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# Energy security: Definitions, dimensions and indexes

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ABSTRACT

Energy security has been an actively studied area in recent years. Various facets have been covered in the literature. Based on a survey of 104 studies from 2001 to June 2014, this paper reports the findings on the following: energy security definitions, changes in the themes of these definitions, energy security indexes, specific focused areas and methodological issues in the construction of these indexes, and energy security in the wider context of national energy policy. It is found that the definition of energy security is contextual and dynamic in nature. The scope of energy security has also expanded, with a growing emphasis on dimensions such as environmental sustainability and energy efficiency. Significant differences among studies are observed in the way in which energy security indexes are framed and constructed. These variations introduce challenges in comparing the findings among studies. Based on these findings, recommendations on studying energy security and the construction of energy security indexes are presented.



**Contents**



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## 1. Introduction

Energy security is an issue of critical importance to many different stakeholders, including policy makers, businesses (in particular major energy consumers), and the larger community whose quality of life depends on uninterrupted energy supply. Studies on energy security can be found in many academic publications and in government and think-tank reports [1–104]. However, a quick search shows that there is no consensus on a widely accepted definition of energy security. Studies such as Chester [105] and Vivoda [58] point out that the nature of energy security is polysemic and multi-dimensional. One would therefore expect that the meaning of energy security is highly context dependent, such as a country's special circumstances, level of economic development, perceptions of risks, as well as the robustness of its energy system and prevailing geopolitical issues.

In defining energy security, some researchers focus primarily on the security of supply aspect such as energy availability and prices [30,37], while other researchers argue for a more comprehensive definition that includes downstream effects such as the impact on economic and social welfare [58]. The definition and dimensions of energy security appear to be dynamic, and evolve as circumstances change over time. For instance, as energy technologies advance, awareness of climate change and sustainability increases, the relevant facets of energy security are reshaped.

There has been increasing interest in the quantification of energy security risk using indicators and indexes. Various studies have proposed a wide variety of energy security indexes, either to compare performance among countries or to track changes in a country's performance over time. In these studies, typically, a basket of indicators are first identified based on some specific considerations or theoretical framework. This is followed by data collection and normalisation, weighting and aggregation of the chosen indicators to give one or more composite energy security indexes. A quick review of these studies shows that there are large variations in the choice of indicators and how such composite energy security indexes are framed and constructed.

In the literature, a systematic analysis of the definitions and dimensions of energy security, including underlying shifts over time in the relative importance of the various facets of energy security, is lacking. The use of energy security indexes for self-assessment, tracking progress and/or cross-country comparisons is expected to grow. However, there is a gap in the systematic assessment of these indexes, such as their specific focus and the manner which they are constructed. This paper therefore has the following two primary objectives. First, through an extensive literature survey, it attempts to fill gaps in the literature by providing insights into how energy security definitions and dimensions have evolved over time. Second, the methods used in the construction of energy security composite indexes are reviewed. This paper serves to provide an understanding of how the concept of energy security has evolved across time and also highlight existing methodologies to the construction of energy security indexes, establishing a good foundation for readers who may want to establish energy security indexes for their own countries.

An outline of the rest of the paper is as follows. The next section presents some findings from our extensive literature survey. Section 3 deals with the definition of energy security and the observed changes in focus over time. Section 4 looks into energy security indicators and indexes, and the methods for constructing energy security indexes are dealt with in Section 5. Section 6 discusses energy security in the wider context of energy policy. Further discussion and conclusions, including some indication of path forward and further work are presented in Section 7.

## 2. Overview of literature survey

The literature survey covers 104 energy security studies. They are listed chronologically in Table 1 [1–104]. They include papers from peer-reviewed journals, and reports of national agencies, international organisations, and business/professional associations. The main journals are *Applied Energy*, *Energy*, *Energy Policy* and *Renewable and Sustainable Energy Reviews*. Examples of reports are those of the International Energy Agency (IEA), Institute for 21st Century Energy of the U.S. Chamber of Commerce, World Economic Forum (WEF), and World Energy Council (WEC). The survey covers the publications from 2001 to June 2014[1]. The studies are classified into three types: journal papers, official reports, and "others". Publications in the category "others" are reports by think tanks, research institutes, and business/professional associations. The total numbers by type are 74, 12, and 18, respectively. More than two-thirds, or 71%, are journal papers. Official reports are primarily those by governmental or international agencies. Unlike journal papers, the reports by governmental agencies generally present the official position, and the interpretation of energy security as a result is influenced by national obligations, concerns, and interests. International agencies, on the other hand, are more concerned about regional energy security issues. Reports under the category "others" are more varied as compared to the other two types of studies.

To study changes on issues of interest over time, we divide the time span into three periods, i.e. 2001–2005, 2006–2009, and 2010–2014. They are referred to as the first, second, and third period, and the numbers of studies are 11, 39, and 54, respectively. The average number of studies per year has increased over time. Fig. 1 shows the distribution of studies by publication type. The share of journal publications has increased steadily and reached nine out of every ten studies in the third period. It is thus clear that interest in energy security as a research topic has been growing significantly.

Most of the studies are country-specific where energy security for a country (or region) is analysed. Fig. 2 shows the distribution of studies by country/region. It can be seen that energy security is a concern for both developed and developing economies alike. A majority of the studies deal with large energy importers, such as China, Europe, Japan, and the United States. It is also noted that the countries studied vary in terms of energy endowments and their energy mix, which reflects the fact that energy security is a universal concern to net energy importers. Out of the 104 studies, 83 provide specific definitions of energy security (which are analysed in the next section), and 51 cover energy security indicators and/or indexes (which are analysed in Sections 4 and 5). The publications in each case are indicated in Table 1.

[1] Prior to 2001, publications on energy security were rare, generally with one or two per year. They are therefore not considered in this study.

**Table 1**
List of energy security studies, where themes in energy security definition are energy availability (A), infrastructure (B), energy prices (C), societal effects (D), environment (E), governance (F) and efficiency (G).

| Source | Year | Country/region | Publication type | | | Energy security definition given | Energy security indicators or index provided | Themes in energy security definition | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | Journal paper | Official report | Others | | | A | B | C | D | E | F | G |
| EC [1] | 2001 | Europe | | | × | × | | × | × | | × | × | | |
| Bielecki [2] | 2002 | N/A | × | | | × | | × | × | × | | | | |
| DTI [3] | 2002 | Britain | | × | | × | × | × | × | × | × | | × | |
| Stern [4] | 2002 | Europe | | | × | × | | × | × | | | | | |
| Lieb-Dóczy et al. [5] | 2003 | Europe | × | | | × | | × | × | | | | | |
| Blyth and Lefevre [6] | 2004 | Australia, Italy, UK and US | | × | | × | × | × | × | × | × | | | |
| de Joode et al. [7] | 2004 | Netherlands | | | × | × | | × | × | × | × | | | |
| Lesbirel [8] | 2004 | Japan | × | | | × | | × | × | | × | | | |
| Andrews [9] | 2005 | US | × | | | × | | × | × | | × | | | |
| Onamics [10] | 2005 | Central/Eastern Europe | | | × | × | × | × | × | | | | | |
| Wright [11] | 2005 | UK | × | | | × | | × | | | | | | |
| Department of Energy and Climate Change [12] | 2006 | UK | | | × | × | | | × | × | × | × | × | |
| Doorman et al. [13] | 2006 | Nordic countries | × | | | × | | × | × | | | | | |
| Grubb et al. [14] | 2006 | UK | × | | | × | | × | × | × | | | | |
| Turton and Barreto [15] | 2006 | Europe | × | | | × | | × | | | | | | |
| Yergin [16] | 2006 | US | × | | | × | | × | × | × | | | × | |
| Sovacool and Brown [17] | 2007 | US | × | | | × | × | × | | × | × | × | | |
| Costantini et al. [18] | 2007 | EU | × | | | × | | × | | × | × | × | | |
| Hoogeveen and Perlot [19] | 2007 | EU | × | | | × | | × | × | | × | × | | |
| IAEA [20] | 2007 | 7 countries | | × | | | × | | | | | | | |
| IEA [21] | 2007 | OECD countries | | × | | | × | | | | | | | |
| Intharak et al. [22] | 2007 | Asia-Pacific countries | | × | | × | × | × | × | × | | × | | |
| Wu and Morisson [23] | 2007 | Selected Asia-Pacific economies and EU | | | × | | × | | | | | | | |
| Kemmler and Spreng [24] | 2007 | Developing countries | × | | | × | | × | | | × | × | | × |
| Keppler [25] | 2007 | Europe | | | × | × | | × | × | × | | | | |
| Ölz et al. [26] | 2007 | IEA countries | | | × | × | | × | × | × | | × | | |
| O'Leary et al. [27] | 2007 | Ireland | | | × | × | | × | × | × | | | × | |
| Rutherford et al. [28] | 2007 | New Zealand | × | | | × | | × | × | × | | | | |
| Scheepers et al. [29] | 2007 | EU-27 | | × | | × | × | × | × | | | | | |
| Spanjer [30] | 2007 | Europe | × | | | × | | × | | × | | | | |
| Streimikiene et al. [31] | 2007 | Lithuania, Latvia, Estonia | × | | | | × | | | | | | | |
| Center for Energy Economics [32] | 2008 | South Asia | × | | | × | | × | × | × | × | | | × |
| ESCAP [33] | 2008 | Asia-Pacific countries | | | × | × | | × | | × | | | | |
| Frondel and Schmidt [34] | 2008 | Germany and US | | | × | | × | | | | | | | |
| Gnansounou [35] | 2008 | 37 industrialised countries | × | | | × | × | × | × | | | | | |
| Gupta [36] | 2008 | 26 net oil-importing countries | × | | | | × | | | | | | | |
| Jamasb and Pollitt [37] | 2008 | UK and Europe | × | | | × | | × | | × | | | | |
| Kessels et al. [38] | 2008 | N/A | | | × | × | | × | × | × | | | × | × |
| Mabro [39] | 2008 | N/A | | | × | × | | × | × | × | | | | |
| Nuttall and Manz [40] | 2008 | N/A | × | | | × | | × | × | | | | | |
| Patlitzianas et al. [41] | 2008 | N/A | × | | | × | | × | × | | | | | |

**Table 1** (*continued*)

| Source | Year | Country/region | Publication type | | | Energy security definition given | Energy security indicators or index provided | Themes in energy security definition | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | Journal paper | Official report | Others | | | A | B | C | D | E | F | G |
| Patterson [42] | 2008 | N/A | | | × | × | | × | × | | | | | |
| Augutis et al. [43] | 2009 | Lithuania | × | | | | × | | | | | | | |
| CNA [44] | 2009 | US | | | × | × | | × | × | | | | | × |
| Greenleaf et al. [45] | 2009 | EU | | | × | × | × | × | | × | × | × | | |
| Hughes [46] | 2009 | N/A | × | | | × | | × | | | | | × | × |
| Jansen [47] | 2009 | N/A | | | × | × | × | × | | × | | × | | |
| Jun et al. [48] | 2009 | South Korea | × | | | × | | × | × | × | | | | |
| Kruyt et al. [49] | 2009 | Western (OECD) Europe | × | | | × | | × | × | × | | × | | |
| Le Coq and Paltseva [50] | 2009 | EU | × | | | × | × | × | × | × | | | | |
| Balat [51] | 2010 | Turkey | × | | | × | | × | × | × | | | × | × |
| Cabalu [52] | 2010 | 7 countries | × | | | × | × | × | × | × | | | | |
| Jansen and Seebregts [53] | 2010 | N.A. | × | | | × | | × | × | × | | | | |
| Lefèvre [54] | 2010 | France, UK, | × | | | × | × | × | | × | × | | | |
| Löschel et al. [55] | 2010 | Germany, Netherlands, Spain and US | × | | | × | × | | | | × | | | |
| Findlater and Noël [56] | 2010 | Baltic states | × | | | × | | × | × | | | | | |
| Sovacool and Brown [57] | 2010 | OECD and US (22 Countries) | × | | | × | × | × | | × | | × | | × |
| Vivoda [58] | 2010 | Asia-Pacific countries | × | | | × | × | × | × | × | × | × | × | × |
| Augutis et al. [59] | 2011 | Lithuania | × | | | × | × | × | × | × | | × | | |
| Bazilian et al. [60] | 2011 | South Africa | × | | | × | | × | × | × | × | | | |
| Cohen et al. [61] | 2011 | OECD (26 for oil, 20 for gas) | × | | | | × | | | | | | | |
| Ediger and Berk [62] | 2011 | Turkey | × | | | | × | | | | | | | |
| Jewell [63] | 2011 | IEA countries | | × | | | × | | | | | | | |
| Leung [64] | 2011 | China | × | | | × | | × | × | × | × | | | |
| Sovacool [65] | 2011 | Asia-Pacific countries | × | | | × | | × | | × | | × | | × |
| Sovacool and Mukherjee [66] | 2011 | N/A | × | | | × | | × | | × | | × | × | |
| Sovacool et al. [67] | 2011 | ASEAN, EU and 7 other countries | × | | | × | × | × | × | × | × | × | × | × |
| Angelis-Dimakis et al. [68] | 2012 | Greece | × | | | | × | × | | × | × | | | |
| Augutis et al. [69] | 2012 | Lithuania | × | | | | × | | | | | | | |
| Dunn and Dunn [70] | 2012 | US | | | × | | × | | | | | | | |
| ERIA [71] | 2012 | East Asian countries | | × | | × | × | × | | | | | | |
| Goldthau and Sovacool [72] | 2012 | N/A | × | | | × | | × | × | × | × | × | × | × |
| Hughes [73] | 2012 | Province of Prince Edward, Canada | × | | | × | × | × | × | × | | × | | |
| Institute for 21st Century Energy [74] | 2012 | US | | × | | | × | | | | | | | |
| Institute for 21st Century Energy [75] | 2012 | OECD and large energy users | | × | | | × | | | | | | | |
| Martchamadol and Kumar [76] | 2012 | Thailand | × | | | × | × | × | | × | × | × | | |
| Pasqualetti and Sovacool [77] | 2012 | N/A | × | | | × | | × | × | × | × | × | × | × |
| Sheinbaum-Pardo et al. [78] | 2012 | Mexico | × | | | | × | | | | | | | |
| Vivoda [79] | 2012 | Japan | × | | | × | | × | × | × | | × | | |
| Winzer [80] | 2012 | Austria, Italy and Great Britain | × | | | × | × | × | × | | | | | |
| WEF [81] | 2012 | 105 countries | | × | | × | × | × | × | | | | | |
| WEC [82] | 2012 | WEC countries | | × | | × | × | × | × | | | | × | |

| | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Wu et al. [83] | 2012 | China | × | × | × | × | × | × | | | |
| Below [84] | 2013 | US | × | × | × | × | × | | | | × |
| Chuang and Ma [85] | 2013 | Taiwan | × | | × | | | | | | |
| Escribano Francés et al. [86] | 2013 | EU | × | × | | × | × | × | × | × | × |
| Ge and Fan [87] | 2013 | China | × | × | | × | × | × | | | |
| Gunningham [88] | 2013 | Indonesia | × | × | | × | × | × | | | |
| Knox-Hayes et al. [89] | 2013 | 10 Countries | × | × | | × | × | × | × | × | × | × |
| Selvakkumaran and Limmeechokchai [90] | 2013 | Sri Lanka, Thailand and Vietnam | × | | × | | | | | | |
| Sovacool [91] | 2013 | 18 countries | × | × | × | × | × | × | × | × | × | × |
| Sovacool [92] | 2013 | Asia-Pacific countries | × | × | × | × | | × | | × | × | × |
| Zhang et al. [93] | 2013 | China | × | | × | | | | | | |
| Demski et al. [94] | 2014 | United Kingdom | × | × | | × | × | × | | | |
| Jewell et al. [95] | 2014 | Global/regional | × | × | × | × | × | × | | | |
| Kamsamrong and Sorapipatana [96] | 2014 | Thailand | × | | × | | | | | | |
| Wu [97] | 2014 | China | × | × | | × | | × | | × | × | |
| Odgaard and Delman [98] | 2014 | China | × | × | | × | × | × | | | × | × |
| Portugal-Pereira and Esteban [99] | 2014 | Japan | × | × | | × | × | × | × | × | × | × |
| Ranjan and Hughes [100] | 2014 | Multiple | × | × | × | × | | × | | × | | |
| Sharifuddin [101] | 2014 | Malaysia | × | | × | | | | | | |
| Sun et al. [102] | 2014 | China | × | × | | × | × | × | | | |
| Yao and Chang [103] | 2014 | China | × | × | × | × | | × | × | × | | |
| Zhao and Liu [104] | 2014 | China | × | × | | × | | × | | × | × | |

## 3. Definitions of energy security and changing emphasis

Numerous definitions of energy security have been offered by researchers and policy makers. There has been some broad agreement with what it should cover but no consensus on what it exactly should be. Variations can be observed in the definitions given in the studies in Table 1. Changes in emphasis over time, as a result of changes in the global energy landscape, are expected. These issues are studied in the sections that follow.

### 3.1. Definitions of energy security

Based on the 83 energy security definitions, our review reaffirms the opinion that energy security is indeed a highly context-dependent concept. Apart from several key ideas that are normally present, there is no widely accepted definition. Of the definitions, 11, 32, and 40 are given in the publications in the first, second, and third time period respectively. From these definitions and the corresponding studies, we are able to identify the following seven major energy security themes or dimensions: Energy availability, infrastructure, energy prices, societal effects, environment, governance, and energy efficiency. The themes employed in each definition or study is indicated in Table 1. The coverage differs among studies and very few studies include all the seven themes. These seven themes are elaborated below.

#### 3.1.1. Energy availability

Diversification and geopolitical factors are key issues that determine energy availability. Through diversification of supply sources, energy importers can reduce and better mitigate the risks of import disruptions. Concerns about geopolitical issues include events such as outbreaks of wars, destabilized regimes, or regional tensions which can lead to oil or gas supply disruptions. Energy supply diversity can take several forms. A country which imports energy from many different countries has high *source diversity*. A country with large land area has higher potential for *spatial diversity* as it can distribute energy facilities across different sites and reduce the impact of critical incidents in a specific location. Another source of spatial diversity is the promotion of distributed generation of renewable energy. A country can enhance *energy mix diversity* by having a more balanced energy supply of different energy types. For countries that rely on renewable energy sources which are intermittent, *technology diversity* is an important consideration. The transportation and delivery energy imports can be diversified to enhance *transport route diversity*. One way to reduce such risks is to reduce imports that pass through known chokepoints[2] or having multiple supply pipelines to reduce the dependence on any individual pipeline.

#### 3.1.2. Infrastructure

Infrastructure is integral in providing stable and uninterrupted energy supply. These facilities include energy transformation facilities, e.g. oil refineries and power plants, and distribution and transmission facilities, e.g. pipelines, electricity transmission lines, sub-stations and energy storage facilities. Adequate investments on these facilities ensure that sufficient energy is available in the short and long terms. The reliability of these facilities is crucial to prevent shortages or blackouts. With the use of supervisory control and data acquisition systems to manage power systems, infrastructure is increasingly exposed to cyber-security

[2] For instance, EIA [106] identifies seven world oil transit chokepoints with about half of the global world production passing through these choke points each year. Military conflicts or other situations that result in the closure of one or more of these choke points will have disastrous consequences to energy importers.

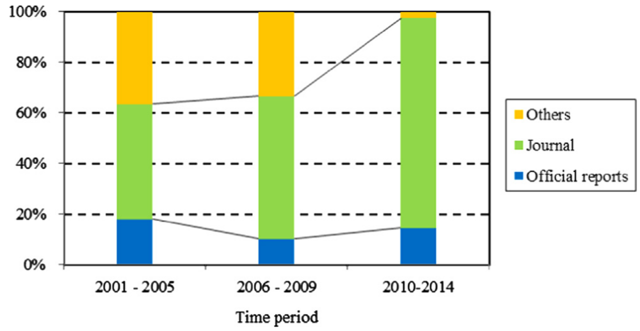


**Fig. 1.** Distribution of energy security studies by publication type for different time periods.

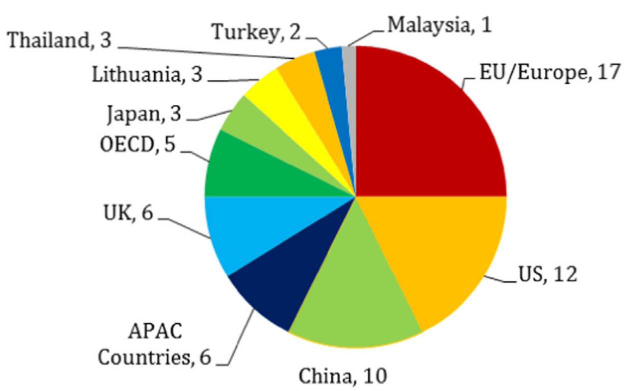


**Fig. 2.** Number of energy security studies by country/region where APAC refers to Asia-Pacific.

risks [107],[3]. The need for adequate and robust infrastructure with spare capacity is also essential for "uninterrupted physical availability of energy products on the market" [1]. Similar to strategic stocks, good infrastructure is a prerequisite to stable energy supplies and an important component of "economic energy security" [22].

### 3.1.3. *Energy prices*

Energy prices determine the affordability of energy supplies and have a number of dimensions such as the absolute price level, price volatility, and the degree of competition in energy markets. Since crude oil is traded in US dollars internationally, exchange rates and purchasing power of different currencies play a role in determining how much a country and its people pay for energy imports. Volatile prices of fossil fuels can cause problems in securing energy supplies and affect the ability of policymakers to plan for capacity expansion and other shorter term measures. Most studies emphasize the importance of energy prices as part of the energy security equation [2,79].

### 3.1.4. *Societal effects*

As energy is a basic necessity of life, social welfare has been included in the energy security definition in some studies. Societal concerns include energy poverty, where certain segments of the population could be denied the basic energy services. There may be acceptability issues in which communities oppose energy projects that may cause damage to their living environment. Lesbirel [8] posits that a goal of energy security is to "insure against the risks of harmful energy import disruptions in order to ensure adequate access to energy sources to sustain acceptable levels of social and economic welfare". The Center for Energy Economics [32] emphasize that energy security should ensure that "the economic and social development of the country is not materially constrained". The UK Department of Energy and Climate Change [12] stresses on the social equity aspect of energy security.

### 3.1.5. *Environment*

Sustainability and environmental issues are closely associated with energy due to carbon and other emissions that contribute to global warming and air pollution. Other environmental risks associated with energy are inundation of forests as a result of hydropower projects or oil leaks and spills during crude oil exploration or transportation. The European Commission [1] highlights the importance of environmental concerns and sustainability in energy security. Pasqualetti and Sovacool [77] emphasize the importance of "provision of available, affordable, reliable, efficient, environmentally benign, properly governed and socially acceptable energy services" for energy security.

### 3.1.6. *Governance*

Sound government policies help to hedge against and mitigate short-term energy disruptions. Forward-looking governments support the effective planning of infrastructure needs to ensure long-term energy security. Policies related to energy taxes and subsidies impacts the energy security of the nation. Increasingly, countries are engaging in energy diplomacy with foreign policies geared towards ensuring energy supplies from exporting regions. In addition, the government has an important role to play as the key information gatherer, since high quality data facilitates effective large-scale planning for energy security. The government's role in policymaking, regulatory process, diplomacy and information collection has been highlighted in Department of Energy and Climate Change [12] and Goldthau and Sovacool [72].

### 3.1.7. *Energy efficiency*

Energy improving technologies, systems, and practices help to reduce energy needs and improve energy security. A concept closely related to energy efficiency is energy intensity, which is the energy required to produce each unit of output. Lowering the energy intensity of an economy can improve energy security by reducing the amount of energy it needs to function. For example, an energy-intensive industry such as steel making will be adversely affected by energy disruptions or high energy prices, as compared to one that is less energy intensive. Kemmler and Spreng [24] include "promoting energy efficiency and reducing energy intensity" as a main policy to tackle energy security problems. Hughes [46] also advocates reducing energy use as one of the 4 'R's (review, reduce, replace, and restrict) of energy security.

Of the 83 energy security definitions, the theme of "energy availability" is included in 82 (99%), "infrastructure" in 60 (72%), and "energy prices" in 59 (71%). The corresponding figures for environment and societal effects are 28 (34%) and 31 (37%), respectively. The remaining themes, i.e. "governance" and "energy efficiency", are included in 21 (25%) and 18 (22%), respectively. Based on these results, the ranking of the seven themes in terms of importance and relevance in descending order is energy availability, infrastructure, energy prices, societal effects, environment, governance, and energy efficiency. The fact that energy availability tops the list, followed by infrastructure and energy prices, is not surprising. What is more interesting is that the remaining four

[3] An example is the Stuxnet worm that was detected in Iran's nuclear power plants in September 2011. It was reported that other countries affected were Indonesia, India, Azerbaijan and the US [107].

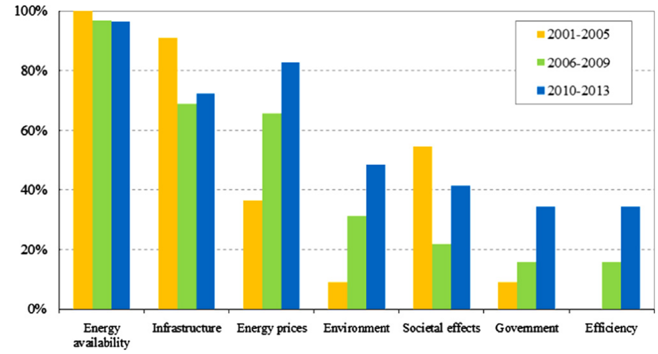


**Fig. 3.** Coverage of each energy security theme in energy security definitions by time period.

themes are taken into account in a reasonably large number of definitions.

### 3.2. Changing emphasis over time

As global energy, economic, and geopolitical landscape evolve with time, the national focus, concerns and perception of energy security continues to shift. It is thus of interest to study possible changes with regards to the emphasis on the energy security themes. Fig. 3 shows the percentage of the definitions which include each theme by time period.

The importance of energy availability has changed little over time. It is taken into account in nearly all definitions in all time periods. Infrastructure is high on the list within the first time period. Energy prices, which are closely linked to international oil prices, displayed an increasing trend of interest over the periods of study. Environmental issues were covered in only one out of the eleven definitions in the first period but almost one in every two over the third period. This development is particularly interesting as it shows the growing importance and emphasis of the environmental dimension, in particular climate change, in energy security discussions. The importance of societal effects dropped from the first to the second period, after which a reversal was observed. Governance and energy efficiency were covered in few or none of the definitions in the first period, but they were included in about one-third of the definitions in the third period.

From the above, energy availability is without doubt the top consideration in energy security definitions. At the same time, the number of themes or dimensions incorporated has increased over time. The coverage has become more comprehensive and encompassing, and issues related to the environment, governance and energy efficiency have gained in importance. This development indicates that while ensuring a secure energy supply remains utmost important, there is a growing need or awareness to utilise energy resources in an environmentally-friendly and prudent way as well as with good governance. In short, issues related to energy security have over time become more complex.

What is incorporated in an energy security definition generally dictates the scope and focus of an energy security study. It may be concluded that energy security has increasingly been evaluated in a more holistic and integrated manner. At the same time, it is clear that there are close linkages between some of the seven energy security themes, for instance, the trade-offs between energy supply and the environment dimension, and between energy supply and the society effects. Some of these issues will be discussed in Section 6. This also implies that the analysis of energy security increasingly necessitates a systems approach or viewpoint.

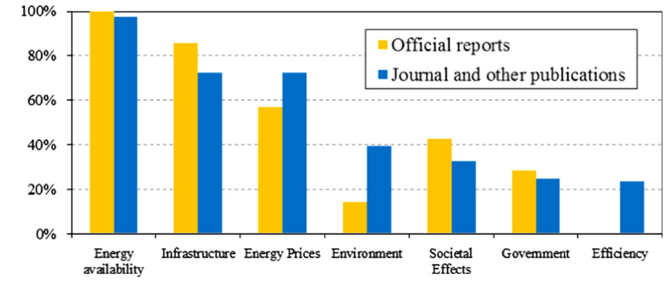


**Fig. 4.** Coverage of each energy security theme in energy security definitions by publication type.

### 3.3. Other observed features

The definitions of energy security from 2001 to 2014 are stratified according to their sources, and the results obtained are shown in Fig. 4. It is observed that the differences between definitions employed in official reports as compared to those used in other publications are relatively small. Nevertheless, there is less emphasis on the environment and energy efficiency dimensions in official reports, and it is possible that these two issues are considered under government portfolios outside the energy ministry and are looked into separately from energy security policies. Official reports are more concerned with infrastructure issues and societal effects which appear to be reasonable as these are more immediate and localized problems for policymaking. Although not shown in Fig. 4, there is a strong preference for quantitative studies among official reports, and energy security indicators or indexes are proposed in all these reports.[4]

The 83 energy definitions can also be divided into two groups: quantitative and qualitative studies of energy security which respectively account for 51 and 32 of the definitions. Quantitative studies are those in which numerical indicators or indexes are proposed to track energy security performance. One would expect that in order to quantify energy security, the focus of a quantitative study is more likely to be on attributes which are measurable, such as energy prices and energy intensity. On the other hand, qualitative studies may explore issues such as geopolitics and governance which are difficult to quantify. The results obtained, as shown in Fig. 5, indicate that the percentages for both quantitative and qualitative studies are quite similar for each theme, and there is no strong evidence to suggest that the themes considered are different between the two groups. One could therefore treat quantitative studies as an extension of qualitative studies with appropriate indicators or proxies used to represent factors that are qualitative in nature.

## 4. Quantifying energy security performance

Using energy security indicators or indexes to gauge energy security performance or risk of a country has been growing in popularity. Energy security is difficult to measure using a simple indicator. Instead, it is often studied using a basket of indicators (or metrics) that represent the various dimensions it encompasses based on a specific framework.[5] Each of these indicators is given a certain weight according to its perceived importance and an appropriate aggregation technique is used to combine them to give

[4] The results reported here are based on only seven official reports. Due to the small sample size, they must be interpreted with caution.

[5] Examples of indicators which are commonly used in these studies are energy intensity (the ratio of primary energy consumption to GDP), international oil prices, diversity measures for sources of energy supplies or fuel mix such as the Herfindahl–Hirschman index (HHI), and carbon emission indicators.

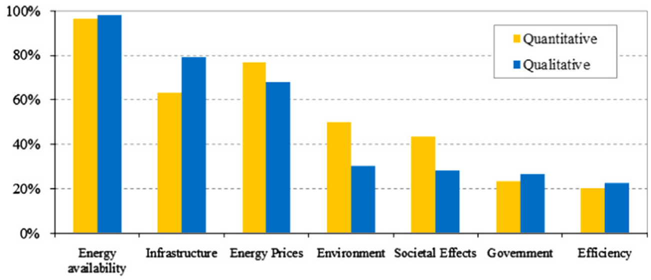


**Fig. 5.** Coverage of each energy security theme in energy security definitions for quantitative and qualitative energy security studies.

an index. The energy security indexes derived in this way are termed as composite indexes.[6] A number of organisations and national energy agencies have created energy security indexes using this approach and use them for policy evaluation and analysis. The "Index of U.S. Energy Security Risk" and "International Index of Energy Security Risk" proposed by the Institute for 21st Century Energy [74,75] are examples of such indexes.

There is a high degree of subjectivity in energy security index construction. The accounting framework used, including the choice of indicators and the weights assigned, can be fairly arbitrary. Data availability and quality issues often arise, and in some studies inputs through surveys or expert opinion are sought. Despite these drawbacks and difficulties, some studies point out that the indexes are useful for a number of purposes, such as in country self-assessment, tracking progress, scenario analysis, and cross-country comparisons. For example, a country can use the index to quantify and track the impacts of some developments, such as the discovery or development of a new and major energy source, increases in international oil prices, energy diversification, and energy efficiency improvement efforts.

Attempts to measure energy security performance using indicators and indexes are reported in 51 out of the 104 energy security studies shown in Table 1. The number of such studies has increased over time. Of the 42 energy security studies published in 2008 or earlier, 13 (or 31%) deal with some energy security indicators or indexes. The corresponding figure for the 62 post-2008 studies is 38 (61%). The growing interest in energy security assessment using some quantitative measure is in line with the development in several other areas of energy studies, such as in economy-wide energy efficiency assessment [110].

The publications in Table 1 that deal with energy security indicators and indexes are reproduced in Table 2 in which a number of features of interest are shown. The second column of the table gives the name of the energy security indicator or index as it is given in the source. The third column summarizes the energy security dimensions or issues covered. From these two columns, it can be seen that great diversity exists among studies on how energy security indicators/indexes are named and on the focused areas in the development of these indicators/indexes. For example, the study by the UK Department of Trade and Industry [3] focuses on market issues and forecasts, whereas the Institute for 21st Century Energy [75] studies energy security with eight focused dimensions. These diversities lead to very low comparability among studies. Even for the same country, different conclusions could be drawn from different studies.

Other features summarised in Table 2 are the number of indicators used, type of study (time-series or spatial), specific focused areas in index construction, and the methods used in composite index construction. All these features are discussed in the sub-sections that follow except the last, which is dealt with in Section 5.

### 4.1. Number of indicators

As shown in Table 2, the number of energy security indicators ranges from one to as many as 68.[7] The distribution is shown in the plot in Fig. 6 where each dot represents a study. About 75% of the studies employ no more than 20 indicators. Studies with over 40 indicators include Augutis et al. [59] and Augutis et al. [69], where 61 and 68 indicators are presented respectively. The relatively large numbers are due to the use of very specific indicators (i.e. technical indicators related to nuclear energy) for each energy technology. In Scheepers et al. [29], 63 indicators are presented as the EU standards for studying energy supply security. At the other extreme, studies with only a handful of indicators tend to use complex indicators that take in multiple data points. An example is the geopolitical energy security measure (GES) in Blyth and Lefevre [6] which combines market concentration risk, political stability, and market liquidity into one measure. Another is the risky external energy supply (REES) indicator proposed by Le Coq and Paltseva [50] which is based on import fuel shares, fungibility of imports, political risk, distance between supplier and consumer countries, and import dependency.

When the number of indicators used is small, the energy security index is generally very sensitive to changes in any of the indicators. A change in an indicator level may lead to a large swing in the index and this may lead to the issue of index stability. Conversely, when number of indicators used is large, changes in individual indicators may be muted out by the majority of unchanging indicators. In the literature, the more widely accepted practice seems to be using a representative set of indicators that can produce a broad overview of the energy security situation. This provides a balance between stability and sensitivity of the index. A basket of 10 to 25 indicators should be reasonable, as this translates into an average weight ranging from 4% to 10% for each indicator (assuming all the indicators are assigned equal weight). In practice, the appropriate or "ideal" number will depend on, among other factors, the scope and complexity of a study, such as whether sub-indexes are constructed on top of the overall energy security index. For example, Institute for 21st Century Energy [74] uses 34 indicators. Other than the overall "Index of U.S. Energy Security", the study also provides four sub-indexes, respectively for the geopolitical, economic, reliability, and environmental dimensions. Data availability and quality is another determining factor. In ERIA [71], which deals with energy security in East Asian countries, data are not available for some of the indicators for a number of countries.

### 4.2. Temporal versus spatial studies

Studies of energy security can be broadly classified as temporal and spatial types of studies. In the former, energy security is evaluated for two or more years and changes over time can be studied. In the latter, comparisons are made between countries. In our survey, the number of temporal studies and that of spatial studies are about equal, or 29 and 27, respectively. Further analysis shows that there is no significant difference in the number of indicators used between both types of studies. Seventeen studies include both temporal and spatial analyses. In these studies, it is possible to discern whether countries are converging or diverging

[6] See, for example, Nardo et al. [108] and Dobbie and Dail [109] on composite index construction.

[7] In Table 2, Sovacool [65] listed 200 energy security indicators; however these were not implemented in totality for a single country or region.

**Table 2**
Studies incorporating specific energy security indicators and indexes. The following notations are used: temporal (T), spatial (S), projection (P), 4As (I), specific energy supply (II), economic (III), environmental (VI), social (V), others (VI), normalization (N), weighting (W), and aggregation (A); under SFA, primary area (p), secondary area (s); under normalisation (N), min–max (m), distance to a reference (r), standardization (z), others (o); under weighting (W), equal weights (1), import/fuel share (2), PCA (3), AHP (4), DEA (5), others (6), under aggregation (A), additive (+), others (o).

| Source | Name of indicator/ index | Energy security dimensions/issues considered | No. of indicators | Type of study | | | Specific focused area (SFA) | | | | | | Index construction | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | T | S | P | I | II | III | IV | V | VI | N | W | A |
| DTI [3] | Security of supply indicators | Supply and demand forecasts; market signals; market response | 11 | | | × | | | × | | | × | | | |
| Blyth and Lefevre [6] | Geopolitical energy security proxy measure; power system reliability proxy measure | | 2 | | × | × | | | | | | | | 2 | + |
| Onamics [10] | aggregate country index | Energy supply diversity; internal political and economic stability; domestic energy efficiency | 12 | | × | | | | × | | | × | | 1 | + |
| Sovacool and Brown [17] | Energy sustainability index | Oil security; electricity reliability; energy efficiency; environmental quality | 10 | × | | | | × | | × | | × | | | |
| IAEA [20] | Energy indicators for sustainable development | Equity; health; energy use and production patterns; security | 31 | × | | | | | | | | × | | | |
| IEA [21] | Energy security index | Energy price; physical availability | 2 | | × | × | s | | p | | | × | | | |
| Intharak et al. [22] | Energy security indicators | Availability; accessibility; acceptability; affordability | 16 | | × | × | p | | s | | | | | | |
| Wu and Morisson [23] | Energy insecurity index | | 3 | × | × | × | | | | | | | | 6 | + |
| Scheepers et al. [29] | Crisis capability index; supply/demand index | Crisis capability; demand/supply | 63 | | × | × | | | | | | × | | | |
| Streimikiene et al. [31] | Energy indicators for sustainable development (EISD) | Economic; environmental | 12 | × | × | | | | × | × | | | | | |
| Frondel and Schmidt [34] | Energy supply risk indicator | Crude oil; natural gas | 1 | × | × | | | × | | | | | o | 2 | + |
| Gnansounou [35] | Composite index of vulnerability | | 5 | | × | | | | | | | | m | 3 | o |
| Gupta [36] | Oil vulnerability index | | 7 | | × | | | × | | | | | m | 3 | + |
| Patlitzianas et al. [41] | Sustainable energy policy indicators | Security of energy supply; competitive energy market; environmental protection | 36 | | | | × | | × | × | | | | | |
| Augutis et al. [43] | Lithuanian power energy supply security | Technical, economic; socio-political; environmental | 22 | × | | × | | | × | × | × | × | o | 6 | + |
| Greenleaf et al. [45] | Energy security indicators | Based on root causes such as extreme events, insufficient investments in new capacity, load balancing failure, supply shortfall, etc. | 11 | | × | × | | | | | | × | | | |
| Jansen [47] | Energy services security indicators | Reliability; energy costs; policy framework; public acceptance | 38 | | | | | | p | | s | × | | | |
| Le Coq and Paltseva [50] | Risky external energy supply (REES); contribution to EU risk exposure (CERE) | Oil; gas; coal | 2 | | × | | | × | | | | | o | 2 | + |
| Cabalu [52] | Composite gas supply security index (GSSI) | | 4 | × | × | | | | | | | | m | 6 | o |
| Lefèvre [54] | Energy security price index (ESPI); energy Security physical availability index (ESPAI) | Price; physical availability | 2 | × | × | × | s | | P | | | | m | 6 | + |
| Löschel et al. [55] | Ex-post and ex-ante indicators | Ex-ante; ex-post | 2 | × | × | | | | | | | × | o | | |
| Sovacool and Brown [57] | Energy security index | Availability; affordability; energy and economic efficiency; environmental stewardship | 10 | × | × | | p | | S | s | | s | z | 1 | + |
| Vivoda [58] | Energy security assessment instrument | Energy supply; demand management; efficiency; economic, environmental; human security; military security; domestic socio-cultural-political; technological; international; policy | 44 | | | | | | × | × | × | × | | | |
| Augutis et al. [59] | Energy security level | Technical; economic; socio-political; energy sources | 61 | × | | × | | s | P | | s | p | o | 1 | + |
| Cohen et al. [61] | Diversification of oil and natural gas supplies; global and country-specific diversification indices | Crude oil; natural gas | 2 | × | × | | | × | | | | | | 2 | + |
| Ediger and Berk [62] | Oil import vulnerability index | | 4 | × | | | | | | | | | m | 3 | + |
| Jewell [63] | IEA model of short-term energy security (MOSES) | Crude oil, oil products, natural gas, coal, biomass and waste, biofuels, hydropower, nuclear power | 35 | | × | | | × | | | | | | | |
| Sovacool [65] | Metrics and indicators for Asian energy security | availability; dependency; diversification; decentralization; innovation;, investment; trade; production, price stability; affordability; governance; access; reliability; literacy; resilience; land use; water; pollution; efficiency; greenhouse gas emissions | 200 | | | | p | | S | p | | × | | | |

**Table 2** (*continued* )

| Source | Name of indicator/ index | Energy security dimensions/issues considered | No. of indicators | Type of study | | | Specific focused area (SFA) | | | | | | Index construction | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | T | S | P | I | II | III | IV | V | VI | N | W | A |
| Sovacool et al. [67] | Energy security performance | Availability; affordability; technology development and efficiency; Environmental sustainability; regulation and governance | 20 | × | × | | p | | S | p | | | m | 1 | + |
| Angelis-Dimakis et al. [68] | Overall sustainability index | social; economic; environmental | 9 | × | | | | | × | × | × | | m | 1 | + |
| Augutis et al. [69] | Energy security level | Technical; economic; socio-political | 68 | × | | × | | | × | × | × | | o | 1 | + |
| ERIA [71] | Energy security index | Development of domestic resources; acquisition of overseas resources; transportation risk management; securing a reliable domestic supply chain; management of demand; preparedness for supply disruptions; environmental sustainability | 16 | × | × | | | | | | | × | | | |
| Dunn and Dunn [70] | W&J energy index | | 1 | × | | | | | | | | | o | 2 | + |
| Hughes [73] | Energy security indicators | Availability; affordability; acceptability | 3 | | | | p | | S | | s | | | | |
| Institute for 21st Century Energy [74] | Index of U.S. energy security risk | Geopolitical; economic; reliability; environmental | 37 | × | | × | | | × | × | | × | r | 6 | + |
| Institute for 21st Century Energy [75] | International energy security risk index | Global fuels; fuel imports; energy expenditures; price and market volatility; energy use intensity; electric power sector; transportation sector; environmental | 28 | × | × | | | × | × | × | | × | r | 6 | + |
| Martchamadol and Kumar [76] | Energy security indicators | Energy demand; availability of energy supply resources; environmental concerns; energy market; energy price/cost/expenditure | 19 | × | | × | s | | P | p | | × | z | 3 | + |
| Sheinbaum-Pardo et al. [78] | Mexican sustainability indicators | Social; environmental; economic | 8 | × | | | | | × | × | × | | o | 1 | + |
| Winzer [80] | Energy security levels | Sources of risk; scope of the impact measure; severity filter | 8 | × | × | | | | | | | × | o | | |
| WEF [81] | Energy architecture performance index (EAPI) | Economic growth and development; environmental sustainability; access and security of supply | 16 | × | × | | s | | P | p | | | o | 1 | + |
| WEC [82] | Energy sustainability index | Energy security; social equity; environment impact mitigation; political strength; societal strength; economic strength | 21 | × | × | | | | × | × | × | × | o | 2 | + |
| Wu et al. [83] | Composite index of China's energy security | Energy supply security; energy using security | 14 | × | | | | | | | | × | m | 4 | + |
| Chuang and Ma [85] | Multi-dimensional energy security indicators | Dependence; vulnerability; affordability; acceptability | 7 | | | × | p | | S | | | × | | | |
| Selvakkumaran and Limmeechokchai [90] | Energy security indicators | Oil security; gas security; sustainability | 15 | | × | × | | × | | × | | | | | |
| Sovacool [91] | Energy security index | Availability; affordability; efficiency; sustainability and governance | 20 | × | × | | p | | S | s | | × | | 1 | + |
| Sovacool [92] | Energy security index | Availability; affordability; technology development and efficiency; environmental sustainability; regulation and governance | 20 | × | × | | p | | S | p | | × | | 1 | + |
| Zhang et al. [93] | Oil import risk index | External dependence; supply stability; trade economy; transportation safety | 8 | × | | | | | × | | | × | m | 5 | + |
| Jewell et al. [95] | Indicators of energy security | Sovereignty; resilience | 19 | | | × | | | | | | × | | | |
| Kamsamrong and Sorapipatana [96] | Energy supply security index | Physical energy security; economic energy security; environmental sustainability | 5 | | | × | s | p | P | | | | m | | o |
| Portugal-Pereira and Esteban [99] | Electricity security of supply indicator | Availability and reliability of the electricity generation and supply systems; technological development; global environmental sustainability; local environmental protection | 9 | | | × | p | | P | | | × | | | |
| Ranjan and Hughes [100] | Energy security index | Diversity; availability; affordability; acceptability | 4 | | | | p | | | | | × | o | | |
| Sharifuddin [101] | Core aspects of energy security for Malaysia | Availability; stability; affordability; efficiency; environmental Impact | 35 | × | × | | p | | S | | | × | z | 2 | o |
| Yao and Chang [103] | Energy security status | Availability of energy resources; applicability of technology; acceptability by society; affordability of energy resources | 20 | | | | p | | S | s | | × | o | 1 | o |

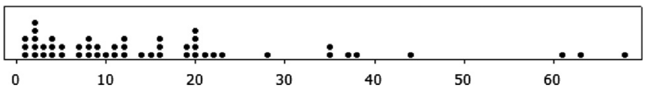


**Fig. 6.** Distribution of the number of indicators for 51 energy security studies.

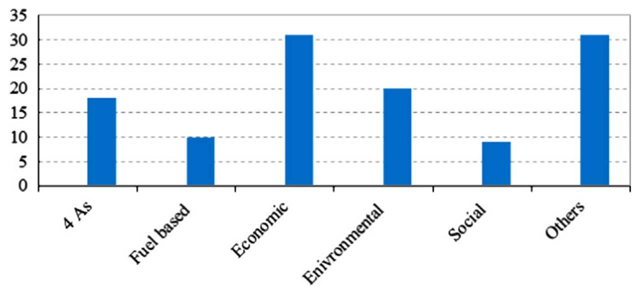


**Fig. 7.** Number of studies focusing on each SFA in energy security index development.

in energy security performance. The International Energy Security Risk Index in Institute for 21st Century Energy [75] is one such study. Fifteen studies include projections or scenarios to study energy security for the future. In some studies projections are made based on the IEA World Energy Outlook reference scenarios.[8] Others such as the ECOFYS report [45] design specific baseline and policy scenarios to predict the effects of different policies on future energy security performances.

### 4.3. *Specific focused areas in index construction*

As already pointed out, energy security indexes are often constructed with specific areas of concern. For example, a country-specific study tends to focus more on issues that are relevant to the country while a multi-country study will deal with issues that are of general concern. For simplicity, we shall refer to the primary areas of concern that a study takes into account in index construction as "specific focused areas" (SFAs). We have made an attempt to identify SFAs based on the indicators and indexes in the surveyed studies. Five such areas can be identified and we shall refer to them as SFA-1 to SFA-5, where SFA-1 focuses on 4As (see below), SFA-2 on specific energy supply, SFA-3 on the economic dimension, SFA-4 on the environmental dimension, and SFA-5 on the social dimension. It is not surprising that these SFAs are closely linked to the themes on energy security definitions identified in energy security quantification. A description of each SFA follows.

The 4As in SFA-1 refers to availability (availability of energy resources), accessibility (issues such as geopolitical, geographical, workforce, technological and other constraints that limit the extract of energy resources), acceptability (the environmental concerns such as energy-related carbon emissions and the environmental impacts of energy systems), and affordability (closely linked to energy prices). Since its introduction in Intharak et al. [22], SFA-1 has been adopted in a number of studies.

SFA-2 focuses primarily on individual energy sources. The study by Le Coq and Paltseva [50], which deals with the external energy security supply in the European Union, is an example. In this study, a Risky External Energy Supply Index was calculated for each fossil fuel type. These indexes allow analysis of energy security issues surrounding each energy type to facilitate the identification of threats. An aggregate index for total primary energy supply can be formed by weighting the indexes of individual energy sources.

As increases in energy prices will have an economic impact, many energy security indexes include an economic dimension (SFA-3). To some extent, this is similar to the affordability dimension of SFA-1. However, studies classified under SFA-3 are generally broader and have more economic-related indicators. For example, Streimikiene et al. [31] use a total of 11 indicators for the economic dimension, including the aggregate energy intensity and energy intensity of various economic sectors.

With the growing importance of sustainability, environmental and sustainability indicators have increasingly become part of the energy security consideration, and environmental concerns (SFA-4) have become a focused area of energy security indexes in some studies. In the energy security index proposed by Sovacool [91], environmental sustainability is included as a dimension and within the dimension are indicators on land use, water, climate change and pollution.

Social issues (SFA-5) are important in countries where energy poverty or electricity connectivity is a major concern. In constructing an energy system assessment for measuring the sustainability of the Greek energy system, Angelis-Dimakis et al. [68] use three indicators to form the social dimension. The indicators are the share of households with access to commercial energy sources, the share of household income spent on energy, and the share of household expenditure spent on energy for each income group.

Apart from the five SFAs, there are other dimensions or perspectives that are associated with some studies. For completeness, we introduce SFA-O as the category "others" in which the areas of concern are not covered in the five SFAs. These areas include, for example, the crisis capability and demand and supply dimensions in Scheepers et al. [29], and the root cause and market structure approach in Greenleaf et al. [45] and Wu et al. [83] in which the indicators are simply divided into "energy supply security" and "energy using security".

Based on the above classification, the SFAs for each of the 53 studies in Table 2 have been identified and they are shown in the table. More than one SFA may be covered in the construction of an energy security index. For example, in Intharak et al. [22], the primary area is SFA-1. This, however, entails a special consideration given to the economic dimension (SFA-3). In the Energy Sustainability Index introduced by the World Energy Council [101], consideration is given to the economy (SFA-3), environmental (SFA-4), social (SFA-5), and other factors (SFA-O) such as political strength. Where there is a distinction between SFAs in terms of importance in a study, the most or more important one is denoted as "p" (primary) while the other as "s" (secondary) in Table 2.

Based on the above classification, the tally for the six SFAs is shown in Fig. 7. Ignoring SFA-O, it can be seen that economic dimension (SFA-3) appears to be the most important focused area, followed by environmental concerns (SFA-4), 4As (SFA-1), energy supply (SFA-2), and the social aspect (SFA-5), in descending order. Further analysis shows some evidence that the focused areas as captured by SFAs in a study are dictated by the concerns and priorities of the stakeholders of the study. For instance, the 4As concept in SFA-1 is usually used in cross-country comparisons as it compares countries across various dimensions for a balanced analysis. Studies with SFA-2 normally deal with fossil fuels, in particular oil and natural gas, and hence involve major oil and gas importers, or countries that depend on other major energy sources such as nuclear energy in some cases [59,63]. The relatively large number of studies associated with SFA-4 validates our earlier findings that the environmental dimension is increasingly given

[8] The reference scenarios given in various editions of IEA World Energy Outlook may be referred to in these studies. The 2013 reference scenarios can be found in [111].

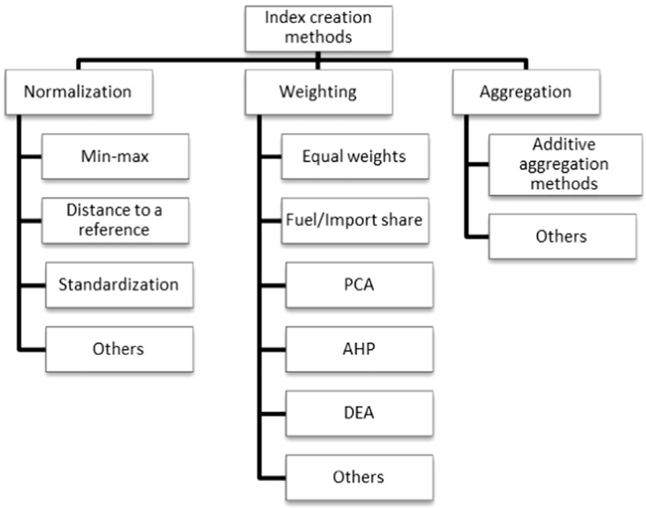


**Fig. 8.** Normalisation, weighting and aggregation methods in energy security index construction.

more attention in energy security assessment. The social dimension (SFA-5) is usually associated with countries which have a less advanced energy system where energy poverty is a major problem.

The foregoing shows the great diversity of studies dealing with energy security indicators and indexes in terms of focused areas. The manner in which an energy security index is constructed ultimately determines what it measures and constitutes and what are being left out. If care is not taken to ensure a comprehensive index is produced, certain energy security problems might not surface from the analysis of such an index. Indexes can also be crafted to further the interest of certain groups. For example, environmentalists would focus more on SFA-4, whereas business interests would argue that SFA-3 should be given a higher priority. It is therefore important to define the energy security issues to be analysed, i.e. how energy security is defined as dealt with in earlier sections, to ensure that a study is meaningful and can adequately serve the intended purposes in energy security index construction.

At this stage, a preliminary conclusion from the analysis of SFAs is that the discussion of energy security is largely concerned with the contentions between the economic dimension (SFA-3) the environment dimension (SFA-4). This is the issue of the "energy trilemma", namely energy security, economic competitiveness, and environmental sustainability.[9] Apart from that, many studies go beyond the energy trilemma and include other aspects of concern to stakeholders, such as political stability [10], health [20], and crisis response [29].

## 5. Energy security index construction

Having framed the energy security definition and SFAs, selected the appropriate indicators, and collected the requisite data, three additional steps are needed to arrive at a composite energy security index. They are (a) normalising the indicators, (b) weighting the normalised indicators, and (c) aggregating the normalized indicators. Depending on the method chosen, these three steps may involve a series of computations, during which adjustments and refinement may be made to the index construction framework. The methods that can be applied in each step are summarised in Fig. 8. Additional information about these methods can be found in [108]. From our literature survey, normalisation is dealt with in 28 studies, and weighting and aggregation in 30 and 31 studies respectively. These studies are indicated in Table 2 in which some related information is also provided.[10]

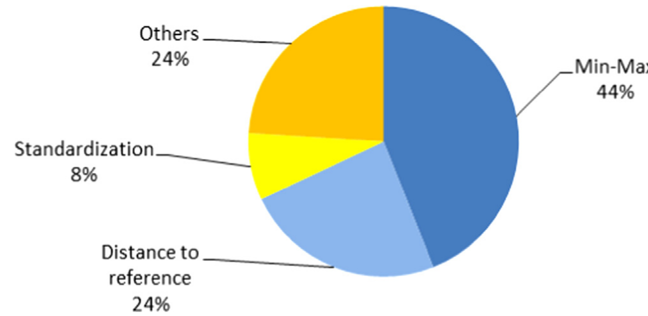


**Fig. 9.** Distribution of normalisation methods in energy security index construction.

### 5.1. Normalization

The selected indicators usually have different units and are on different scales. Transformation is needed before they can be aggregated to form a composite index. The common practice is through normalisation using one of the following three methods: Min–max, distance to reference, and standardization. The min-max method involves taking the minimum and maximum values observed to form a scale, following which other values are placed with reference to these values. An advantage of this method is its ability to gauge performance based on the best and worst performance, while a drawback is the need to recalibrate when additional data points are added. The distance to reference method measures the deviation of an indicator from a benchmark. Different benchmarks may be chosen as reference points and comparisons are straightforward based on the distance from the selected benchmark. A drawback is that the results obtained may be very sensitive to the benchmark chosen. In the standardization method, the indicators are often normalised through the well-known *z*-transformation where scaling is based on deviation from the mean. This method is attractive when comparisons are made among countries. The drawbacks are that the sample size should be sufficiently large and recalibration is needed when new data points are added.

The breakdown by normalisation method for the 28 studies is shown in Fig. 9. The min–max method is the most popular method. As an example, Cabalu [52] calculates the relative indicators for gas intensity of countries using this method. The second most popular method is the distance to reference method, followed by standardization. The study by the Institute for 21st Century Energy Institute for 21st Century Energy [74] takes the 1980 value as reference for each indicator, and Sovacool and Brown [57] use the *z*-score method. Eleven of the 28 studies, or 39%, use some other methods. For example, one such method, proposed by Augutis et al. [59], involves constructing a scale that determines the normal, pre-critical and critical state for each indicator. It may be concluded that energy security indicators has been normalised in a number of different ways and none of them has really played a dominant role.

[9] The energy trilemma will be dealt with in Section 6.

[10] It is observed that in some studies normalisation is skipped. In a number of studies, the indicators are normalised but not weighted and aggregated to form indexes.

### 5.2. Weighting

The weights of the indicators can be assigned based on expert opinions or other subjective procedures. The inputs of experts or stakeholders are sought through various knowledge elicitation methods such as surveys, interviews or through more established methods such as the Delphi method. Weights can also be computed using specific algorithms from the data collected for the indicators. In this way, subjective opinions are not introduced but a common criticism of such methods is that they are only consider the variability in the data and have no real theoretical underpinnings or relation to the actual scenario.

More specifically, in Fig. 8, the first or equal weights method is simple but there is no differentiation in terms of the importance of an indicator. The fuel/import share method takes into account the relative importance of each fuel type in energy mix or imports but it is clearly not suitable for non-fuel indicators. The principle component analysis (PCA) method corrects overlapping information between correlated indicators and the importance of an indicator is not considered. Analytic hierarchy process (AHP) is based entirely on expert opinion. In data envelopment analysis (DEA), a benchmark is established to measure the performance of multiple countries and thus it is not useful for studies that involve a single country or only a few countries.

Fig. 10 shows the breakdown by weight assignment method for the 30 studies. Assigning equal weights to all indicators appears to be the most common approach, and it accounts for over a third of the studies. Quantitative methods such as the fuel consumption or fuel import share and PCA are also quite popular, and they altogether make up close to 40% of the studies. AHP, DEA, and all other methods account for the remaining quarter. Again, the preferred weighting method in the literature varies substantially among studies. The fact that assigning equal weights is the most widely adopted does not necessarily mean that it is the best method. Rather, this is more of an indication that it is convenient to be treated as the "default" method due to its simplicity or the difficulty of coming up with an alternative that is superior and acceptable to all stakeholders.

### 5.3. Aggregation

Aggregation involves combining the weighted indicators into a composite index. In some studies, indicators are first combined into sub-indexes, which are further aggregated into a main index using another set of weights for the sub-indexes. The simplest and most popular aggregation method is the additive aggregation method, where the indicators are first multiplied by the weights assigned and then summed to arrive at the index. It is used in 83% of the energy security indexes that aggregates their indicators. The remaining 17% of indexes use some other methods including, for example, the root mean square of indicators to produce the index. Concerns about aggregation that have been brought up include loss of information and increasing the complexity of energy security issues through artificial manipulations.

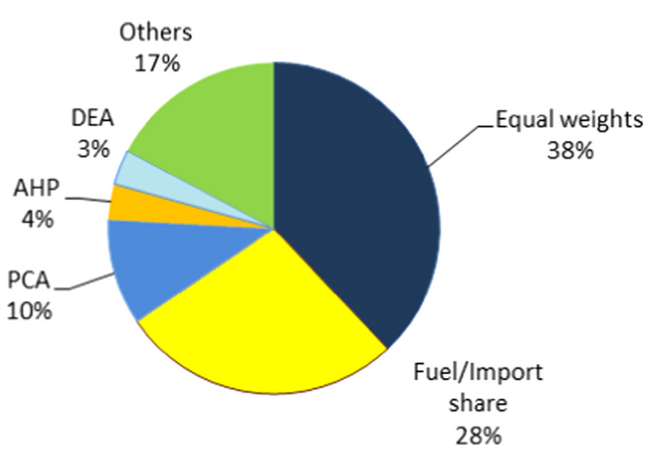


**Fig. 10.** Distribution of weight assignment methods in energy security index construction.

**Table 3**
Normalisation versus weighting methods as they have been used in energy security index construction, where the numerical value denotes number of studies.

| *Weighting method* | *Normalisation method* | | | |
|---|---|---|---|---|
| | Min–max | Distance to reference | Standardization | Others |
| Equal weights | 2 | – | 2 | 5 |
| Fuel share/import share | 1 | – | – | 3 |
| PCA | 3 | – | 1 | – |
| AHP | 1 | – | – | – |
| DEA | 1 | – | – | – |
| Others | 2 | 2 | 1 | 1 |

### 5.4. Other index construction issues

Table 3 shows the linkages between normalization and weighting methods for the surveyed studies. It shows the preference among researchers in using these two groups of methods together. The most striking feature is the great diversity observed. There is clearly no consensus as to which is the "best" combination of normalisation and weighting methods. Even the most popular pairing, i.e. PCA normalization and equal weights, is only marginally more than several other combinations.

There are many indexing methods which have been adopted in other fields but not in energy security index construction. They include indicators above and below the mean and percentage annual differences over consecutive years for normalisation, unobserved components methods, budget allocation process, public opinion and conjoint analysis for weighting the indicators, and geometric aggregation and non-compensatory multi-criteria approach for aggregation. There is considerable scope for further research and development with regards to the methodological aspect in energy security index construction.

From a technical perspective, energy security index research and development is still in the stage of infancy. Most existing work is limited to applying very simple indexes to perform a small set of scenario analyses. Uncertainty and sensitivity analysis techniques for assessing the quality of composite indexes as proposed in [112] has seldom been applied. Furthermore, in practice, inferences drawn from the indexes can become very sensitive to the fidelity of the input data. Although some authors, such as Dobbie and Dail [109] propose the use of simulations to perform sensitivity analysis on the index level and associated rankings, these are essentially *post-mortem* analysis that cannot pro-actively hedge against the effects of data ambiguity. Thus an important area of future research is in the development of robust data-driven energy security indexes that are immunized against various practical input uncertainties.

## 6. Energy trilemma

At the national or supra-national level, it is not sufficient to deal with energy security in isolation of other important energy issues. A more holistic view calls for policies to address multiple competing energy goals, such as the concept of the "energy trilemma" [82].

Energy trilemma is defined as balancing the trade-offs between three major energy goals, namely energy security, economic competitiveness, and environmental sustainability. Although there is due consideration for the economic and environmental dimensions of energy security as pointed in Section 4.3, a formal treatment in the energy security literature of the concept of energy trilemma in a comprehensive and rigorous manner is lacking.

Fig. 11 depicts a schematic of the energy trilemma, in which there are overlapping portions between energy security and the other two energy goals. For example, for a country to be economically competitive, it has to ensure that energy costs are kept reasonably low for businesses. A country would also prefer a secure and clean energy source. Some conflicts within these relationships become obvious upon further examination. For instance, to increase energy security, a country with cheap coal deposits would want to rely on this resource at the expense of environmental sustainability. Efforts to diversify energy sources may also run against the two other goals. For instance, countries which have large hydroelectric potential may want to utilize hydropower to reduce the dependence on fossil fuels. However the possible environmental degradation [91] and huge capital costs may be in conflict with the economic competitiveness and environmental sustainability goals.

Another issue is the promotion of renewables as an alternative to conventional energy sources to increase energy security. While it is true that renewables may reduce the need for energy imports and are generally more sustainable than conventional energy sources, it is plagued by issues such as intermittency and high operating costs. Biofuels may also introduce new threats to water and food security. Thus, without formulating feasible solutions to unintended consequences of relying on renewables, they may not seem as attractive as what proponents of renewable energy sources make them out to be.

These relationships between the various energy goals also highlight the broader sustainability issue. Sustainability should be the overarching principle when evaluating energy goals and policies. This is due to the fact that energy policies which may lead to high energy security in the short run may not be sustainable in the long run. However, sustainable energy policies need to fulfil the prerequisite condition of having energy security. Therefore, in policy discussions, energy security should not be considered in isolation. Instead, it should be considered in the larger context of the energy trilemma and sustainability to avoid formulating short-sighted policies which address energy security in the short run but contribute to longer-term problems.

## 7. Discussions and conclusion

Energy security is an emerging field. The number of studies reported has grown rapidly in recent years. In the literature, many

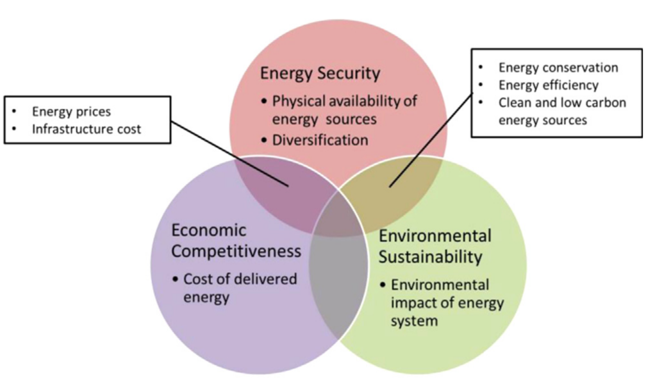


**Fig. 11.** Energy security and the energy trilemma.

definitions of energy security have been proposed. There is also a growing interest and emphasis on how it should be measured, which in turn leads to the development and use of energy security indicators and indexes. In this study, we surveyed 104 studies with a focus on how energy security has been defined, its scope and dimensions, and the indicators and indexes that have been used to measure it.

We found that, despite the large number of reported studies, comprehensive reviews on energy security definitions and indexes are few and far between. On definitions, for instance, Chester [105] analyses explicit and implicit definitions of energy security and concludes that the "concept of energy security is inherently slippery because it is polysemic in nature". Winzer [80] further reviews over 30 energy security definitions using a framework to analyse these proposed definitions according to various attributes such as sources of risk and scope of impacts. Månsson et al. [113] study the measurement of energy security using an energy supply chain perspective and show how energy security is an interdisciplinary concept and how different schools of thought measure and regard energy security differently. Attempts to outline the progress in the field of energy security indicators and indexes include the earliest study by Kruyt et al [49] which look at various indicators that have been used to measure energy security. Vivoda [58] and Sovacool [65] further build on this work by proposing over 200 indicators to enable a comprehensive measure of energy security. All these studies provide valuable insights into certain aspects of energy security definitions, or energy security indicators and indexes. A trend analysis on how the definitions have evolved and a comprehensive review on the methods to construct the indexes have not been reported in the literature so far. The main contribution of our study is therefore to bridge this gap by analysing existing energy security studies based on these two areas to facilitate further development of energy security indexes in the future.

Our study identifies 83 energy security definitions in the literature. Not surprisingly and as has already been reported in some earlier studies, there are great diversities among these definitions. After going through the 83 definitions, we have identified seven major energy security themes. A comparison of these themes and the dimensions identified in Sovacool [65] shows a high degree of agreement. Out of the six themes, energy availability is found to be the most important and is taken into account in nearly all the definitions. In addition, it is shown that the scope of energy security has expanded and issues such as environmental, governance and energy efficiency which were normally not considered in earlier years are now often covered. A larger number of themes has therefore been considered, and energy security has been viewed and treated in a more holistic manner, in more recent years. This development has implications on how energy security indexes are constructed since a more comprehensive list of indicators are needed or used as a result.

Our study also identifies 53 studies that deal with energy security indicators. The number of indicators used varies significantly, from a few to more than 60, among studies. About two-thirds of the studies employ no more than 20 indicators. About one-third of the surveyed studies published in 2008 or earlier incorporated energy security indicators. The proportion increases to about two-third for the post-2008 studies. There are two major types of studies that use energy security indicators: those that deal with performance over time and those that compare performance among countries. In the literature, the numbers of studies are about the same for both types. There is no significant difference in the number of indicators used for both types of studies. A number of studies include projections or scenarios to predict energy security for the future. We have defined five major "specific focused areas" based on which energy security indexes have been constructed. The economic dimension is found to be the top focused area. Interesting, the environmental dimension fares fairly well and ranks second. This shows the strong linkages among the three goals of the energy trilemma in the context of energy security index construction. In terms of the steps in index construction, our analysis on the normalisation, weighting, and aggregation methods used show great diversities among studies. The min–max method in normalisation is found to be the only one that is more commonly applied. Diversities in the choice of indexing methods, number of indicators used, and specific focused areas lead to very low comparability among studies on energy security indexes.

Some recommendations can be made on the paths forward and further work. First, the definition of energy security should be revisited periodically to ensure that it remains relevant. With ever changing environment and new developments in the energy field, energy security as a context-dependent concept will need to be revised regularly to reflect changes in priorities or newly emerged threats. However, there are very few studies that explore perceptions on energy security and how they can change over time. In addition, it has been shown in some studies that the definition of energy security can be manipulated to promote various causes of action even within a single country. Hence, a possible future research area is to determine whether there is a correlation between a country's national circumstances, such as resource endowment, level of economic development and other factors, and how energy security is defined. Another interesting question that can be further explored is the difference between how governments and the general public conceptualize energy security and their willingness to pay to improve energy security.

Second, as has been pointed out, energy security index research and development is still in the stage of infancy from a methodological perspective. A widely accepted procedure for constructing energy security indexes does not exist as yet. This opens up considerable scope for further research. There are several new areas that can be explored, including the use of simulation and other methods to improve the robustness of composite energy security indicators and also the interaction of different normalisation, weighting, and aggregation and its effects on the results obtained. Further research may be conducted to develop indexes that are robust against practical data ambiguities, such as incomplete information and missing data. It is unlikely that a "standard" procedure will emerge in the near future for energy security index construction. There is therefore a need for researchers and analysts to have a better understanding of the various analytical methods that are available to them, including their strengths and weaknesses, in energy security index construction. In most cases, the suitability of an analytical method is context and data dependent. Hence, the energy system of the country studied, the study objective and the quality of the data available need to be carefully analysed to ensure that the method used is appropriate. The same issues apply to multi-country studies in which case certain trade-offs are likely to be made. Along this line, further work that looks into the impacts of different indexing methods on energy security index construction and devises guidelines on energy security index construction for practitioners will be an attractive research area.

Lastly, it is clear that energy security cannot be considered in isolation when energy policies are formulated. In general, for any country, competing energy goals forming the energy trilemma should be considered to ensure that balanced and sustainable energy policies are implemented. A formal treatment in the energy security literature of the concept of energy trilemma in a comprehensive and rigorous manner is currently lacking, and this is a potential area for further work. For example, the energy trilemma concept brings about novel research areas such as the possible feedback loops within energy system and the application of a systems approach. This may bring about implications on how energy security is to be evaluated in views of the linkages of various competing ends among which energy security is one of them. For example, increases in fossil fuel prices may push economies towards nuclear energy of renewable sources of energy such as solar, increasing the diversity of energy sources and hence energy security. Such effects need to be investigated further to ascertain the overall impact such events have on the energy security of a country.

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