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Dimensions, Components and Metrics of Energy Security: Review and Synthesis

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Abstract

Size, technological scale and monetary investment have kept energy connected to geopolitical contention. With the shale revolution putting peak oil concerns aside and the global rearrangement of energy consumer and producer roles, the emergence of China and India have focused attention on energy security. This paper reviews tens of dimensions, components and metrics that may be used to define energy security, and the methods that may be used to calculate an energy security index. The 4As (availability, affordability, accessibility and acceptability), the five Ss (surety, survivability, supply, sufficiency and sustainability) and other similar approaches are discussed with corresponding metrics. A concise and inclusive novel energy security index is synthesized, with seven non-overlapping dimensions: physical availability, technology development, economic affordability, social accessibility, governance, unconventional threats, and natural environment. Since the dimensions of an energy security index are not perceived as having equal importance by different economic actors or the research literature, a small group of energy, economics, technology, geopolitics and environment experts was asked to rate their importance of the seven dimensions of the proposed index. Physical availability was rated as the most important, and natural environment as the least important dimension. In forthcoming research, this energy security index will be combined with the appropriate qualitative methods to reframe geopolitical problems.

Keywords: energy security, energy security index, expert interviews, geopolitics.
JEL Classification: Q34, Q35.

1. Introduction

Energy has been crucial for economic development throughout human history, the *"precondition of all commodities, a basic factor equal with air, water, and earth"* (E. F. Schumacher, Nobel laureate economist, 1977). Yet, energy is an ill-distributed economic good, subject to price fluctuations, with repercussions in many domains of life. Because of its size, technological scale and monetary investment, energy has always been entwined with geopolitics, and intricately connected to governments and political contention.

Energy may be regarded as a geopolitical tool to pursue state goals, adding an element of hard power with overlapping military, political and economic dimensions (Morgenthau, 1985; Klare, 2008). The ability of a country to access the energy resources that it needs to maintain the current level of its national power without compromising its foreign policy, economic, social and environmental objectives, is referred to as energy security. Energy security is paramount to human security (Sovacool and Mukherjee, 2011) and has become an increasingly popular concept for policy makers, academics and entrepreneurs. The attention has been caused by the emergence of new giants of the world economy and their rising energy demand. Energy security challenges relate to satisfying the energy demand of developing nations with rapidly rising income such as China and India. At the same time, peak oil concerns are not as relevant as they were before the shale revolution (Crooks, 2015), and there is more confidence about the physical availability of oil.

Yet, defining energy security more concretely brings to mind the parable of the three blind men and the elephant (Narula and Reddy, 2015). One may be lost in a multitude of dimensions, components and metrics. There is no universal definition of energy security (Kruyt et al., 2009; APERC, 2007), which Chester (2010) has aptly described as *"slippery"* and *"polysemic"*. As a result, energy security has become an umbrella term for different policy goals (Winzer 2012).

This paper reviews the research literature that proposes specific dimensions, components, metrics and methods that may be used to calculate a numerical index for energy security. Then, it synthesizes a concrete definition of energy security with the assistance of a small group of experts. A geopolitical perspective is adopted. In an assessment of energy security of 18 countries from 1990 to 2010, Sovacool (2013), a world-class expert in the field, identified a number of shortcomings of energy security index studies, among which ignoring geopolitical relationships. This is a particularly exciting time to study the geopolitics of energy security: the global energy landscape is in the middle of a game-changing revolution in source rock resources; consumer countries have turned into producers; producer countries have turned into consumers; and the volatility of oil prices has skyrocketed in response to events that are difficult to predict in a multipolar world.

The rest of this paper is structured as follows: Section 2 reviews literature dimensions and components of energy security; Section 3 reviews literature metrics and methods for measuring energy security; Section 4 formulates an energy security index with dimensions assessed by experts. The paper is rounded up with a short discussion and conclusions contained in Section 5.

2. Dimensions and components of energy security

As pointed out by Cherp and Jewell (2014), a classic definition of energy security has been provided by Yergin (1988), who visualized energy security as the assurance of *"adequate, reliable supplies of energy at reasonable prices"*, adding a geopolitical component by qualifying that this assurance must be provided *"in ways that do not jeopardize national values or objectives"*.

Energy security means different things to different countries, depending on: their geographical location; their natural resource endowment; their economic disposition (Luft and Korin, 2009); their status as producer/exporter, consumer/importer or transit (Johansson 2013), their vulnerability to energy supply disruptions; their political system; their ideological views and perceptions (Marquina, 2008); and the status of their international relations, e.g. reliance on Russian gas depends on historical experiences during the Cold War (Leonard and Popescu, 2007, as cited by Johansson, 2013). Examined over different historical time frames, the concept of energy security is dynamic and fluid, with evolving energy policy challenges (Manson et al., 2014; Winzer, 2012).

So, how may energy security be defined and measured in a concrete form? Energy security is composed of a small number of dimensions; each dimension contains components; and each component may be measured by metrics, i.e. quantitative or qualitative indicators. When all metrics, components and dimensions are aggregated, an energy security index is obtained. To measure energy security, its dimensions, components and metrics must be defined and quantified based on available data.

Dimensions and components may be combined in numerous ways. In a paper evaluating the energy security in the Asia Pacific, Sovacool (2011) reported that were at least 45 different definitions of energy security that shared a great deal of similarity, and led to difficulties in terms of the operationality of the concept. Ang et al. (2015) identified 83 energy security definitions in the literature. Some of the most eminent will now be reviewed.

In an extension to the original International Energy Agency (IEA) definition of energy security, the Asia Pacific Energy Research Centre (APERC, 2007) highlighted the so-called four As of energy security: (1) availability of the supply of energy resources; (2) affordability of the price of energy resources so that economic performance is not affected adversely; (3) accessibility to all social actors; and (4) acceptability from a sustainability standpoint. The first two As (availability and affordability) constitute the classic approach to energy security (20th century), while the latter two (accessibility and acceptability) reflect certain contemporary concerns (21st century) e.g. fuel poverty and global climate change. Other definitions of energy security also use the term availability to imply stable and uninterrupted supply of energy (IEA, 2007; EC, 2000; Yergin, 2006), while some authors use the term reliability to refer to the role of energy infrastructure (Jun et al., 2009; WEC, 2016). As for accessibility, it has been at the center of energy security debates and policy approaches into the 21st century (Kopp, 2014). Cherp and Jewell (2014) compared the four As to the five As of access to health care (availability, accessibility, accommodation, affordability and acceptability).

The four-A definition may be enhanced or expanded. For instance, it may be argued that different energy sources relate to the dimensions of energy security differently, e.g. with oil, physical and economic availability may be its preeminent aspect, while with shale oil and gas, environmental acceptability may be an important concern. Furthermore, in a paper entitled *"The uniqueness of the energy security, justice and governance problem"*, Goldthau and Sovacool (2011) talked about the following three key energy challenges: energy security, energy justice, and a low carbon transition, highlighting the need to consider energy security as a democracy issue, equity as an important aspect of accessibility, and global climate change as an important aspect of acceptability. In a final example, in a 2013 speech in Yale University, Daniel Yergin has argued (Yale University, 2013) that there are three new dimensions of energy security: (1) physical security in respect to threats like terrorism; (2) integrated energy shocks caused by natural disasters such as hurricanes and superstorms, in which electric power, fuel, emergency services, etc. are all down at the same time and entire regions are immobilized; and (3) cyberthreats that can affect large scale production and create global havoc.

A similar set of four dimensions of energy security has been proposed by Sovacool and Rafey (2011): (1) availability, i.e. diversifying fuels, preparing for disruption recovery, and minimizing dependence on foreign supplies; (2) affordability, i.e. providing affordable energy services, and minimizing price volatility; (3) efficiency and development, i.e. improving energy efficiency, altering consumer attitudes, and developing energy infrastructure; and (4) environmental and social stewardship, i.e. protecting the natural environment, communities and future generations.

Alhajji (2007) differentiated between six dimensions of energy security: economic, environmental, social, foreign policy, technical and security. Vivoda (2010) listed seven salient energy security dimensions: environment, technology, demand side management, socio-cultural or political factors, human security, international elements like geopolitics, and the formulation of energy security policy; and 44 attributes of energy security.

In a paper examining hydrogen energy systems, Ren et al. (2014) considered five dimensions of energy security: (1) availability, which referred to geological reserves for hydrogen production; (2) accessibility, referring to government support; (3) affordability, which referred to the cost of hydrogen production; (4) acceptability, which referred to environmental impacts; and (5) applicability, which was about technological maturity.

In a paper surveying the attitudes of energy consumers towards energy security, Knox-Hayes et al. (2013) extracted the following dimensions of energy security: (1) availability, indicating security of supply and affordability; (2) welfare, indicating equity and environmental quality; (3) efficiency, representing various factors including low energy intensity and small-scale energy (with some overlap with welfare); (4) affordability, indicating (among other factors) price affordability and small-scale energy; (5) environment, appearing to be very similar to welfare; (6) transparency, standing for equity, transparency and education; (7) climate, connected to global climate change and having significant overlap with welfare and environment; and (8) equity, overlapping with other dimensions.

In a paper examining the role of coal in energy security, Sovacool et al. (2011) considered the following four criteria, which correspond to dimensions of energy security: (1) availability, i.e. fuel diversification and reduced dependence on foreign supplies; (2) affordability, i.e. affordable energy services and reduced price volatility; (3) efficiency, i.e. innovation, performance of energy equipment, and consumer behavior; and (4) stewardship, i.e. social and environmental sustainability.

In a paper assessing five different energy security policy packages, Sovacool and Saunders (2014) discussed the complexity of energy security by citing Drexel Kleber, the Director of the Strategic Operations Power Surety Task Force of the US Department of Defense, who argued that energy security is an amalgamation of the following five Ss: (1) surety, i.e. certainty of access to energy and fuel sources; (2) survivability, i.e. resilience and durability against potential damage; (3) supply, i.e. physical availability of energy resources; (4) sufficiency, i.e. adequacy of supply from various sources; and (5) sustainability, i.e. prolongation of supply with mitigation of environmental impacts. The authors conceptualized energy security as having the following dimensions: (1) availability of energy fuels and services, which they call the bedrock of energy security; (2) affordability, i.e. stable and affordable costs for current and future generations (encompassing a sense of sustainability also included in the fourth component); (3) safety and technological resilience; (4) environmental, social and economic sustainability; and (5) governance, i.e. quality, transparency and accountability. Finally, the authors explored five energy security policy packages, targeting: (1) oil self-sufficiency, i.e. lessening dependence on foreign fuels; (2) energy affordability, i.e. maintaining cheap prices; (3) energy access, i.e. providing universal access to grids and services for heating and cooking; (4) climate change mitigation by reducing greenhouse gas emissions and lowering the carbon footprint of the energy sector;

and (5) water availability, i.e. promoting forms of energy production that can operate in areas of water stress and scarcity.

In a paper on the energy security in Asia Pacific, Sovacool (2011) presented the following dimensions of energy security identified by experts: availability, i.e. self-sufficiency; dependency, i.e. being energy independent; diversification, referring to variety and disparity; decentralization, i.e. small-scale energy; innovation, i.e. research and development; investment and employment; trade, encompassing geopolitics and interconnectedness; production, i.e. economic growth, reliability; price stability, including predictability; affordability, i.e. low cost, competition, subsidization, profitability; governance, including the concepts of transparency, accountability, legitimacy as well as resource curse; access, i.e. equity and energy poverty; reliability, i.e. safety; literacy, referring to education and quality of knowledge; resilience, i.e. stockpiling and adaptation; land use management; water quality and availability; ambient and indoor pollution and human health; energy efficiency, including conservation; and mitigation of greenhouse gas emissions. Regarding energy independence, self-sufficiency may be a more pragmatic target since even a producer/exporter country cannot really extricate itself from the global energy markets and their vulnerabilities (Zhao, 2019).

In a paper synthesizing a framework for energy security, Sovacool and Mukherjee (2011) presented the following dimensions with corresponding components: (1) availability, i.e. security of supply and production, dependency and diversification; (2) affordability, i.e. price stability, access and equity, decentralization and affordability; (3) technology development and efficiency, i.e. innovation and research, safety and reliability, resilience and adaptive capacity, efficiency and energy intensity, and investment and employment; (4) environmental and social sustainability, i.e. land use, water, climate change, and pollution; and (5) regulation and governance, i.e. governance, trade and regional interconnectivity, competition and markets, and knowledge and access to information. These authors also presented a comprehensive list of simple, intermediate and complex indicators of different aspects of energy security.

In the aforementioned paper assessing the energy security performance of 18 countries in Asia Pacific from 1990 to 2010 (Sovacool, 2013), the following dimensions and components were listed (with some metrics mentioned): (1) availability, with the components of security of supply, production, dependency and diversification; (2) affordability, with the components of stability, access, equity and affordability; (3) technology development and efficiency, with the components of innovation and research, energy efficiency, safety and reliability, and resilience; (4) environmental sustainability, with the components of land use, water, climate change, and pollution; and (5) regulation and governance, with the components of governance, trade and connectivity, competition, and information. Furthermore, the following shortcomings of energy security index studies were identified: (a) topical focus, either on industrial countries of the EU, OECD and North America or geared towards sustainable development and energy poverty; (b) scope and coverage, with many index studies being sector specific (e.g. electricity, oil, fossil fuels), ignoring geopolitical considerations, and using unbalanced or limited metrics; (c) transparency, i.e. hiding underlying assumptions, dynamics and weights, so that indexes play the role of *"Trojan horses … dressed a certain way to get inside the gates of energy policymaking."*; and (d) continuity, i.e. being snapshots rather than covering a number of years.

3. Metrics of energy security

Having discussed the dimensions and components of energy security, this section turns attention to specific metrics and methods proposed by the literature.

There is a multitude of energy security indicators: Sovacool and Mukherjee (2011) assembled 320 simple indicators and 52 complex indexes of energy security. Sovacool and Brown (2009) considered energy security to be defined according to the following criteria (i.e. dimensions), which may be measured with corresponding metrics:

1. *Availability*, measured by: oil and natural gas import dependence; availability of alternative fuels.
2. *Affordability,* measured by: retail electricity, gasoline and petrol prices.
3. *Energy and economic efficiency,* measured by: energy intensity; electricity use per capita; average fuel economy of passenger vehicles.
4. *Environmental stewardship,* measured by sulfur dioxide (SO_2) and carbon dioxide (CO_2) emissions.

In a paper evaluating the energy security performance of eighteen countries from 1990 to 2010, Sovacool et al. (2011) presented a more detailed list of dimensions, components and corresponding metrics:

1. *Availability*, having the following components and corresponding metrics: security of supply, measured by the total primary energy supply per capita; production, measured by the average reserve to production years ratio for coal, natural gas and oil; dependency, measured by self-sufficiency of domestic production; and diversification, measured by the share of renewable energy in the total primary energy supply.
2. *Affordability,* with the following components and metrics: stability, measured by the percentage change of electricity prices; access, measured by the population electrification percentage; equity, measured by the percentage of population relying on traditional solid fuels; and affordability, measured by the retail price of gasoline (adjusted for Purchasing Power Parity).
3. *Technology development and efficiency,* with the following components and metrics: innovation and research, measured by the research intensity (expressed as the percentage of government expenditures on research and development compared to all expenditures); energy efficiency, measured by energy intensity (i.e. energy consumption per GDP); safety and reliability, measured by grid efficiency (i.e. transmission and distribution losses); and resilience, measured by the years of energy reserves left.
4. *Environmental sustainability*, with the following components and metrics: land use, measured by the percentage of forest cover; water, measured by the percentage of population with access to improved water; climate change, measured by CO_2 emissions per capita; and pollution, measured by SO_2 emissions per capita.
5. *Regulation and governance*, with the following components and metrics: governance, measured by a worldwide governance rating; trade and connectivity, measured by energy exports; competition, measured by energy subsidies per capita; and information, measured by the percent completeness of energy data.

An even more detailed definition of energy security involved the following dimensions, components and corresponding metrics (Ren and Sovacool, 2014):

1. *Availability*, measured by: security of supply, equal to $\frac{\text{total production energy}}{\text{total consumed energy}}$; self-sufficiency, equal to $\frac{\text{imported energy}}{\text{total consumed energy}}$; diversification, measured by a diversity index such as the Shannon-Wiener; renewable energy, equal to $\frac{\text{renewable energy}}{\text{total consumed energy}}$; and technological maturity, a qualitative metric.
2. *Affordability*, measured by: price stability, equal to the deviations of price about a global mean value; dependency, equal to $\frac{\text{total imported energy}}{\text{population}}$; market liquidity, a qualitative metric; decentralization, equal to $\frac{\text{total energy by distributed and small scale generation}}{\text{total energy production}}$; electrification, equal to the percentage of population with reliable access to grid; and equity, equal to the percentage of households depending on wood, straw, etc. for cooking and heating.
3. *Acceptability*, measured by the following qualitative metrics: environment, a composite of several "*micro aspects*" that are "*measured individually*"; social satisfaction, national governance, international governance, transparency, and investment and employment.
4. *Accessibility*, measured by the following qualitative metrics: import stability, trade, political stability, military power, and safety and reliability, all qualitative metrics.

How are metrics, components and dimensions aggregated to form an energy security index? A simple way of aggregating 10 indicators into an easy-to-compute energy security index was described by Brown et al. (2014). Relying on the dimensions, components and metrics of Sovacool and Brown (2009), the following 10 variables were converted to z-scores and added with signs determined by their impact on energy security: oil import dependence (%), petroleum transport fuels (%), natural gas import dependence (%), real electricity retail prices (US cents/kWh), real gasoline prices ($/liter), on-road fuel intensity (gallons per mile), energy per GDP intensity (tBTU/2005 US$ GDP), electricity use (kWh per capita), SO_2 emissions (million tons) and CO_2 emissions (million tons). Thus, values for a simple energy security index were obtained for 1970 and 2010

There are more sophisticated methods of aggregating values, so that metrics (and thus components) may carry different weights. As an example, Radovanović et al. (2018) aggregated the following indicators using Principal Component Analysis (PCA): energy intensity; energy dependence; GDP per capita; final energy consumption per capita; carbon intensity; electricity prices; electricity consumption per capita; production of energy from renewable sources; and sovereign credit rating. Eurostat and Fitch ratings data were used for the values of these metrics. Such an approach relies on numerical criteria for estimating the weights of the metrics, but excludes, e.g. the subjective judgment of an expert. In the opinion of this author, this is (in part) why Sovacool has very wisely relied on expert interviews and surveys in some of his published research (Sovacool, 2009; Sovacool, 2011; Sovacool and Tambo, 2016; Zhang et al., 2017).

4. Synthesizing a novel energy security index

This section proposes a novel energy security index with seven dimensions (Section 4.1), and presents the ratings of the overall importance of these dimensions by a small panel of experts (Section 4.2).

4.1. Formulating the energy security index

Having reviewed the dimensions, components, metrics and methods of energy security, a meaningful, concise and inclusive novel energy security index is now synthesized. An effort was made to combine the dimensions and components that have been presented with as small overlap as possible. The following seven dimensions and components are proposed:

1. *Physical availability*, the historical bedrock of energy security (IEA, 2007; Kruyt et al., 2009; Luft and Korin, 2009; Narula and Reddy, 2015), accounting for: security of supply; self-sufficiency (encompassing oil and gas import dependence); Strategic Petroleum Reserves (SPR, acting as a buffer and a deterrent); energy diversification (including the participation of renewable energy sources in the mix).
2. *Technology development*, accounting for: (state and maturity of) infrastructure, e.g. matching of available oil to refinery infrastructure; energy (grid) efficiency (the *"fifth fuel"*); energy consumption and conservation in the building sector, transportation systems and the industry; decentralization, i.e. diffusion of small scale and prosumer systems; research (intensity), development and innovation on energy (security).
3. *Economic affordability*, perhaps the second most important energy security dimension historically, accounting for: affordability of electricity and gasoline prices (expressed in Purchasing Power Parity); stability (i.e. lack of volatility) and predictability of prices; competition, subsidization (per capita), profitability; energy intensity (i.e. electricity use per capita and monetary unit of GDP); fuel economy of passenger vehicles (also related to technology).
4. *Social accessibility*, i.e. social stewardship, accounting for: dependency (expressed as imported energy per capita); electrification, i.e. percent of the population with (reliable) access to the electricity grid; energy democracy, e.g. percent of households that are fuel poor; social equity, e.g. percent of households relying on traditional energy sources (such as wood) for cooking and heating; consumer awareness, knowledge and attitudes, e.g. towards renewable energy (Paravantis et al., 2018; Stigka et al., 2014)
5. *Governance*, taking into account: quality of governance, measured by, e.g. the Worldwide Governance Indicators (WGI) of the World Bank (https://info.worldbank.org/governance/wgi) that rate voice and accountability, political stability (which may be measured by the number of years since the previous regime change) and absence of violence, government effectiveness, regulatory quality, rule of law, and control of corruption (i.e. transparency and accountability, no crony capitalism); type of polity (democracy or otherwise); military power (possibly a qualitative variable); data quality and intelligence; good regulatory policies (e.g. avoiding overregulation, setting reasonable and objective performance criteria, avoiding picking winners and losers) and adoption of *"fit"* energy policies, i.e. catering to all societal energy tribes (Caputo, 2009; Thomson, 1987).
6. *Unconventional threats*, including asymmetric, paramilitary or nonconventional threats to energy infrastructure, such as: revolutions (e.g. Iranian revolution, Arab Spring); accidents caused by human error; durability and safety (of infrastructure, also related to technology); terrorism incidents, including cyberwarfare.

7. *Natural environment,* accounting for: (existence of) tragedy of the commons (i.e. overexploitation of resources that are public goods), resource curse (i.e. presence of abundant energy and natural resources in poor countries); (mitigation of) environmental pollution, e.g. SO_2 emissions (per capita); (mitigation of) global climate change, e.g. CO_2 emissions (per capita); forest cover; land use (management); water availability, i.e. quality and quantity, (lack) of water stress and scarcity, population access to improved water; environmental (sustainability) management; health problems caused by environmental threats, e.g. (high concentration of) toxic substances; (impacts of) black-swan type of natural disasters.

How are the different dimensions of energy security perceived by different economic actors? In his paper examining seven suppositions about energy security in the United States, Sovacool (2011) presented the following expert suppositions pertaining to energy security issues: (1) security of supply and trade; (2) energy democracy; (3) energy research; (4) energy efficiency; (5) affordability; (6) environmental pollution; and (7) climate change. Empirical research carried out by the author concluded that different dimensions of energy security are indeed perceived to be of different importance by those working in different sectors of the economy:

- The private sector considered the following four energy security dimensions to be the most important (rating over 4.5 out of a maximum of 5): (1) conducting research and development on new and innovative energy technologies; (2) providing available and clean water; (3) minimizing the destruction of forests and the degradation of land and soil; and (4) minimizing air pollution.
- Among government occupations, more (i.e. eight) dimensions were rated over 4.5, including the four of the private sector plus the following: (5) reducing greenhouse gas emissions; (6) minimizing the impact of climate change; (7) assuring equitable access to energy services to all of its citizens; and (8) informing consumers and promoting social and community education about energy issues.
- With universities, even more dimensions were rated over 4.5, including the four of the private sector plus the following: (5) reducing greenhouse gas emissions; (6) minimizing the impact of climate change; (7) informing consumers and promote social and community education about energy issues; (8) assuring equitable access to energy services to all citizens; (9) ensuring transparency and participation in energy permitting, siting, and decision making; and (10) having low energy intensity.
- The non-profit sector rated the following dimensions over 4.5: (1) providing available and clean water; (2) minimizing air pollution; (3) conducting research and development on new and innovative energy technologies; (4) minimizing the destruction of forests and the degradation of land and soil; (5) reducing greenhouse gas emissions; (6) minimizing the impact of climate change; (7) informing consumers and promoting social and community education about energy issues; (8) assuring equitable access to energy services to all citizens; (9) ensuring transparency and participation in energy permitting, siting, and decision making; and (10) having a secure supply of coal, gas, oil and/or uranium.
- Finally, those working in intergovernmental occupations rated the first two dimensions of the private sector and the following dimensions with a score over 4.5: (3) minimizing air pollution; (4) having a secure supply of coal, gas, oil and/or uranium; (5) promoting trade in energy products; technologies, and exports; (6) reducing greenhouse gas emissions; (7) informing consumers and promoting social and community education about energy

issues; (8) assuring equitable access to energy services to all citizens; and (9) having low energy intensity.

How are the dimensions of energy security covered by the research literature? In a paper examining 40 years of energy security trends, Brown et al. (2014) found that 91 peer-reviewed academic articles covered the dimensions of energy security differently. In particular, availability was covered by 82% of the examined articles; affordability by 51% of the articles; energy and economic efficiency by 34% of the articles; and environmental stewardship by 26% of the articles. As to the precise nature of these dimensions of energy security, a Factor Analysis carried out by the authors concluded that: availability was mostly a function of oil import dependence, on road fuel intensity, and natural gas import dependence (in decreasing order of importance); affordability was a function of electricity and gasoline retail prices; energy and economic efficiency was a function of electricity use per capita, and energy per GDP intensity; and environmental stewardship was a function of CO_2 and SO_2 emissions.

4.2 Assessing the importance of the dimensions of the energy security index

To get an idea about the relative importance of the seven dimension of energy security proposed in this paper, it was decided that expert interviews be used, a method used by Benjamin Sovacool, the eminent energy security scholar (Sovacool, 2009; Sovacool, 2011). A small group of engineering, economic and geopolitical energy experts was selected, including junior and senior academic faculty (with experience in energy, environment, transportation and geopolitics) and senior professionals (with experience in environment and water management). The interviews contained a brief semi-structured part (the results of which are reported here) and a longer structured part (which is not reported here). During the semi-structured part, the experts were (1) asked to rate the importance of the seven dimensions of energy security, and (2) give their opinion on the way the dimensions were defined. Input received during this phase was used to improve the scope of the dimensions and clarify the definitions.

Ratings were on a scale from one to 10. The author included his own ratings in the group, deciding that little personal bias could be introduced in the framework of a semi-structured interview (Pezalla et al., 2015). The expert's average ratings of the importance of each energy security dimension is shown in Figure 1. Physical availability was deemed to be the most important dimension (in accordance with its extensive coverage in the research literature), receiving an average rating of 8.8 (out of 10). Technology development, economic affordability and governance were next, with an average importance of 8. Social accessibility and unconventional threats received an average rating of 6.8. Finally, the natural environment was considered the least important dimension (in agreement with the lack of experts working in the non-profit sector), with an average rating of 5.8.

Some further interview findings are now reported:

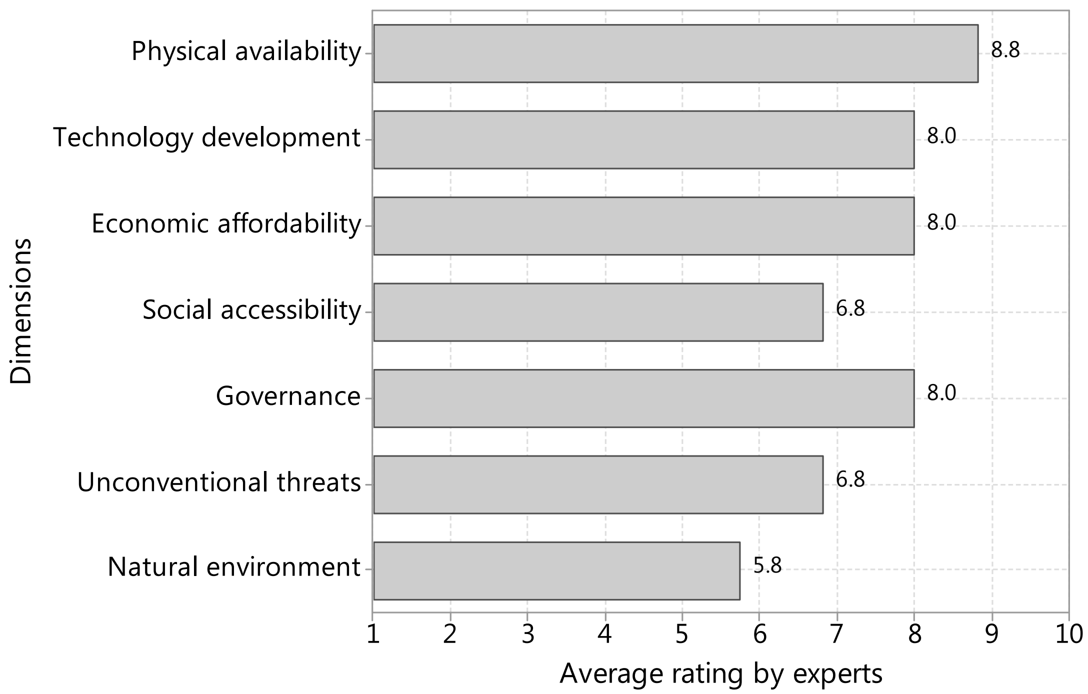
- Most experts tended to rate dimensions nearer their discipline as more important, reflecting a form of cognitive bias.
- A couple of experts thought that there was a little overlap among some of the dimensions, but could not suggest ways of overcoming it.
- An intelligence expert argued that data quality and intelligence should be a separate dimension.
- There was a debate as to whether the impact of conventional warfare should be included in one of the existing dimensions or create an additional war dimension; the author

thought that was is accounted for implicitly through its impacts in almost all dimensions, following the usual practice of the reviewed literature.

- Finally, the author's ratings compared well with those of the other experts.

These expert ratings should be interpreted with caution because they represent nothing more than an overall sense of relative importance of the dimensions of energy security. Specific countries must have prioritized energy issues differently at certain historical milestones, e.g. OPEC versus western countries during the Oil Shocks of the 1970s; or Ukraine, Russia and the European Union during the gas crises of the late 2000s. So, the relative importance of each energy security dimension in fact depends upon the historical time frame and region or country considered.

Figure 1. Average expert rating of the importance of the dimensions of energy security



5. Discussion and conclusions

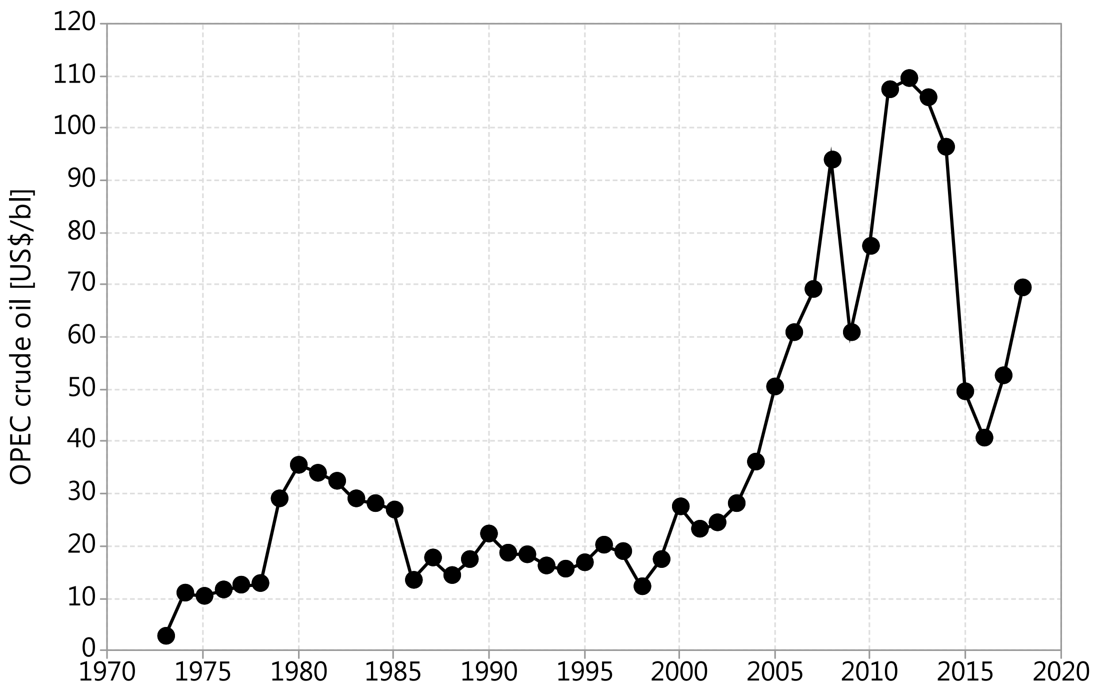
This review showed that the research literature that analyzes energy security (with the objective of measuring it) employs four to five (occasionally a few more) dimensions. Each dimension is considered to have a few components, each of which may be measured by a metric, i.e. a quantitative or qualitative indicator. The values of the metrics are then aggregated into an energy security index using simple (e.g. based on z-scores) or more involved (Principal Component Analysis or Factor Analysis) numerical and multivariate statistical techniques.

Experts asked to rate the dimensions of the energy security index proposed in this research thought that the physical availability was the most important, and the environment the least important dimension of energy security. Oftentimes, one component of the energy security may antagonize another. As an example, with the economic growth, China is facing significant urban air pollution (smog) problems; these undermine the health of the urban population and create a wave of protests by the growing middle class.

How may a quantitative energy security index be used to address geopolitical issues? As cited previously, Sovacool and Brown (2009) used their index to assess the energy security performance of 22 OECD countries from 1970 to 2007 and found out, e.g. why Denmark was the most energy secure while Spain the least energy secure of the countries examined. Such a numerical approach may indicate that a country, e.g. should reduce its energy intensity (by that many BTUs per unit of GDP) by a specific amount or improve its on-road fuel economy (by that many miles per gallon), if it is to increase its energy security by a specific percentage. This approach also enables the evaluation of the impact of events that are very infrequent or difficult to quantify, e.g. power outages or terrorist events, on the overall energy security level of an individual country or an entire region. Using an energy security index that accounts for geopolitical events allows the incorporation of geopolitical risk in energy policy, helps focus on specific sectors, and makes setting realistic policy targets more straight-forward.

This paper synthesized a novel energy security index with seven dimensions that are distinct and have minimal overlap. Nevertheless, quantitative methods are not the Holy Grail, and they should be combined with good qualitative research. An a conspicuous example, the unprecedented volatility is oil prices after 2007 shown in Figure 2 (in keeping with the geopolitical unpredictability in world affairs) was predicted by David L. Goldwyn (US Department of State's Special Envoy and Coordinator for International Energy Affairs from 2009 to 2011) in a McKinsey Executive Rountable Series in International Economics that tools place on June 21, 2007 (Council on Foreign Relations, 2007). No econometric time series or other quantitative method could have caught that.

Figure 2. OPEC crude oil price (in US$ per barel)



In forthcoming research, this energy security index (computed on historical and current energy data) will be combined with the appropriate qualitative methods (such as expert interviews) to contribute to the proper reframing of geopolitical problems.

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References

Alhajji, A. F., 2007. What Is Energy Security? Definitions and Concepts. Middle East Economic Survey, L, 45.

Ang, B. W., Choong, W. L., and Ng, T. S., 2015. Energy Security: Definitions, Dimensions and Indexes. Renewable and Sustainable Energy Reviews, 42, 1077-1093.

Asia Pacific Energy Research Center (APERC), 2007. A Quest for Energy Security in the 21st Century: Resources and Constraints. Japan: Asia Pacific Energy Research Center. Available at http://aperc.ieej.or.jp/file/2010/9/26/APERC_2007_A_Quest_for_Energy_Security.pdf [accessed: 31 May 2019].

Brown, M. A., Wang, Y., Sovacool, B. K., and D'Agostino, A. L., 2014. Forty Years of Energy Security Trends: A Comparative Assessment of 22 Industrialized Countries. Energy Research and Social Science, 4, 64-77.

Caputo, R., 2009. Hitting the Wall: A Vision of a Secure Energy Future. Synthesis Lectures on Energy and the Environment: Technology, Science and Society, Lecture #3, Morgan and Claypool Publishers.

Cherp, A., and Jewell, J., 2014. The Concept of Energy Security: Beyond the Four As. Energy Policy, 75, 415-421.

Chester, L., 2010. Conceptualising Energy Security and Making Explicit its Polysemic Nature. Energy Policy, 38, 887-895.

Council on Foreign Relations, 21 June 2007. Energy Security: What It Means and How to Achieve It [Video File]. Available at https://youtu.be/kUIqF81wZJE [accessed: 31 May 2019].

Crooks, E., 25 April 2015. The US Shale Revolution – How it Changed the World (and Why Nothing Will Ever Be the Same Again). Financial Times. Available at https://www.ft.com/content/2ded7416-e930-11e4-a71a-00144feab7de [accessed: 31 May 2019].

European Commission (EC), 2000. Towards a European Strategy for the Security of Energy Supply. Green Paper, Luxembourg: Office for Official Publications of the European Communities.

Goldthau, A., and Sovacool, B. K., 2011. The Uniqueness of the Energy Security, Justice and Governance Problem. Energy Policy, 21, 232-240.

International Energy Agency (IEA), 2007. Energy Security and Climate Policy: Assessing Interactions. Paris: IEA/OECD.

Johansson, B., 2013. A Broadened Typology on Energy and Security. Energy, 53, 199-205.

Jun, E., Kim, W., and Chang, S. H., 2009. The Analysis of Security Cost for Different Energy Sources. Applied Energy, 86(10), 1894-1901.

Klare, M., 2008. Rising Powers, Shrinking Planet, the New Geopolitics of Energy. New York: Metropolitan Books.

Knox-Hayes, J., Brown, M. A., Sovacool, B. K., and Wang, Y., 2013. Understanding Attitudes Toward Energy Security: Results of a Cross-National Survey. Global Environmental Change, 23, 609-622.

Kopp, S. D., 2014. Politics, Markets and EU Gas Supply Security. Case Studies of the UK and Germany. Berlin, Germany: Springer. Available at http://www.springer.com/gp/book/9783658083236 [accessed: 31 May 2019].

Kruyt, B., van Vuuren, D. P., de Vries H. J. M., and Groenenberg H., 2009. Indicators for Energy Security. Energy Policy, 37, 2166-81.

Leonard, M., and Popescu, N., 2007. A Power Audit of the EU-Russia Relations. London, UK: European Council on Foreign Relations.
Luft, G., and Korin, A., 2009. Energy Security: In the Eyes of the Beholder. In Energy Security Challenges for the 21st Century: A Reference Handbook, Luft, G., and Korin, A. (eds), Santa Barbara, California, USA: Praeger Security International.
Manson, A., Johansson, B., and Nilsson, L. J., 2014. Assessing Energy Security: An Overview of Commonly Used Methodologies. Energy, 73, 1-14.
Marquina, A., 2008. The Southeast–Southwest European Energy Corridor. In Energy Security: Visions from Asia and Europe, Marguina A. (ed.), UK: Palgrave Macmillan, 54-68.
Morgenthau, H., 1985. Politics among Nations: The Struggle for Power and Peace. 6th ed., New York, USA: Knopf.
Narula, K., and Reddy S., 2015. Three Blind Men and an Elephant: The Case of Energy Indices to Measure Energy Security and Energy Sustainability. Energy, 80, 148-158.
Paravantis, J. A., Stigka, E., Mihalakakou, G., Michalena, E., Hills, J. M., and Dourmas, V., 2018. Social Acceptance of Renewable Energy Projects: A Contingent Valuation Investigation in Western Greece. Renewable Energy, 123, 639-651.
Pezalla, A. E., Pettigrew, J., and Miller-Day, M., 2012. Researching the Researcher-As-Instrument: An Exercise in Interviewer Self-Reflexivity. Qualitative research, 12(2), 165–185. Available at https://www.ncbi.nlm.nih.gov/pmc/articles/PMC4539962 [accessed: 31 May 2019].
Radovanović, M, Filipović, S., and Golušin, V., 2018. Geo-Economic Approach to Energy Security Measurement – Principal Component Analysis. Renewable and Sustainable Energy Reviews, 82(P2), 1691-1700.
Ren, J., and Sovacool, B. K., 2014. Quantifying, Measuring, and Strategizing Energy Security: Determining the Most Meaningful Dimensions and Metrics. Energy, 76, 838-849.
Ren, J., Andreasen, K. P., and Sovacool, B. K., 2014. Viability of Hydrogen Pathways that Enhance Energy Security: A Comparison of China and Denmark. International Journal of Hydrogen Energy, 39, 15320-15329.
Sovacool, B. K., 2009. Energy Policy and Cooperation in Southeast Asia: The History, Challenges, and Implications of the Trans-ASEAN Gas Pipeline (TAGP) network. Energy Policy, 37, 2356-2367.
Sovacool, B. K., 2011. Evaluating Energy Security in the Asia Pacific: Towards a More Comprehensive Approach. Energy Policy, 39, 7472-7479.
Sovacool, B. K., 2011. Seven Suppositions about Energy Security in the United States. Journal of Cleaner Production, 19, 1147-1157.
Sovacool, B. K., 2013. An International Assessment of Energy Security Performance. Ecological Economics, 88, 148-158.
Sovacool, B. K., and Brown, M. A., 13 January 2009. Competing Dimensions of energy Security: An International Perspective. Working Paper #45, Working Paper Series, Ivan Allen College, School of Public Policy, Georgia Tech, Atlanta: GA.
Sovacool, B. K., and Mukherjee, I., 2011. Conceptualizing and Measuring Energy Security: A Synthesized Approach. Energy, 36, 5343-5355.
Sovacool, B. K., and Rafey, W., January/February 2011. Snakes in the Grass: The Energy Security Implications of Medupi. The Electricity Journal, 24(1), 92-100.
Sovacool, B. K., and Tambo, T., 2016. Comparing Consumer Perceptions of Energy Security, Policy, and Low-Carbon Technology: Insights from Denmark. Energy Research and Social Science, 11, 79–91.
Sovacool, B. K., Cooper, C., and Parenteau, P., 2011. From a Hard Place to a Rock: Questioning the Energy Security of a Coal-Based Economy. Energy Policy, 39, 4664-4670.
Sovacool, B. K., Mukherjee, I., Drupady I. M., and D'Agostino, A. L., 2011. Evaluating Energy Security Performance from 1990 to 2010 for Eighteen Countries. Energy, 36, 5846-5853.
Sovacool, B.K., and Saunders, H., 2014. Competing Policy Packages and the Complexity of Energy Security. Energy, 67, 641-651.
Stigka, E., Paravantis, J. A., and Mihalakakou, G. K., 2014. Social Acceptance of Renewable Energy Sources: a Review of Contingent Valuation Applications. Renewable and Sustainable Energy Reviews, 32, 100-106.

Thomson, M., 1987. Among the Energy Tribes: A Cultural Framework for the Analysis and Design of Energy Policy. Policy Sciences, 17, 321-329.
Vivoda, V., 2010. Evaluating Energy Security in the Asia-Pacific Region: A Novel Methodological Approach. Energy Policy, 38, 5258-5263.
Winzer, C., 2012. Conceptualizing Energy Security. Energy Policy, 46, 36-48.
World Energy Council (WEC), 2016. World Energy Trilemma I 2016. Defining Measures to Accelerate the Energy Transition. London, UK: WEC. Available at https://www.worldenergy.org/wp-content/uploads/2016/05/World-Energy-Trilemma_full-report_2016_web.pdf [accessed: 31 May 2019].
Yale University, 3 October 2013. The Quest: Energy, Security, and the Remaking of the Modern World [Video File]. Available at https://youtu.be/M_Y8Jy2JBf8 [accessed: 31 May 2019].
Yergin, D., 1988. Energy Security in the 1990s. Foreign Affairs, 67(1), 110-132.
Yergin, D., 2006. Ensuring Energy Security. Foreign Affairs, 85(2), 69–82.
Zhang, L., Yu, L., Sovacool, B. K., and Ren, J., 2017. Measuring Energy Security Performance within China: Toward an inter-provincial prospective. Energy, 125, 825-836.
Zhao, H., 2019. Chapter Five - Energy Security: From Energy Independence to Energy Interdependence. In H. Zhao, The Economics and Politics of China's Energy Security Transition (pp. 99-120). London, UK: Academic Press.