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Quantifying, measuring, and strategizing energy security: Determining the most meaningful dimensions and metrics

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A B S T R A C T

Various metrics exist for energy security assessment along with a diffuse array of different strategies for improving national performance. These independent and interacted metrics overlap, however, and are rarely considered systematically. The objective of this study is to translate often subjective concepts of energy security into more objective criteria, to investigate the cause-effect relationships among these different metrics, and to provide some recommendations for the stakeholders to draft efficacious measures for enhancing energy security. To accomplish this feat, the study utilizes a DEMATEL (Fuzzy Decision-making Trial and Evaluation Laboratory) methodology to analyze collected data, reveal cause-effect relationships, and prioritize energy security strategies. To apply our theoretical results in practice, we include a brief case study of China. We conclude that the availability and affordability dimensions of energy security are most impactful to a nation's overall energy security, and that the promotion of renewable energy and diversification are compelling national energy security strategies, both for China and other countries.

1. Introduction

As the global economy continues to grow and developing countries become more industrialized, policymakers and consumers around the world are increasingly confronting shortages in energy supply, rising prices, and environmental degradation caused by the excessive exploitation and use of fossil fuels. In this complex and constantly changing energy landscape, determining what energy security is, or how it ought to be conceived, is an arduous endeavor. It touches on themes in the energy studies literature as diverse as research strategy [1], energy transitions [2,3], infrastructural scale [4], international conflict [5], and poverty [6].

Part of the problem is connected to the diffuse, yet growing, nature of energy security threats. Enhancing energy security is, in one sense, about mitigating energy related risks like British Petroleum's *Deepwater Horizon*, the nuclear meltdown at Fukushima in Japan, and recent methane explosions in Russia and Mexico. Being energy secure also means averting attacks on energy infrastructure such as the assault targeting an Algerian gas facility in January 2013, which left 37 employees dead. It entails fostering technological reliability and preventing electricity blackouts, and it is interwoven with sensitive geopolitical power struggles over energy resources, such as those occurring in the South China Sea. It, moreover, can relate to the impact our energy systems have on the global climate and on our local environment [7].

Therefore, energy security—defined as equitably providing available, affordable, reliable, efficient, environmentally benign, proactively governed and socially acceptable energy services to end-users—invariably fuses traditional conceptions of national security with emerging concepts of human rights, sustainable development, and individual security [7]. Many studies have been carried out on energy security recently, and they often develop multi-dimensional metrics or indicators for conceptualizing energy security, or they measure energy security performance. All these studies are useful and helpful in their own way, but they do suffer from two general shortcomings. Firstly, they rarely consider the intersection of energy security metrics, and often ignore complex independences and interactions among these metrics. Secondly, it difficult to translate the findings from academic studies into actionable strategies that policymakers can both understand and

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implement. Thus, there is an important question that remains to be answered: how are the issues of energy security best quantified, measured, and strategized?

To provide an answer, in this paper we review the academic literature and argue that energy security best consists of the four dimensions of availability, affordability, acceptability, and accessibility. We utilize the DEMATEL (Fuzzy Decision-making Trial and Evaluation Laboratory) method [8,9] to identify cause-effect relationships among energy security metrics, and to determine the most salient and meaningful dimensions and energy security strategies. The Fuzzy DEMATEL method offers a systematic way of transforming subjective and vague preferences into more concrete and objective factors [10–14]. In this particular study, we apply the method to determine optimal energy security strategies for China, a country confronting massive and interconnected energy security challenges. We conclude that the availability and affordability dimensions have the most influence on energy security, and that the promotion of renewable energy and diversification ought to be the most compelling strategy for national planners in Asia and beyond.

2. Determining energy security: materials and methods

This section of the paper briefly surveys the literature on energy security, proposes our four energy security dimensions and 24 metrics, and then summarizes our Fuzzy DEMATEL model. It employs a research framework presented in Fig. 1, which shows how we progressed from (2.1) carrying out a literature review, (2.2) identifying energy security dimensions and corresponding those dimensions to metrics, (2.3) establishing directed-influence matrices for using DEMATEL, and (2.4) presenting the fuzzy DEMATEL methodology.

2.1. Literature review

Our literature review focused primarily on three aspects of energy security in the academic literature: its associated dimensions and metrics, previous attempts at measuring performance, and identifying shortcomings and challenges with modern energy security conceptualizations.

2.1.1. Metrics of energy security

As many readers of this journal already know, the literature on energy security metrics and indicators is voluminous and growing by the day. As a brief sample of some of the best studies arising from this burgeoning field, Vivoda recently sought to create a “novel methodological” approach to energy security and proposed 11 broad dimensions and 44 attributes that could be utilized to assess national performance on energy issues [15]. Sovacool and Mukherjee similarly devised 5 dimensions consisting of 20 components and 300 simple indicators along with 52 complex indicators [16] and Sovacool identified 20 dimensions and 200 indicators [17]. Kruyt et al. proposed 24 simple and complex indicators for energy security [18], Von Hippel et al. argued in favor of six dimensions and more than 60 separate attributes, issues, and strategies [19]. Even the U.S. Chamber of Commerce created an “index of U.S. security risk” comprising 4 sub-indexes, 9 categories, and 37 metrics [20]. Similarly, Brown and Sovacool [21], Sovacool and Brown [22], and Sovacool and Brown [23] have also proposed “energy sustainability indices” and “energy security indices” for industrialized countries. Gupta [24] and Ediger et al. [25] have both looked at the energy security risks and indicators surrounding oil and fossil fuels. Others have employed diversity indices such as the Herfindhal-Hirschman Index to investigate vulnerability and diversification Very high influence.

2.1.2. Energy security measurement and assessment

In the economics literature, an equally significant number of studies have investigated the topic and attempted to assess or measure national energy security performance. Chuang and Ma [29] utilized a multi-dimensional criteria system consisting of dependence, vulnerability, affordability and acceptability, and six specified indicators to assess the effectiveness of Taiwan's energy policies on its energy security. Shin et al. [30] simulated the effect of key policies on the improvements of 19 key energy security indicators based on quality function deployment and system dynamics. Yao and Chang [31] used five metrics to analyze the trend of China's energy security over 30 years of reform. Kiriyama and Kajikawa used citation network analysis to disaggregate energy security into geopolitical, economic, policy related, and technological components [32]. Martchamadol and Kumar [33] developed the “AESPI (Aggregated energy security performance indicator)” by combining 25 individual indicators in social, economic and environmental aspects to assess energy security of the past and future status. Wu et al. [34] used 14 indicators to assess the relationship between climate protection and China's energy security. Augutis et al. [35] utilized a similar method to assess Lithuanian energy security. Portugal-Pereira and Esteban [36] used five dimensions including availability, reliability, technological and development, global environmental sustainability, and local environmental protection to assess Japan's electricity security under different generation portfolio scenarios. Geng and Ji [37] developed seven evaluation indicators in four dimensions to asses China's energy security from 1994 to 2011. Indeed, the list could go on even further.

Major energy institutions have also expressed interest in measuring energy security. The International Atomic Energy Agency proposed a comprehensive set of 30 indicators spanning social, economic, and environmental dimensions [38]. Their work was extended and used by Vera et al. into four dimensions—the quality and price of energy services, impact on social wellbeing, environmental impacts, and availability and adequacy of regulators and regulations—and 41 indicators that they then applied to Brazil, Cuba, Lithuania, Mexico, Russia, the Slovak Republic, and Thailand [39]. The International Energy Agency (2004) designed an “Energy Development Index” to provide a “simple composite measure of a country's or region's progress in its transition to modern fuels and of the degree of maturity of its energy end-use.” They later devised a different set of metrics to evaluate the risk of system disruptions, imbalances between supply and demand, regulatory failures, and diversification among a subset of OECD countries [40]. The Energy Research Center of the Netherlands (ECN) has also developed a comprehensive “Supply and Demand Index” to better assess diversification of energy sources, diversification of imports and suppliers, the long-term political stability in origins of supply, and rates of resource depletion [41]. Gnansounou built from this work to create a composite index of supply and demand investigating reductions in energy intensity, oil and gas import dependency, the carbon content of primary fuels, electricity weaknesses, and diversification of transport fuels [42].

2.1.3. Shortcomings and challenges

These works are excellent, and essential for any serious scholar, analyst, or regulator with an interest in energy security. However, almost all of them suffer from a few common shortcomings:

- *Topical focus*. A vast majority of studies are designed exclusively for industrialized countries, mostly those belonging to the OECD or in Europe and North America. Frondel et al. [43], as one example, look only at the G7. These studies thus center on pressing concerns related to electricity supply, nuclear power, and automobiles, but are not applicable to developing or least

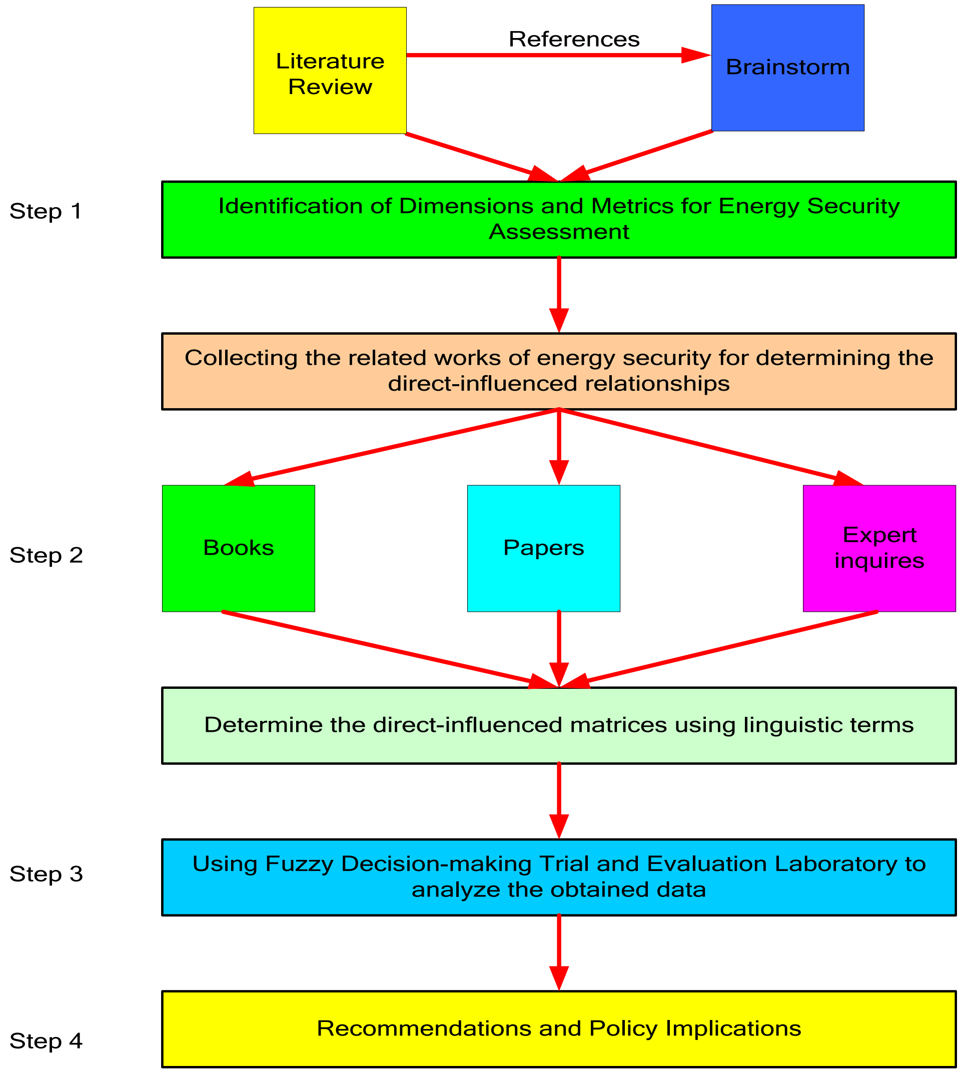

Fig. 1. Research Framework of the proposed study.

developed countries that have patchy and incomplete electricity networks, limited nuclear power units, and non-motorized forms of transport. Others, such as IAEA [38] and IEA [40], go the opposite way and are geared toward sustainable development and energy poverty rather than energy security as a whole.

- *Scope and Coverage*. Many indices are sector-specific, i.e. designed for electricity only [41], oil [24], or fossil fuels [25], and many focus on energy supply rather than demand. Geopolitical relationships or trade flows are seldom included, and other dimensions such as sustainability or equity or efficiency are often ignored. Put another way, such tools underexpose or undervalue essential aspects of energy security on the demand side, involving behavior and consumer responses. Moreover, metrics are often frequently unbalanced. The IAEA [38], for instance, has sixteen metrics for "economics" but only 4 for "social" elements. Trade in energy carriers other than coal, oil, and natural gas is generally excluded and not modeled, yet it is fuelwood, charcoal, and dung that matters most in developing countries. Others rely on only a handful of metrics. The IEA's Energy Development Index, for example, is composed only of three metrics: per capita commercial energy consumption, share of commercial energy in total final energy use, and the share of population with access to electricity.
- *Transparency*. Most models and indices make hidden tradeoffs between aggregation and transparency. Kruyt et al. [18] have noted that as models get more complex, they tend to hide underlying assumptions and dynamics that make it difficult to see the values and weights behind them. This makes them "Trojan horses" since they are dressed a certain way get inside the gates of energy policymaking, so to speak, but no more reliable. They all have structural and problematic assumptions, but most of the time these are opaque. Stirling [44] has cautioned that logarithmic functions, such as Shannon–Wiener, Simpson, and Herfindahl-Hirschman Indices require extensive modeling skill and econometrics training, meaning they are complicated and not intuitively understood by most policymakers.
- *Continuity*. Very few of the metrics and indicators assess energy security performance over time. They often take a particular snapshot of a particular point, but do not compare performance over a series of years. In other words, these indexes and metrics presume that the classifications they model are constant and unchanged over time, leading to very problematic assessments.

In order to overcome these four shortcomings and also fulfill our objective of determining the most meaningful dimensions and metrics of energy security, we screened almost three-dozen recent, recently published peer-reviewed works [15–46], and integrated their metrics and definitions of energy security into four dimensions, which we explain in the next section.

2.2. Toward 4 dimensions and 24 metrics

To provide a comprehensive yet simple, usable, way of evaluating energy security, in this study we propose, based on the findings from our literature review, that it consists of availability, affordability, acceptability and accessibility. This way of conceptualizing energy security has been affirmed by some previous work [45,46]. Availability relates to the physical or geological existence of energy resources and the ability for a given community or country to secure those resources. Affordability includes economic considerations such as price, externalities, equity, and price stability. Acceptability refers to social and environmental concerns associated with energy production and use. Accessibility relates to geopolitical elements and the robustness or resilience of the entire system. We discuss each of these, briefly, in turn and how they can be broken down into 24 metrics. We must emphasize that though there are elements of these four dimensions that overlap none of them can be replaced by others; that is, each of the four are necessary to achieve energy security.

2.2.1. Availability (A1)

We argue that the dimension of availability consists primarily of factors that influence the energy resources and security of energy supply for a given country. We propose that such a dimension can be broken down into five distinct metrics:

- Security of supply (A_{11}): measures the adequacy of supply in meeting national energy demand. This metric can be measured by determining the ratio between the total production energy and the total consumed energy.
- Self-sufficiency (A_{12}): represents dependency on imported energy, and can reflect the resilience to the interruption of imported energy. It can be measured by determining the ratio between the imported energy and the total consumed energy.
- Diversification (A_{13}): reflects the diversity of used energy sources for energy supply, and the ability to mitigate the risk caused by overdependence on several major energy sources. It can be measured by a diversity index of the possible energy resources for supply, such as the Shannon–Wiener index.
- Renewable energy (A_{14}): refers the share of renewable energy sources in total primary energy supply. It can be measured by determining the fraction between renewable energy and the total consumed energy.
- Technological maturity (A_{15}): measures overall reliability and reflects to some extent the state of national energy infrastructure. In this study we treat it as a qualitative metric.

2.2.2. Affordability (A_2)

We argue that the dimension of affordability consists primarily of factors which influence energy prices for households and industries. We propose that such a dimension can be broken down into six metrics:

- Price stability (A_{21}): measures the stability of the energy market, and can reflect the resilience to market risks and the soundness of national energy policies. It can be measured by determining the total absolute derivations of the price in different time to the global mean value.
- Dependency (A_{22}): assesses imported energy per capita. It can be measured by the total importuned energy divided by the number of the population.
- Market liquidity (A_{23}): refers to the ability of energy sources to be sold without causing a significant movement in the price and with minimum loss of value. In this study we treat it as a qualitative metric.
- Decentralization (A_{24}): reflects the extent to which distributed generation and smaller-scale energy systems are utilized. It can be measured by determining fraction of the total energy generated by distributed generation and smaller-scale energy systems in the total energy production.
- Electrification (A_{25}): measures the percentage of the population that has access to reliable grid connections.
- Equity (A_{26}): Measures the percentage of the households depending on traditional solid fuels such as wood and straw for cooking and heating.

2.2.3. Acceptability (A_3)

We argue that this dimension mainly refers to the environmental and social consequences of energy production and use. We break it down into eight metrics:

- Environment (A_{31}): measures negative impacts on the environment such as greenhouse gases emissions, water pollution and land use caused by the use of energy. This metric can be further divided into several micro-aspects, and each of them can be measured individually.
- Social satisfaction (A_{32}): refers to public attitudes and perceptions of energy systems. In this study we treat it as a qualitative metric.
- National governance (A_{33}): measures the ability to which national institutions can properly govern and regulate the energy sector. In this study we treat it as a qualitative metric.
- International governance (A_{34}): measures the degree to which a country meets international norms of good governance such as rule of law and minimal corruption. In this study we treat it as a qualitative metric.
- Transparency (A_{35}): reflects the transparency of energy information, and it can indicate the extent of public knowledge about energy. In this study we treat it as a qualitative metric.
- Efficiency (A_{36}): used to measure utilization level of energy, and it aims at evaluating the loss of energy. In this study we utilize energy intensity as a proxy for efficiency.
- Innovation (A_{37}): measures the advancement of energy technologies based on research & development. In this study we treat it as a qualitative metric.
- Investment and employment (A_{38}): refers to the sunk investment and jobs contributed by the development of energy industry. In this study we treat it as a qualitative metric.

2.2.4. Accessibility (A_4)

Our final five metrics all relate to accessibility, and they emphasize geopolitical and resilience aspects of national energy systems:

- Import stability (A_{41}): assesses the stability of energy imports from foreign countries. In this study we treat it as a qualitative metric.
- Trade (A_{42}): reflects the international politics and international relations that influence energy trade. In this study we treat it as a qualitative metric.

Table 1
Linguistic terms and their equivalent fuzzy numbers.

Linguistic terms	Abbreviations	Fuzzy variables
No influence	N	(0,0,0.25)
Very low influence	VL	(0,0.25,0.50)
Low influence	L	(0.25,0.50,0.75)
High influence	H	(0.50,0.75,1.00)
Very high influence	VH	(0.75,1.00,1.00)

- Political stability (A_{43}): serves as an indicator of the durability and stability of domestic political institutions. In this study we treat it as a qualitative metric.
- Military power (A_{44}): measures the overall safety and security of a nation. In this study we treat it as a qualitative metric.
- Safety and reliability (A_{45}): Measures the resilience of energy system to risks, terrorism and natural disasters. In this study we treat it as a qualitative metric.

2.3. *Direct-influenced relationships*

Based largely on our review of the literature above, as well as further thoughts offered in Refs. [18,33,47], we proceeded to identify a set of direct-influenced relationships among the four 'A's and the metrics that correspond to each of them. Five linguistic variables including "No influence (N)", "Low influence (L)", "Medium influence (M)", "High influence (H)", and "VH (very high influence)" were used to describe the relationship between dimensions and metrics, and each linguistic term was given an equivalent fuzzy number presented in Table 1. Those interested in seeing our entire fuzzy set theory can peruse Appendix A.

Table 2 introduces our direct-influence matrix with respect to the four macro-dimensions of energy security. We argue that enhancing the availability dimension of energy security will contribute significantly to the affordability and acceptability dimensions, and also benefits accessibility, because making energy more easily available can both lower its price and mitigate the negative impacts of pollution [16,19,48,49]. Thus, availability is considered to have very high (VH) influences on affordability and acceptability. Meanwhile, making energy available can also improve the reliability of an energy system, so availability is considered to have high (H) influence on the accessibility dimension. Improving the affordability dimension mainly consists of enhancing the stability of energy prices, market liquidity, decentralization and electrification [16,17,30]. These will generally tend to culminate in social satisfaction and sound governance [16,50–52], meaning affordability is considered to have very high (VH) influences on acceptability, and affordability is also considered to have very high (VH) influences on accessibility [16,53,54]. Tables 3–6 present the direct-influenced matrices with respect to the metrics in availability, affordability, acceptability and accessibility.

Table 2
Direct-influenced matrix using linguistic terms with respect to the four dimensions of energy security.

	Availability	Affordability	Acceptability	Accessibility
Availability	N	VH	H	VH
Affordability	VL	N	VH	VH
Acceptability	L	L	N	VL
Accessibility	H	H	N	N

Source: Evaluation based on [18,33,47].

Table 3
Direct-influenced matrix for availability.

	(A_{11})	(A_{12})	(A_{13})	(A_{14})	(A_{15})
Security of supply (A_{11})	N	H	N	N	N
Self-sufficiency (A_{12})	N	N	N	N	N
Diversification (A_{13})	H	VH	N	H	N
Renewable energy (A_{14})	VH	VH	VH	N	N
Technological maturity (A_{15})	L	N	N	N	N

Source: Evaluation based on [16,19,48,49]

2.4. *Fuzzy DEMATEL model*

With our 24 metrics and the relationships between them chosen, our next step was to utilize the DEMATEL approach to analyze the cause-effect relationships between our metrics and to determine strategies for energy security enhancement.

The process known as "Decision making trial and evaluation laboratory," or DEMATEL, has been widely used to investigate systems with complicated and intertwined problems (e.g. sustainability), and to identify the factors that influence them [55,56]. Fuzzy DEMATEL extends the process to incorporate more subjective or qualitative concerns, and it is further illustrated and introduced in Refs. [55–60].

To apply Fuzzy DEMATEL to energy security, we proceeded as follows. We transformed the linguistic terms in Tables 2–6 into fuzzy triangular numbers according to Table 1, mentioned above. These include five triangular numbers representing "No influence ((0,0,0.25))", "Low influence ((0,0.25,0.50))", "Medium influence ((0.25,0.50,0.75))", "High influence ((0.50,0.75,1.00))", and "Very high influence ((0.75,1.00,1.00))." The result is a fuzzy direct influenced-matrix determined by the k-th stakeholder/decision-maker denotes by$\tilde{A}^k$, as shown in Eq. (1).

$$\tilde{A}^k = \begin{bmatrix} 0 & \tilde{a}_{12} & \cdots & \tilde{a}_{1n} \\ \tilde{a}_{21} & 0 & \cdots & \tilde{a}_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ \tilde{a}_{n1} & \tilde{a}_{n2} & \cdots & 0 \end{bmatrix} \tag{1}$$

$$\tilde{a}_{ij} = \left(a_{ij}^L, a_{ij}^M, a_{ij}^U\right), i = 1, 2, \cdots, n; j = 1, 2, \cdots, n \tag{2}$$

where$\tilde{A}^k$ represents the fuzzy direct-influenced matrix determined by the stakeholder/decision-maker.

The normalized initial direct-relation matrix $\tilde{D}$ could be obtained by Eqs. (3)–(5).

$$r = \max_{i=1,2,\cdots,n} \left(\sum_{j=1}^{n} a_{ij}^U \right) \tag{3}$$

$$\tilde{D} = \left[\tilde{d}_{ij}\right]_{n \times n} \tag{4}$$

$$\tilde{d}_{ij} = \left(d_{ij}^L, d_{ij}^M, d_{ij}^U\right) = \left(\frac{a_{ij}^L}{r}, \frac{a_{ij}^M}{r}, \frac{a_{ij}^U}{r}\right) \tag{5}$$

Table 4
Direct-influenced matrix for affordability.

	(A_{21})	(A_{22})	(A_{23})	(A_{24})	(A_{25})	(A_{26})
Price stability (A_{21})	N	N	H	N	VH	L
Depedency (A_{22})	VL	N	VL	N	H	H
Market liquidity (A_{23})	VH	VL	N	N	H	H
Decentralization (A_{24})	L	N	L	N	VL	VL
Electrification (A_{25})	N	N	N	N	N	L
Equity (A_{26})	N	N	N	N	L	N

Source: Evaluation based on Ref [16,17,30]

Table 5
Direct-influenced matrix for acceptability.

	(A_{31})	(A_{32})	(A_{33})	(A_{34})	(A_{35})	(A_{36})	(A_{37})	(A_{38})
Environment (A_{31})	N	VH	H	H	N	N	N	N
Social satisfaction (A_{32})	N	N	N	H	N	N	N	L
National governance (A_{33})	H	H	N	H	H	H	H	H
International governance (A_{34})	L	VL	L	N	L	L	VL	VL
Transparency (A_{35})	N	H	L	L	N	N	N	N
Efficiency (A_{36})	VH	H	H	L	N	N	L	N
Innovation (A_{37})	VH	VH	VH	VH	N	VH	N	N
Investment and employment (A_{38})	H	H	VH	L	N	H	H	N

Source: Evaluation based on Ref [16,50–52].

Table 6
Direct-influenced matrix for accessibility.

	(A_{41})	(A_{42})	(A_{43})	(A_{44})	(A_{45})
Import stability (A_{41})	N	N	N	N	H
Trade (A_{42})	N	N	VH	L	H
Political stability (A_{43})	N	VH	N	N	VH
Military power (A_{44})	N	VH	H	N	VH
Safety and reliability (A_{45})	N	N	N	N	N

Source: Evaluation based on [16,53,54].

where $\tilde{D}$ is the normalized initial direct-relation matrix, and it is assumed that at least one i such that $\sum_{j=1}^{n} a_{ij}^{U} < r$.

The sum of each row j of matrix $\tilde{D}$ represents the direct influences of the j-th factor on other factors, and $\max_{1\le j\le n} \sum_{i=1}^{n} \tilde{a}_{ji}$ represents the factor has the highest influence on other factors. The sum of each column i represent the direct influences on the i-th factor affected by the other factors, and $\max_{1\le i\le n} \sum_{j=1}^{n} \tilde{a}_{ji}$ represents the factor which is the most influenced by the other factors.

The powers of $\tilde{D}$ represent the indirect effects between any factors and satisfies $\lim_{w\to\infty} \tilde{D} = 0$, and the total relation matrix $\tilde{T}$ could be calculated by Eqs. (6)–(14).

$$\tilde{T} = [\tilde{t}_{ij}]_{n\times n} = \lim_{w\to\infty}\left(\tilde{D} + \tilde{D}^2 + \cdots + \tilde{D}^w\right) \tag{6}$$

$$\tilde{t}_{ij} = \left(t_{ij}^{L}, t_{ij}^{M}, t_{ij}^{U}\right) \tag{7}$$

$$\tilde{N}_k^{\text{def}} = L + \Delta \times \frac{\left(a_k^m - L\right)\left(\Delta + a_k^u - a_k^m\right)^2\left(R - a_k^l\right) + \left(a_k^u - L\right)^2\left(\Delta + a_k^m - a_k^l\right)^2}{\left(\Delta + a_k^m - a_k^l\right)\left(\Delta + a_k^u - a_k^m\right)^2\left(R - a_k^l\right) + (a_k^u - L)\left(\Delta + a_k^m - a_k^l\right)^2\left(\Delta + a_k^u - a_k^m\right)} \tag{16}$$

$$\left[t_{ij}^{L}\right]_{n\times n} = D^L \times \left(I - D^L\right)^{-1} \tag{8}$$

$$D^L = \begin{bmatrix} d_{11}^L & d_{12}^L & \cdots & d_{1n}^L \\ d_{21}^L & 0 & \cdots & d_{2n}^L \\ \vdots & \vdots & \ddots & \vdots \\ d_{n1}^L & d_{n2}^L & \cdots & d_{nn}^L \end{bmatrix} \tag{9}$$

$$\left[t_{ij}^{M}\right]_{n\times n} = D^M \times \left(I - D^M\right)^{-1} \tag{10}$$

$$D^M = \begin{bmatrix} d_{11}^M & d_{12}^M & \cdots & d_{1n}^M \\ d_{21}^M & d_{22}^M & \cdots & d_{2n}^M \\ \vdots & \vdots & \ddots & \vdots \\ d_{n1}^M & d_{n2}^M & \cdots & d_{nn}^M \end{bmatrix} \tag{11}$$

$$\left[t_{ij}^{U}\right]_{n\times n} = D^U \times \left(I - D^U\right)^{-1} \tag{12}$$

$$D^U = \begin{bmatrix} d_{11}^U & d_{12}^U & \cdots & d_{1n}^U \\ d_{21}^U & d_{22}^U & \cdots & d_{2n}^U \\ \vdots & \vdots & \ddots & \vdots \\ d_{n1}^U & d_{n2}^U & \cdots & d_{nn}^U \end{bmatrix} \tag{13}$$

where $\tilde{T}$ represents the total relation matrix and I is the identity matrix.

The total effect that directly and indirectly exerted by the i-th factor, could be calculated by Eq. (14).

$$\tilde{R}_i = \sum_{j=1}^{n} \tilde{t}_{ij} \tag{14}$$

The total effect including direct and indirect effects received by the j-th factor could be calculated by Eq. (15).

$$\tilde{C}_j = \sum_{i=1}^{n} \tilde{t}_{ij} \tag{15}$$

Therefore, when $i = j$, the sum $\tilde{R}_i + \tilde{C}_i$ represents the total effects given and received by the i-th factor. In other words, $\tilde{R}_i + \tilde{C}_i$ is a measure of the degree of the importance of the i-th factor in the system. The difference $\tilde{R}_i - \tilde{C}_i$ called “relation” shows the net effect contributed by the i-th factor to the system.

After the calculation of the coordinate values $(\tilde{R}_i + \tilde{C}_i, \tilde{R}_i - \tilde{C}_i)$ of all the factors, $\tilde{R}_i + \tilde{C}_i$ and $\tilde{R}_i - \tilde{C}_i$ can be “defuzzied” to crisper values through a defuzification method, as presented in Eq. (16). This equation denotes by $R_i + C_i$ and $R_i - C_i$. $R_i + C_i$ can be used to measure the importance of the i-th factor acting as a role in the studied system.

where $\tilde{N}_k^{\text{def}}$ represents the defuzzied value of the fuzzy number $\tilde{a}_k = (a_k^l, a_k^m, a_k^u)$, $L = \min_{k=1,2,\cdots,n}(a_k^l)$, $R = \max_{k=1,2,\cdots,n}(a_k^u)$, and $\Delta = R - L$

The $R_i - C_i$ shows that the group category (cause group or effect group) to which the i-th factor belongs. In other words, the group category (cause group and effect group) to which each factor belongs to can be determined according the value of this index. Generally, if$R_i - C_i$ is positive, the i-th factor belongs to the cause group, and if $R_i - C_i$ is negative, the i-th factor belongs to the effect group.

If the i-th factor is an effect, the value of $R_i + C_i$ represents the independent degree of the i-th factor, and the smaller this value, the more independent it is, and it means that there are less other factors will influence factor i. In contrary, if the value of $R_i + C_i$ is large, it means that it is a key factor to be addressed; however, it is not the cause of the problem. If the i-th factor is a cause, and the value of $R_i + C_i$ is small, it means that this factor only can affect a few other factors. On the contrary, if the value of $R_i + C_i$ is large, it means it is a core driving factor and should be given priority for improving the whole of the system.

3. Energy security in theory: results and discussion

In this section, we present the results of our fuzzy DEMATEL analysis. Table 7, derived from Table 2 above, illustrates how we transformed our linguistic terms above into fuzzy numbers. For instance, cell (1,2) in Table 2 is 'VH', meaning it can be transformed into its equivalent fuzzy number (0.75, 1.00, 1.00). Similarly, other elements (linguistic terms) in Table 2 can also be transformed into fuzzy numbers. Then, a normalized initial direct-influenced matrix can be obtained by Eqs. (3)–(5), as presented in Table 8.

Subsequently, the total-relation fuzzy matrix with respect to the four dimensions of energy security can be determined by Eqs. (6)–(13), and presented in Table 9. It is worth pointing out the total-relation fuzzy matrix has incorporated both the direct and indirect effects among the metrics. Finally, the results of the DEMATEL analysis with respect to the four dimensions have been presented in Table 10 according to Eqs. (14)–(16).

Because readers may find some of these Tables hard to digest, Fig. 2 presents our results graphically. As it indicates, distinctions between causes and effects can be identified based on the values of (R_i–C_i). It is apparent that availability is regarded as a cause because the value of (R_i–C_i) is greater than zero, whereas affordability, acceptability and accessibility have been regarded as effects. Thus, the dimension of availability (A_1) is the essence of energy security, and as such it can also be interpreted as the root of many energy security problems.

Moreover, the importance of the four dimensions can be prioritized according to the values of ($R_i + C_i$). Here, affordability (A_2) and availability (A_1) are the two most important dimensions of energy security, because the values of ($R_i + C_i$) with respect to affordability and availability are the largest, followed by accessibility and acceptability.

Zooming in to discuss priorities within certain dimensions, the most salient metrics within availability appear to be the fraction of renewable energy in total primary energy supply (A_{14}), diversification of energy sources (A_{13}), level of self-sufficiency (A_{12}), security of supply (A_{11}), and technological maturity (A_{15}). Meanwhile, diversification (A_{13}), renewable energy, and security of supply (A_{11}), and self-sufficiency (A_{12}) are regarded as net receivers (effects). Based on the integrated analysis of the importance of these metrics, and the cause-effect relationships among them, it could be concluded that the fraction of renewable energy in total primary energy supply (A_{14}) and diversification of energy sources (A_{13}) are the two most important drivers for improving the performance of availability dimension, because the improvement of these two metrics can improve the performances of other metrics across the effects group, as Fig. 3 demonstrates.

Table 7
Direct-influenced matrix using fuzzy numbers with respect to the four dimensions of energy security.

	Availability	Affordability	Acceptability	Accessibility
Availability	(0,0,0.25)	(0.75,1.00,1.00)	(0.50,0.75,1.00)	(0.75,1.00,1.00)
Affordability	(0,0.25,0.50)	(0,0,0.25)	(0.75,1.00,1.00)	(0.75,1.00,1.00)
Acceptability	(0.25,0.50,0.75)	(0.25,0.50,0.75)	(0,0,0.25)	(0,0.25,0.50)
Accessibility	(0.50,0.75,1.00)	(0.50,0.75,1.00)	(0,0,0.25)	(0,0,0.25)

In the affordability dimension, market liquidity (A_{23}), price stability (A_{21}), and electrification (A_{25}) are regarded as the most important three metrics, followed by equity (A_{26}), import dependency (A_{22}) and decentralization (A_{24}). The metrics of price stability (A_{21}), import dependency (A_{22}), market liquidity (A_{23}) and decentralization (A_{24}) are investigated as causes, whereas the other two metrics (electrification and equity) are regarded as net receivers (effects), as Fig. 4 suggests. In addition, electrification and equity are both very influential factors that belong to effect group, but they are not the origins of the problems in affordability dimension. In other words, the improvements of price stability (A_{21}) and market liquidity (A_{23}) are of vital importance for enhancing the integrated performance of affordability dimension.

In the dimension of acceptability, we identified national governance (A_{33}) as the most important metric followed by metrics of moderate importance such as international governance (A_{34}), innovation (A_{37}), investment and employment (A_{38}), energy utilization efficiency (A_{36}), social satisfactions (A_{32}) and the environment (A_{31}), with transparency (A_{35}) coming last. The cause group consists of national governance (A_{33}), transparency (A_{35}), efficiency (A_{36}), innovation (A_{37}), and investment and employment (A_{38}), whereas environmental impacts, (A_{31}), social satisfaction (A_{32}), and international governance (A_{34}) are regarded as net receivers (effects), as Fig. 5 indicates. It could be concluded that national governance is not only the most important influential metric acceptability dimension, but also the key driver for enhancing other elements of acceptability.

Lastly, in the dimension of accessibility, we identified trade (A_{42}) as the most important metric, follows by domestic politics (A_{43}), military power (A_{44}), safety and reliability of energy system (A_{45}), and import stability (A_{41}). All the metrics except safety and reliability (A_{45}) are regarded as causes, as Fig. 6 illustrates.

4. Energy security in practice: application to China

It is one thing to discuss and analyze energy security in theory; it is perhaps equally useful to apply theoretical concepts in practice. To do so in this paper, we present a brief case study of China. As the case of China shows, our proposed methodology for prioritizing the metrics of energy security, and investigating the cause-effect relationships among them, is generic, and it can be applied to virtually any country. In other words, the proposed methodology is object-oriented. Our illustrated modular approach based on DEMATEL can be employed by stakeholders to determine the prior sequence of the factors that affect energy security and find the key origins of the problems hindering the secure future of energy supply.

As many readers are likely aware, China is representative of a developing country which faces severe energy security problems [48]. The application of our Fuzzy DEMATEL model does reveal both the extent of Chinese energy security vulnerabilities and optimal solutions to those problems.

Drawing from our Fuzzy DEMATEL results, from a macroscopic point of view, the improvement of both availability and affordability is essential to enhancing China's energy security. We found that availability is both the most important driver for promoting national energy security and the most influential metric. Therefore, drafting some strategic policies and plans, and implementing some actions to improve the performance of metrics within the availability dimension, are a prerequisite in the near future for sound Chinese energy policy. China has already taken some actions to achieve this target such as the 'The Twelfth Five-Year Plan,' which intends to reduce greenhouse emissions, increase energy efficiency, develop

Table 8
Normalized initial direct-relation matrix with respect to the four dimensions of energy security.

	Availability	Affordability	Acceptability	Accessibility
Availability	(0, 0, 0.077)	(0.231,0.308,0.308)	(0.154,0.231,0.308)	(0.231,0.308,0308)
Affordability	(0, 0.077, 0.154)	(0,0,0.077)	(0.231,0.308,0.308)	(0.231,0.308,0.308)
Acceptability	(0.077, 0.154, 0.231)	(0.077, 0.154, 0.231)	(0, 0, 0.077)	(0, 0.077, 0.154)
Accessibility	(0.154, 0.231, 0.308)	(0.154, 0.231, 0.308)	(0, 0, 0.077)	(0, 0, 0.077)

Table 9
Total-relation fuzzy matrix for energy security dimensions.

	Availability	Affordability	Acceptability	Accessibility
Availability	(0.067, 0.260, 1.175)	(0.314, 0.602, 1.558)	(0.237, 0.476, 1.367)	(0.319, 0.609, 1.472)
Affordability	(0.060, 0.289, 1.091)	(0.074, 0.279, 1.175)	(0.257, 0.460 1.196)	(0.262, 0.518, 1.288)
Acceptability	(0.087, 0.266, 1.012)	(0.107, 0.323, 1.157)	(0.038, 0.161, 0.893)	(0.045, 0.270, 1.038)
Accessibility	(0.173, 0.357, 1.173)	(0.213, 0.434, 1.341)	(0.076, 0.216, 1.012)	(0.089, 0.260, 1.090)

Table 10
Final results of DEMATEL analysis for energy security dimensions.

	$\tilde{R}_i$	$\tilde{C}_i$	$\tilde{R}_i + \tilde{C}_i$	$\tilde{R}_i - \tilde{C}_i$	$R_i + C_i$	$R_i - C_i$
Availability	(0.936,1.947,5.572)	(0.387,1.172,4.452)	(1.323,3.119,10.024)	(−3.516,0.775,5.185)	4.145	0.724
Affordability	(0.653,1.546,4.751)	(0.708,1.637,5.231)	(1.360,3.183,9.981)	(−4.578,−0.092,4.043)	4.185	−0.087
Acceptability	(0.276,1.019,4.100)	(0.607,1.313,4.468)	(0.884,2.332,8.568)	(−4.192,−0.293,3.493)	3.351	−0.237
Accessibility	(0.552,1.268,4.616)	(0.714,1.658,4.889)	(1.266,2.925,9.505)	(−4.337,−0.390,3.902)	3.937	−0.244

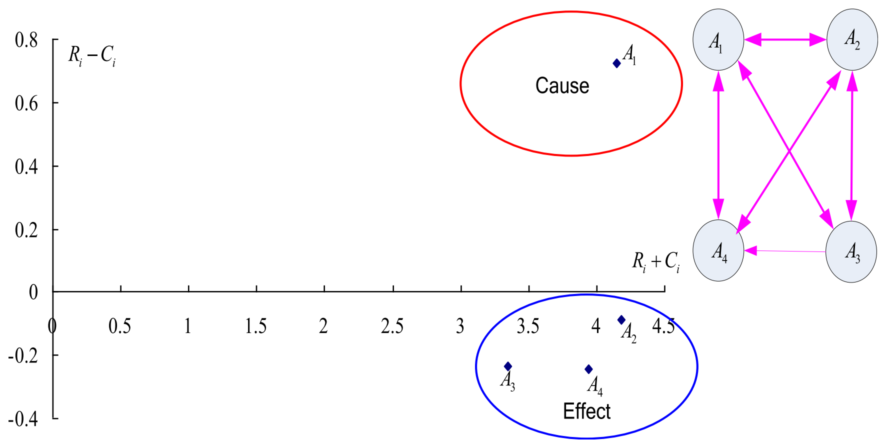

Fig. 2. Cause-effect relationship diagram for energy security dimensions.

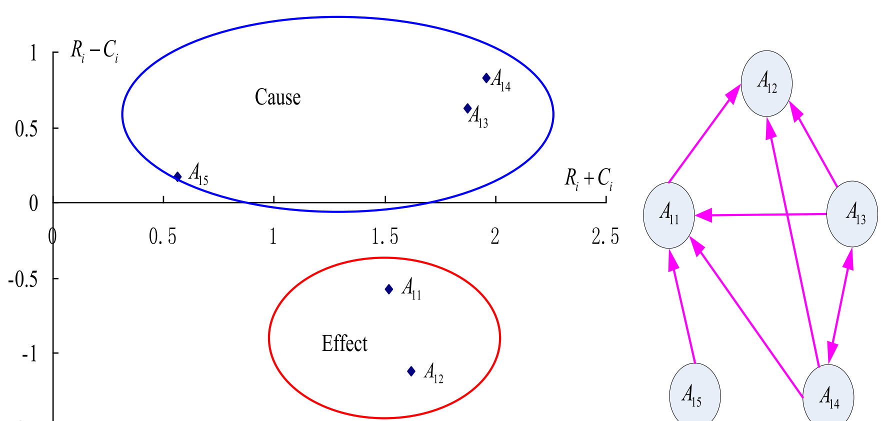

Fig. 3. Cause-effect relationship diagram for metrics related to availability.

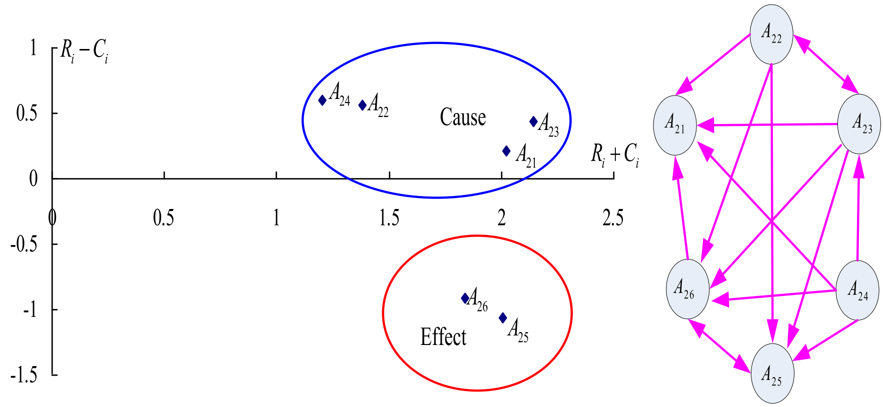

Fig. 4. Cause-effect relationship diagram for metrics related to affordability.

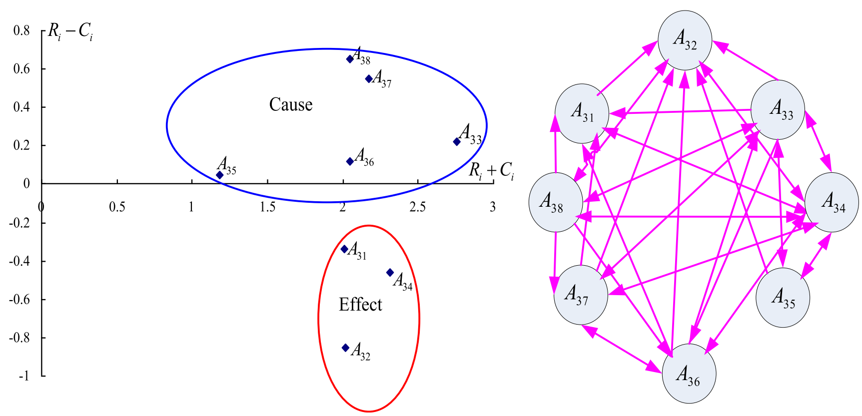

Fig. 5. Cause-effect relationship diagram for metrics related to acceptability.

alternative energy scenarios [61,62], and to seek more international cooperation to develop energy resources overseas [63,64].

In order to improve availability dimension of China's energy security, two significantly effective actions can be adopted according to the results of this study. Firstly, increase the fraction of renewable energy in total primary energy supply: the fraction of renewable energy reached only 250 million tce (tons of coal equivalent) accounting to appropriate 9% of China's total primary energy supply in 2008 [65]. Hydropower occupies most of this fraction, and the other potential energy resources such as solar power, biomass and wind power have not been commercialized in large scale.

Secondly, diversify energy sources. China's energy structure is coal-based, and coal provides around 70% of the total primary energy consumption, and it is estimated that China's exploitable reserves of coal are only about 45 years [66,67]. Oil is ranked after coal accounting to around 10% of the total primary energy consumption [67], but it is mostly imported from overseas. Thus, the diversification of energy sources can decrease the risk of future shortages of coal and oil. This diversification can even be within particular

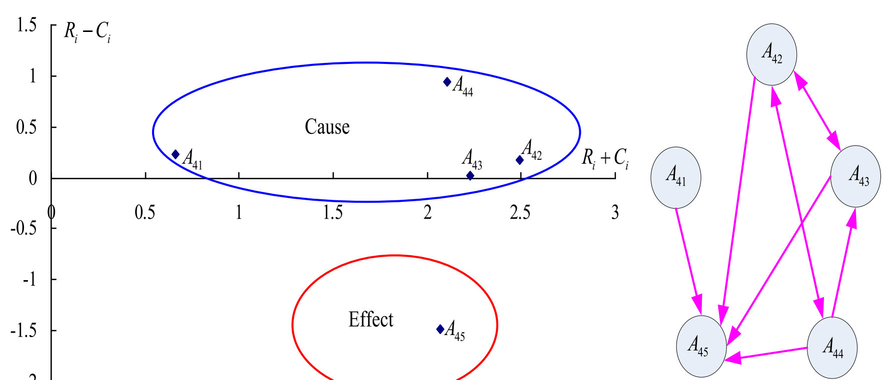

Fig. 6. Cause-effect relationship diagram for metrics related to accessibility.

energy sources, such as importing oil from diverse countries and the diversity in transport modes for oil transportation [68].

As to the affordability dimension, our Fuzzy DEMATEL analysis concluded that market liquidity and price stability are the most important drivers. These aspects of energy security can be improved in China by eliminating monopolies and promoting energy price reform [69], and formulating strategic, proactive plans to respond to rapidly changing prices [69]. Decentralization, such as developing smaller scales of power and distributed generation, can also enhance the affordability dimension among rural households or industrial enterprises susceptible to interruptions in energy supply.

As to the acceptability dimension, we concluded with our Fuzzy DEMATEL analysis that governance was the most significant factor for enhancing energy security. In this regard, lowering energy consumption and promoting energy efficiency, and enlarging the investment towards the R&D of new energy technologies, which in China fall under the jurisdiction of the government, are the top priorities to be implemented. These measures can benefit environmental protection concerning energy use, improve social satisfaction, and increase China's international reputation. It follows that regulations such as 'The Twelfth Five-Year Plan' and Renewable Energy Law in China should be continued and scaled up.

Our Fuzzy DEMATEL analysis determined that geopolitics is the most influential driver for the accessibility dimension. In this vein, the Strait of Malacca as a single chokepoint on which China has little sway affords about three quarters (77%) of China's oil imports [69]. Thus, the appropriate management of geopolitics is a prerequisite to guarantee the accessibility of China's energy security. As a consequence, China should find ways, politically or militarily, to guarantee the safety of crude transportation by the Strait of Malacca. Moreover, China should work to minimize its dependence for oil from unstable regions with political unrest such as Middle East and Africa, and perhaps pay more attention to regions without civil unrest such as Canada and South America [68].

5. Conclusion and policy implications

According to our results, some recommendations and policy implications emerge. First, from a theoretical and macroscopic point of view, the four energy security "As" of availability, affordability, acceptability, and accessibility are not of equivalent importance. Availability and affordability are clearly more salient and influential at impacting other elements of energy security (i.e., our 24 distinct metrics) than the dimensions of acceptability and accessibility. This implies that countries around the world may need to consider investing more on cultivating domestic energy resources and making energy affordable. Meanwhile, more attention should be paid to the tradeoff between of availability and affordability, as sometimes there are conflicts between these two most influential dimensions. For instance, the development of renewable energy resources is beneficial to improve 'availability' but it may also simultaneously lower 'affordability'. Moreover, the harmonious development of the four dimensions of energy security is also quite important as they are not independent but interrelated [70].

Second, from a practical point of view, our analysis emphasizes the value of renewable energy and diversification as compelling national energy security strategies. Increasing the fraction of renewable energy in total primary energy supply positively influences numerous other metrics of energy security and diversification. It is beneficial in decreasing a suite of energy security risks including import dependency, reliance on volatile energy exporter, greenhouse gas emissions, and social satisfaction. Diversification of supply, both between energy systems (diversifying from coal to coal, natural gas, wind, and solar) or within energy systems (diversifying oil imports from Sudan to the Sudan, Canada, and Venezuela), can also hedge against future threats to availability Similarly, our analysis suggests that in the dimension of affordability market liquidity and price stability are prerequisites for achieving many of the other elements of affordability such as equity and electrification. In addition, strong national governance is seen as the most important catalyst for achieving acceptability and trade is the most salient metric for enabling accessibility.

As such, national energy strategies may need reconfigured to treat energy security metrics and dimensions not as equal partners that exist in a matrix, but as unequal elements that exist in a hierarchy. Not all energy security metrics and dimensions are created equal, and the metrics of energy security are also classified into 'cause' and 'effect' groups. Moreover, different stakeholders may hold different views on the relationships among the metrics of energy security, and the exploration of various opinions through the process of Fuzzy DEMATEL are quite beneficial for incorporating the preferences and willingness of different stakeholders. What results is a view of energy security that is complex and almost constantly shifting, but one that is also more accurate and responsive to energy security realities.

Appendix A

As readers of this journal may already know, fuzzy numbers are a fuzzy subset of real numbers, representing the expansion of the idea of the confidence interval. A fuzzy set $\tilde{a}$ is in a universe of discourse X characterized by a membership function $\mu_{\tilde{a}}(x)$ which associates with each element x in X, a real number in the interval [0,1]. The function value represents the grade of membership of x in$\tilde{a}$. The triangular fuzzy number is usually used in fuzzy study, and $\tilde{a}$ can be defined by a triplet (a^L, a^M, a^U). The concept of triangular fuzzy number [71,72] could be formulated by Eq. (1).

$$\mu_{\tilde{a}}(x) = \begin{cases} 0 & x \le a^L \\ \dfrac{x - a^L}{a^M - a^L} & a^L < x \le a^M \\ \dfrac{x - a^U}{a^M - a^U} & a^M < x \le a^U \\ 0 & x > a^U \end{cases} \tag{A.1}$$

The operational laws of two triangular fuzzy numbers [73–75], $\tilde{a} = (a^L, a^M, a^U)$ and. $\tilde{b} = (b^L, b^M, b^U)$

$$\tilde{a} + \tilde{b} = \left(a^L, a^M, a^U\right) + \left(b^L, b^M, b^U\right) = \left(a^L + b^L, a^M + b^M, a^U + b^U\right) \tag{A.2}$$

$$\tilde{a} - \tilde{b} = \left(a^L, a^M, a^U\right) - \left(b^L, b^M, b^U\right) = \left(a^L - b^U, a^M - b^M, a^U - b^L\right) \tag{A.3}$$

$$\tilde{a} \times \tilde{b} = \left(a^L, a^M, a^U\right) \times \left(b^L, b^M, b^U\right) = \left(a^L \cdot b^L, a^M \cdot b^M, a^U \cdot b^U\right) \tag{A.4}$$

$$\tilde{a} / \tilde{b} = \left(a^L, a^M, a^U\right) / \left(b^L, b^M, b^U\right) = \left(a^L / b^U, a^M / b^M, a^U / b^L\right) \tag{A.5}$$

$$k\tilde{a} = k \times \left(a^L, a^M, a^U\right) = \left(ka^L, ka^M, ka^U\right) \tag{A.6}$$

$$(\tilde{a})^{-1} = \left(1/a^U, 1/a^M, 1/a^L\right) \tag{A.7}$$

where k, a^L, a^M, a^U, b^L, b^M, and b^U are real numbers.

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