, 2014. Anhui Statistical Yearbook. China Statistics Press, Beijing.

Asdrubali, F., Baldinelli, G., D'Alessandro, F., Scrucca, F, 2015. Life cycle assessment of electricity production from renewable energies: Review and results harmonization. Renewable Sustainable Energy Rev. 42, 1113–1122.

Asia Pacific Energy Research Centre (APERC), 2007. A Quest for Energy Security in the 21st century. Institute of Energy Economics, Tokyo.

Asif, M., Muneer T., 2007. Energy supply, its demand and security issues for developed and emerging economies. Renewable Sustainable Energy Rev. 11(7), 1388-1413.

Bai, H., Qiao, S., Liu, T., Zhang, Y.X., Xu, H, 2016. An inquiry into inter-provincial carbon emission difference in China: Aiming to differentiated KPIs for provincial low carbon development. Econ. Indic. 60, 754–765.

Bambawale, M.J., Sovacool, B.K., 2011. China's energy security: the perspective of energy users. Appl. Energy 88(5), 1949–1956.

Bao, C., Fang, C.L., 2013. Geographical and environmental perspectives for the sustainable development of renewable energy in urbanizing China. Renewable Sustainable Energy Rev. 27, 464–474.

Beijing Municipal Bureau of Statistics, 2014. Beijing Statistical Yearbook. China Statistics Press, Beijing.

Behzadian, M., Kazemzadeh, R.B., Albadvi, A., Aghdasi, M., 2010. PROMETHEE: A comprehensive literature review on methodologies and applications. Eur. J. Oper. Res. 200(1), 198–215.

Bielecki, J. 2002. Energy security: is the wolf at the door? Q. Rev. Econ. Financ. 42(2), 235–250.

Brans, J.P., 1982. Lingenierie de la decision. Elaboration dinstrumentsdaide a la decision. Methode PROMETHEE. In: Nadeau, R., Landry, M. (Eds.), Laide a la Decision: Nature, Instrument Set Perspectives Davenir. Presses de Universite Laval, Qu ebec, Canada, 183–214.

Brans, J.P., Vincke, Ph., Mareschal, B., 1986. How to select and how to rank projects: The PROMETHEE method. Eur. J. Oper. Res. 24(2), 228–238.

British Petroleum, 2011. BP Statistical Review of World Energy 2011. <http://www.bp.com/content/dam/bp-country/de_de/PDFs/brochures/statistical_review_of_world_energy_full_report_2011.pdf>

British Petroleum, 2015. BP Energy Outlook 2035. <http://www.bp.com/en/global/corporate/energy-economics/energy-outlook-2035/country-and-regional-insights/china-insights.html>

Cabalu, H., 2010. Indicators of security of natural gas supply in Asia. Energy Policy 38(1), 218–225.

Chang, D.Y., 1996. Applications of the extent analysis method on fuzzy AHP. Eur. J. Oper. Res. 95(3), 649–655.

Chen, W.Y., Li, H.L., Wu, Z.X., 2010. Western China energy development and west to east energy transfer: Application of the Western China Sustainable Energy Development Model. Energy Policy 38(11), 7106–7120.

Chen, Y., Ebenstein, A., Greenstone, M., Li, H., 2013. Evidence on the impact of sustained exposure to air pollution on life expectancy from China's Huai River policy. Proc. Natl. Acad. Sci. U. S. A. 110(32), 12936-12941.

Chongqing Municipal Bureau of Statistics, 2014. Chongqing Statistical Yearbook. China Statistics Press, Beijing.

Cohen G., Joutz, F., Loungani, P., 2011. Measuring energy security: Trends in the diversification of oil and natural gas supplies. Energy Policy 39(9), 4860–4869.

Dorian, J.P., Franssen, H.T., Simbeck, D.R., 2006. Global challenges in energy. Energy Policy 34(15), 1984-1991.

Fujian Provincial Bureau of Statistics, 2014. Fujian Statistical Yearbook. China Statistics Press, Beijing.

Geng, J.B., Ji, Q., 2014. Multi-perspective analysis of China's energy supply security. Energy 64, 541-550.

Gansu Provincial Bureau of Statistics, 2014. Gansu Development Yearbook. China Statistics Press, Beijing.

Guangdong Provincial Bureau of Statistics, 2014. Guangdong Statistical Yearbook. China Statistics Press, Beijing.

Guangxi Statistical Bureau, 2014. Guangxi Statistical Yearbook. China Statistics Press, Beijing.

Guizhou Provincial Bureau of Statistics, 2014. Guizhou Statistical Yearbook. China Statistics Press, Beijing.

Güngör, Z., Serhadlıoğlu, G., Kesen, S.E., 2009. A fuzzy AHP approach to personnel selection problem. Appl. Soft Comput. 9(2), 641–646.

Hainan Provincial Bureau of Statistics, 2014. Hainan Statistical Yearbook. China Statistics Press, Beijing.

Hebei Provincial Bureau of Statistics, 2014. Hebei Economic Yearbook. China Statistics Press, Beijing.

Heilongjiang Provincial Bureau of Statistics, 2014. Heilongjiang Statistical Yearbook. China Statistics Press, Beijing.

Henan Provincial Bureau of Statistics, 2014. Henan Statistical Yearbook. China Statistics Press, Beijing.

Heo, E., Kim, J., Boo, K.J., 2010. Analysis of the assessment factors for renewable energy dissemination program evaluation using fuzzy AHP. Renewable Sustainable Energy Rev. 14(8), 2214–2220.

Hippel, D.V., Suzuki, T., Williams, J. H., Savage, T., Hayes, P., 2011. Energy security and sustainability in Northeast Asia. Energy Policy 39(1), 6719–6730.

Hubei Provincial Bureau of Statistics, 2014. Hubei Statistical Yearbook. China Statistics Press, Beijing.

Hughes, L., 2012. A generic framework for the description and analysis of energy security in an energy system. Energy Policy 42, 221–231.

Hunan Provincial Bureau of Statistics, 2014. Hunan Statistical Yearbook. China Statistics Press, Beijing.

Inner Mongolia Autonomous Regional Bureau of Statistics, 2014. Inner Mongolia Statistical Yearbook. China Statistics Press, Beijing.

International Energy Agency, 2001. Toward a Sustainable Energy Future. International Energy Agency, Paris. <http://www.oecd-ilibrary.org/energy/towards-a-sustainable-energy-future_9789264193581-en>

International Energy Agency, 2007. Energy Security and Climate Policy — Assessing Interactions. OECD, Paris. <https://www.iea.org/publications/freepublications/publication/energy_security_climate_policy.pdf>

Jacobson, M.Z., 2002. Control of fossil-fuel particulate black carbon and organic matter, possibly the most effective method of slowing global warming. J. Geophys. Res. 107(D19), ACH 16-1–ACH 16-22.

Jiangsu Provincial Bureau of Statistics, 2014. Jiangsu Statistical Yearbook. China Statistics Press, Beijing.

Jiangxi Provincial Bureau of Statistics, 2014. Jiangxi Statistical Yearbook. China Statistics Press, Beijing.

Jilin Provincial Bureau of Statistics, 2014. Jilin Statistical Yearbook. China Statistics Press, Beijing.

Jun, E., Kim W., Chang S.H., 2009. The analysis of security cost for different energy sources. Appl. Energy 86(10), 1894-1901.

Kruyt, B., van Vuuren, D.P., de Vries, H.J.M., Groenenberg, H., 2009. Indicators for energy security. Energy Policy 37(6), 2166–2181.

Le Coq C., Paltseva, E., 2009. Measuring the security of external energy supply in the European Union. Energy Policy 37(11), 4474-4481.

Lee, S.K., Mogi, G., Lee, S.K., Kim J.W., 2011. Prioritizing the weights of hydrogen energy technologies in the sector of the hydrogen economy by using a fuzzy AHP approach. Int. J. Hydrogen Energy 36(2), 1897–1902.

Lefèvre, N., 2010. Measuring the energy security implications of fossil fuel resource concentration. Energy Policy 38(4), 1635–1644.

L'Eglise, T., De Lit, P., Fouda, P., 2001. A multicriteria decision-aid system for joining process selection. In Assembly and Task Planning, 2001, Proceedings of the IEEE International Symposium on (324-329). IEEE.

Liaoning Provincial Bureau of Statistics, 2014. Liaoning Statistical Yearbook. China Statistics Press, Beijing.

Liu, G., 2014. Development of a general sustainability indicator for renewable energy systems: A review. Renewable Sustainable Energy Rev. 31, 611–621.

Liu, G., Baniyounes, A., Rasul, M.G., Amanullah, M.T.O., Khan, M.M.K., 2012. Fuzzy logic based environmental indicator for sustainability assessment of renewable energy system using life cycle assessment. Procedia Eng. 49, 35–41.

Löschel, A., Moslener, U., Rübbelke, D.T., 2010. Indicators of energy security in industrialised countries. Energy Policy 38(4), 1665–1671.

Macharis, C., Springael, J., 2004. PROMETHEE and AHP: the design of operational synergies in multicriteria analysis. Strengthening PROMETHEE with ideas of AHP. Eur. J. Oper. Res 153, 307-317.

Martchamadol, J., Kumar S., 2012. Thailand's energy security indicators. Renewable Sustainable Energy Rev. 16(8), 6103–6122.

Ministry of Land and Resources of People's Republic of China, 2014.China Mineral Resources 2014. Geological Publishing House, Beijing.

National Bureau of Statistics of China (NBSC), 2013. China Energy Statistical Yearbook. China Statistics Press, Beijing.

National Bureau of Statistics of China (NBSC) , 2014. China Statistical Yearbook. China Statistics Press, Beijing.

Neff, T.L., 1997. Improving energy security in Pacific Asia: diversification and risk Reduction for Fossil and nuclear fuels. Pacific Asia Regional Energy Security Project. <http://oldsite.nautilus.org/archives/papers/energy/NeffPARES.pdf>

Ningxia Hui Autonomous Region Bureau, 2014. Ningxia Statistical Yearbook. China Statistics Press, Beijing.

Ocampo-Duque, W., Ferré-Huguet, N., Domingo, J.L., Schuhmacher, M., 2006. Assessing water quality in rivers with fuzzy inference systems: a case study. Environ. Int. 32(6), 733–742.

OECD, 2006. OECD Investment Policy Reviews: China. OECD Publishing.

Qinghai Provincial Bureau of Statistics, 2014. Qinghai Statistical Yearbook. China Statistics Press, Beijing.

Ren, J.Z., Sovacool, B.K., 2014. Quantifying, measuring, and strategizing energy security: Determining the most meaningful dimensions and metrics. Energy 76, 838-849.

Ren, J.Z., Sovacool, B.K., 2014. Enhancing China's energy security: Determining influential factors and effective strategic measures. Energ. Convers. Manage. 88, 589–597.

Rong, F., Victor, D.G., 2011. Coal liquefaction policy in China: Explaining the policy reversal since 2006. Energy Policy 39(12), 8175–8184.

Shaanxi Provincial Bureau of Statistics, 2014. Shaanxi Statistical Yearbook. China Statistics Press, Beijing.

Shakya, S.R., Shrestha R.M., 2011. Transport sector electrification in a hydropower resource rich developing country: Energy security, environmental and climate change co-benefits. Energy. Sustain. Dev. 15(2), 147-159.

Shandong Provincial Bureau of Statistics, 2014. Shandong Statistical Yearbook. China Statistics Press, Beijing.

Shanghai Municipal Bureau of Statistics, 2014. Shanghai Statistical Yearbook. China Statistics Press, Beijing.

Shanxi Provincial Bureau of Statistics, 2014. Shanxi Statistical Yearbook. China Statistics Press, Beijing.

Sichuan Provincial Bureau of Statistics, 2014. Sichuan Statistical Yearbook. China Statistics Press, Beijing.

Sovacool, B.K., 2011. Evaluating energy security in the Asia pacific: Towards a more comprehensive approach. Energy Policy 39(11), 7472–7479.

Sovacool, B.K., 2013a. Assessing energy security performance in the Asia Pacific, 1990–2010. Renewable Sustainable Energy Rev. 17, 228-247.

Sovacool, B.K., 2013b. An international assessment of energy security performance. Ecol. Econ. 88, 148–158.

Sovacool B K., 2016. Differing cultures of energy security: An international comparison of public perceptions. Renewable Sustainable Energy Rev. 55: 811-822.

Sovacool, B.K., Brown, M.A., 2010. Competing dimensions of energy security: an international review. Annu. Rev. Env. Resour. 35, 77–108.

Sovacool, B.K., Mukherjee I., Drupady, I.M., D'Agostino, A.L., 2011. Evaluating energy security performance from 1990 to 2010 for eighteen countries. Energy 36(10), 5846-5853.

Sovacool, B.K., Mukherjee I., 2011. Conceptualizing and measuring energy security: A synthesized approach. Energy 36(8), 5343-5355.

Sovacool, B.K., Valentine, S.V., Bambawale, M.J., Brown, M.A., de Fátima Cardoso, T., Nurbek, S., Suleimenova, G., Li J., Xu, Y, Jain, A., Alhajji, A.F., Zubiri, A., 2012. Exploring propositions about perceptions of energy security: An international survey. Environ. Sci. Policy, 16(1), 44-64.

Tianjin Municipal Bureau of Statistics, 2014. Tianjin Statistical Yearbook. China Statistics Press, Beijing.

U.S. Energy Information Administration, 2015. International energy data and analysis. <http://www.eia.gov/beta/international/analysis.cfm?iso=CHN>

Vivoda, V., 2009. Diversification of oil import sources and energy security: A key strategy or an elusive objective? Energy Policy 37(11), 4615–4623.

Vivoda, V., 2010. Evaluating energy security in the Asia-Pacific region: A novel methodological approach. Energy Policy 38(9), 5258-5263.

Wang S.S., Zhou D.Q., Zhou, P., Wang, Q.W., 2011. CO_2 emissions, energy consumption and economic growth in China: a panel data analysis. Energy Policy 39(9), 4870–4875.

Winzer, C., 2012. Conceptualizing energy security. Energy Policy 46, 36–48.

Wu, G., Liu L.C., Han Z.Y., Wei Y.M., 2012. Climate protection and China's energy security: Win-win or tradeoff. Appl. Energy 97, 157–163.

Xinjiang Uygur Autonomous Region Bureau, 2014. Xinjiang Statistical Yearbook. China Statistics Press, Beijing.

Yang, J., Chen, B., 2015. Measuring Energy Security of China. Energy Security and Development (57-67). Springer India.

Yang S.G., Zhu, H., 2007. Central sinking, financial weakening and studies on realizing the central rising by financial support. Econ. Res. J. 5, 55-67.

Yao L.X., Chang Y.H., 2014. Energy security in China: a quantitative analysis and policy implications. Energy Policy 67, 595–604.

Yergin, D., 1988. Energy security in the 1990s. Foreign Aff. 67(1), 110-132.

Yergin, D., 2006. Ensuring energy security. Foreign Aff. 85(2), 69–82.

Yunnan Provincial Bureau of Statistics, 2014. Yunnan Statistical Yearbook. China Statistics Press, Beijing.

Zhang, Y., Zhang, J.Y., Yang, Z.F., Li, J., 2012. Analysis of the distribution and evolution of energy supply and demand centers of gravity in China. Energy Policy, 49, 695–706.

Zhejiang Provincial Bureau of Statistics, 2014. Zhejiang Statistical Yearbook. China Statistics Press, Beijing.

Figure captions

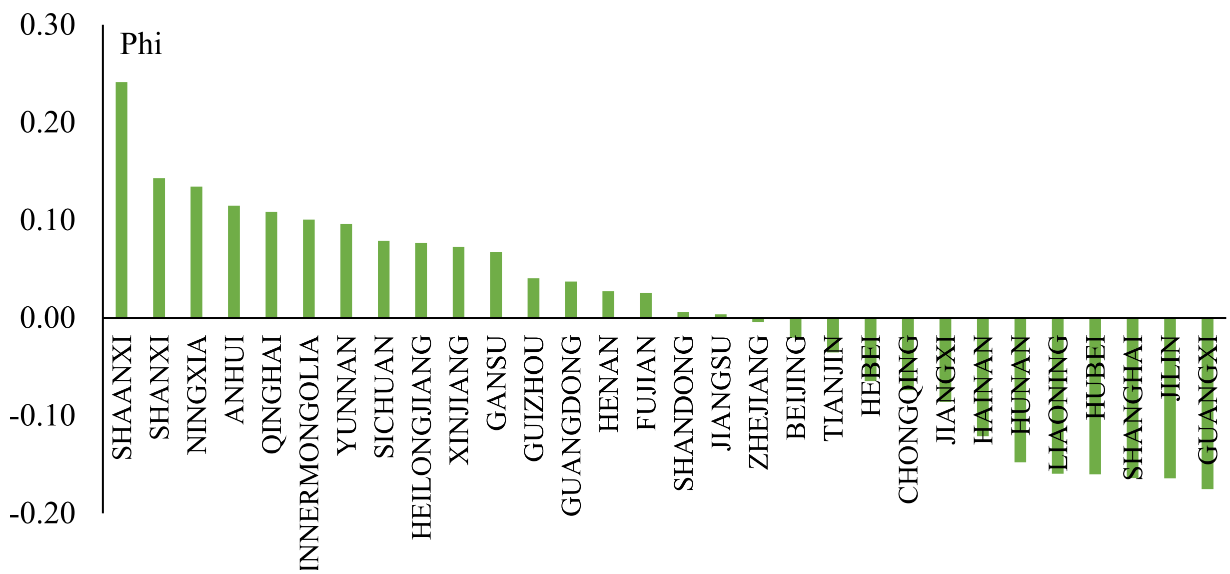
Figure 1. Net energy security flow ranking 30 Chinese Provinces

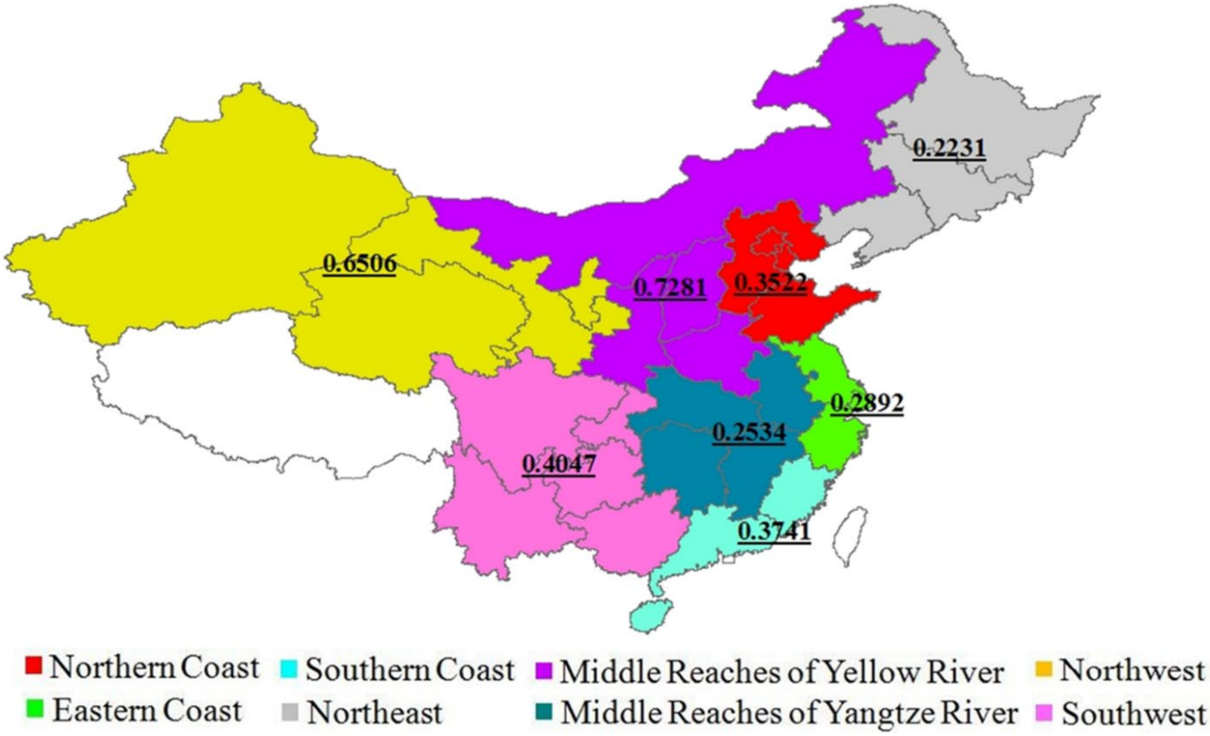
Figure 2. The average energy security performance of eight Chinese regions

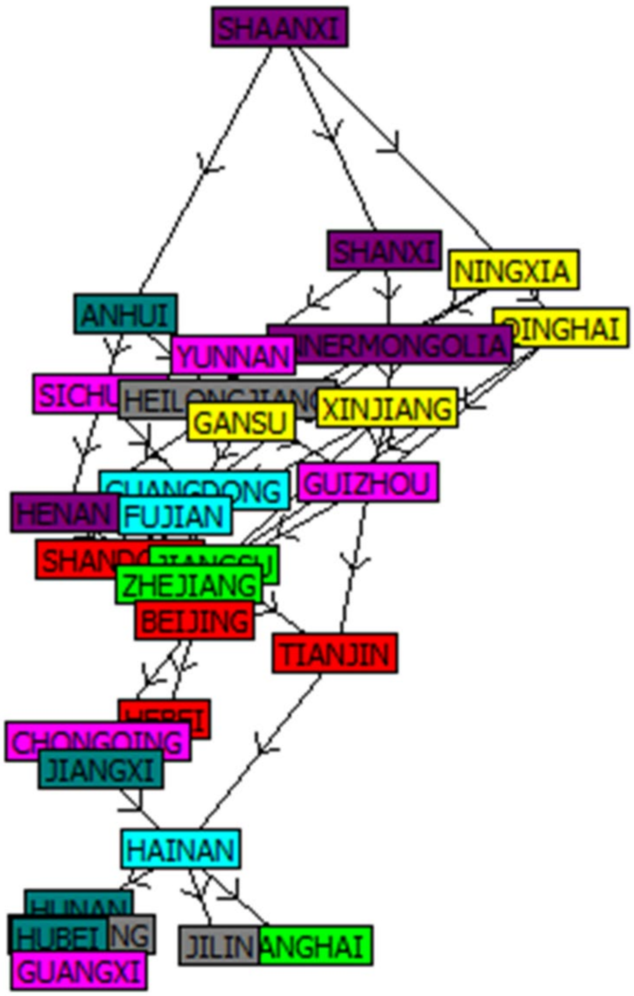
Figure 3. The Visual PROMETHEE network of Energy Security Performance for 30 Chinese Provinces

Figure 4. Energy security performance scores for eight Chinese regions

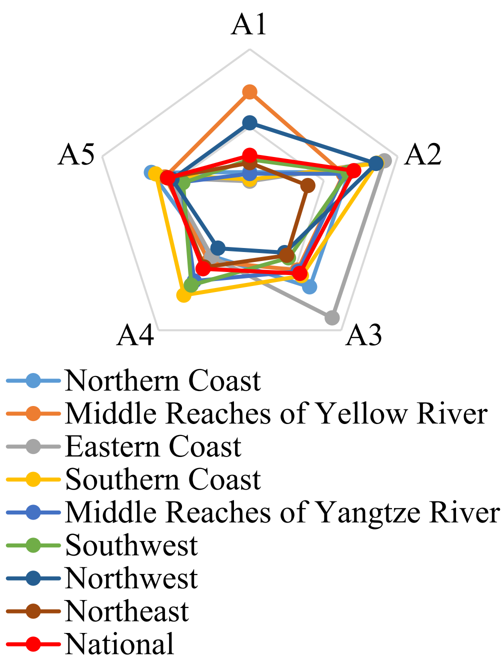
Figure 5. The result of our Energy Security Performance Sensitivity Analysis




0.2231
0.6506
0.7281
0.3522
0.2892
0.2534
0.4047
0.3741
Northern Coast
Southern Coast
Middle Reaches of Yellow River
Northwest
Eastern Coast
Northeast
Middle Reaches of Yangtze River
Southwest



SHAANXI
SHANXI
NINGXIA
ANHUI
YUNNAN
GANSU
XINJIANG
GUIZHOU
HENAN
FUJIAN
ZHEJIANG
BEIJING
TIANJIN
JIANGXI
HAINAN
HUBEI
JILIN
GUANGXI


A1
A2
A3
A4
A5
Northern Coast
Middle Reaches of Yellow River
Eastern Coast
Southern Coast
Middle Reaches of Yangtze River
Southwest
Northwest
Northeast
National

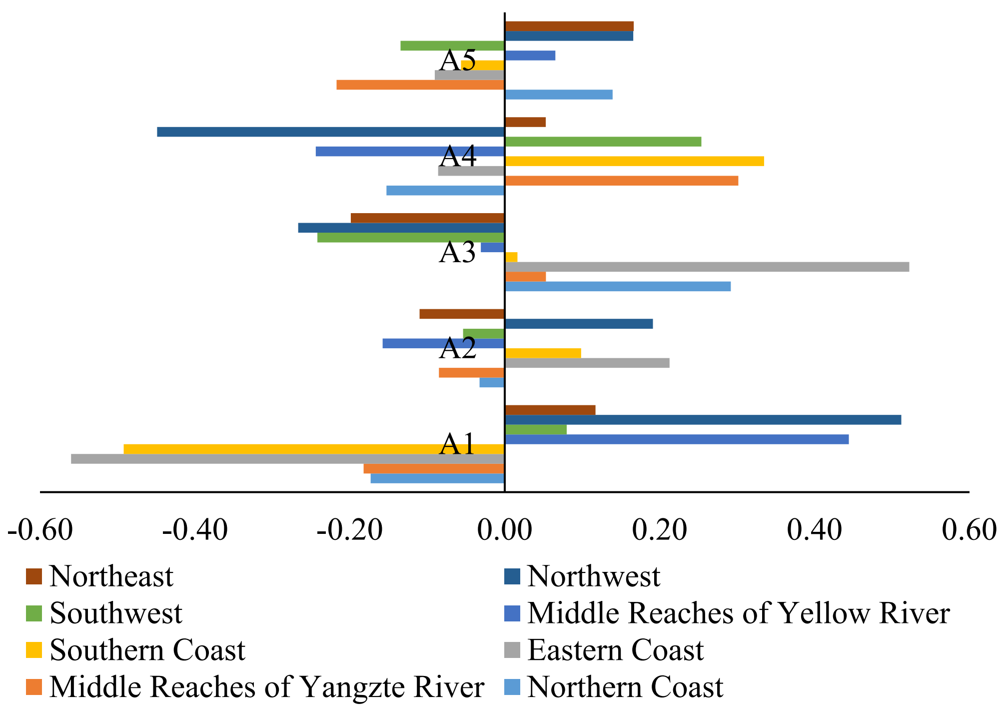

A5
A4
A3
A2
A1
-0.60
-0.40
-0.20
0.00
0.20
0.40
0.60
Northeast
Northwest
Southwest
Middle Reaches of Yellow River
Southern Coast
Eastern Coast
Middle Reaches of Yangzte River
Northern Coast

Table 1. Dimensions, components and metrics of energy security

Dimensions	Components	Metrics	Unit	Definition	Preference
A_1: Availability and diversity	A_{11}:Security of supply	I_1: Primary energy production per capita	tce	Comprises the production of coal, crude oil, natural gas and other new and renewable energy.	Greater preferred
	A_{12}:Energy potential	I_2: Fossil fuel reserves per capita	tce	Proven recoverable reserves at the end of a given year divided by total local population.	Greater preferred
	A_{13}: Dependency	I_3: Self sufficiency	%	Ratio of total primary energy production divided by total primary energy consumption.	Greater preferred
	A_{14}: Diversification	I_4: Diversity of energy consumption	-	$SWI = \sum_{i=1}^{m} p_i \ln\left(p_i\right)$	Greater preferred
A_2: Affordability and equality	A_{21}:Stability	I_5: Stability of gasoline prices	-	Standard deviation of gasoline prices divided by the average price.	Greater preferred
	A_{22}:Electricity generation cost	I_6: Coal-fired power tariff	Yuan/kWh	Actual prices paid by the electricity grid to power plant for the electricity.	Smaller preferred

	A_{23}: Electricity equality	I_7: Share of electricity in total energy consumption	%	Annul electricity consumed divided by local total energy consumption.	Greater preferred
	A_{24}: Affordability of gasoline	I_8: Quantity of gasoline bought with GDP	10^4 tons per person	Local per capita GDP divided by the average gasoline prices for a given year.	Greater preferred
A_3: Technology and efficiency	A_{31}: Energy efficiency	I_9: Energy intensity	tce/10^4 Yuan	TPES in tons of standard coal equivalent per 10000 yuan of GDP.	Smaller preferred
	A_{32}: Grid efficiency	I_{10}: Electricity transmission and distribution losses	%	Including losses in transmission between sources of supply and points of distribution and in the distribution to consumers.	Smaller preferred
	A_{33}: Grid reliability	I_{11}: Average blackout hours per household	Hours	Annual blackout hours per household.	Smaller preferred
	A_{34}: Capacity factor	I_{12}: Utilization of power plants	%	Annual operation hours of power plants divided by the total hours for a year.	Greater preferred

A_4: Environmental sustainability	A_{41}: Land use	I_{13}: Forest coverage	%	Forest area divided by local land area.	Greater preferred
	A_{42}: Water pollution	I_{14}: Waste water emissions per capita	Tons per person	Annual tons of emitted wasted water divided by local population.	Smaller preferred
	A_{43}: Climate change	I_{15}: GHG emissions per unit of GDP	tce /10^4Yuan	Annual tons of carbon dioxide emissions from fuel combustion divided by local population.	Smaller preferred
	A_{44}: Acidification potential	I_{16}: Sulfur dioxide emissions per capita	Tons per person	Annual tons of sulfur dioxide emissions from fuel combustion divided by local population.	Smaller preferred
	A_{45}: Photochemical potential	I_{17}: Nitrogen dioxide emissions per capita	Tons per person	Annual tons of nitrogen dioxide emissions from fuel combustion divided by local population.	Smaller preferred
A_5: Governance and	A_{51}: Market potential	I_{18}: Investment in energy industry	%	Ratio of investment in energy industry divided by total local investment.	Greater preferred

innovation	A_{52}: Innovation and research	I_{19}: Research intensity	%	Ratio of local government expenditure on R&D divided by government total expenditures.	Greater preferred
	A_{53}: Energy & environment management	I_{20}: Energy saving & environment protection	%	Ratio of local government expenditure on energy saving & environment protection divided by government total expenditures.	Greater preferred

Source: research interviews, brain storming, and workshop discussion.

Table 2. The linguistic terms and corresponding fuzzy scales

Linguistic scales	Abbreviation	Triangular fuzzy scales
Equally important	E	(1, 1, 1)
Weakly important	W	(2/3, 1, 3/2)
Fairly strongly important	FS	(3/2, 2, 5/2)
Very strongly important	VS	(5/2, 3, 7/2)
Absolutely important	A	(7/2, 4, 9/2)
Reciprocals of these	RW,RFS,RVS,RA	Reciprocals of the fuzzy numbers

Table 3. Comparison matrix for the five dimensions of energy security

	availability and diversity (A_1)	affordability and equality (A_2)	technology and efficiency (A_3)	environmental sustainability (A_4)	governance and innovation (A_5)
A_1	(1, 1, 1)	(2/3, 1, 3/2)	(3/2, 2, 5/2)	(3/2, 2, 5/2)	(5/2, 3, 7/2)
A_2	(2/3, 1, 3/2)	(1, 1, 1)	(3/2, 2, 5/2)	(3/2, 2, 5/2)	(5/2, 3, 7/2)
A_3	(2/5, 1/2, 2/3)	(2/5, 1/2, 2/3)	(1, 1, 1)	(1, 1, 1)	(3/2, 2, 5/2)
A_4	(2/5, 1/2, 2/3)	(2/5, 1/2, 2/3)	(1, 1, 1)	(1, 1, 1)	(3/2, 2, 5/2)
A_5	(2/7, 1/3, 2/5)	(2/7, 1/3, 2/5)	(2/5, 1/2, 2/3)	(2/5, 1/2, 2/3)	(1, 1, 1)

Table 4. Weights of dimensions and metrics for energy security evaluation

Weight of dimensions		Weight of metrics		Global weight	
A_1	0.2964	A_{11}	0.3315	I_1	0.0983
		A_{12}	0.3315	I_2	0.0983
		A_{13}	0.1685	I_3	0.0499
		A_{14}	0.1685	I_4	0.0499
A_2	0.2964	A_{21}	0.2095	I_5	0.0621
		A_{22}	0.2481	I_6	0.0735
		A_{23}	0.2941	I_7	0.0872
		A_{24}	0.2484	I_8	0.0736
A_3	0.1588	A_{31}	0.3408	I_9	0.0541
		A_{32}	0.2431	I_{10}	0.0386
		A_{33}	0.2429	I_{11}	0.0386

		A_{34}	0.1732	I_{12}	0.0275
A_4	0.1588	A_{41}	0.2491	I_{13}	0.0395
		A_{42}	0.2490	I_{14}	0.0395
		A_{43}	0.2490	I_{15}	0.0395
		A_{44}	0.1265	I_{16}	0.0201
		A_{45}	0.1265	I_{17}	0.0201
A_5	0.0896	A_{51}	0.2027	I_{18}	0.0182
		A_{52}	0.3987	I_{19}	0.0357
		A_{53}	0.3987	I_{20}	0.0357

Table 5. The results of Energy Security Performance for 30 Chinese Provinces

Rank	Province	Phi+	Phi-	Phi	Score
1	SHAANXI	0.4216	0.1803	0.2413	1.0000
2	SHANXI	0.3853	0.2423	0.1430	0.7640
3	NINGXIA	0.3967	0.2623	0.1344	0.7433
4	ANHUI	0.3398	0.2248	0.1150	0.6968
5	QINGHAI	0.3894	0.2808	0.1086	0.6814
6	INNERMONGOLIA	0.3647	0.2639	0.1007	0.6624
7	YUNNAN	0.3434	0.2472	0.0961	0.6514
8	SICHUAN	0.3190	0.2400	0.0790	0.6103
9	HEILONGJIANG	0.3333	0.2565	0.0768	0.6050

10	XINJIANG	0.3505	0.2777	0.0728	0.5954
11	GANSU	0.3300	0.2627	0.0673	0.5822
12	GUIZHOU	0.3320	0.2913	0.0406	0.5181
13	GUANGDONG	0.3093	0.2721	0.0372	0.5100
14	HENAN	0.2887	0.2615	0.0272	0.4860
15	FUJIAN	0.3012	0.2753	0.0258	0.4826
16	SHANDONG	0.2847	0.2786	0.0061	0.4353
17	JIANGSU	0.2949	0.2913	0.0037	0.4295
18	ZHEJIANG	0.2881	0.2923	-0.0042	0.4106
19	BEIJING	0.2808	0.3009	-0.0201	0.3724
20	TIANJIN	0.2901	0.3254	-0.0353	0.3359
21	HEBEI	0.2548	0.3195	-0.0647	0.2653
22	CHONGQING	0.2422	0.3160	-0.0738	0.2435
23	JIANGXI	0.2364	0.3221	-0.0858	0.2146
24	HAINAN	0.2284	0.3495	-0.1211	0.1299
25	HUNAN	0.2028	0.3507	-0.1478	0.0658
26	LIAONING	0.1974	0.3567	-0.1594	0.0379
27	HUBEI	0.1944	0.3544	-0.1601	0.0363
28	SHANGHAI	0.2209	0.3847	-0.1638	0.0274
29	JILIN	0.2116	0.3759	-0.1642	0.0264
30	GUANGXI	0.1891	0.3644	-0.1752	0.0000

Table 6. Energy Security Performance Scores for 30 Chinese provinces

Province	Performance Score				
	A_1	A_2	A_3	A_4	A_5
BEIJING	16.65	80.45	66.07	52.14	53.65
TIANJIN	25.88	62.31	56.63	33.50	60.14
HEBEI	18.60	63.58	64.14	41.26	70.70
SHANXI	100	57.92	44.20	39.22	68.82
INNERMONGOLIA	93.09	64.12	34.47	36.65	60.66
LIAONING	20.41	45.37	42.88	38.33	48.71
JILIN	20.14	34.72	34.98	51.57	63.38
HEILONGJIANG	39.93	37.99	43.48	59.62	55.15
SHANGHAI	14.05	77.30	89.69	35.93	42.76
JIANGSU	16.20	95.93	100	36.21	67.38
ZHEJIANG	14.55	100	80.96	52.55	56.13
ANHUI	27.71	73.22	66.12	53.94	47.45
FUJIAN	17.11	86.03	62.26	61.88	55.71
JIANGXI	16.63	71.16	54.22	67.59	36.99
SHANDONG	22.43	63.32	75.67	37.38	81.61
HENAN	23.95	68.74	69.61	45.58	42.81
HUBEI	16.61	56.99	53.26	52.50	49.99
HUNAN	18.54	54.59	39.10	69.19	51.37
GUANGDONG	15.17	97.56	70.32	54.53	100
GUANGXI	15.30	72.76	37.68	68.46	37.46

HAINAN	16.12	74.38	37.45	100	35.07
CHONGQING	22.83	58.38	41.45	47.14	64.40
SICHUAN	25.71	64.61	62.52	71.09	44.88
GUIZHOU	48.44	62.78	34.18	53.52	37.85
YUNNAN	32.98	73.95	36.71	80.51	41.43
SHAANXI	72.36	62.95	60.41	58.75	57.34
GANSU	31.47	82.58	38.86	44.1	48.85
QINGHAI	57.52	92.87	28.83	35.51	64.69
NINGXIA	55.09	88.53	48.79	28.25	54.63
XINJIANG	66.14	77.79	36.61	31.44	42.19

Table A1. Comparison matrix with respect to the five dimensions

	availability and diversity (A_1)	affordability and equality (A_2)	technology and efficiency (A_3)	environmental sustainability (A_4)	governance and innovation (A_5)
A_1	E	W	F	F	V
A_2	RW	E	F	F	V
A_3	RF	RF	E	E	F
A_4	RF	RF	E	E	F
A_5	RV	RV	RF	RF	E

Table A2. Comparison matrix with respect to availability and diversity

	Security of supply (A_{11})	Energy potential (A_{12})	Dependency (A_{13})	Diversification (A_{14})
A_{11}	E	W	F	F
A_{12}	RW	E	F	F
A_{13}	RF	RF	E	W
A_{14}	RF	RF	RW	E

Table A3. Comparison matrix with respect to affordability and equality

	Stability (A_{21})	Electricity generation cost (A_{22})	Electricity equality (A_{23})	Affordability of gasoline (A_{24})
A_{21}	E	W	RF	RW
A_{22}	RW	E	E	RW
A_{23}	F	E	E	W
A_{24}	W	W	RW	E

Table A4. Comparison matrix with respect to technology and efficiency

	Energy efficiency (A_{31})	Grid efficiency (A_{22})	Grid reliability (A_{33})	Capacity factor (A_{34})
A_{31}	E	W	F	F
A_{32}	RW	E	W	RW

A_{33}	RF	RW	E	F
A_{34}	RF	W	RF	E

Table A5. Comparison matrix with respect to environmental sustainability

	Land use (A_{41})	Water pollution (A_{42})	Climate change (A_{43})	Acidification potential (A_{44})	Photochemical potential (A_{45})
A_{41}	E	RW	RW	F	F
A_{42}	W	E	E	F	F
A_{43}	W	E	E	F	F
A_{44}	RF	RF	RF	E	W
A_{45}	RF	RF	RF	RW	E

Table A6. Comparison matrix with respect to governance and innovation

	Market potential (A_{51})	Innovation and research (A_{52})	Energy & environment management (A_{53})
A_{51}	E	RF	RF
A_{52}	F	E	W
A_{53}	F	RW	E