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Review article

# A review on energy security indices to compare country performances

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A B S T R A C T

The use of energy security indices has been increasing recently, as indicator-based approaches are particularly suitable to model multiple dimensions and compare countries. Moreover, indices represent effective communication tools for policymakers. This paper analyzes 63 indices quantifying the energy security performance of countries. In particular, their scope, geographical coverage, number of countries analyzed, time frame covered, number of indicators considered, data treatment approach, multivariate analysis, normalization, weighting and aggregation of the indicators, and the assessment of uncertainty, sensitivity and robustness are reviewed. Results show that there is a considerable lack of transparency, especially about the selection of the indicator set, normalization method, indicator weighting scheme and aggregation function. Furthermore, the index construction steps of data treatment and multivariate analysis are either not performed or under-reported. Finally, only few studies provide an uncertainty, sensitivity or robustness analysis, even though such an analysis has the potential to greatly improve the confidence into the results. Based on the findings of this paper, research gaps are identified and recommendations for future research provided. Even though the present analysis was conducted on energy security, the findings can be applied to indices in any field in order to support well-informed decision-making.

## 1. Introduction

Human civilization has become highly complex and in order for our societies to function, a reliable supply of a variety of energy sources is necessary. Raw materials are extracted and transformed into secondary products that are used for a multitude of purposes, such as transportation, heating of buildings, manufacturing, etc. Securing a reliable supply of such materials is therefore crucial for the overall well-being of a nation. Compared to ancient times when communities were living in isolation, global trade volume is steadily rising (World Trade Organization, 2018). Some of the most traded export products are processed petroleum oils and petroleum gases, with crude oil in the lead. As our societies still heavily rely on these products to function (BP, 2018), energy security has become a geopolitical issue.

Initial concerns about energy security arose in the 1970s as a result of the oil crises (Blum and Legey, 2012). Starting in October 1973, the first oil crisis exhibited the vulnerabilities of developed economies to oil price shocks (Issawi, 2015). Members of the Organization of Arab Petroleum Exporting Countries (OAPEC) introduced an oil embargo on the Netherlands, the United Kingdom, Portugal, Japan, Canada, the United States of America (USA), Rhodesia and South Africa. The reason of the embargo was the Yom Kippur War, which was not energy-related (Rabinovich, 2007). This is known as the "oil weapon", i.e. the practice of using oil as leverage for political gains. Consequently, the price of a barrel of oil rose from USD 3 to USD 12 globally. As a result, the International Energy Agency (IEA) was created in 1974 with the initial aim of responding to physical oil supply disruptions. Soon, the IEA became an international source for information and statistics about the energy sector in general (Paravantis et al., 2018). Over the years, it started to advise its member and non-member states on policymaking and grew into a leading intergovernmental organization on energy security. A similar situation happened in 1979 during the second oil crisis, in which due to the Iranian Revolution, global oil supply decreased and prices more than doubled over a period of one year (Kohl, 1982).

While initially risks were perceived in the form of conflicts between or within countries, the September 11 attacks in 2001, Hurricane Katrina in 2005 and the Russia-Ukraine gas dispute in 2005–2006 extended the awareness by including threats related to man-made and natural disasters and terrorist or cyberattacks by non-state actors (Irie, 2017). Nowadays, energy security is a matter of national security for many developed countries (Månsson et al., 2014). However, due to countries' different natural resources, political systems, economic welfare, ideologies, geographical locations, and international relations, energy security can mean different things and the priorities may vary

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(Luft and Korin, 2009). Hence, it is not surprising that a plethora of definitions do exist (Winzer, 2012).

Starting with the IEA as the most important multinational energy platform (Paravantis et al., 2018), energy security is defined as the *"uninterrupted availability of energy sources at an affordable price"* (International Energy Agency, 2014). It sees energy security as having a long-term dimension dealing with investments to supply energy according to economic developments and sustainable environmental needs and a short-term dimension focusing on the ability to cope with sudden changes in the supply-demand balance. Therefore, for the IEA, energy insecurity represents the consequences on the economy and society of a lack of physical availability of energy or unaffordable prices. The Asia Pacific Energy Research Centre (APERC) formulates the same ideas with further focus: *"energy security is the ability of an economy to guarantee the availability of energy resource supply in a sustainable and timely manner with the energy price being at a level that will not adversely affect the economic performance of the economy"* (Asia Pacific Energy Research Centre (APERC), 2007). Whereas environmental sustainability was not directly incorporated in IEA's definition but only in its related long-term dimension, the APERC explicitly mentions it. Also the European Commission agrees as it defines the energy security as the *"uninterrupted physical availability of energy products on the market, at a price which is affordable for all consumers (private and industrial), while respecting environmental concerns and looking towards sustainable development"* (European Commission, 2000). The IEA, APERC, and European Commission's views on energy security are thus focused on the following three elements:

1. The physical availability and accessibility of supply sources.
2. The economic affordability.
3. The long-term environmental sustainability.

Numerous additional authors provide definitions centered on the same elements of physical availability and affordability, with potential inclusion of environmental sustainability (e.g. (Abdo and Kouhy, 2016; Bahgat, 2006; Bielecki, 2002; Costantini and Gracceva, 2004; Costantini et al., 2007; Franki and Višković, 2015; Goldemberg, 2000; Kovačovská, 2010)).

On a similar line of thought, Yergin (1988) adds a geopolitical dimension by stating that energy security is the *"assurance of an adequate, reliable supply of energy at a reasonable price and in ways that do not jeopardize major national values and objectives"*. Also incorporating the physical availability of energy, but not explicitly mentioning price or geopolitical factors is the definition from Cherp and Jewell (2013) who describe energy security as the *"uninterrupted provision of vital energy services"*. Furthermore, politics and governmental actions are sometimes included too, as Willrich (1976) sees energy security to be the *"assurance of sufficient energy supplies to permit the national economy to function in a politically acceptable manner"* or Hughes (2006) the *"governmental actions or policies that ensure a community has access to reliable and secure sources of energy at a reasonable price"*. Additionally, some stakeholders such as the Malaysian government see energy security as being totally independent of imports: *"a situation where we enjoy self-reliance, self-contained energy supply which meets the energy consumption demand at all times without forcing the national utility to resort to harsh energy dispatch operations"* (Hashim, 2010). Finally, it is possible to express energy security with its antonym in terms of a loss: *"energy insecurity is the loss of welfare that may occur as the result of a change in price or availability of energy"* (Bohi and Toman, 1996).

Following these energy security definitions, decision-makers need to be able to derive effective policies for their countries. Hence, as a first step, they need to be able to quantify the energy security of their country in order to situate their own performance and compare it to the one from other countries. Given the multiple dimensions of energy security (Azzuni and Breyer (2017) identify 15 of them), this is not straightforward to achieve as one needs to assess all the different dimensions simultaneously. This is why indicator-based approaches are particularly suitable. As energy security is difficult to measure using one simple measure, the various indicators are meant to accurately represent the different dimensions under study (Ang et al., 2015a). Through means of Multi-Criteria Decision Analysis (MCDA) methods, it is possible to combine the individual indicators into an overall score, usually called index or composite indicator, which exhibits the performance of the alternatives. Thanks to the effective communication tool for policy-making that indices offer, their popularity has been increasing recently (Ang et al., 2015a).

Numerous MCDA methods to combine individual indicators into an index are reported in the literature (Greco et al., 2016; Joint Research Centre of the European Commission, 2008). The rankings resulting by using different methods might not always be consistent (Narula and Reddy, 2015; Saisana and Philippas, 2012). Given the fact that the rankings of alternatives might change, decision-makers need to be aware of the underlying consequences of selecting a specific index construction methodology. Furthermore, an index' credibility is greatly enhanced if an uncertainty, sensitivity or robustness analysis is provided (Saisana et al., 2005). However, seldom is this studied or reported.

To tackle these gaps, this paper reviews energy security indices used to compare the performance of countries. In particular, the index construction methodologies are analyzed according to the common index construction steps consisting of data treatment, normalization, weighting, aggregation and uncertainty analysis (Joint Research Centre of the European Commission, 2008). The paper is organized as follows. Section 2 details the literature screening and assessment methodology. Section 3 discusses the identified energy security indices according to their construction methodologies. Finally, Section 4 concludes the paper and provides recommendations for future research. It has to be noted that this review does not provide an assessment of the individual indicators used to construct the different indices as this information is obtainable from other references (e.g. (Ang et al., 2015a; Sovacool and Brown, 2010; Sovacool and Mukherjee, 2011)) and it does not provide detailed explanations of the operational research methods cited as these are thoroughly explained in a multitude of other sources (e.g. (Belton and Stewart, 2002; Greco et al., 2016; Ishizaka and Nemery, 2013; Joint Research Centre of the European Commission, 2008)). Overall, the aim of this paper is to shed light upon the construction methodologies used to build energy security indices and to identify best practices as well as areas for future research.

## 2. Literature screening and assessment methodology

The first set of energy security indices was gathered by assembling the ones listed in the studies of Valdés (2018), Ang et al. (2015a), Erahman et al. (2016), Apergis et al. (2015) and Bandura (2008). For the sake of completeness, missing studies were added by searching Web of Science (Clarivate Analytics, 2018) and Google Scholar (Google, 2018). "Energy security", "composite indicator", "index", "country performance, "country ranking" and "energy security indicators" were keywords used. In order to make the list up-to-date, publications until December 2018 were considered.

After removing duplicates, this resulted in a set of 102 studies. Based on the abstracts and if necessary on the full paper contents, these studies were then filtered according to their scope. In fact, only the ones analyzing countries and providing quantitative results (e.g. through a case study, providing country scores or rankings) were retained. While most studies are indeed relevant for countries, a substantial amount of them do not provide quantitative results, but only qualitatively discuss relevant indicators or provide frameworks which could be used for a quantitative assessment. This process resulted in a final set of 63 studies that are reviewed in detail in Section 3. Each of these provides a quantitative index measuring the energy security of at least one country.

As set out in the literature, several steps to build indices are necessary (Joint Research Centre of the European Commission, 2008). Hence, multiple attributes of each of these indices were analyzed. To start with, the index' name and its scope were discerned. Furthermore, its geographical coverage (location), the number of countries analyzed, the considered time frame and the number of individual indicators forming the corresponding index were identified. Regarding the construction of the index, the methodology of imputing missing values and trimming outperformers was identified. In fact, hardly any data set is complete, especially if numerous countries are to be analyzed, and outperformers can have a significant effect on the rankings (Hawkins, 1980; Joint Research Centre of the European Commission, 2008). Furthermore, the way the statistical coherence of the indicator set (multivariate analysis) is verified is identified. Then, the type of normalization method applied, indicator weighting scheme considered and aggregation function used is analyzed. As there are numerous ways to normalize, weight and aggregate indicators, the number of different combinations applied was retained. Finally, it was verified if an uncertainty, sensitivity or robustness analysis was conducted.

## 3. Results and discussion

This section presents the results and discusses the index construction methodologies of the 63 energy security indices reviewed. For each of these indices, Table 1 provides its:

- Source
- Name
- Scope or dimensions
- Geographical coverage (location)
- Number of countries analyzed
- Time frame: If more than one year was considered, then the first and last years are reported. The number in parenthesis represents the number of time steps for which the indicator was quantified. For example, "1990–2010 (5)" means that the index was quantified for five different years in the range 1990–2010. Usually the intervals are equidistant, hence "1990–2010 (5)" means that the index was quantified for 1990, 1995, 2000, 2005 and 2010
- Number of individual indicators considered
- Method to impute missing values
- Method to trim outperformers
- Method to perform multivariate analysis (verify the statistical coherence of the indicator set)
- Normalization method
- Weighting scheme of the indicators
- Aggregation function
- Number of combinations of normalization methods and aggregation functions considered
- Uncertainty, sensitivity and/or robustness analysis

The remaining content of this section is entirely based on the information provided in Table 1.

As shown in Fig. 1, no publication was reported before 2004. Furthermore, the amount of publications drastically increased in 2011.

### 3.1. Geographical coverage and number of countries

Regarding geographical coverage, Fig. 2 shows the distribution of the studies by country/region. Most of the indices are global, i.e. countries from different continents are analyzed. This might be attributed to the fact that energy security has become a global geopolitical problem and that most of the countries in the world are net energy importers (World Bank, 2014). Hence, energy security cannot be assessed in isolation, as almost every country is dependent on products from another one at some stage in the energy supply chain. Some of these global indices are yearly updated and include most of the countries in the world (e.g. (Boccauthor and Hanna, 2016; Centre for Environmental Law and Policy, 2018; World Economic Forum, 2018; World Energy Council, 2018)). Next to global studies, European, Asian and North American countries are commonly assessed. Regarding assessments of fewer countries, China, Lithuania, Thailand, the USA, Greece and Singapore represent the most popular ones. While South American countries are more rarely assessed, there is a considerable lack of measuring the energy security of African countries. Even though the continent is rich in energy resources, its supply is poor (Ispy Publishing, 2018). Given the fact that the population of Africa is predicted to double by 2050 and that it has the highest predicted compounded average annual energy consumption growth rate until 2040 (International Energy Agency, 2017), comprehensive studies on Africa's energy security are necessary not only for African nations themselves, but also for the world, as the increase in population and energy consumption will most likely not come without harmful effects on the environment.

19 of the 63 indices were quantified for one country only (see Fig. 3). These studies were conducted by local researchers that assess their own country's energy security and are primarily used to assess trends over time. It has however to be noted that these indices could easily be applied to further countries, if the necessary data is available. Furthermore, the studies including between 2 and 20 countries are for the major part regional studies (e.g. Southeast Asia, Middle East and North Africa, Baltic States) or countries belonging to a similar group (e.g. Asian net gas importers, developing nations, major economies). The indices that were quantified for 21–30 countries are mainly covering the European Union (EU) and countries from the Organization for Economic Cooperation and Development (OECD), or the major economies in the world. Studies that have more than 30 countries are all global worldwide assessments. The indices that cover the most countries are the Environmental Performance Index (EPI) (180 countries) (Centre for Environmental Law and Policy, 2018), the Energy Security Index (162 countries) (Wang and Zhou, 2017), the Energy Affinity Index (160 countries) (María Marín-Quemada and Muñoz-Delgado, 2011), the Global Energy Architecture Performance Index Report (125 countries) (Boccauthor and Hanna, 2016), the Energy Trilemma Index (125 countries) (World Energy Council, 2018) and the Energy Transition Index (114 countries) (World Economic Forum, 2018). Overall, there is a large number of indices that cover numerous countries (32 indices cover more than 10 countries).

### 3.2. Time frame

The studies differ significantly on the assessment time frame. 16 of them mainly used data from a single year (Boccauthor and Hanna, 2016; Bompard et al., 2017; Centre for Environmental Law and Policy, 2018; Doukas et al., 2012; Eckle et al., 2011; Gnansounou, 2008; Gupta, 2008; Iddrisu and Bhattacharyya, 2015; Kanchana et al., 2016; Le Coq and Paltseva, 2009; Moghim and Garna, 2018; Onamics, 2005; Wang and Zhou, 2017; World Energy Council, 2011, 2018; Zhang et al., 2017). Some of these studies are updated yearly (e.g. (Boccauthor and Hanna, 2016; Centre for Environmental Law and Policy, 2018; World Energy Council, 2018)), hence trends and successful policy strategies can be identified. However, their construction methodology might have changed as well. Hence, comparisons of different editions of the same index has to be treated with caution, as ranking differences might be partially due to the methodological changes and not to the updated country performances only.

Two studies provide one assessment based on indicator data ranging over several years: Hughes and Shupe (2010) consider the values obtained via linear regression over multiple years and María Marín-Quemada and Muñoz-Delgado (2011) the arithmetic average during the period 2000–2008. The rest of the studies provide indices quantified for at least two years.

Particularly large time frames are available for the U.S. Energy Security Risk Index (USA, 71 years), the Washington and Jefferson (W&J) Energy Index (USA, 61 years) (Dunn and Dunn, 2012), the Overall Sustainability Index (Greece, 47 years) (Angelis-Dimakis et al., 2012),

**Table 1**
List of the 63 energy security indices providing quantitative results on country performances. The following notations are used. For missing data, average (A), taken from another country (C), perpetual inventory method (P), regression (R) and taken from another year (Y). For trimming of outperformers, 1.5 times the interquartile range (I) and subjective (S). For the multivariate analysis, Bartlett's test (B), correlations (C), Kaiser-Meyer-Olkin (K) and ANOVA (A). For normalization, categorical (C), distance to a reference (D), min-max (M), none (N), percentile rank (P), rank (R) and standardized (S). For weighting, AHP (A), DEA (D), equal weights (E), factor analysis (F), import/fuel share (I), PCA (P) and subjective (S). For aggregation, additive (A), DEA (D), geometric (G), ordered weighted average (O), PROMETHEE (P), root mean square (R) and rhombi area (RA).

| Source | Name of index | Scope/ dimensions | Geographical coverage | Number of countries | Time frame | Number of indicators | Missing data | Trimming of outperformers | Multivariate analysis | Normalization | Weighting | Aggregation | Number of combinations | Uncertainty |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Ang et al. (2015b) | Singapore Energy Security Index (SESI) | Economic; energy supply chain; environmental | Singapore | 1 | 1990–2010 (5) | 22 | | | | C | S | A | 1 | ✓ |
| Angelis-Dimakis et al. (2012) | Overall sustainability index | Social; economic; environmental | Greece | 1 | 1960–2006 (47) | 9 | | | | M | E | A | 1 | |
| Antanasijević et al. (2017) | Sustainability performance | Sustainable performance | Europe | 30 | 2004–2014 (3) | 38 | | | | N | E | P | 1 | |
| Augutis et al. (2009) | Lithuanian power energy supply security | Technical; economic; socio-political; environmental | Lithuania | 1 | 2005–2020 (7) | 22 | | | | D | S | A | 1 | |
| Augutis et al. (2011) | Energy security level | Technical; economic; socio-political; energy sources | Lithuania | 1 | 2007–2010 (2) | 61 | | | | C | E, I | A | 1 | |
| Augutis et al. (2012) | Energy security level | Technical; economic; socio-political | Lithuania | 1 | 2007–2010 (2) | 68 | | | | C | E, I | A | 1 | ✓ |
| Badea et al. (2011) | Security of energy supply index | Security of energy supply | European Union | 27 | 2010–2030 (2) | 8 | | | | R | S | O | 1 | ✓ |
| Blyth and Lefevre (2004) | Geopolitical energy security measure; power system reliability measure | Geopolitical energy security proxy measure; power system reliability proxy measure | Dummy countries | 4 | 2001–2030 (4) | 2 | | | | N | I | A | 1 | |
| Boccauthor and Hanna (2016) | Energy Architecture Performance Index (EAPI) | Economic growth and development; environmental sustainability; energy access and security | Global | 125 | 2015 | 18 | Y | S | | M, P, S | S | A | 3 | ✓ |
| Bompard et al. (2017) | National energy security index | Security of energy supply from abroad (external) and national energy infrastructures (internal) | Italy | 1 | 2014 | 2 | | | | N | I | A | 1 | ✓ |
| Brown et al. (2014) | Energy security performance index | Availability; affordability; energy and economic efficiency; environmental stewardship | OECD | 22 | 1970–2010 (2) | 10 | Y | | C | S | F | A | 1 | |
| Cabalu and Alfonso (2013) | Gas Supply Security Index (GSSI) | Gas intensity; import dependency; production to consumption ratio; geopolitical risk | Asian economies | 6 | 1996–2009 (14) | 4 | | | | M | E | R | 1 | |
| Cabalu (2010) | Gas Supply Security Index (GSSI) | Gas intensity; import dependency; production to | Asian net gas importing countries | 7 | 2006–2008 (2) | 4 | | | | M | E | R | 1 | ✓ |

(continued on next page)

**Table 1** (*continued*)

| Source | Name of index | Scope/ dimensions | Geographical coverage | Number of countries | Time frame | Number of indicators | Missing data | Trimming of outperformers | Multivariate analysis | Normalization | Weighting | Aggregation | Number of combinations | Uncertainty |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | consumption ratio; geopolitical risk | | | | | | | | | | | | |
| Centre for Environmental Law and Policy (2018) | Environmental Performance Index (EPI) | Environmental health; ecosystem vitality | Global | 180 | 2018 | 24 | A, C, R | | | D, M | S | A | 1 | |
| Cohen et al. (2011) | Country specific index | Crude oil; natural gas | Major countries | 21 | 1990–2008 (4) | 2 | | | | N | I | A | 1 | |
| Doukas et al. (2012) | Energy sustainability index | Renewable energy sources promotion | Rural communities | 8 | 2009 | 9 | | | C | M | P | A | 1 | |
| Dunn and Dunn (2012) | Washington and Jefferson (W&J) energy index | Share of total primary energy consumption produced domestically | United States | 1 | 1949–2009 (61) | 1 | | | | N | I | A | 1 | |
| Eckle et al. (2011) | Security of energy supply | Environment; economy; social; security of supply | European Union | 1 | 2050 | 13 | | | | M | S | A | 1 | ✓ |
| Ediger and Berk (2011) | Oil import vulnerability index | Import dependence; price; non-diversification of import; oil share in total energy import | Turkey | 1 | 1968–2007 (40) | 5 | | | C | M | P | A | 1 | |
| Erahman et al. (2016) | Energy security index | Availability; affordability; accessibility; acceptability; efficiency | Global | 71 | 2008–2013 (6) | 14 | | I | A, B, K | M | E, P | A | 1 | |
| Frondel and Schmidt (2008) | Energy supply risk indicator | Crude oil; natural gas | Germany and the U.S. | 2 | 1980–2004 (25) | 1 | | | | N | I | A | 1 | |
| Geng and Ji (2014) | Energy supply security index | Energy external availability; affordability of energy import; energy technologies and efficiency; energy resource reserves | China | 1 | 1994–2011 (18) | 7 | | | | M | E | R | 1 | |
| Glynn et al. (2017) | Supply/demand index | Sovereignty; infrastructure robustness; market resilience | Ireland | 1 | 2008–2014 (4) | 39 | | | | M | I, S | A | 1 | |
| Gnansounou (2008) | Composite index of vulnerability | Net import of electricity; concentration and risk of non-acceptance by the public of a dominated technology of electricity generation; non-diversification of electricity generation | Industrialized countries | 37 | 2003 | 5 | | | C | M | E | R | 1 | |
| Gupta (2008) | Oil vulnerability index (OVI) | Supply and market risks | Net oil-importing countries | 26 | 2014 | 7 | | | C | M | P | A | 1 | |
| Hu and Kao (2007) | | | Asia-Pacific | 17 | | 4 | P | | C | N | D | D | 1 | |

(*continued on next page*)

**Table 1** (*continued*)

| Source | Name of index | Scope/ dimensions | Geographical coverage | Number of countries | Time frame | Number of indicators | Missing data | Trimming of outperformers | Multivariate analysis | Normalization | Weighting | Aggregation | Number of combinations | Uncertainty |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Energy-saving target ratio | Energy; labor; capital; GDP | | | 1991–2000 (10) | | | | | | | | | |
| Hughes and Shupe (2010) | Energy security index | Availability; temporal accessibility; current accessibility; affordability; acceptability | Countries exporting oil to Eastern Canada | 11 | 1998–2008 (1) | 5 | | | | M | A | A | 1 | ✓ |
| Iddrisu and Bhattacharyya (2015) | Sustainable energy development index | Technical; economic; social; environmental; institutional | Global | 82 | 2009 | 11 | Y | | | M | E | A | 1 | |
| Institute for 21st Century Energy (2016) | International energy security risk index | Global fuels; fuel imports; energy expenditures; price and market volatility; energy use intensity; electric power sector; transportation sector; environmental | Large energy-consuming countries | 25 | 1980–2004 (25) | 29 | | | | D | S | A | 1 | |
| Institute for 21st Century Energy (2017) | Index of U.S. energy security risk | Geopolitical; economic; reliability; environmental | US | 1 | 1970–2040 (71) | 37 | | | | D | S | A | 1 | |
| Kamsamrong and Sorapipatana (2014) | Energy Supply Security Index (ESSI) | Physical energy security; economic energy security; environmental sustainability | Thailand | 1 | 2010–2030 (2) | 5 | | | | M | E | R | 1 | |
| Kanchana et al. (2016) | Energy dependence index | External supply dependence; external demand dependence; economic interdependence | Southeast Asia | 9 | 2012 | 12 | | | | M | E | A, R | 1 | ✓ |
| Le Coq and Paltseva (2009) | Risky external energy supply (REES); Contribution to EU Risk Exposure (CERE) | Oil; gas; coal | EU member countries | 24 | 2006 | 2 | | | | N | I | A | 1 | |
| Lefèvre (2010) | Energy Security Price Index (ESPI); Energy Security Physical Availability Index (ESPAI) | Price; physical availability | France, UK | 2 | 2004–2030 (14) | 2 | | | | N | I | A | 1 | |
| Li et al. (2016) | Energy security index | Vulnerability; efficiency; sustainability | Singapore, South Korea, Japan and Taiwan | 4 | 1990–2012 (23) | 9 | | | C | N | E, P | A | 1 | ✓ |
| María Marín-Quemada and Muñoz-Delgado (2011) | Energy affinity index | International energy relations (competition and complementarities) | Global | 160 | 2000–2008 (1) | 2 | | | | M | I | A | 1 | |
| | | | Thailand | 1 | | 25 | | | C | S | P | A, R | 1 | |

(*continued on next page*)

**Table 1** (*continued*)

| Source | Name of index | Scope/ dimensions | Geographical coverage | Number of countries | Time frame | Number of indicators | Missing data | Trimming of outperformers | Multivariate analysis | Normalization | Weighting | Aggregation | Number of combinations | Uncertainty |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Martchamadol and Kumar (2014) | Aggregated Energy Security Performance Indicator (AESPI) | Social; economic; environmental | | | 1986–2030 (45) | | | | | | | | | |
| Moghim and Garna (2018) | Environmental resilience score | Air pollution; GHG emissions; access to drinking water; access to improved sanitation; environmental risks; energy use | Global | 141 | 2012 | 6 | | | | M | E | A | 1 | |
| Molyneaux et al. (2012) | Resilience index | Security of electricity supply | OECD and developing nations | 11 | 1973–2009 (2) | 7 | | | | M | E | G | 1 | ✓ |
| Obadi and Korcek (2017) | Energy security index | Energy and economic efficiency; affordability; availability; environmental stewardship | European Union | 26 | 2005–2014 (2) | 11 | | | C | S | E | A | 1 | |
| Onamics (2005) | Energy security index | Energy supply diversity; internal political stability; domestic energy efficiency | Central and Eastern Europe | 12 | 2005 | 12 | | | | D | E | A | 1 | |
| Prambudia and Nakano (2012) | Energy security performance | Availability; affordability; efficiency; acceptability | Indonesia | 1 | 2010–2030 (6) | 12 | | | | D | E | | 1 | |
| Radovanović et al. (2017) | Energy security index | Energy intensity; consumption; dependency; GDP; carbon intensity; share of renewable and nuclear energy | European Union | 28 | 1990–2012 (23) | 6 | | | | | S | A | 1 | |
| Ramanathan (2005) | Energy consumption and carbon dioxide emissions | Energy consumption; carbon emissions; GDP | Middle East and North Africa | 17 | 1992–1996 (2) | 4 | | | | N | D | D | 1 | |
| Roupas et al. (2009) | Oil Vulnerability Index (OVI) | Oil consumption; market liquidity; diversification; import dependence; geopolitical risks | European Union | 27 | 1995–2007 (13) | 6 | | | C | N | P | A | 1 | |
| Selvakkumaran and Limmeechokchai (2013) | Energy security indicators | Oil security; gas security; sustainability | Sri Lanka, Thailand and Vietnam | 3 | 1990–2010 (5) | 15 | | | | M | E | A | 1 | |
| Sharifuddin (2014) | Core aspects of energy security for Malaysia | Availability; stability; affordability; efficiency; environmental impact | Indonesia, Malaysia, Philippines, Thailand and Vietnam | 5 | 2002–2008 (3) | 35 | | | | S | E, I | A | 1 | |
| | | | Mexico | 1 | | 8 | | | | M | E | A | 1 | |

(*continued on next page*)

**Table 1** (*continued*)

| Source | Name of index | Scope/dimensions | Geographical coverage | Number of countries | Time frame | Number of indicators | Missing data | Trimming of outperformers | Multivariate analysis | Normalization | Weighting | Aggregation | Number of combinations | Uncertainty |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Sheinbaum-Pardo et al. (2012) | Mexican sustainability indicators | Social; environmental; economic | | | 1990–2008 (2) | | | | | | | | | |
| Song et al. (2013) | Energy efficiency | Energy consumption; economically active population; capital; GDP | BRICS | 5 | 2009–2010 (2) | 4 | | | | N | D | D | 1 | |
| Sovacool and Brown (2010) | Energy security index | Availability; affordability; efficiency; environmental stewardship | OECD | 22 | 1970–2007 (2) | 10 | Y | | | S | E | A | 1 | |
| Sovacool et al. (2011) | Energy security performance | Availability; affordability; technology development and efficiency; environmental sustainability; regulation and governance | Major economies and ASEAN countries | 18 | 1990–2010 (5) | 20 | | | | M | E | A | 1 | |
| Wang and Zhou (2017) | Energy security index | Security of energy supply-delivery; safety of energy utilization dimension; stability of political-socioeconomic environment | Global | 162 | 2014 | 23 | | | B, K | S | S | A | 1 | |
| World Economic Forum (2018) | Energy Transition Index (ETI) | System performance score; transition readiness score | Global | 114 | 2013–2018 (2) | 40 | Y | | | M | S | A | 1 | |
| World Energy Council (2011) | Energy sustainability index | Energy security; social equity; environmental impact mitigation; political strength; societal strength; economic strength | Global | 92 | 2011 | 22 | Y | | | M | S | A | 1 | |
| World Energy Council (2018) | Energy trilemma index | Energy security; energy equity; environmental sustainability | Global | 125 | 2017 | 35 | | | | R | S | A | 1 | |
| Wu et al. (2007) | Energy insecurity index | Importance of oil; dependence on imported oil (especially from the Middle East) | Asia-Pacific and Europe | 25 | 1995–2015 (3) | 3 | | | | N | S | A | 1 | |
| Wu et al. (2012) | Composite index of China's energy security | Energy supply security; energy using security | China | 1 | 1996–2009 (14) | 14 | | | | M | A | A | 1 | |
| Yao and Chang (2014) | Energy security status | Availability of energy resources; applicability of technology; acceptability by society; affordability of energy resources | China | 1 | 1980–2010 (7) | 20 | | | | C | E | RA | 1 | |

(*continued on next page*)

**Table 1** (*continued*)

| Source | Name of index | Scope/ dimensions | Geographical coverage | Number of countries | Time frame | Number of indicators | Missing data | Trimming of outperformers | Multivariate analysis | Normalization | Weighting | Aggregation | Number of combinations | Uncertainty |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Zeng et al. (2017) | Integrated energy security indicator | Economic; energy supply; environmental | Baltic States | 3 | 2008–2012 (5) | 9 | | | | M, N | D | A, D | 4 | ✓ |
| Zhang et al. (2011) | Total-factor energy efficiency | Labor force; energy consumption; capital stock; GDP | Developing countries | 23 | 1980–2005 (26) | 4 | P | | | N | D | D | 1 | |
| Zhang et al. (2013) | Oil import risk index | External dependence; supply stability; trade economy; transportation safety | China | 1 | 1993–2011 (19) | 8 | | | | M | D | D | 1 | |
| Zhang et al. (2017) | Energy security performance | Availability and diversity; affordability and equality; technology and efficiency; environmental sustainability; governance and innovation | China | 30 | 2013 | 20 | | | | M | A | P | 1 | ✓ |
| Zhou and Ang (2008) | Energy efficiency performance index | Capital; labor; energy consumption; GDP; carbon emissions | OECD | 21 | 1997–2001 (5) | 8 | | | | N | D | D | 3 | |

the Aggregated Energy Security Performance Indicator (AESPI) (Thailand, 45 years) (Martchamadol and Kumar, 2014) and the Oil Import Vulnerability Index (Turkey, 40 years) (Ediger and Berk, 2011). It is to be noted that all of the indices providing yearly values for strictly more than 26 years are quantified for one country only. This is probably due to data availability issues or efforts to access data, as the larger the set of countries, the more likely it is to encounter uncomplete data sets. While some studies provide yearly values for the last three to four decades (e.g. (Frondel and Schmidt, 2008; Institute for 21st Century Energy, 2016; Radovanović et al., 2017; Zhang et al., 2011)), others also cover large time ranges but only calculate few values. For example, the energy security index developed by Sovacool and Brown (2010) is applied to 22 OECD countries for the years 1970 and 2007. Similarly, Molyneaux et al. (2012)'s resilience index is quantified for 1973 and 2009. Such studies allow to compare actual performance with older ones. However, recent trends are not identifiable. Hence this is where indices with yearly updates are particularly handy. A compromise is to quantify the index for constant time ranges, e.g. every five years, as it is done in Ang et al. (2015b), Selvakkumaran and Limmeechokchai (2013) and Sovacool et al. (2011).

Furthermore, unlike most of the studies which use historical data, a few ones make projections into the future. For example, Eckle et al. (2011) quantify the energy security of the EU27 for the year 2050. Furthermore, the U.S. Energy Security Risk Index is available until 2040 (Institute for 21st Century Energy, 2017), and further indices until 2030 (Badea et al., 2011; Blyth and Lefevre, 2004; Kamsamrong and Sorapipatana, 2014; Lefèvre, 2010; Martchamadol and Kumar, 2014; Prambudia and Nakano, 2012). Due to the same reasons as for the studies over large time frames, the ones providing projections are usually quantified for a single country only (except Badea et al. (2011) who assess the energy security of EU27 countries for 2030). The studies making projections into the future or scenario analyses require a substantial effort in order to precisely quantify the individual indicators. They are inherently prone to uncertainties, as disruptive events are hard to predict and can have enormous consequences. An example of a disruptive event is the 2011 Tōhoku earthquake and tsunami (Norio et al., 2012) which resulted in the Fukushima Daiichi nuclear disaster (International Atomic Energy Agency, 2015). This event has led to drastic energy policy shifts all around the world, in particular towards reluctance of electricity produced via nuclear energy. Overall, only few global studies provide recent yearly trends that allow to draw trends and studies showing projections into the future are even more rare. However, these are important as they are tools that can be used for anticipation and preventive policymaking.

### 3.3. Number of indicators

The 63 indices use various numbers of individual indicators, as shown in Fig. 4. Whereas some studies include a single indicator only, the maximum number is 68 (Augutis et al., 2012). Most studies consider at least 9 indicators and 52% of them between 5 and 20. Multiple indicators are usually necessary to represent the different dimensions of energy security. Some studies group the indicators into such dimensions, so when aggregating the indicators (see Section 3.7), intermediate scores can be built. For example, the Energy Transition Index comprises 40 indicators that are grouped into nine dimensions (World Economic Forum, 2018). Furthermore, the nine dimensions are separated into two scores: (1) the system performance and (2) the transition readiness. The average of these two scores is the overall index' value.

Obviously, the selection of the indicators is highly dependent on the scope of the study (see column "Scope/dimensions" of Table 1). Not surprisingly, the multitude of indices, all measuring energy security, do have heterogeneous indicator sets. Reasons for this discrepancy is that countries have different natural resources, political systems, economic welfare, ideologies, geographical locations and international relations. Hence energy security can mean different things and the priorities may

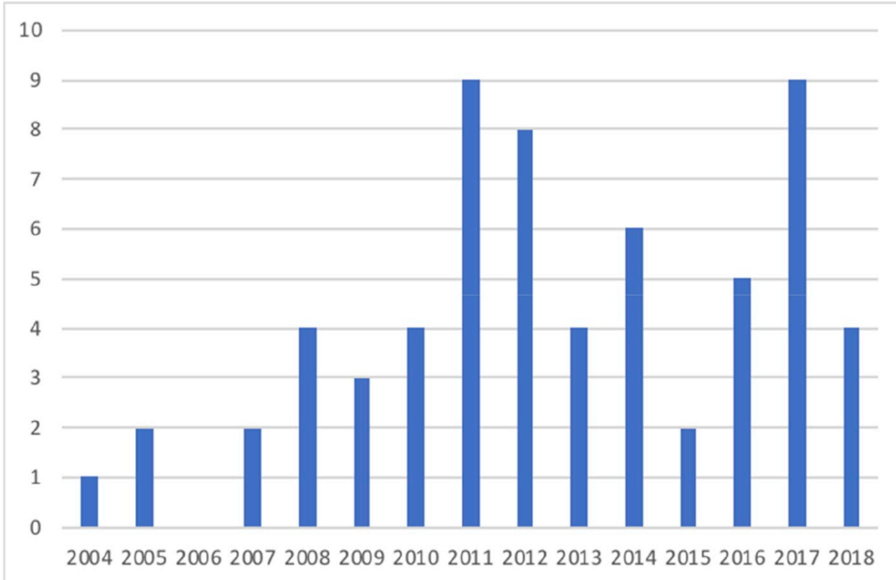


**Fig. 1.** Distribution of the publications' time evolution according to the publications listed in Table 1.

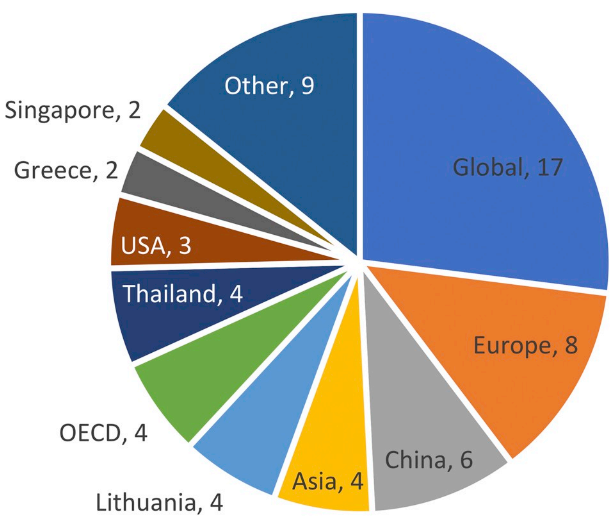


**Fig. 2.** Distribution of energy security indices per country/region.

vary (Luft and Korin, 2009; Paravantis et al., 2018). Nevertheless, as pointed out by Ang et al. (2015a), "the choice of indicators … can be fairly arbitrary". However, there are methods available to minimize the degree of subjectivity, such as:

- Involvement of stakeholders: Assembling the preferences of stakeholders through questionnaires, interviews or workshops.
- Literature reviews and indicator assessment: Through literature reviews, a first set of indicators could be developed. Consequently, each of the indicators could be assessed according to relevant indicator selection criteria. An indicator should be retained only if it scores at least sufficiently in each of the criteria. Foxon et al. (2002) identify five of such criteria:
  1. Comprehensiveness: Is the indicator relevant to measure the phenomenon in question?
  2. Applicability: Is the indicator applicable to all countries?
  3. Tractability: Is sufficient and reliable data available to quantify the indicator?
  4. Transparency: Are the reasons for selecting the indicator transparent?
  5. Practicability: Does the indicator set fulfill the purpose of the decisions to be assessed?

In most cases, the driving reason for not including certain indicators is data availability.

### 3.4. Data treatment and statistical coherence

The first step of treating the data is to make it comparable across countries and years (Centre for Environmental Law and Policy, 2019). In fact, some indicators might have to be divided by the size of a country's economy, area or population. For example, the energy intensity of a country is usually measured as its energy consumption divided by the country's GDP. It would not make sense to consider the absolute energy consumption, as it is logical that larger countries consume more even though they might be more efficient than smaller ones.

Secondly, there are situations in which the data for an indicator is available for almost all the countries, with few exceptions. Even though data is not available for all the countries, the indicator should still be retained, as it might comprehensively represent the phenomenon in question. In such a situation, the missing values need to be imputed. A rule of thumb states that if an indicator has less than 5% of its values missing, then it does not have to be removed (Little and Rubin, 2014). There exists multiple ways to impute missing values, as presented in Little and Rubin (2014). Only rarely is the data imputation step of constructing indices detailed, making it difficult to assess common ways to proceed. In fact, only a few studies report how missing data was inserted. The most common method to impute the missing vales is to take the most recent available data point of the country in question (Boccauthor and Hanna, 2016; Brown et al., 2014; Iddrisu and Bhattacharyya, 2015; Sovacool and Brown, 2010; World Economic Forum, 2018; World Energy Council, 2011). Usually this results in situations in which a country's value dating a few years back is taken. Other methods considered are taking the average value of the other countries (Centre for Environmental Law and Policy, 2018), the value taken from another similarly performing or geographically neighboring country (Centre for Environmental Law and Policy, 2018), using the perpetual inventory method (Hu and Kao, 2007; Zhang et al., 2011) or through regression analysis (Centre for Environmental Law and Policy, 2018).

The third task in treating the data is the discussion of the presence of outperformers in the data set (Joint Research Centre of the European

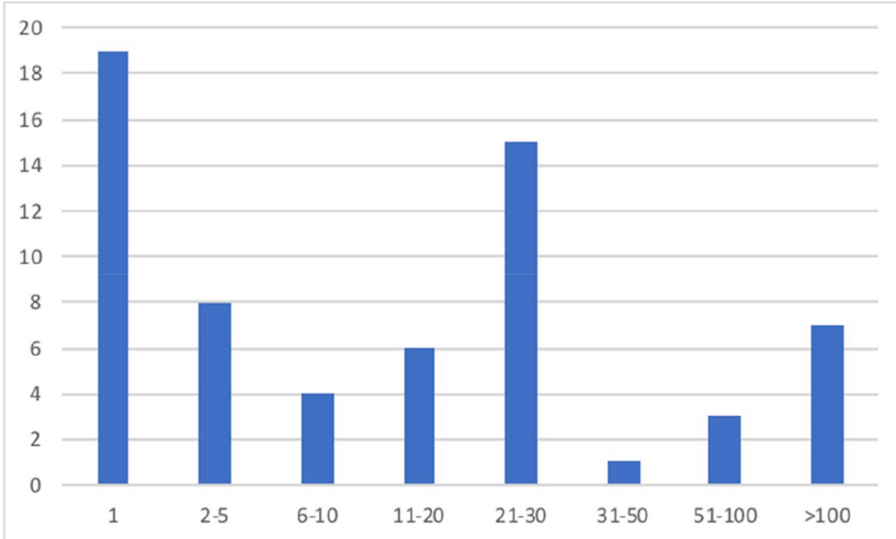


**Fig. 3.** Distribution of the number of countries included in the 63 indices.

Commission, 2008). Outperformers are extreme observations with respect to the other values of an indicator. They can have a strong impact on the final result, depending on which normalization method is applied (Hawkins, 1980; Joint Research Centre of the European Commission, 2008). While in rare instances the effects of outperformers is intentionally reduced by considering a specific normalization method (e.g. some skewed indicators of the EPI are normalized with a logarithmic transformation, which allows to better differentiate the countries whose relative performance would otherwise be obscured by the outperformers (Centre for Environmental Law and Policy, 2018)), very few studies explicitly trim the outperformers before the normalization step. The two methods applied in the energy sector are:

1. The Interquartile Range (IQR) (Erahman et al., 2016): Values are considered outperformers if they lay far away from the first and third quartiles (Q1 and Q3 respectively). The rule of thumb is to consider 1.5 times the IQR from Q1 and Q3 as thresholds. In mathematical terms, $x_i$ is an outperformer if $x_i < Q1 - 1.5*IQR$ or $x_i > Q3 + 1.5*IQR$.
2. Setting a maximum performance value determined based on expert knowledge (Boccauthor and Hanna, 2016): Values exceeding a predefined acceptable performance level are trimmed to the determined threshold.

Once the data set is complete and the analysis of outperformers performed, the subsequent step in building indices is to conduct a multivariate analysis (Joint Research Centre of the European Commission, 2008). A multivariate analysis consists in verifying the statistical coherence of the data set in order to determine the underlying structure of the data (e.g. how the individual indicators are grouped, i.e. identify potential dimensions) and determining if the indicators are suitable to build an index. Only rarely is a multivariate analysis studied or at least reported. If a multivariate analysis is performed, then it usually is an assessment of the correlation and covariance values between indicators (Brown et al., 2014; Doukas et al., 2012; Ediger and Berk, 2011; Gnansounou, 2008; Gupta, 2008; Hu and Kao, 2007; Li et al., 2016; Martchamadol and Kumar, 2014; Obadi and Korcek, 2017; Roupas et al., 2009). In all of these studies, the multivariate analysis was performed because Principal Component Analysis (PCA) or factor analysis was used

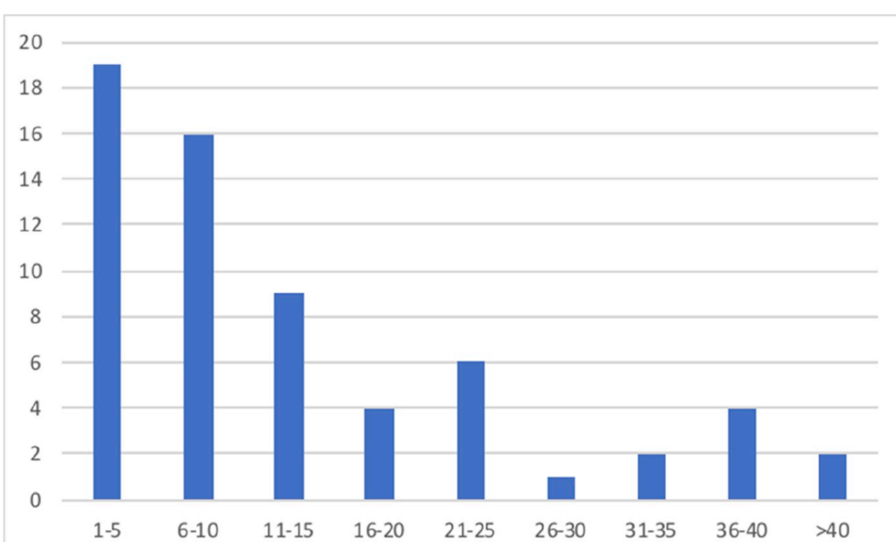


**Fig. 4.** Distribution of the number of individual indicators included in the indices.

to determine the indicator weights (see Section 3.6). In fact, for these two methods, the indicator weights are dependent on the correlation structure of the data set. Seldom are other statistical coherence tests undertaken. Erahman et al. (2016) uses a method called ANOVA (ANalysis Of VAriance) (González-Rodríguez et al., 2012). Furthermore, both Erahman et al. (2016) (Erahman et al., 2016) and Wang and Zhou (2017) (Wang and Zhou, 2017) apply the Bartlett and Kaiser-Meyer-Olkin tests (Williams et al., 2010). A further method is Cronbach's Alpha (Cronbach, 1951), which analyses the internal consistency of the data set. Cronbach's Alpha is the most widely used tool to assess the reliability of a scale (Streiner, 2003). It measures how closely related a set of indicators are as a group. A value lower than 0.7 indicates questionable internal consistency and thus implies a need for further multivariate analysis on the indicators (Nunnally and Bernstein, 1978), whereas a value higher than 0.9 indicates excessive redundancy among indicators (Streiner, 2003). Overall, there should be a positive manifold between indicators. A general positive degree of correlation (0.3–0.9) is in fact desirable as it demonstrates that the indicators measure the same construct. Very high correlation values (>0.9) are signs of redundancy and the corresponding indicators should either be removed or grouped. Negatively correlated indicators (<-0.3) are also problematic and if they are not absolutely relevant to quantify the phenomenon under study, they should be removed too (Saisana and Philippas, 2012).

### 3.5. Normalization

Following the development of a complete and justified data set through data treatment and multivariate analysis, the next step in building an index is the normalization of the indicators (Saisana and Saltelli, 2011). Normalization is necessary in most cases, because the indicators are usually measured through different units. Hence, normalization brings all indicators to a common scale so that they can be compared with each other and combined into an index. It harmonizes the dataset to render the scales comparable. Jahan and Edwards (2015) identify, classify and evaluate 31 different normalization methods. They review their advantages and disadvantages, and provide recommendations on the most appropriate ones to use in specific situations. The normalization methods adopted can affect the ranking of the countries, because they imply different trade-offs between indicators (Carrino, 2017). However, in the energy sector, only one global index assesses the influence of several normalization methods on the ranking, but no information is published about the findings (Boccauthor and Hanna, 2016).

For energy security indices, the most common method is min-max, which is used in 44% of the indices (see Fig. 5). The min-max method linearly transforms the data between zero (worst score) and one (best score). It preserves the distribution of the values of the indicators and is sensitive to outperformers. Outperformers render the differentiation of non-outperforming countries difficult as most of their scores are clustered closely together. Nevertheless, thanks to its ease of application and simple understanding potential, it is the most widely used. Interestingly, 17 studies (or 27%) do not normalize the indicators. Three reasons for this seem to emerge:

1. These studies include rather few indicators. Hence the likelihood of them being expressed in the same unit increases, rendering the normalization step unnecessary.
2. The indicators used already include normalization in their calculation method.
3. The aggregation function considered does not need data normalization (e.g. Data Envelopment Analysis (DEA), see Section 3.7).

Another popular method is the standardization, also called z-scores, which is applied in seven studies (11%). The standardization is a linear transformation of the data set resulting in a normalized data set with a mean of zero and a standard deviation of one. It preserves the distribution of the values of the indicators and the data set is not bounded (there are no fixed minimums or maximums). A drawback of this method is that the number of countries studied should be sufficiently large (Ang et al., 2015a). The distance to a reference (6 studies, 10%) is, as its name suggests, the variation from a selected threshold or benchmarking value. An agreed acceptable level of performance or the performance in a certain year could be selected as the reference. Finally, ordinal normalization methods are used to a lesser extent. In fact, the categorical method is used in four studies (6%), the rank in two (3%) and the percentile rank in one (2%). Ordinal normalization methods are insensitive to outperformers, as the scale is transformed into ordinal numbers and the distances between performance of the countries are lost. Countries performing significantly better than others are disadvantaged. While rank and percentile rank have defined calculation formulas, the categorical method can be tailored according to stakeholders' preferences. In fact, the number of performance levels can be arbitrarily selected (e.g. with three levels: "high", "medium" and "low"; with five levels: "very high" and "very low" could be added). Furthermore, while usually the standard deviation of the data set is used as a threshold to classify the countries into these ordinal levels of performance, subjective thresholds could be considered too.

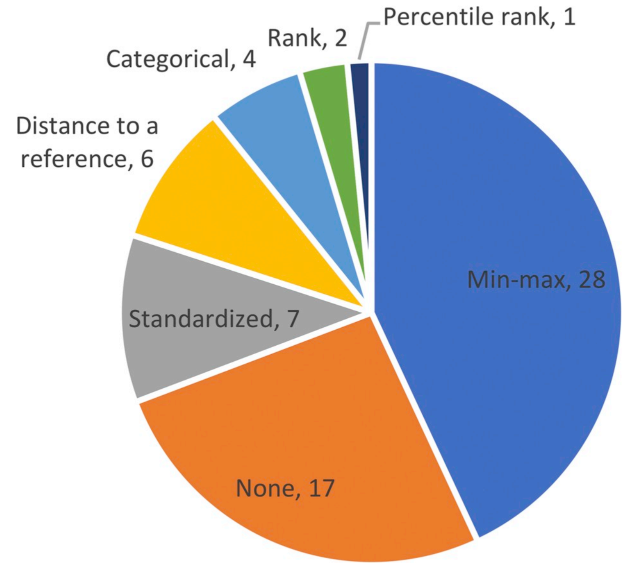


**Fig. 5.** Distribution of normalization methods used to construct energy security indices.

### 3.6. Weighting

Weighting is the process of assigning a relative importance to each indicator (Rowley et al., 2012). As for the normalization methods, a multitude of ways to do so exists. Weighting methods can be categorized into three main groups (El Gibari et al., 2018): (1) equal weighting, (2) data-based methods in which the weights are determined from the data itself (e.g. fuel/import share, DEA, PCA, outranking methods),[1] and (3) participatory-based methods where preferences/opinions from stakeholders are considered (e.g. Budget Allocation Process (BAP), Analytic Hierarchy Process (AHP)). The most popular weighting methods are (see Fig. 6):

- Equal weights (38%): This is clearly the most common method applied. All the indicators are assigned an equal weight. This method

[1] From a MCDA viewpoint, data-based methods are sometimes viewed as controversial as they do not represent any preferences of the decision-makers (Lindén, 2018).

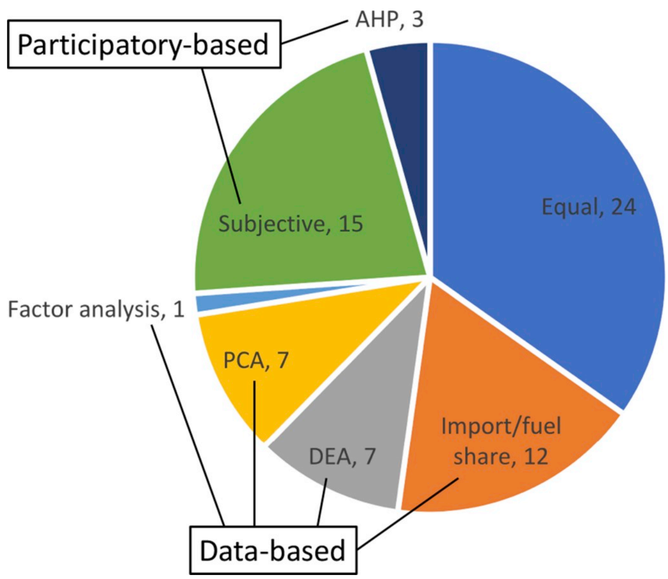


**Fig. 6.** Distribution of indicator weighting schemes considered to construct energy security indices.

is useful in the absence of preferences from stakeholders, if the effect of the authors' subjectivity is to be minimized, or to not introduce bias if the goal is aimed at analyzing other aspects of index construction methodologies.

- Fuel/import share (19%): This method considers the share of fuels in the energy mix or the share of the imports. Hence, it is not applicable for non-fuel type indicators.
- DEA (11%): As for all the data-based methods, in DEA the indicator weights are endogenously determined from the data set itself (Cooper et al., 2011). Several DEA models are available, with the most common one being an optimization problem where the most suitable weight vector for each country is sought for (Charnes et al., 1978).
- PCA (11%): PCA analyzes the correlation between indicators and determines the number of underlying dimensions (called the principal components). Its objective is to explain the variance of the data towards the index. It is suitable if the aim is to reduce the number of indicators to a smaller set that represents most of the index' variance.
- Factor analysis (2%): Factor analysis has been used in one study only (Brown et al., 2014).
- AHP (5%): To determine indicator weights, stakeholders are tasked to evaluate the importance of each indicator towards reaching the overall goal (Saaty, 2004). The indicators are compared against each other bilaterally.
- Subjective methods (24%): Next to AHP, other subjective methods are applied. In some cases, the selection process of the indicator weights is not detailed as it probably is a subjective choice of the authors. Other methods are the BAP or Delphi method where weights are drawn from the preferences of stakeholders assembled through interviews, questionnaires or workshops.

Overall, a substantial amount of studies do not provide any justification for the indicator weights or use equal weights due to a lack of information. However, a transparent process is necessary as indicator weights can have a major impact on the results, because rankings might change if the weights are varied (Saisana and Philippas, 2012). Solutions are:

- Involvement of stakeholders: The knowledge and opinions of energy experts from governmental organizations, the industry, academia or research institutions could be gathered through questionnaires, interviews or workshops. By using the BAP, Delphi method or AHP for example, an indicator weighting profile that suits their preferences can be derived.
- Monte Carlo simulation: A Monte Carlo simulation could be performed in which random weights are applied to the indicators. Furthermore, instead of keeping the weights totally random, a tolerance limit with a defined upper and lower bound according to stakeholders' preferences could be determined. Hence, the weights would be kept random within a predefined interval. This allows to obtain performance ranges for the countries and the variability of the results can be identified. Saisana and Philippas (2012) present such a study in their audit of the Sustainable Society Index.
- Implicit weights: In an ideal setting, each individual indicator should have the same effect on the overall index (Becker et al., 2017; Billaut et al., 2009; Maxim, 2014). In other words, each indicator should result in the same variance of the index. However, redundancy between indicators where a subset of them is overrepresented is not uncommon (Lindén, 2018). By setting the condition that each indicator should have the same influence on the index, it is possible to determine the corresponding indicator weights (called implicit weights).

### 3.7. Aggregation

Aggregation functions combine the normalized data sets with the indicator weighting profiles in order to calculate a single score for each country. This score is the index' value or performance and allows to build a ranking of the countries. Aggregation functions withhold different levels of compensation, i.e. different capacities of balancing the indicators' performances out (Langhans et al., 2014). The most popular aggregation functions are (see Fig. 7):

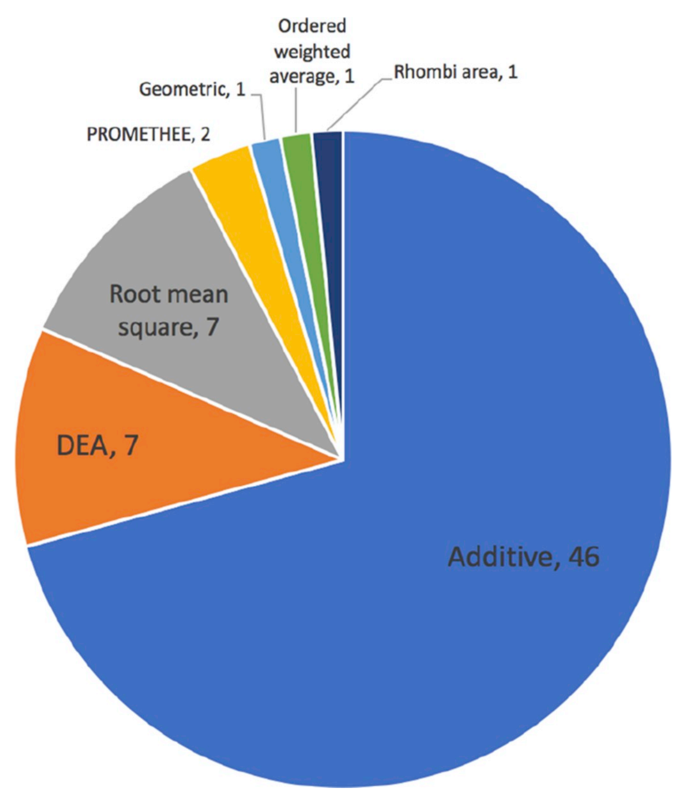


**Fig. 7.** Distribution of aggregation functions used to construct energy security indices.

1. Additive function (73%): This is by far the most common aggregation function. It is suitable if stakeholders' preferences are linear, meaning that it is accepted that the indicators can fully balance each other out. Hence, low-performing indicators can be fully compensated by high-performing ones. Its popularity is traceable through its straightforward application and simple understanding.
2. DEA (11%): DEA is an optimization method that combines the weighting and aggregation steps. Hence, Figs. 6 and 7 include the same seven DEA studies.
3. Root mean square (11%).
4. Preference Ranking Organization METHod for Enrichment of Evaluations (PROMETHEE) (3%) (Antanasijević et al., 2017; Zhang et al., 2017).
5. Geometric function (Molyneaux et al., 2012), ordered weighted average (Badea et al., 2011) and rhombi area (Yao and Chang, 2014) (each 2%).

### 3.8. Uncertainty, sensitivity and robustness analysis

During the process of building an index, many decisions are made, such as the selection of the indicator set, data normalization, indicator weighting and aggregation. The validity of these decisions and the resulting indices may thus be contested. Uncertainty, sensitivity and robustness analysis support the confidence into an index and its underlying policy messages.

As reported by Saisana and Saltelli (2011), "uncertainty analysis focuses on how uncertainty in the input factors propagates through the structure of the index and affects the index' values. Sensitivity analysis assesses the contribution of the individual source of uncertainty to the output variance". The aim is to identify the source that mostly affects the results. Robustness analysis is the procedure of analyzing the combined effect of all the uncertainties and assess their effect on the output variance. A robust model/ranking will not be affected significantly by a change of the input conditions due to uncertainties, whereas a sensitive model/ranking is. Uncertainty, sensitivity and robustness analysis are thus interlinked (Narula and Reddy, 2015; Saisana et al., 2005).

In summary, the main sources of uncertainty in indices, for which sensitivity or robustness analyses can be undertaken, are:

1. Inclusion and exclusion of individual indicators: A large source of uncertainty is the development of the indicator set (Niemeijer and de Groot, 2008). In fact, adding or removing indicators might affect the results. Molyneaux et al. (2012) compare their index with and without the indicator of electricity generation efficiency. They notice only small and predictable changes in the results, allowing them to conclude that their index is robust to the removal of that indicator. Furthermore, Ang et al. (2015b) increase the number of indicators of their index from 22 to 28, which leads to an alteration of the results.
2. Modelling data errors based on available information: While some indicators might be determined very precisely, the quantification of others can be more difficult, hence they are less reliable. For such indicators, instead of considering a single value, the uncertainty could be modeled as an interval of performance in the form of a probability distribution, as presented in Badea et al. (2011).
3. Using different data treatment schemes for data imputation or trimming outperformers: Molyneaux et al. (2012) presents a sensitivity analysis towards outperforming countries and conclude that some countries are particularly sensitive to them.
4. Using different data normalization methods: Only one study applies more than one normalization method (Boccauthor and Hanna, 2016). Even though it is stated in their methodological report that the min-max, standardized and percentile rank methods are analyzed, it is unclear which one(s) was used to produce the final results. Also, the effect of using these different normalization methods is not presented, nor discussed.
5. Using different indicator weighting profiles, e.g. (1) equal weighting, (2) data-based methods or (3) participatory-based methods. Ang et al. (2015b) compare Singapore's energy security by using uneven subjective indicator weights and equal weights over all indicators. Results show minor differences only, but it is pointed out that the results might be more sensitive if the indicators have extreme differences of performances (some very high, others very low). Furthermore, Li et al. (2016) compare equal weights with the weights obtained with PCA. Even though trends over time are constant, their findings show results variations to some extent. Additionally, Augutis et al. (2012) assess the performance of the Lithuanian energy security level with regard to two different weighting profiles. Also Kanchana et al. (2016) study the effect of considering equal weights versus three different subjective weighting schemes. Once more, they identify that the different weights do have some effects on the index' value. Zhang et al. (2017) compute their energy security performance score 20 times with each time increasing the weight of one of the 20 indicators and keeping the others equal. They identify that some dimensions of energy security are more sensitive to indicator weights than others. Finally, Hughes and Shupe (2010) calculate the scores of their 11 countries by considering different subjective weights and consequently also experience changes in the results. One more method worse mentioning that, according to the author's best knowledge, has not been tested for energy security indices, is using Monte Carlo simulations to draw random weights. This would allow to obtain distribution of scores and hence analyze the stability of the results.
6. Using different aggregation functions: Only one study uses more than one aggregation function, in which the additive function is compared with DEA (Zeng et al., 2017). Results show that, among the Baltic states, Latvia maintains the highest level of energy security irrespectively of the aggregation approach considered.

Only three studies built their index' score on more than one combination of normalization method and aggregation function. The first one is the Global Energy Architecture Performance Index that uses three normalization methods, but the results are not presented (Boccauthor and Hanna, 2016). The second one is Zeng et al. (2017) who compare the additive aggregation function with DEA. The third one is Zhou and Ang (2008) in which three different DEA models are applied. Given the fact that the index construction methodology highly affects the rankings, a multitude of combinations could be used in order to assess ranking robustness.

Finally, some studies analyze the variation of the results through scenario analyses (e.g. (Bompard et al., 2017; Eckle et al., 2011)). Others verify the change of the index resulting from a change of the indicator values to a past date (Cabalu, 2010).

Overall, of the 63 energy security indices, only 13 (21%) present some type of uncertainty, sensitivity or robustness analysis. Hence, there is a considerable lack, proving that such analyses are still in the infancy stage for energy security indices.

## 4. Conclusions and policy implications

Given the multiple dimensions of energy security, indicator-based approaches are particularly suitable especially for country comparisons, as the resulting indices are simple to understand and represent effective communication tools for policymakers. This paper reviewed 63 energy security indices with respect to their scope, geographical coverage, number of countries analyzed, time frame covered, number of indicators considered, data treatment approach, multivariate analysis, normalization, weighting and aggregation of the indicators, and the assessment of uncertainty, sensitivity and robustness.

Results show that many indices are quantified for European, Asian and North American countries. South American and especially African countries are largely under-reported. These continents experience a fast population growth that is inevitably linked with rising energy needs. In order to secure a reliable and environmentally friendly energy supply aimed at supporting economic development, comprehensive energy security assessments of South American and African countries are necessary.

While most studies construct indices based on historical data, only few studies make projections into the future or provide scenario analyses. In fact, these are difficult to conduct and inherently associated with high degrees of uncertainty. However, they are important tools as they show future trends that can support policymakers to take the right decisions in due time.

Furthermore, there is a considerable lack of transparency in the different index construction steps. First, the selection of the indicator set is seldomly detailed or justified. It can be that different indicator sets would be developed if different stakeholders perform this task. Hence this could affect the results and validity of the index. This is why it is crucial to (1) develop a precise theoretical framework that describes the phenomenon to be measured, (2) assess the indicators one-by-one and mention the reasons why additional indicators were not included, (3) perform a multivariate analysis that provides additional insights into the data or identifies redundancy and (4) perform uncertainty, robustness and sensitivity analyses to assess how much the index varies according to the different indicator sets. If the results stay stable, it is possible to draw robust policies and confidence in the index is increased. Second, many data sets include missing values and outperformers, but the data imputation step is rarely described, nor the effects of the presence of outperformers, which have a great distortion potential, discussed. Third, the same holds for the selection of the indicator weighting scheme, which is often either chosen arbitrarily or equal weights are considered due to a lack of information. However, by either involving stakeholders, performing Monte Carlo simulations or analyzing the indicators' implicit weights, a justified weighting scheme can be determined. Fourth, even though an index' value and therefore its credibility is highly dependent on its construction methodology, only three studies have applied more than one combination of normalization method and aggregation function. Hence, for any published index, it would be very interesting to analyze how much the rankings change if the construction methodology is varied. Fifth, as discussed previously, uncertainty, sensitivity and robustness analysis are rarely conducted, even though they have the potential to greatly improve the confidence into the results.

Overall, major progress has been achieved in building energy security indices, partially thanks to an increased awareness of the importance of securing a reliable energy supply for our societies. Nevertheless, several areas in which further research is needed were identified and corresponding approaches to explore these gaps were provided in the respective sections.

As a closing note, thanks to their effective communication potential and easily understandability, indices will always be developed and used for policymaking. However, they can also be misleading if they are not built or analyzed properly. Hence, to make effective policies, decision-makers should verify the index' construction methodology and theoretical framework. Furthermore, it is crucial for them to perform a robustness assessment, which leads to each country having a performance range instead of a single score. Basing the performance of a country on one score only may lead to inaccurate results or results' misinterpretation, as the reasons for a country ranking at a certain position may be due to the construction methodology only, hence it may not be an objective representation of its performance. Additionally, it can be that a good performance is to be traced back to few indicators only, hence such a country would be advantaged by the index construction methodology followed. By conducting robustness assessments, such outcomes are minimized because the most likely performances of the countries are derived. Furthermore, by providing the details of the index construction methodology and publishing the indicator performance matrix, decision-makers can analyze the data set themselves and thus tailor the robustness assessment according to their own needs.

## Declaration of competing interest

The author declares no competing financial interest.

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