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

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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