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Conceptualizing and measuring energy security: A synthesized approach

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ABSTRACT

This article provides a synthesized, workable framework for analyzing national energy security policies and performance. Drawn from research interviews, survey results, a focused workshop, and an extensive literature review, this article proposes that energy security ought to be comprised of five dimensions related to *availability*, *affordability*, *technology development*, *sustainability*, and *regulation*. We then break these five dimensions down into 20 components related to security of supply and production, dependency, and diversification for availability; price stability, access and equity, decentralization, and low prices for affordability; innovation and research, safety and reliability, resilience, energy efficiency, and investment for technology development; land use, water, climate change, and air pollution for sustainability; and governance, trade, competition, and knowledge for sound regulation. Further still, our synthesis lists 320 simple indicators and 52 complex indicators that policymakers and scholars can use to analyze, measure, track, and compare national performance on energy security. The article concludes by offering implications for energy policy more broadly.

1. Introduction

With energy services key to both modern economies and postmodern lifestyles, energy security is paramount to human security. Coal, oil, natural gas, and uranium are currently needed to energize our vehicles, light schools and workplaces, produce food, manufacture goods, and cool and warm our residences. The late economist E.F. Schumacher once mused that energy was "not just another commodity, but the precondition of all commodities, a basic factor equal with air, water, and earth" [1]. Yet because of its ubiquitous nature, the benefits of improved energy security are often nonrivalrous and non-excludable, similar to other public goods like national defense or clean air. As Bielecki [2] has written, "energy security is a public good which is not properly valued by the market and the benefits of which are available equally to those who pay for it and to those who do not. Consequently, the market may tend to produce a level of energy security that is less than optimal".

Thus a paradox arises: energy security is integral to modern society, yet its very ubiquity makes it prone to market failure and under-distribution. Moreover, the notions of energy security can either be so narrow that they neglect the comprehensiveness of energy challenges, or so broad that they lack precision and coherence. Trying to measure energy security by using contemporary methods in isolation – such as energy intensity or electricity consumption per capita – is akin to trying to drive a car with only a fuel gauge, or to seeing a doctor who only checks your cholesterol [3]. Though considerable effort has been dedicated by the United Nations and other multilateral groups to the development of composite indicators of transportation productivity, environmental quality, and industrial efficiency, there are no standard metrics to evaluate energy security. Or, as Vivoda recently surmised, "with increasingly global, diverse energy markets and increasingly transnational problems resulting from energy transformation and use, old energy security rationales are less salient, and other issues, including climate change and other environmental, economic and international considerations are becoming increasingly important. As a consequence, a more comprehensive operating definition of 'energy security' is necessary, along with a workable framework for analysis of energy security policy" [4].

In this article, we attempt to propose such a workable framework. Utilizing a mixed methods approach, the article suggests that energy security ought to encompass five dimensions related to *availability*, *affordability*, *technology development*, *sustainability*, and *regulation*. It breaks these five dimensions down into 20 components related to security of supply and production, dependency, and diversification for *availability*; price stability, access and equity, decentralization, and low prices for *affordability*; innovation and research, safety and reliability, resilience, energy efficiency, and investment for technology *development*; land use, water, climate change, and air pollution for *sustainability*; and governance, trade, competition, and knowledge for sound *regulation*. It then

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categorizes 320 simple indicators and 52 complex indicators that policymakers and scholars can use to analyze, measure, track, and compare national performance on energy security. The article concludes by offering implications for energy policy more broadly.

The importance of our study is twofold. First, it provides clarity and focus to the often ambiguous concept of energy security. Rather than emphasizing a fuel-based definition of energy security (such as "oil security" or "coal security"), or limiting energy security dimensions to geopolitics, or to the supply or demand side of energy, the study argues that energy security is a complex goal involving questions about how to equitably provide available, affordable, reliable, efficient, environmentally benign, properly governed and socially acceptable energy services.

Second, an impressive and growing number of studies attempting to measure and quantify energy security have surfaced in the past few years. Collectively considered, they reveal distinct areas of overlapping emphases, but also make some notable shortcomings apparent. Such literature, for example, commonly expresses the energy security concerns of industrialized countries belonging to the Organization of Economic Cooperation and Development, and centers on aspects of energy security such as electricity supply, nuclear power, and gasoline powered automobiles. They are thus not applicable to developing or least developed countries that have patchy and incomplete electricity networks, limited nuclear power units, and non-motorized forms of transport, something we address by collecting data from scholars in the developing world (predominantly through our research interviews). Furthermore, such studies often rely on only a handful of dimensions or metrics (such as per capita commercial energy consumption, share of commercial energy in total final energy use, share of population with access to electricity, and energy intensity) that are sectoral in focus, i.e. investigating *only* electricity, or energy efficiency, or household energy consumption. In response, this study synthesizes this vast literature into a condensable and usable number of dimensions and metrics looking at multiple sectors and concerns simultaneously.

2. Research methods

To better understand the concept of energy security and propose workable indicators and metrics, we relied on a four phase methodological process entailing research interviews, a survey, a focused workshop, and a review of the academic literature.

We began by conducting semi-structured research interviews with global energy security experts using a "modified Delphi method" [5,6] that involved asking key scholars a series of open ended questions. The lead author conducted 68 semi-structured research interviews over the course of February 2009 to November 2010, including visits to the International Energy Agency, U.S. Department of Energy, United Nations Environment Program, Energy Information Administration, World Bank Group, Nuclear Energy Agency, and International Atomic Energy Agency. Participants at these institutions were asked three questions:

1. Which dimensions of energy security are most important?
2. What metrics best capture these dimensions?
3. How might these metrics be used to create a common index or scorecard to measure national performance on energy security?

Responses were sometimes captured with a digital audio recorder and always transcribed before being coded manually and synthesized. To adhere to Institutional Review Board guidelines followed at the authors' university, particular responses must be listed anonymously to protect confidentiality. However, for reference purposes, Appendix 1 provides a complete list of all institutions visited. This article is the first that we know of to utilize such a qualitative method of appraising energy security, since most energy policy articles rely on quantitative methods.

To supplement qualitative research interviews that are difficult to code, a quantitative survey instrument was used, asking experts to list important energy security dimensions and metrics. In most cases these were distributed during the interviews. The lead author distributed 74 printed copies of the survey to energy experts working in 15 countries at 35 institutions in Asia, Europe, and North America. We received 70 completed surveys back (for a response rate of 95%). This unusually high response rate is largely attributed to the collegial relationship between the authors and respondents, as well as some incessant nagging. Since energy experts were purposively targeted, Fig. 1 shows that the sample of respondents does have some notable biases: almost 90 percent have a postgraduate education, most are between the ages of 36–55, respondents were predominately male, and worked in academia.

Third, a focused, intensive, three day workshop was convened in Singapore in November 2009. This workshop hosted 37 participants from 17 countries, and was centered on discussing the same three questions as the interviews. The workshop consisted of nine formal sessions – with topics ranging from energy security indicators in use at the International Institute for Applied Systems Analysis (IIASA) and the International Energy Agency (IEA), to metrics for affordability, diversification, and energy efficiency – and was structured around intensive 2 h discussions among all participants on each topic. To encourage candor the workshop was conducted under the Chatham House Rule, though Appendix 2 lists the participants.

Lastly, respondents from the interviews, survey respondents, and workshop were asked to recommend any studies or relevant academic literature published on the topic of energy security metrics and indicators in the past ten years. An independent literature review was then conducted looking for the key phrases "energy security", "security of supply", or "energy" and "security" in the titles and abstracts of articles published in *Energy Policy*, *Energy*, *Electricity Journal*, and *The Energy Journal* in the past five years. These articles were perused for those devising energy security metrics and indicators. The most relevant of these works are depicted in references [3,4,6–34].

Taken together, these efforts constitute a unique mixed methods approach unlike most other assessments of energy security which rely on individual methods in isolation. That said, the research interviews, essentially, are the "heart" of the paper. The bulk of data presented below comes from them, rather than the survey or the literature review, primarily because the amount and value of information collected from them was significant. Although the survey consisted of mostly closed ended questions, meaning responses never exceeded 4 pages in length, some of the interviews took more than 3 h, and the average interview lasted 70 min and produced seven single spaced pages of comments. The transcribed interviews (about 500 pages) also dwarfed the length, and specificity, of the literature review; the authors found about a dozen excellent peer-reviewed articles, most of which the study cites below, but these total less than 200 pages in combined length, and not every article was entirely about energy security, whereas every interview delved deeply into the specific subject matter.

The use of such a mixed methods approach has strengths and weaknesses. One strength is its ability to synthesize qualitative data "rich" in description and analytical power along with quantitative data, something only a few other studies have done so far [see [2,4] for examples]. Another strength is the incorporation of viewpoints from a broad range of stakeholders, including those in Asia and from emerging economies. However, some shortcomings to this

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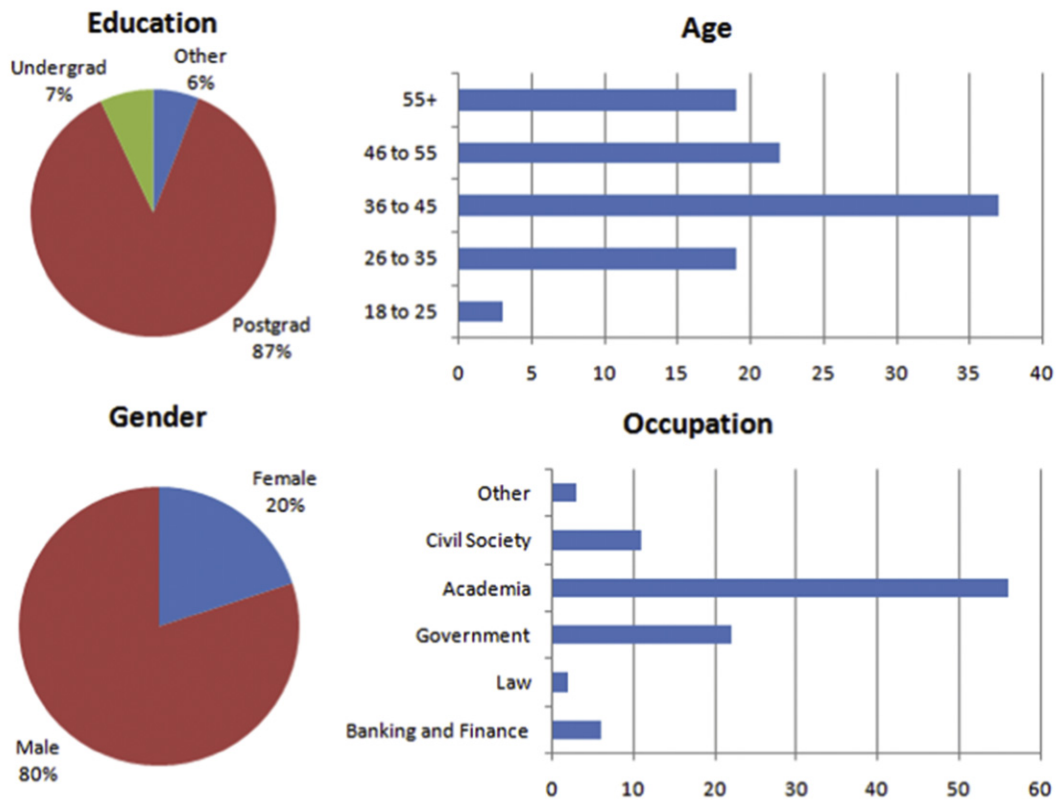

Fig. 1. Demographic details of the Energy Security Survey ($n = 70$).

approach include the somewhat subjective nature of coding qualitative data, the limited sample size of respondents and articles (the author searched only major energy studies journals with articles written in English), and the messiness of trying to find patterns in such as vast amount of data.

3. The multidimensional nature of energy security

There appears to be an expansive range of definitions of energy security in the policy and scholarly literature, with one recent review identifying 45 distinct definitions of the concept in practice [35].

Table 1
Energy security dimensions, values, and components.

Dimension	Explanation	Underlying Values	Components
Availability	Having sufficient supplies of energy. Being energy independent. Promoting a diversified collection of different energy technologies. Harnessing domestically available fuels and energy resources. Ensuring prudent reserve to production ratios	Self sufficiency, resource availability, security of supply, independence, imports, variety, balance, disparity	Security of Supply and Production Dependency Diversification
Affordability	Producing energy services at the lowest cost, having predictable prices for energy fuels and services, and enabling equitable access to energy services.	Cost, stability, predictability, equity, justice, reducing energy poverty	Price Stability Access and Equity Decentralization Affordability
Technology Development and Efficiency	Capacity to adapt and respond to the challenges from disruptions, researching and developing new and innovative energy technologies, making proper investments in infrastructure and maintenance. Delivering high quality and reliable energy services.	Investment, employment, technology development and diffusion, energy efficiency, stockholding, safety and quality	Innovation and Research Safety and Reliability Resilience Efficiency and Energy Intensity Investment and Employment
Environmental and Social Sustainability	Minimizing deforestation and land degradation, possessing sufficient quantity and suitable quality of water, minimizing ambient and indoor pollution, mitigating GHG emissions associated with climate change, adapting to climate change.	Stewardship, aesthetics, natural habitat conservation, water quality and availability, human health, climate change mitigation, climate change adaptation.	Land Use Water Climate Change Pollution
Regulation and Governance	Having stable, transparent, and participatory modes of energy policymaking, competitive markets, promoting trade of energy technology and fuels, enhancing social and community knowledge about education and energy issues	Transparency, accountability, legitimacy, integrity, stability, resource curse, geopolitics, free trade, competition, profitability, interconnectedness, security of demand, exports	Governance Trade and Regional Interconnectivity Competition and markets Knowledge and Access to Information

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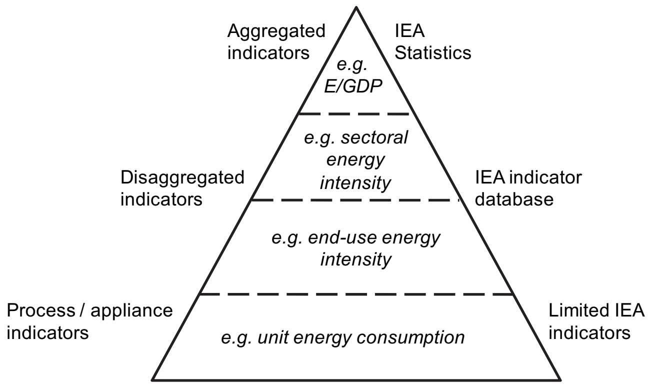

Fig. 2. The International Energy Agency "Pyramid" of Energy Indicators.

Whether it is the 'five Ss' [36], the 'four As' [37], or the 'four Rs' [38] of energy security, this multitude of definitions serves some strategic value: it enables policy actors to advance very different notions to justify their actions and policies on energy security grounds. One resulting implication is that the concept has become diffuse and often incoherent. Some authors, including those of this article, have yet to define it consistently in their own work. Or, as illustrated by one participant, "energy security is like a Rorschach inkblot test – you can see whatever you want to see in it".

Yet a holistic notion of energy security is needed in order to capture the complexity of the concept. As one respondent noted, "to focus only on energy security as revolving around coal or oil misses key relationships between fuels and also the entire spectrum of broader social, political, and economic issues that truly matter to energy users and countries". Another remarked that "an ecosystem is characterized not only by individual components, but by the interactions among all of those parts; because of this similar complexity with energy security, it is inappropriate to take a fragmented view by concentrating on an isolated piece of the system". Another commented that "any definition of energy security worth its salt needs to include at least the three prisms of poverty, economy, and environment, measuring things ranging from energy equity and access and energy intensity and industrial energy use to destruction of the environment and use of water". Put another way, the ideal of energy security is more than the sum of its parts; it is a synergistic concept that rests on multiple interconnected dimensions, akin to a complex ecosystem that is comprised of individual species *and* their interactions. Similar sentiments in favor of a broad, multidimensional definition of energy security have been advanced by [3,22,23,39,40].

Drawing predominately from the research interviews, we identify five key dimensions to energy security. *Availability* includes having sufficient energy resources, stockpiles, and fuels, as well as the appropriate infrastructure to transform these reserves into energy services. *Affordability* includes equitably enabling access to energy services at the lowest cost with stable prices. *Technology development* includes adapting to and recovering from interruptions in supply, investing in new research as well as proper maintenance, and ensuring reliability. *Sustainability* includes minimizing energy-related degradation to forests, land, water, air-sheds and the global climatic system. *Regulation* includes having legitimate and participatory modes of energy policymaking, competitive markets, and well informed energy consumers. Table 1 shows how each of these dimensions corresponds with a set of underlying values as well as twenty separate components in aggregate.

4. Towards an integrated metric framework

Summarizing the various dimensions and components of energy security is helpful in identifying major themes. However, more useful still is correlating these dimensions with usable metrics and indicators that can be utilized to assess national energy security policies and performance. Numerous studies on energy policy have noted that having comparative indicators is a prerequisite for setting energy targets as well as for evaluating future scenarios [3,10,21,30,41]. These studies have also concluded that measurement can enhance policymaking by condensing large amounts of complex data into recognizable patterns that can then enable regulators and analysts to find the best energy solutions in a menu of available options. It then becomes possible to highlight comparisons between classes of countries, elucidate best practices, and better understand how dimensions of energy security improve or worsen over time. This makes it possible for analysts and scholars to assess the interrelationship between energy security and major events such as military conflicts, environmental calamities, trade embargoes, or the introduction new transformational energy policies or technologies. Similarly, having focused metrics for energy security enables one to identify tradeoffs within the different dimensions of energy security and also highlight areas in need of improvement.

Frequently, metrics are divided into simple and complex. The IEA, for example, visually arranges energy indicators according to a pyramid depicted in Fig. 2. Aggregated indicators that form the basis of IEA statistics fall at the top, disaggregated indicators the middle, process indicators at the bottom.

Table 2
Simple, Intermediate, and Complex Indicators for Energy Security.

Aspect of Energy Security	Quantity (Simple)	Quality (Intermediate)	Context (Complex)
Energy Imports	Share of imported energy in total energy balance, or made more specific by type of fuel (e.g., oil, coal, natural gas, uranium)	Nature of energy imports (type of imported energy and mode of import)	Specific context of energy imports for particular country or community
Energy Production and Infrastructure	Diversity of primary energy supply in domestic production	Domestic energy resources, reserve-to-production ratios	Country specific energy production and infrastructure challenges
Energy Production and Infrastructure	National power generation capacity (total or per capita)	Domestic energy infrastructure investments	Mitigation readiness and capacity
Vulnerability to Disruption	Energy consumption per capita	Costs of imports versus export earnings	Sectoral vulnerability for transport, residential, industry, tertiary, agriculture
Vulnerability to Disruption	Energy intensity of GDP	GDP intensity by type of energy or sector	
Vulnerability to Disruption	Fuel Economy	Fuel economy for on-road passenger vehicles, or new vehicles	
Equity and Access to Energy Services	Percentage of households with a reliable connection to the electricity grid	Share of household income spent on energy services	GINI coefficient of energy use
Diversification	Renewable share of energy fuel mix	Diversify of primary energy supply	Hirshman and Shannon indices of diversity
Greenhouse Gas Emissions	Total greenhouse gas emissions or per capita greenhouse gas emissions	Greenhouse gas emissions by sector	Carbon dioxide intensity of specific energy carriers

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Table 3
Simple and Complex Energy Security Indicators and Metrics.

Dimension	Components	Simple Indicators and Metrics	Complex Indicators and Metrics
Availability	Security of supply and production	• Total energy reserves • Total energy reserves per capita • Proven recoverable energy reserves • Proven recoverable energy reserves per capita • Average reserve-to-production ratios for the four primary energy fuels (uranium, coal, natural gas, and oil) in remaining years • Coal reserves per capita • Oil reserves per capita • Uranium reserves per capita • Natural gas reserves per capita • Total oil reserves • Total uranium reserves • Total natural gas reserves • Total coal reserves • Total renewable energy resource endowment • Total energy supply (including imports) • Self Sufficiency (% demand met by domestic production) • Strategic fuel stock ratio • Total primary energy supply per capita • Total primary energy supply per GDP • Reserve-to-production ratio for uranium • Reserve-to-production ratio for petroleum • Reserve-to-production ratio for coal • Reserve-to-production ratio for natural gas • Average field recovery rate for oil • Average field recovery rate for natural gas • Total installed electricity generation capacity • Total electricity demand • Peak-load electricity demand • Base load electricity demand • Refining capacity (as percentage of production) • Refining capacity (volume refined per year) • Percent served by residential solar home systems • Percent served by cogeneration or CHP • Percent served by alternative transport fuels • Annual amount of coal production • Number of oil wells drilled for exploration • Number of coal mines • Growth in energy production per year • Total energy consumption per capita • Annual electricity consumption per capita	• Supply/Demand (SD) Index • Willingness to pay for security of supply
	Dependency	• Oil import dependence ratio • Coal import dependence ratio • Natural gas import dependence ratio (including liquefied natural gas) • Uranium import dependence ratio • Net electricity imports • Annual change in net electricity imports • Annual change in net fuel imports • Ratio of exports and imports to consumption • Number of international electricity interconnections • Total oil imports (barrels of oil) • Ratio of value of oil imports to GDP • Oil consumption per unit of GDP • % of imports coming from the Middle East • % of imports coming from outside the region • Annual transfers of wealth to oil producers (in USD) • Balance of payments related to energy imports	• Stability of exporting countries • Transparency International corruption rating for exporting countries • Historical relationship with exporting countries • State Fragility Index rating of exporting countries • Worldwide Governance Indicator rating of exporting countries
	Diversification	• Diversification in energy production • Diversification in total primary energy supply	• Shannon–Wiener Index • Herfindahl-Hirschman Index (HHI) Index

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Table 3 (*continued*)

Dimension	Components	Simple Indicators and Metrics	Complex Indicators and Metrics
		• Diversification in oil supply • Diversification in coal supply • Diversification in natural gas supply • Diversification of fuels for electricity • Diversification of fuels for transport • Diversification of fuels for heating and cooling • Geographic dispersion of energy facilities • Diversification of ownership of energy companies • Number of flex fuel vehicles • Number of power plants that can run on multiple fuels (e.g., co-firing of biomass and coal) • Share of nuclear energy in total primary energy supply • Share of hydroelectricity in total primary energy supply • Share of non-hydroelectric renewable resources in total primary energy supply • Share of non-carbon energy sources in energy • Rate of contractually flexible electricity demand	• Mean Variance Portfolio (MVP) Theory
Affordability	Price Stability	• End-use energy prices by fuel • End-use energy prices by sector (residential, commercial, industrial) • Regional price differences (average price in most expensive/cheapest deciles) • Electricity and petrol price volatility (annual % change) • % energy use covered by long-term contracts • Fuel price volatility • Carbon price volatility • Currency exchange rate volatility	• Price of macroeconomic shocks caused by volatility
	Access and Equity	• Percent of households with high quality connections to the electricity grid • Rate of electrification (number of new connection per year) • Percent of population reliant on charcoal, dung, and biomass for cooking • Percent of people that use mechanical power for productive, non-industrial applications, such as water pumping, agricultural mechanization, and grinding and milling • Rate of electrification expansion (annual % change) • Annual number of new electricity customers served (number of new customers served) • Revenues lost from electricity theft • Average number of household electric appliances • Vehicle ownership • Income distribution tied to energy use, lowest quintile • Average household expenditure on energy • Annual household electricity consumption (in kWh) • Average kilometers driven per private automobile per capita • % of total dwelling areas that are air conditioned • Annual sales of new air conditioners • Per capita number of televisions • Per capita number of computers • Per capita number of refrigerators • Per capita number of light bulbs • Occupancy rate of vehicles • Average income levels of automobile drivers • Presence of reliable mass transit systems • Ratio of net fuel imports to GDP	• Burden threshold variable • Energy GINI coefficient
	Decentralization	• Percent of energy needs met by distributed generation (units less than 1 MW) • Number of households served by off-grid lighting • Number of households served by micro-grids	

Table 3 (*continued*)

Dimension	Components	Simple Indicators and Metrics	Complex Indicators and Metrics
		• Average construction lead time for new energy infrastructure • % electricity generation met by combined heat and power/cogeneration • Number of installed residential solar photovoltaic systems • Installed capacity of fuel cells • Installed capacity of micro-turbines • Installed capacity of residential wind turbines • Installed capacity of biogas units	
	Affordability	• Share of household income spent on fuel and electricity • Public expenditure on subsidies as percent of GDP • Industrial energy prices • Residential energy prices • Retail gasoline prices • Price of 1 kg of fuel wood • Price of 1 kg of charcoal • Price of 1 L of kerosene • Market prices for coal • Market prices for uranium • Market prices for oil • Market prices for natural gas • Average price of residential electricity per GDP • Sales of industrial electricity per industrial GDP • Inflation caused by import fees • End-use energy retail prices by fuel and sector • Avoided cost of power generation • Marginal cost of electricity power generation • Fuel cost for electricity generation • Transmission and distribution cost for electricity • Carbon price • Wholesale price of electricity	• Ratio of daily disposable income to energy consumption • Equity of access to grid/transmission system • Household energy use for each income group and corresponding fuel mix
Technology Development and Efficiency	Innovation and Research	• Total energy research expenditures • Annual number of new energy patents • Total number of energy patents • Public research intensity (government expenditures on energy research compared to all government expenditures) • Private research intensity (private expenditures on energy research compared to all expenditures) • Research budgets for renewable sources of energy • Research budget for fusion • Research budget for advanced fission • Research budget for hydrogen • Research budget for biofuels • Overall research expenditures (public + private) as a percentage of GDP • Research consistency (% change from year to year in expenditures)	• Research intensity (% government expenditures on energy research comparedto all expenditures)
	Safety and reliability	• Frequency of electric power grid • Voltage control of electric power grid • Number of hours homes have electricity per year • Cost of interruptions • Voltage control of electric power grid • Number of major energy sector accidents and failures (defined as accidents involving at least one fatality and/or $50,000 of property damage) • Number of annual terrorist attacks and disruptions on energy infrastructure • Number of natural disasters • Number of coal mining accidents or deaths per year • Cases of pneumoconiosis (black lung disease) • Frequency of electricity blackouts or supply interruptions • Duration of electricity blackouts or supply interruptions • Annual revenues lost due to electricity blackouts or interruptions • Interruptions in electricity supply per year per customer • Hours of availability of electricity per day • Annual accident fatalities per specific fuel chain • Value of lost load for electricity	• System Average Interruption Duration Index (SAIDI) • System Average Interruption Frequency Index (SAIFI) • Customer Average Duration Index (CAIDI) • Breakdown of energy supply per energy carrier (in MJ) • Crisis Capability Index (CCI) • Average time required to restore service to the average customer per sustained interruption
	Resilience and adaptive capacity	• Gas capacity margins (maximum supply versus maximum demand) • Electricity capacity margins (maximum supply versus maximum demand)	• Emergency preparedness measures • Generator profile (seasonal) • Availability of trained repair personnel

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Table 3 (*continued*)

Dimension	Components	Simple Indicators and Metrics	Complex Indicators and Metrics
		• Secondary frequency control reserve (for electricity transmission) • Tertiary frequency control reserve (for electricity transmission) • Critical electricity surplus • Percentage of energy capacity actually utilized • Peak-load to base load ratios • Generator profiles summer/winter • Emergency stockpiles for oil (days meet demand) • Emergency oil stockpiles (% imports) • Emergency stockpiles for coal (days meet demand) • Emergency coal stockpiles (% imports) • Emergency stockpiles for natural gas (days meet demand) • Emergency natural gas stockpiles (% imports) • Availability of trained repair personnel • Availability of spare parts and supplies • Generation adequacy • System adequacy	• Availability of spare parts and supplies
	Efficiency and energy intensity	• Energy intensity (number of BTUs needed for US$1 of GDP) • Number of LEED certified buildings • Average thermal efficiency of power plants • Fuel economy for new vehicles • Fuel economy for on-road vehicles • Fuel economy for rail (megajoules per ton-kilometer traveled) • Fuel economy for aviation • Fuel economy for freight and heavy trucks (megajoules per ton-kilometer traveled) • Fuel economy for marine transport (megajoules per ton-kilometer traveled) • Electricity transmission and distribution losses • Space heating efficiency • Annual energy efficiency savings (revenues) • Annual energy efficiency savings (billion kWh) • Energy intensity for total manufacturing • Energy intensity for chemicals manufacturing • Energy intensity for primary metals manufacturing • Energy intensity for paper, pulp, and print • Energy intensity for non-metallic minerals • Energy intensity for metal products and equipment • Energy intensity for food, beverages, and tobacco • Energy intensity for cement manufacturing • Energy intensity for iron and steel • Energy intensity for aluminum	• Energy payback ratio for total energy sector • Energy end use efficiency for buildings • Standard Assessment Procedure rating for households
	Investment and employment	• Planned new energy projects including construction status of approved projects • Direct employment in the energy sector • Indirect employment in the energy sector • Induced employment in the energy sector • Technical expertise (number of engineers or energy employees) • Unemployment in the energy sector (%) • Expenditures on financial support mechanisms for renewable energy • Investment in electricity transmission (billions of dollars/year) • Net capital investment in energy infrastructure • Total amount of stranded costs or sunk costs • Average age of energy capital stock • Average power plant age • Planned new generation capacity • Average rate of return on energy investments	• Average construction lead time for new energy infrastructure • Net total investments in energy infrastructure (billions of dollars)
Environmental and social sustainability	Land use	• Total environmental footprint of energy facilities • Energy pollution's impact on habitats • Generation of energy-related industrial and municipal solid waste • Generation of energy-related hazardous waste • Generation of energy-related radioactive waste • Deforestation related to energy use and fuel collection	• Cost of noise pollution • Loss of farmland due to decline in soil quality

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Table 3 (*continued*)

Dimension	Components	Simple Indicators and Metrics	Complex Indicators and Metrics
	Water	• Energy-related mercury discharges to water supplies • Occurrence of annual climate-changed related droughts • Thermal discharges to water sources • Water withdrawals per kWh • Water consumption per kWh • Water use per kWh • Water use efficiency • Energy intensity of water treatment • Volume of tritium leaked into local water supplies • Water used per ton of coal mined • Water used per ton of uranium mined • Water used per barrel of oil refined	• Annual economic damages from energy-related water contamination • Economic damage to fisheries from energy production
	Climate change	• Share of zero-carbon fuels in energy mix • Total greenhouse gas emissions from energy production and use (including land use changes) • Per capita greenhouse gas emissions from energy production and use (including land use changes) • Total greenhouse gas emissions from energy production and use (excluding land use changes) • Per capita greenhouse gas emissions from energy production and use (excluding land use changes) • Energy-related methane emissions • Energy-related nitrous oxide emissions • Carbon content of primary fuels • Annual revenue related to carbon credits • Presence of climate change goals and targets • CO_2 emissions from fuel combustion • CO_2 emissions from electricity sector	• Carbon dioxide intensities of transport (per km driven) • Carbon dioxide intensity of electricity (per kWh) • Carbon dioxide intensity of industrial output • Carbon dioxide intensity of buildings (per square foot)
	Pollution	• Annual nitrogen oxide emissions • Annual nitrous oxide emissions • Annual sulfur dioxide emissions • Annual emissions of volatile organic compounds • Annual benzene emissions • Annual emissions of particulate matter • Annual emissions of lead • Annual emissions of mercury • Annual emissions of carbon monoxide • Annual emissions of cadmium • Annual emissions of black carbon • Per capita nitrogen oxide emissions • Per capita nitrous oxide emissions • Per capita sulfur dioxide emissions • Per capita emissions of volatile organic compounds • Per capita benzene emissions • Per capita emissions of particulate matter • Per capita emissions of lead • Per capita emissions of mercury • Per capita emissions of carbon monoxide • Per capita emissions of cadmium • Per capita emissions of black carbon • Number of annual oil spills (greater than 50 barrels) • Volume of oil spilled each year • Percent of power plants equipped with pollution abatement equipment • Number of households with improved cook stoves • Annual volume of sales from woodlots	• Ratio of waste to units of energy produced • Economic damage from annual oil spills (USD) • Disability adjusted life years associated with biomass use/indoor energy combustion
Regulation and governance	Governance	• Number of electricity system regulators • Percent government revenue dependent on energy • Provision of priority grid access to renewable energy • Strength or sufficiency of environmental permitting and impact assessment requirements • Length of time it takes new business to get electricity service • Frequency of changes in regulatory or institutional mechanisms • Frequency of review of country energy profile • Presence of climate change goals or targets • Number of annual protests relating to energy	• Transparency International Corruption Index • Worldwide Governance Indicators (CIGI/World Bank) • State Fragility Index • UN Human Development Indicators (HDI) • Satisfaction (share of adult population satisfied with policy and planning mechanisms)

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Table 3 (*continued*)

Dimension	Components	Simple Indicators and Metrics	Complex Indicators and Metrics
		• Completeness of existing legislation • Estimated annual revenues lost to corruption in the energy industry • Country credit rating	
	Trade and regional interconnectivity	• Amount of transnational electricity trading (kWh) • Volume of natural gas/oil exported • Annual revenue from exports of energy fuels and technology • Number of free trade agreements signed related to trade of energy fuels • Total electricity interconnection capacity (installed) • Amount of interconnector trading of electricity (kWh traded) • Number of flagged LNG tankers • Number of flagged very large crude carriers (oil tankers) • Volume of energy imports via pipeline • Volume of energy imports via rail • Number of attacks or acts of piracy on flagged marine vessels carrying energy fuels and/or equipment • Number of transnational natural gas pipelines • Number of LNG ports • Number of existing production sharing agreements in the oil sector • Volume of energy shared during emergencies • Foreign direct investment in the energy sector	
	Competition and markets	• Market share by largest three energy suppliers or companies • Rate of return for energy companies • Percent of generation capacity owned by independent power providers • Average annual change of GDP energy intensity • Tax burden of energy sales volume • Ratio of accounts receivable to annual production volume of energy industries • Total amount of annual public energy subsidies • Total amount of annual public energy subsidies per capita	
	Knowledge and access to information	• Periodic publication of official energy planning documents and/or statistics • Number of customers served by net metering • Number of customers served by real time pricing or smart grids • Annual cost of energy-related externalities (to inform policymakers) • Annual cost of automobile accidents (to inform policymakers) • Annual deaths from automobile accidents (to inform policymakers)	• Public resistance to new power generating units • Energy literacy of users

Source: Research interviews as well as [11,13–20,23–28,32–34,47–55].

Other approaches, like those currently being proposed at the Energy Security component of the IIASA's Global Energy Assessment, divide indicators among a continuum of "simplest", "intermediate", and "complex". This system of categorization can be used to disaggregate indicators measuring quantity (simple), quality (intermediate) and context (complex) for the various components of energy security identified above. Table 2 is provided as an illustrative example breaking down some of the energy security components into their constituent simple, intermediate and complex indicators. For instance, a "simple" indicator for energy imports would be the share of imported energy; an "intermediate" one the type of imported energy and mode of import (such as via pipeline, tanker, or rail); a "complex" one the specific qualitative context of imports from a particular location.

Still other studies, such as [20,23,34] classify "simple" indicators as those that can be expressed in "physical" or "monetary" terms, whereas "complex" indicators use diversity indices. For these sorts of studies, the following types of indicators would be classified as "simple":

- Resource estimates and reserves;
- Reserve to production ratios;
- Share of zero-carbon fuels;
- Import dependence;
- Political risk rating;
- Energy prices;
- Ratio of a country's consumption over the total market for a fuel;
- Energy intensity;
- Energy expenditures for research.

"Complex" or "aggregate" indicators would be those derived by diversity indices such as the Herfindahl-Hirschman Index or Shannon–Wiener Index [42–47].

Acknowledging that aggregate indicators differ from disaggregated and process indicators, that indicators can measure quantity, quality and context, and that some can be expressed in physical or monetary terms while others require aggregation into a diversity index, we have chosen to divide our indicators for energy security into "simple" and "complex". We define an indicator as "complex" if it is an established aggregate indicator that includes the measurement of multiple variables or if it involves time intensive, detailed means of measurement. Complex indicators thus allow for depth of assessment. By contrast, simple indicators are those that are more suitable for a rapid, snapshot appraisal of energy security. Synthesizing and distilling from the academic literature, as well as the data collected through interviews, survey responses, and the workshop, Table 3 presents 320 simple indicators and 52 complex indicators corresponding to the 20 energy security dimensions. Some of these indicators do overlap, making the table complicated, but such intricateness directly results from the abundance of data collected from the interviews and other methods.

5. Conclusion

Through our synthesized mixed methods assessment of energy security we offer four conclusions. Firstly, the data that has been compiled from an extensive literature review as well from original primary sources including research interviews, a survey, and a focused intensive workshop, strongly suggest that energy security is a multidimensional phenomenon. Energy reserves and stockpiles, fuel mixes and diversification, price stability and affordability, justice and equity, technology development, energy efficiency, resilience, investment, environmental quality, governance, and regulation all influence – and thus form part of – contemporary national energy security issues. These should supplement current investigations that look exclusively at security of supply, access to oil and coal, or the price of energy services as "elemental" components of energy security.

Secondly, these diffuse elements of energy security can be categorized according to 20 separate and distinct dimensions that then correspond to 320 simple and 52 complex indicators. These metrics are useful and relevant to those attempting to better understand energy security issues, assess best practices, comprehend tradeoffs between energy security dimensions, and identify vulnerabilities within and between countries. The composite index presented here is broad enough to capture meaningful differences among developed and developing economies, energy importers and exporters, big and small countries, and rich and poor communities. It is also more rigorous and complete than existing indices in the field: rigorous in the sense that it has been derived from consultations with dozens of experts trained in different disciplines from different types of countries, complete in the sense that it looks at technical supply and demand side aspects of energy security simultaneously along with social, political, and economic ones across a variety of sectors including electricity and transport. We thus urge policymakers and scholars alike to start applying these metrics to evaluate national and perhaps even sub-national energy security performance.

Thirdly, however, is that collecting data for composite indices of energy security will be difficult. For one, it may not be possible to collect data for even most of the 372 energy security metrics for particular countries, yet alone all of them. Perhaps more feasible would be collecting data for one to two of the simple and complex indicators above for each dimension, meaning analysts could boil down the complete list presented in Table 3 to 20 indicators depending on the country and data availability, using it as an instructive guide rather than an exhaustive checklist. The process of collecting data for an energy security index itself might reveal pressing energy concerns, or gaps in institutional capacity, that need addressed. Data reliability and accuracy will also be paramount issues to contend with.

Fourth, if the energy security dimensions projected here are accurate, the proposed indicators best capture these dimensions, and the challenges to data collection and synthesis above can be overcome, then the logical next step is to begin collecting data on these indicators for countries around the world so that energy security can be systematically investigated, both spatially (between countries) and temporally (compared across time for a particular country). Such metrics could even be used to create a snapshot of a given country's energy security threats, or to reveal whose energy security has rapidly improved or deteriorated. Conversely, such an index could help illustrate tradeoffs between different energy security metrics, as well as which technologies or policies truly enhance energy security across all of its interstitial dimensions. Only then, perhaps, can many of the daunting energy security vulnerabilities facing most countries actually be reduced in practice.

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Appendix 1. Institutional Affiliations of Energy Security Research Interviews (Where the institute is headquartered is mentioned in parentheses)

Arizona State University (United States)
Asia Pacific Energy Research Centre (Japan)
Asian Institute of Technology (Thailand)
Atomic Energy Commission (India)
Center for Energy Policy and Economics (Switzerland)
Center for Policy Research (India)
Center for Security Analysis (India)
Central European University (Hungary)
Chiang Mai University (Thailand)
Chinese Academy of Sciences (China)
Dalhousie University (Canada)
European Commission (Belgium)
Georgia Institute of Technology (United States)
Indian Statistical Institute (India)
Indonesian Institute for Energy Economics (Indonesia)
Institute for the Analysis of Global Security (United States)
International Atomic Energy Agency (Austria)
International Energy Agency (France)
International Institute for Applied Systems Analysis (Austria)
Malaysia Energy Centre (Malaysia)
National University of Singapore (Singapore)
Netherlands Environmental Assessment Agency (Netherlands)
Nuclear Energy Agency (France)
Renewable Energy and Energy Efficiency Partnership (Austria)
Rocky Mountain Institute (United States)
Shandong Institute of Business and Technology (China)
Stanford University (United States)
The Energy and Resources Institute (India)

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The Open University (United Kingdom)
United Nations Environment Program (France)
United Nations Development Program (Austria)
United Nations Industrial Development Organization (Austria)
US Department of Energy (United States)
US Department of Defense (United States)
University of California Berkeley (United States)
University of Helsinki (Finland)
University of Sussex (United Kingdom)
University of Tokyo (Japan)
University of Waikato (New Zealand)
Vanderbilt University (United States)
Vermont Law School (United States)
Virginia Polytechnic Institute and State University (United States)
World Bank (United States)
World Resources Institute (United States)

Appendix 2

Participants at the International Workshop on Energy Security Concepts and Indicators for Asia, Lee Kuan Yew School of Public Policy, November 14–16 2009, Singapore.

Participant	Institution
Shonali Pachauri	International Institute for Applied Systems Analysis
Alan McDonald	International Atomic Energy Agency
Larry Hughes	Dalhousie University
Li Jinke	Shandong Institute of Business and Technology
Shi Dan	Chinese National Academy of Sciences
Nathalie Trudeau	International Energy Agency
Aad Van Bohemen	International Energy Agency
Andreas Goldthau	Central European University
Rekha Krishnan	The Energy and Resources Institute
Sanjay Verma	Indian Ministry of External Affairs
S. Rajagopal	Indian Atomic Energy Commission
Eshita Gupta	The Energy and Resources Institute
Krishnaswamy Srinivasan	Center for Security Analysis
Ami Indriyanto	Indonesian Institute for Energy Economics
Masanari Koike	The University of Tokyo
Gladys Mak	Malaysia Energy Center
Jaap C. Jansen	Energy Research Centre of the Netherlands
Barry Barton	University of Waikato
Scott Valentine	National University of Singapore
Hooman Peimani	Singaporean Energy Studies Institute
Geoffrey Kevin Pakiam	Singaporean Energy Studies Institute
Mely Caballero-Anthony	Nanyang Technological University
Joergen Oerstroem Moeller	Institute of Southeast Asian Studies
Violet Chen	Singaporean Energy Market Authority
Edgard Gnansounou	Laboratory of Energy Systems
Tira Foran	Chang Mai University
Aleh Cherp	Central European University
John Kessels	IEA Clean Coal Centre
Andy Stirling	University of Sussex
Michael Dworkin	University of Vermont Law School
Godfrey Boyle	The Open University
Mike Pasqualetti	Arizona State University
Jack Barkenbus	Vanderbilt University
Marilyn Brown	Georgia Institute of Technology
Christopher Cooper	Oomph Consulting
Gal Luft	Institute for the Analysis of Global Security
Anne Korin	Institute for the Analysis of Global Security

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