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A framework for evaluating global national energy security

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HIGHLIGHTS

- We construct an evaluation framework to identify global spatial disparities in national energy security.
- The framework considers three dimensions: energy supply chain, energy consumption, and political-economic environment.
- The study identifies key deficiencies affecting the energy security performance of several country types.
- We recommend policy prescriptions based on the evaluation results.

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ABSTRACT

Unlike most ES evaluation frameworks in the literature, this study provides a new evaluation technique based on the integrated application of subjective and objective weight allocation methods—SOWA (Subjective & Objective Weight Allocation), and introduces a balance score matrix (BSM) highlighting how well a country manages the trade-offs between the three competing dimensions for evaluating global national energy security. The results show that countries are struggling to develop a comprehensively secure energy system, with only one country out of 162 achieving an 'Excellent' score and 37 countries achieving a 'Good' score, together accounting for approximately one-fourth of the sampled countries. Meanwhile, the spatial disparity in the global performance of national ES is very significant: 'Excellent' and 'Good' groups are concentrated in Western Europe and North America, while the 'Limited' are concentrated in Europe, Middle East and Asia; the 'Weak' and 'Poor' groups are concentrated in Africa and Asia. Overall, this proposed framework allows for the quick identification of deficiencies within three dimensions in the ES context by pinpointing the main weaknesses. The study also offers suggestions for improving the performance of countries in different categories.

1. Introduction

Since the 2000s, the importance of energy security (ES) has been increasing as a public issue amidst concerns among scholars and policymakers driven by rising volatility in energy prices, scarce fossil fuels, pressure to de-carbonize energy systems, and geopolitical supply tensions [1–4]. However, contemporary ES studies differ from historical ones in important ways. During the 1970s and 1980s, ES concerns focused on a stable supply of cheap oil due to the threat of embargoes and price manipulation by exporters [5,6]. Today, ES has returned to the public eye not only because of energy supply issues but also because of its close linkage with other energy policy problems, such as equitable access to modern energy and the mitigation of climate change [7]. Moreover, the centres of energy disturbance extend from America and Europe to Asia, and oil and gas reserves remain concentrated in a few politically unstable countries, such as those in the Middle East [8–10]. ES is undeniably one of the key parameters required for determining the current position and future orientation of development in all countries [11].

Defining ES precisely is difficult, and numerous definitions have been offered by researchers and policymakers. Given the growing dominance of fossil fuels, the liberalization of energy markets, escalating energy demand in developing nations, and continuous instability due to political unrest and large-scale natural disasters, the prior usage of the term 'ES' had been enhanced by a focus on securing the supply of two primary energy sources: oil and gas.

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Therefore, ES is commonly defined as the reliable and adequate supply of the primary energy at reasonable prices. The use of this definition can be found in the publications of the UNDP [12], Bielecki [1], IEA [13], Müller-Kraenner [14], Chester [15], and Cabalu [16]. Usage of the term has also been deeply influenced by geopolitics [17–22]. Diversification is another key issue that determines energy availability and security in ES studies such as those of Jansen et al. [23] and Thangavelu et al. [24]. Energy conversion and delivery infrastructure in the energy supply chain have also been discussed; a good infrastructure is a commonly suggested prerequisite for stable energy supplies and an important component of economic security [22,25]. As global warming and air pollution have received increasing attention, the recent literature has recognised the importance of the close relationship between environmental sustainability and energy consumption [26–30]. Nevertheless, ES also consists of political and governmental dimensions, such as the social stability of the energy supply, as suggested by Chevalier [31], Jansen et al.[23], and Brown et al. [32], and effective energy planning for national ES, as proposed by Goldthau and Sovacool [33] and Yao and Chang [34]. Some studies extend ES concepts to include the efficient use of energy and the improvement of communities' living environment. For instance, Kemmler and Spreng [35] included 'promoting energy efficiency and reducing energy intensity' as a main policy for tackling ES problems, and Hughes argued similarly [36]. Lesbirel posited that ES should ensure that a population has adequate access to energy sources to sustain acceptable levels of social and economic welfare [37]. Vivoda held that a new ES conceptualization must consider providing basic energy services such as access to electricity, which has been ignored by the traditional conceptualization of ES [38]. These definitions in the literature reflect seven major ES themes or dimensions: energy availability, infrastructure, energy prices, societal effects, environment, governance, and energy efficiency. Following recent developments in the literature, ES can be defined as 'equitably providing available, affordable, reliable, efficient, environmentally benign, proactively governed and socially acceptable energy services to end-users' for the purpose of this study, as stated in Sovacool and Brown's review of the ES literature [39].

In addition, researchers have shown a growing interest in establishing a methodology for quantitatively assessing national ES. A number of scientific assessment methods of approaching ES from various angles have been proposed. A recent comprehensive literature survey by Ang et al. [40] indicates considerable diversity among studies that identify ES indicators/indices; the number of ES dimensions ranges from 1 to 20 and the number of indicators ranges from 1 to 320. Meanwhile, as surveyed by Radovanović et al. [41], 11 methodologies have been identified as the most commonly used measures of ES: the Herfindahl-Hirschmann Index, Supply/Demand Index for the long-term security of supply, the Oil Vulnerability Index, the Vulnerability Index, Risky External Energy Supply, Socioeconomic Energy Risk, the US Energy Security Risk Index, the Energy Sustainability Index developed by the World Energy Council (WEC) in association with Oliver Wyman, MOSES—The IEA Model of Short-term Energy Security, the Energy Security Index developed by the EU Joint Research Centre in Italy, and the Energy Architecture Performance Index (EAPI) proposed by the World Economic Forum (WEF). Seeking a balance between maximising comprehensiveness and being pragmatic given data scarcity, Tongsopit et al. [42] and Yao and Chang [34] used fewer dimensions but retained a meaningful and rigorous evaluation of ES. Both studies examined national ES performance through social, economic, and environmental dimensions.

Several observations can thus be made from a literature review on issues concerning the definition and assessment of ES. First, comprehensive dimensions such as economic, environmental, and social dimensions are widely used to define the concept of ES and evaluate national or regional ES performance. Second, comprehensive and comparative analyses of national ES are increasingly important for informing policymakers on energy policies [42]. Third, subjective weight allocation is the most widely used aggregation method [43] among ES assessment studies with comprehensive dimensions. The assessment can never be absolutely accurate, but it should attempt to be as realistic as possible, as Ang et al. [40] assert. In this sense, ample opportunity remains to develop the evaluation method and choices related to the scale and variables.

This paper seeks to comprehensively and systematically assess the overall performance of 162 countries' energy systems, thereby highlighting their spatial disparities, and providing a new evaluation technique based on the integrated application of subjective and objective weight allocation methods, SOWA, which are rarely used in existing studies. In addition, unlike in most ES frameworks in the literature, BSM, a balance score matrix highlighting how well a country manages the trade-offs between these three competing dimensions, is introduced. The benefits of using this scoring system include interpretability, non-linear scaling, and reduced decisive influence from a specific dimension. The framework's application leads to interesting results, and their policy implications are discussed. We expect this study to enrich our knowledge and understanding of ES issues.

The remainder of the paper is organised as follows. In Section 2, the assessment framework, the methodology for calculating the Energy Security Index (ESI), and data sources are briefly presented. Section 3 presents the spatial pattern of national ES across the globe and compares it with those obtained by other studies. Section 4 analyses the average results for each geographic region and the classification of countries in each region. Finally, conclusions and suggested policy paths are presented in Section 5.

2. Material and methodology

Though several approaches to measuring ES have been developed, policymakers constantly struggle to find the proper indicators and approaches that will help formulate stronger energy policies. We construct our ESI in three steps. First, a framework addressing the scope, objectives, and structure of the indicator selection is proposed. Second, the selected indicators are normalised to address the different measuring units used for the indicators. Finally, the normalised indicators are weighted according to their perceived importance and then aggregated to form a composite index.

2.1. Hierarchical structure for energy system assessment

Among the variety of methodologies, two basic approaches can be used to assess ES: the supply-orientated approaches and the methods that apply composite indices. The supply-oriented approaches, which mainly include the Herfindahl–Hirschmann index, supply/demand index, risky external energy supply index, and the IEA Model of Short-term Energy Security (MOSES), are extremely useful methods that emphasize the safety in procuring and transporting energy generating products. However, these models do not incorporate social and environmental concerns when measuring ES. The second set of approaches, including the oil vulnerability index, vulnerability index, socioeconomic energy risk index, US energy security risk index, energy sustainability index, energy security index, and energy architecture performance index, is regarded as acceptable for ES assessments because it allows the use of different indicators according to the researchers' specific purposes. In that sense, we try to use the method of composite indices to provide a comparative analysis of national ES performance with fewer dimensions as well as an evolving dialogue aiming to further our knowledge of effective strategies and policies for fostering the necessary transformation of the energy system.

From existing studies, we have identified the following seven major energy security dimensions: energy availability, infrastructure, energy prices, energy efficiency, environment, societal effects, and governance. Very few studies include all the seven themes due to the lack of data availability and other quality issues. In this study, we restructure the above dimensions according to data availability, and design the framework of this study as shown in Table 1. The framework comprises three ES dimensions: the Security of Energy Supply–Delivery dimension (SESD), the Safety of Energy Utilization dimension (SEUD), and the Stability of the Political-Economic Environment dimension (SPED). SESD involves the major factors of energy availability and infrastructure. SEUD includes two components, equity of energy service and environmental sustainability of energy consumption. The former component of SEUD is employed to describe the capacity of popularizing modern energy at the consumer level, and the other one is used to measure energy efficiency and the influence of energy consumption on the environment. In addition, SPED is mainly concerned with a country's political and socioeconomic strength, which may have an influence on energy policies and investments in the energy sector.

2.1.1. SESD indicators

SESD refers to the ability of the national energy system to cope with disturbances in energy supply and demand from seconds to days. Nine indicators for this dimension are split between the two components of energy supply and delivery. Energy supply indicators measure the diversification of the fuel mix, the dependence on energy imports, and proved energy reserves. The diversity of energy supply reflects the national capacity for diversifying the fuels used to provide power supply services and recover quickly from an attack on or disruption of a fuel supply. Generally, a more diverse system is likely to be less vulnerable to most challenges to the energy supply system. We use the indictors of *electricity generation diversity* and *energy supply diversity* to represent the diversification of the energy system. These indicators are calculated using the Shannon-Weiner index (SWI) as follows:

$$SWI = -\sum_{t=1}^{k} P_t \ln P_t \tag{1}$$

where k is the number of fuels, and P_t is the share of fuel t out of total energy consumption for electricity generation and total energy supply. Meanwhile, *net fuel imports as a percentage of energy use* and the *ratio of energy production to energy consumption* are metrics indicating a country's dependence on foreign energy resource supply. In addition, we select *proved reserves of natural gas*, *proved reserves of coal*, and *crude oil proved reserves* as indicators reflecting the estimated quantity of energy source for the future development, while

Table 1
Framework and indicators for the construction of national ESIs across the globe.

Target	Dimension	Component	Indicator	Unit	Weight		
					Dimension	Component	Indicator
Energy security index (ESI)	Security of energy supply–delivery dimension (*SESD*)	Supply (*Sup*)	Ratio of total energy production to total energy consumption	–	0.40	0.30	0.060
			Net fuel imports as a percentage of energy use	%			0.050
			Proved reserves of natural gas	Trillion cubic feet			0.041
			Proved reserves of coal	Million short tons			0.042
			Crude oil proved reserves	Billion barrels			0.034
			Diversity of energy supply	–			0.038
			Diversity of electricity generation	–			0.035
		Delivery (*Del*)	Days to obtain a permanent electricity connection	Days		0.10	0.125
			Ratio of electricity distribution losses to net generation	–			−0.025
	Safety of energy utilization dimension (SEUD)	Equity (*Equ*)	Final energy consumption per capita	kg of oil equivalent per capita	0.40	0.15	0.062
			Percentage of population with access to electricity	%			0.049
			Percentage of population with access to non-solid fuel	%			0.056
			Annual average of prices of retail gasoline	Average price in USD PPP			−0.017
		Environmental Sustainability (*Env*)	Share of non-fossil fuel of total primary energy supply	%		0.25	0.027
			Share of renewable electricity generation of total electricity generation	%			0.061
			Carbon factor	t/t oil equivalent			0.093
			Energy intensity	MTOE/USD 1000 of GDP (constant 2005 USD)			0.068
	Stability of political-socioeconomic environment dimension (SPED)	Strength (*Str*)	Political stability and absence of violence/terrorism	–	0.20	0.20	0.033
			Regulatory quality	–			0.035
			Government effectiveness	–			0.031
			Rule of law	–			0.034
			Control of corruption	–			0.033
			GDP per capita	Current USD at market prices			0.035

ratio of electricity distribution losses to net generation and the *days to obtain a permanent electricity connection* as indicators reflecting the level of energy delivery.

2.1.2. SEUD indicators

The SEUD dimension measures a nation's ability to ensure the equitable, efficient, and sustainable use of energy fuels for production and life [44]. Eight indicators for this dimension are used to describe its two components: energy equity and environmental sustainability of energy use. The *percentage of the population with access to electricity*, *final energy consumption per capita*, the *percentage of the population with access to non-solid fuel*, and the *annual average price of retail gasoline* are used as indicators of the energy equity component. According to the findings of recent studies [45–47], the *final energy consumption per capita* indicator can be considered to reflect the nation's ability to provide sufficient energy for human wellbeing. On the other hand, the evidence is mounting of a negative relationship between oil prices and oil stock markets [48], suggesting that the higher the price of gasoline, the more likely it is to cause a supply crisis. Four indicators measure the environmental sustainability of energy consumption: the *share of non-fossil fuel of total primary energy supply*, the *share of renewable electricity generation of total electricity generation*, the *carbon factor*, and *energy intensity*. The *carbon factor* is provided by the ratio of CO_2 emissions to total primary energy consumption.

2.1.3. SPED indicators

Furthermore, a country's political–socioeconomic strength may have a strong influence on energy policies and energy sector investments [49], consequently affecting the security of energy supply/delivery and consumption. Political–socioeconomic strength indices can thus be said to provide information about potential risks associated with a country's ES. To assess a country's political stability, social security, and economic strength, we choose five indicators—*political stability* and *the absence of violence/terrorism*, *regulatory quality*, *government effectiveness*, the *rule of law*, and the *control of corruption*—to reflect national political and societal strength, which reflects the status of governance and policymaking. In addition, *GDP per capita* is used to reflect national economic strength.

2.2. Synthesizing the indicators

Having selected the appropriate indicators and collected the requisite data, three additional steps are needed to establish a composite *ESI* and its sub-indices: (a) normalizing the indicators, (b) weighting the normalised indicators, and (c) aggregating the normalised indicators.

2.2.1. Normalisation

The selected indicators usually have different units and operate on different scales. They need to be converted before they can be aggregated to form a composite index. Several normalisation methods are proposed in the literature, such as min–max normalisation [42,50,51], the reference distance method [52], standardization using Z-scores (SZ) [53], and the banding method [19,54,55]. Because of the large amount of data in normalisation operations and as comparisons should be made among countries, we advocate SZ, which is expressed by the following formula:

$$Z_{ic} = \frac{X_{ic} - \overline{X_i}}{\sigma(X_i)} \tag{2}$$

where Z_{ic} is the standardized result of indicator i for country c, calculated based on the mean and standard deviation of a sample of n countries; X_{ic} is the raw data of indicator i for country c; and $\sigma(X_i)$ is the standard deviation of X_i.

Indicators such as the annual average of price of retail gasoline, net fuel imports as a percentage of energy use, days to obtain a permanent electricity connection, ratio of electricity distribution losses to net generation, and energy intensity have negative effects on ES; thus, this paper must normalise the negative numbers of these indicators.

2.2.2. Weighting and aggregation

Indicators can be synthesized into composite scores for three dimensions and an overall *ESI*. Six methods can be found in the literature for weighting indicators: equal weights, import/fuel share, PCA, the analytic hierarchy process (AHP), data envelopment analysis (DEA), and subjective weight allocation (SWA). Unlike most studies, which have used subjective weight allocation, this study overcomes the shortcomings of SWA method by determining the weight of indices with SOWA, a new comprehensive method of combining objective weight allocation based on PCA and subjective weight allocation, with reference to existing studies.

First, to test the validity of the indicators, Kaiser-Meyer-Olkin (KMO), Bartlett's test, PCA, and varimax rotation are employed to objectively determine the weights of 20 assessment indicators. Based on eigenvalues greater than 1, the common factors (F_j, $j = 1, 2, 3, \ldots, p$, p is the number of common factors) are extracted; M_{ij}, the load coefficient of indicator i to j principle factor, characteristic roots (R_j), and the variance contributions of common factors (C_j) are then obtained. Next, using the following formula, indicator i can be weighed based on objective evidence:

$$W_i = \sum_{j=1}^{p} \frac{M_{ij}}{\sqrt{R_j}} \times \frac{C_j}{C} \tag{3}$$

where W_i denotes the weight of indicator i, and C is the cumulative contribution of all principal components.

Second, following [9,56], the weights of the three dimensions in this study are 40%, 40%, and 20%, respectively, and those of the energy supply and delivery components of the SESD are 30% and 10%, respectively. The weights of energy equity and environmental sustainability of energy use in the SEUD are 15% and 25%, respectively. We subsequently obtain subjective weights for five components, which can be represented as W_d, $d = 1, 2, 3, 4, 5$.

Third, we redistribute the weights of 23 indicators according to the normalisation of W_i. The normalisation is performed using the following simple aggregation formula:

$$W_i^* = \frac{W_i}{\sum_{i=1}^{m} W_i} \times W_d \tag{4}$$

where m is the number of indicators in component d. The weights assigned to the indicators are shown in Table 1.

Fourth, ESI_{tot}^c of country c is given by the following simple aggregation formula:

$$ESI_{tot}^c = \sum_{i=1}^{16} W_i^* \times Z_{ic} \tag{5}$$

However, the debate continues about whether ESI_{tot} can be used to assess national ES performance. For instance, according to ESI_{tot}, Chad has a very strong *ratio of total energy production to total energy consumption* (as high as 62.96), which leads to the highest SESD sub-index of the 162 sampled countries. However, its performance on other SEUD indicators, such as *diversity of electricity generation and distribution losses*, is very poor. Its performance is even worse for SPED, with a SPED sub-index value of only −0.247. After synthesizing the indicators and obtaining the national ESI_{tot} of Chad, the value is as high as 0.803, ranking Chad ninth among all the countries in this study. By contrast, Iceland has the strongest SEUD performance but a poor SESD performance due to a lack of large natural deposits of fossil fuels. According to the ESI_{tot}, Iceland ranked third overall. These findings indicate that the decisive influence of single dimension must be reduced to conduct an appropriately comprehensive evaluation.

To overcome the aforementioned limitations, a balance *ESI* score (ESI_{bla}) system that highlights how well a country manages the trade-offs among the three competing dimensions is introduced. The score reflects the overall performance in the three dimensions and enables us to identify countries that perform very well with regard to ES. We give each dimension an easy-to-understand score—A, B, C, or D—by splitting the sub-indices for the three dimensions using the natural breakpoint grading method (NBGM) on the ArcGIS technology platform. The best score, A, is given for the best performers in the dimension. Countries with relatively good performance in that dimension are given a B. Weak performers in that dimension are given a C, and a D is given to countries that underperform. Countries are then provided with a three-letter score. The sequence of the letters in the score corresponds to the specific order: SESD, SEUD, or SPED. Finally, BSM is obtained (see Fig. 1).

2.3. Data sources

In constructing an ES index, data availability affects the choice of indicators. In this study, the data needed for this study have been collected from various sources. Energy and CO_2 emissions data are collected from the International Energy Statistics of the International Energy Agency (IEA) [57] and U.S. Energy Information Administration (EIA) [58]. Data on the *GDP, population*, *annual average of price of retail gasoline*, and *percentage of population with access to electricity* are collected from the World Bank [59]. The political stability and social security data are collected from World Development Indicators (WDIs) of the World Bank [60].

3. Results

3.1. Numerical results for ESI and rating

Aided by NBGM on the ArcGIS technology platform, scores for the three dimensions are obtained according to the evaluation criteria shown in Table 2. Based on the scoring schemes seen in Fig. 1, the countries are then divided into five grades according to ESI_{bal}: Poor, Weak, Limited, Good, and Excellent. In addition, we also find that there are significant differences among countries in the same group in terms of ES performance. Therefore, the sampled countries are further divided into nine types: Poor, Weak (I), Weak (II), Weak (III), Limited (I), Limited (II), Good (I), Good (II), and Excellent.

Table 2
Range of ratings for the three dimensions.

Rating	SESD	SEUD	SPED
A	0.164–0.654	0.380–0.932	0.221–0.404
B	−0.026 to 0.163	0.042–0.379	0.054–0.220
C	−0.233 to −0.027	−0.140 to 0.041	−0.117 to 0.053
D	−0.750 to −0.234	−0.323 to −0.141	−0.284 to −0.118

Fig. 2 and Table 3 present the comparative results for the nine sub-groups. As shown in Fig. 2, countries with Excellent profiles are the top performers in managing trade-offs among the three dimensions. Only one country out of 162, Norway, achieves an AAA balance score, but its balance is tilted heavily towards SEUD. Thirty-seven countries have Good performance on ES. According to the triangular profile, this group can be further divided into two sub-groups, Good (I) and Good (II). Twenty-eight countries with Good (I) performance have a relative balance between the energy system and social development, especially performing well on SPED, which are advanced countries distributed mainly in Europe, Middle East, Oceania and North America. Nine developing countries belong to the Good (II) group, the triangular profile of this sub-group shows a relatively poor performance on SPED.

Like Good group, there is a significant difference in ES triangular profile between two sub-groups of the Limited. Triangular profile of Limited (I) group is tilted heavily towards SESD, with lower SEUD and SPED scores. This sub-group comprises 15 countries with rich endowments of fossil fuels, such as OPEC members in Middle East, Russian Federal, and Malaysia. It's worth mentioning that Limited (I) has the greatest SESD sub-index (0.195) among 9 sub-groups. Instead, nine countries have good performances on both SEUD and SPED and poor performance on SESD due to their limited domestic energy resources, which are large importers of energy, such as Japan, Iceland, Ireland, Netherlands, Luxembourg, and Singapore.

The Weak group comprises 55 countries, accounting for approximately 34% of the sample. According to the triangular profiles, three sub-groups can be obtained, namely, Weak (I), Weak (II) and Weak (III). As shown in Fig. 2, with underperformance on SEUD and SPED, thirty-seven countries illustrating the Weak (I) profile have a balance tilted heavily towards SESD. Meanwhile, the Weak (II) group tilting towards SEUD and Weak (III) tilting towards SPED have 9 countries each. Despite their good performance on a single

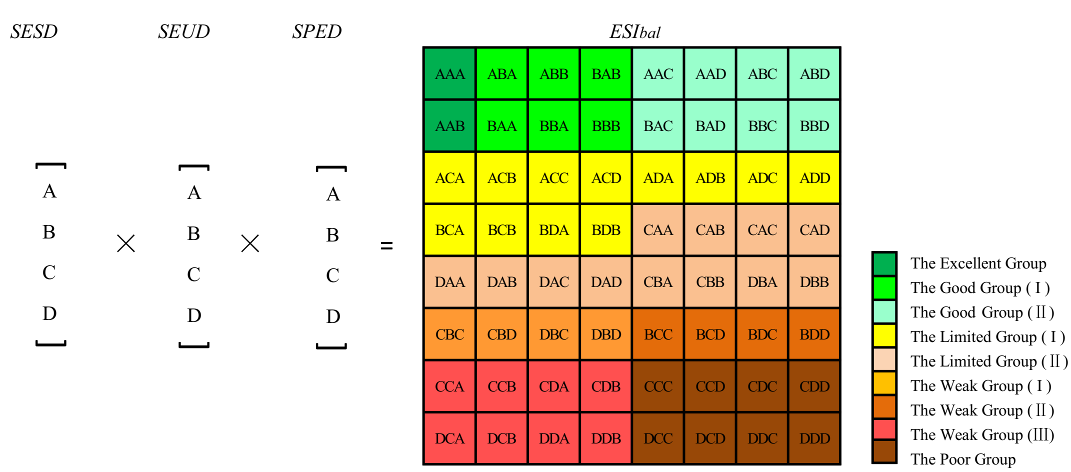

Fig. 1. Balance score matrix.

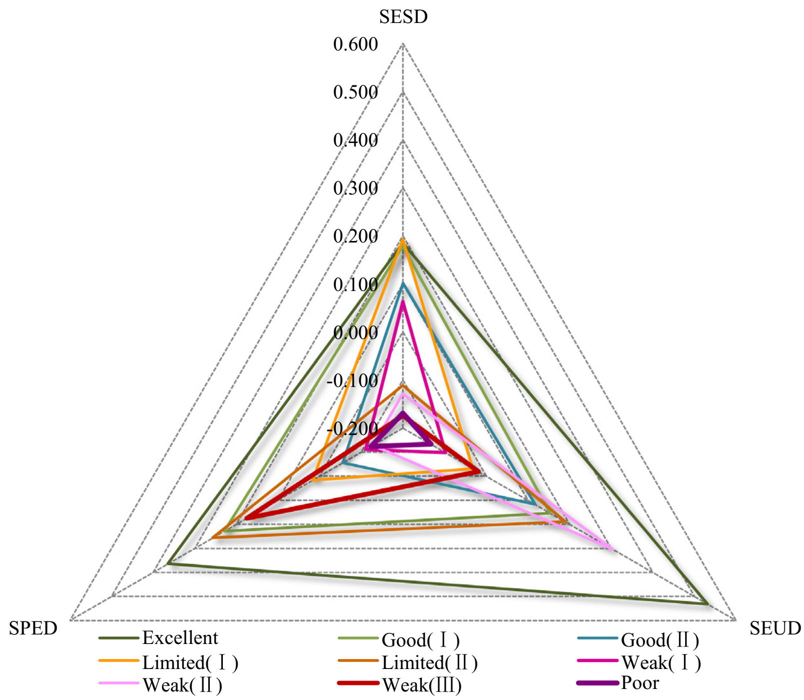

Fig. 2. Triangular profile of ES performance of countries in 9 grades.

Table 3
Numerical results for ESI_{bla}, ESI_{tot}, and sub-indices.

Rating	$\overline{ESI_{bal}}$	$\overline{ESI_{tot}}$	$\overline{SEED}$	$\overline{Sup}$		$\overline{Del}$	$\overline{Equ}$	$\overline{E\_s}$	$\overline{SPED}$	Number of countries
Excellent	AAA	1.081	0.185	0.103	0.081	0.532	0.244	0.288	0.364	1
Good(I)	ABA	0.561	0.178	0.124	0.054	0.154	0.142	0.012	0.229	28
Good(II)	BBC	0.164	0.101	0.037	0.064	0.118	−0.045	0.162	−0.055	9
Limited(I)	ACC	0.178	0.192	0.142	0.050	−0.031	0.045	−0.076	0.017	15
Limited(II)	CAA	0.335	−0.112	−0.094	−0.018	0.190	0.203	−0.013	0.257	9
Weak(I)	BCC	−0.146	0.063	0.025	0.039	−0.098	−0.048	−0.050	−0.111	37
Weak(II)	CBD	0.046	−0.129	−0.116	−0.012	0.303	−0.092	0.396	−0.128	9
Weak(III)	CCB	−0.018	−0.174	−0.106	−0.068	−0.019	0.070	−0.089	0.175	9
Poor	CCC	−0.425	−0.169	−0.086	−0.083	−0.133	−0.098	−0.035	−0.123	45
SD	–	0.414	0.186	0.145	0.124	0.182	0.143	0.159	0.181	–

dimension, ES in the Weak group remains weak because of the offset from the poor performances on the other two dimensions. Moreover, forty-five countries are included in the Poor group, which struggle to progress in all three dimensions.

Furthermore, standard deviation (SD) is used to measure the degree of dispersion in the dimensional score; the results yield an interesting finding: the degree of dispersion is greatest in SESD (its *SD* reaches 0.186), followed by that of SEUD and SEUD (see Table 3). Breaking down SESD and SEUD into its four component aspects provides a more detailed summary (see Fig. 3). Closely examining the sub-index's degree of dispersion, we also find that energy supply is the major component responsible for intergroup differences in SESD and that environmental sustainability is responsible for intergroup differences in SEUD. The striking disparities across countries' capacities to enhance energy supply stability and improve the environmental sustainability of energy consumption always represent the main concern for policymakers in these countries.

3.2. Spatial distribution of regional and national ES performance

Fig. 4 illustrates the geographical distribution pattern of the five rating groups, showing the significant spatial-clustering characteristics of the distribution of national ES. The Excellent and Good groups are concentrated in Western Europe, which has the world's only Excellent country and 17 of the 37 Good countries. Limited countries are distributed mainly in Africa and Asia, which account for over 45% of the sampled countries in this category. The Weak and Poor groups consist mainly of developing countries and the world's least-developed countries in Africa.

3.3. Comparisons with other studies

Two important studies have provided country-level details on ES across the globe that can be used to compare with and verify the findings in this study. In collaboration with Accenture and a panel of experts, the WEF developed an Energy Architecture Performance Index (EAPI) that ranks 105 countries based on how well their energy system serves economic growth and development and ensures the population's access to affordable energy in an environmentally sustainable way. The study uses 18 indicators grouped into three dimensions covering economic growth and development, environmental sustainability, and ES and access. In addition, the Energy Trilemma Index (ETI) is published annually by the WEC in partnership with global consulting firm Oliver Wyman, along with the Global Risk Centre of its parent Marsh & McLennan Companies. The 2014 report provides a comparative ranking of 126 countries and awards countries with a total score

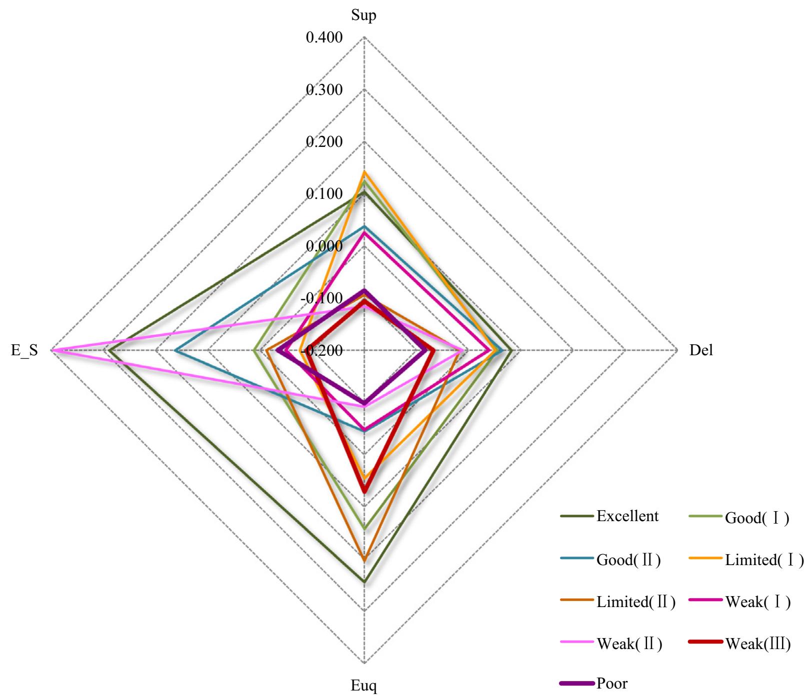

Fig. 3. Component profile for the countries in 9 groups.

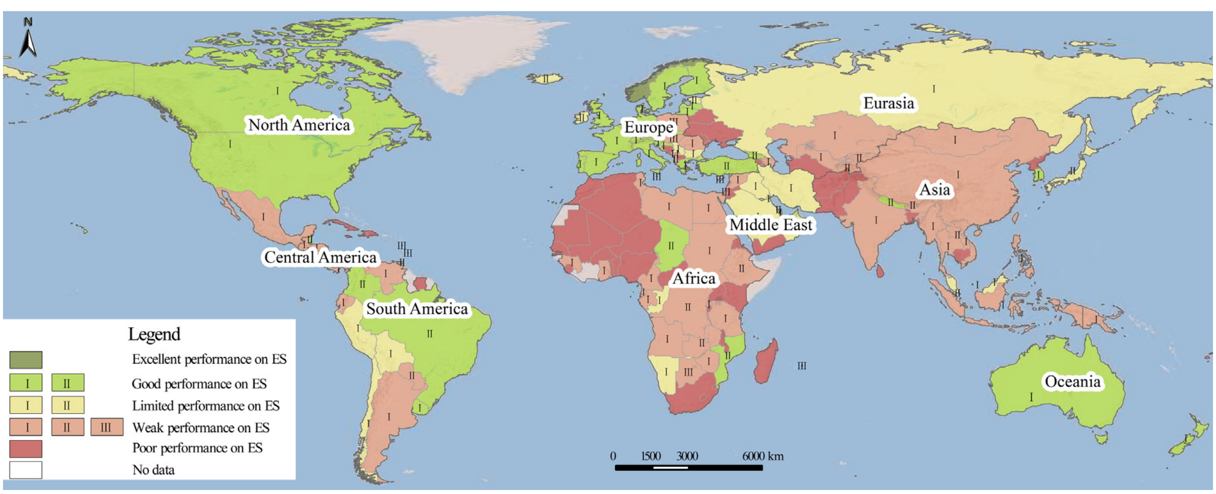

Fig. 4. Global distribution patterns of national ES.

and a balance score based on 22 underlying indicators with subjective weights. The rankings are based on a range of country-level data and databases that capture energy performance and the contextual framework. Energy performance is based on three dimensions—energy supply and demand, energy affordability and access, and the environmental impact of energy use. The contextual indicators consider the broader circumstances of energy performance, including societal, political, and economic strength. Unfortunately, neither of these studies produces a spatial distribution map based on national ES performance. To further this comparative analysis, using the national total scores provided by the studies mentioned above, we produce two national ES distribution maps for 2014 based on the rating scheme shown in Table 4.

Figs. 5 and 6 show that the Excellent and Good groups are concentrated in Western Europe, North America, and South America, while the Limited, Weak, and Poor groups mainly comprise developing countries and the world's least developed countries in Africa and Asia. These results are very similar to the findings in this study. The significant difference between them is that the classification criteria in our study are stricter, focusing far more on the comprehensive feature of national ES and highlighting the challenges and opportunities faced by energy systems in each region and country. As a result, in the WEF and WEC reports, 33 countries are Excellent, and 42 are Good (see Table 5), accounting for 31.4% and 32.5% of

Table 4
Ratings for EAPI and ETI.

Rating	Range (EAPI)	Range (ETI)
Excellent	0.65–1.00	8.00–10.00
Good	0.55–0.64	6.00–7.99
Limited	0.50–0.54	4.00–5.99
Weak	0.45–0.49	2.00–3.99
Poor	0–0.44	0.00–1.99

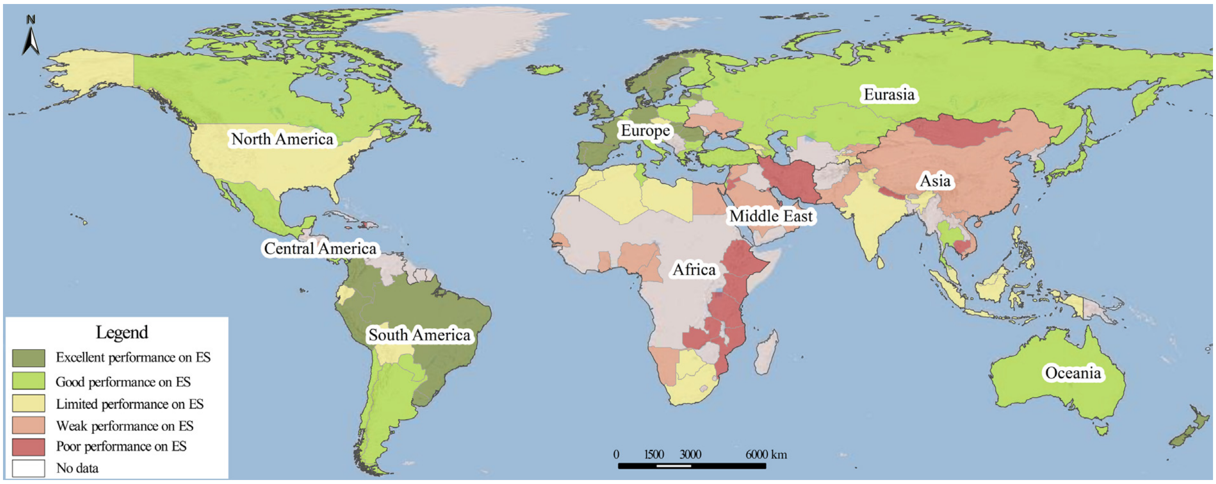

Fig. 5. Global distribution patterns of national ES according to the WEF's EAPI.

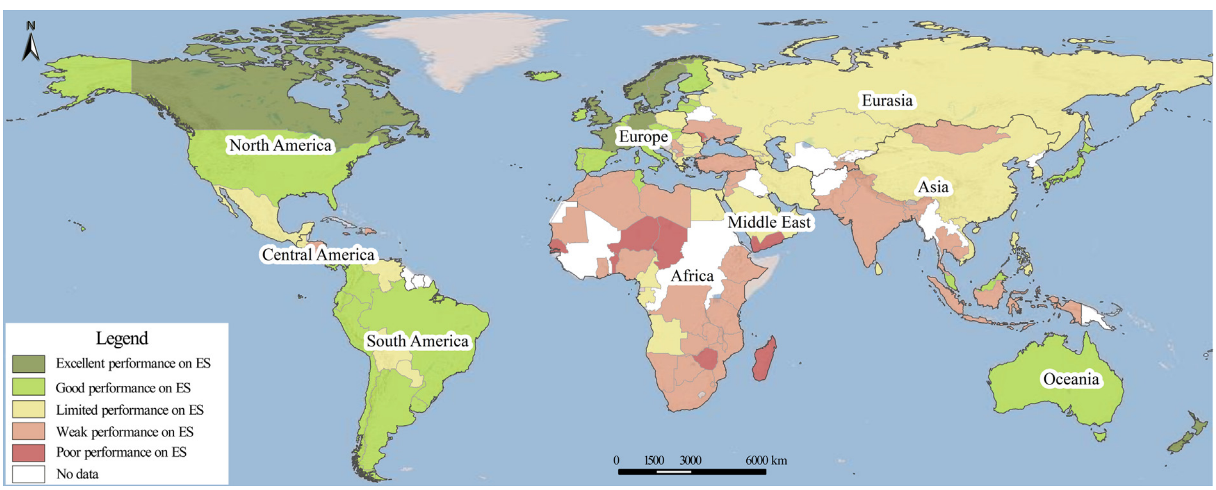

Fig. 6. Global distribution patterns of national ES according to the WEC's ETI.

Table 5
Numbers of countries in the 5 groups: inter-study comparisons.

	Excellent	Good	Limited	Weak	Poor
Our study	1	37	24	55	45
WEC	11	31	40	36	8
WEF	15	18	21	30	21

the total, respectively. In our study, only 38 countries are in these groups (1 Excellent and 37 Good), accounting for 23.5% of the sample.

4. Discussion

As countries have unique resource endowments, policy goals, and challenges, a country's absolute rank may be less meaningful than its relative performance. Therefore, to provide a comparative assessment of the regional and national ability to balance the energy dilemma, the average results for each geographic region and the classification of countries in each region are presented below.

As shown in Table 6, Africa has a poor ES performance, with an $\overline{ESI_{tot}}$ of -0.306. Although the region is well endowed with both fossil fuels and renewable energy sources, the strong ratio of total energy production to total energy consumption is offset by the low diversity of the energy supply mix and electricity generation portfolio; thus, the regional indexes of $\overline{Sup}$ and $\overline{SESD}$ are only -0.048 and -0.073, respectively, ranking Africa at the bottom. In addition, due to the absence of sufficient energy infrastructure, the region cannot provide reliable modern energy services to citizens to promote economic growth and social development. The region's SEUD performance is worse than its SESD performance (see Fig. 7), with the lowest sub-index among the nine regions. Meanwhile, due to myriad causes (e.g. corrupt governments, failed central planning, high levels of illiteracy, a lack of access to foreign capital, and frequent tribal and military conflict) [61], the region's performance on the SPED sub-index—the lowest worldwide—is weak relative to its performance in the other two dimensions. Based on national ES performance, 45 African countries in this study can be assigned

Table 6
Numerical results for ESI_{bla}, $ESI_{tot,}$ and sub-indices in the 9 regions.

Regions	$\overline{ESI_{bal}}$	$\overline{ESI_{tot}}$	$\overline{SEED}$	$\overline{Sup}$		$\overline{Del}$	$\overline{Equ}$	$\overline{E\_S}$	$\overline{SPED}$
Africa	CCD	−0.306	−0.073	−0.048	−0.025	−0.108	−0.150	0.042	−0.124
Asia	CCC	−0.110	−0.033	−0.014	−0.019	−0.037	−0.041	0.004	−0.040
Eurasia	CCC	−0.074	−0.035	0.043	−0.078	0.020	0.057	−0.037	−0.058
Middle East	BCC	0.092	0.068	−0.001	0.069	0.003	0.128	−0.125	0.021
Central America	CCC	−0.053	−0.037	−0.107	0.071	−0.001	0.019	−0.020	−0.015
South America	BBC	0.140	0.076	0.021	0.055	0.103	0.038	0.065	−0.038
Europe	BBB	0.350	0.054	0.061	−0.007	0.115	0.112	0.003	0.181
Oceania	BCB	0.314	0.145	0.083	0.062	0.015	0.033	−0.018	0.154
North America	ABB	0.628	0.336	0.328	0.007	0.099	0.125	−0.026	0.193

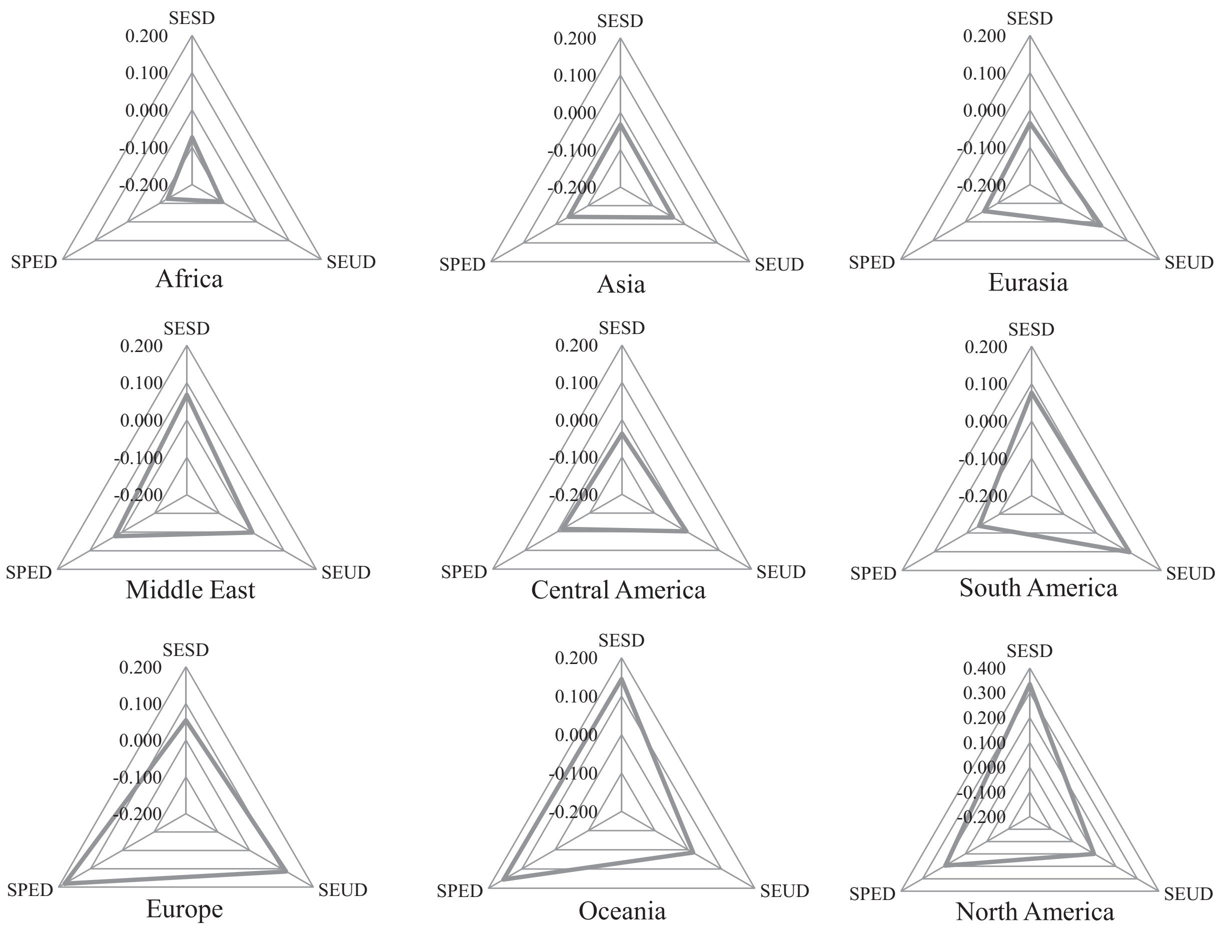

Fig. 7. Triangular profiles of the 9 regions' performance.

to four categories according to the ESI_{bal} (see Fig. 8). Among these countries, Chad and Mozambique are assigned to the Good (II) group due to an upsurge in energy production and a seemingly high environmental sustainability due to its very low energy consumption. Republic of Congo and Namibia are categorized as Limited (I) because they underperform in SEUD and excellent performance in SESD. Eighteen African countries are classified as Weak, whose performance are slightly supported by a single dimension. The 23 remaining African countries are classified as Poor, as they underperform in all three dimensions.

Asia's ES performance profile presents a relative balance with low sub-indices (see Fig. 7), but overall ES performance remains poor (see Table 6), with an $\overline{ESI_{tot}}$ of −0.110. To fuel economic growth and meet the energy needs of the growing population, energy investment is needed on an unprecedented scale in Asia, which has caused a rapid increase in energy imports and the deterioration of energy supply security: the average of SESD sub-index is −0.033, ranking sixth among the nine regions. In addition, similar to the situation in Africa, many developing economies in Asia still struggle to provide their populations with access to modern energy services, resulting in a weak SEUD performance. Meanwhile, the index of $\overline{SPED}$ is −0.040, a weaker performance than that in the other two dimensions. In this study, 23 Asian countries can be assigned to four categories according to their ESI_{bal} (see Fig. 8). Among them, South Korea and Nepal are Good (I) due to their strong SESD and SEUD performances. Furthermore, four countries are Limited because they underperform in the SESD or SEUD. For instance, Malaysia and Brunei Darussalam have strong SESD performance and weak SEUD performance. By contrast, for Japan and Singapore, SEUD is the strongest ES dimension, while SESD is a challenge for them. Ten countries are Weak, whose ES performance is slightly benefited by a single dimension. Myanmar, India,

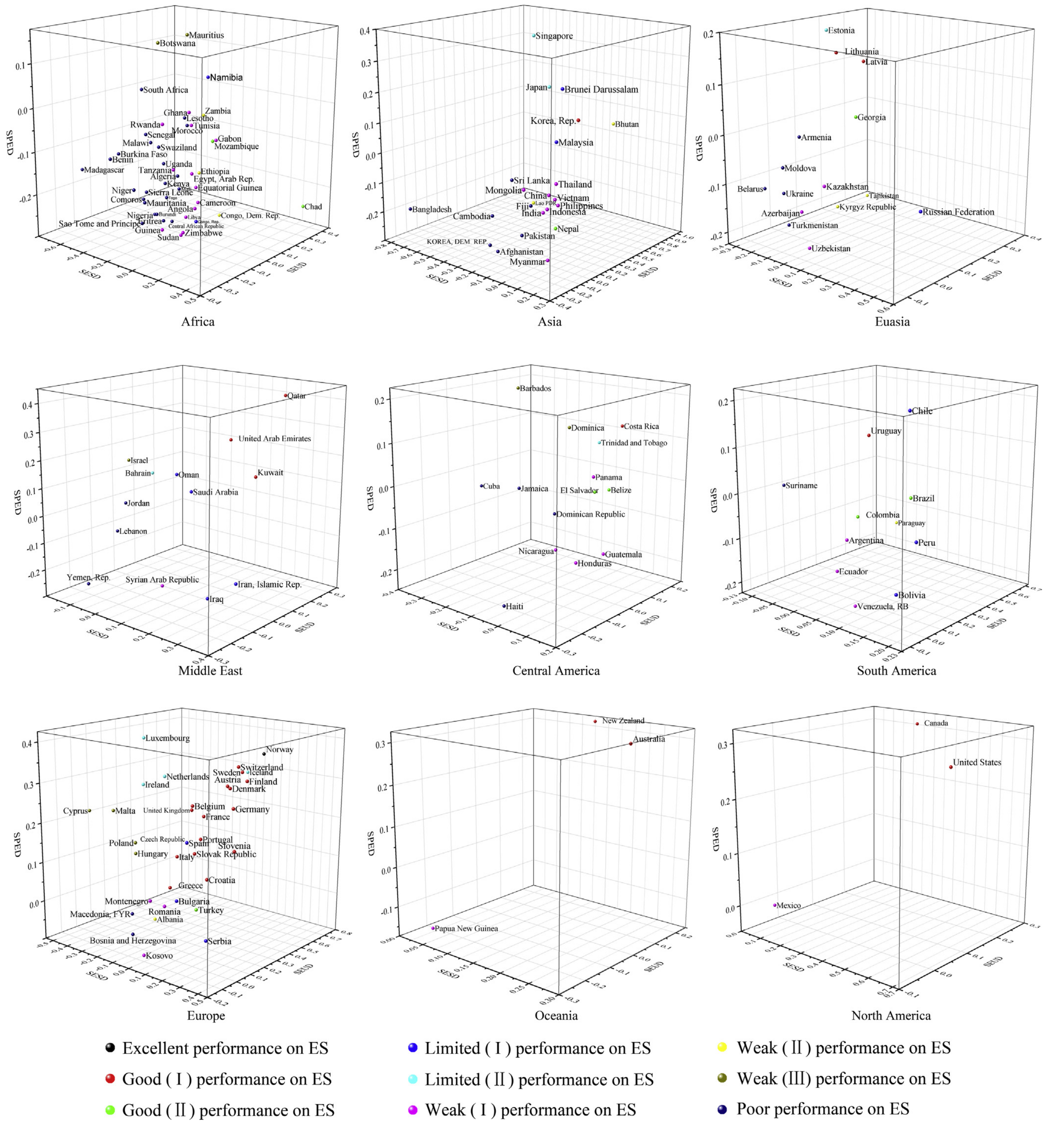

Fig. 8. Classification of countries according to the ESI_{bal} in the geographical regions.

Indonesia, Philippines, Vietnam, China, Mongolia, and Thailand have a good performance on SESD, although their performance on SEUD and SPED lags obviously. Instead, both Bhutan and Lao PDR face the same challenges in balancing the competing sides of the ES triangular profile, with good SEUD ranking offset by underperformance on SESD and SPED. The seven remaining countries in Asia are Poor because they underperform in all three dimensions.

Eurasia's triangular profile consists of a weak SESD performance, a weak SEUD performance, and a weak SPED performance (see Table 6). Blessed with enormous oil and natural gas deposits and located at the strategic crossroads between the major consuming countries of Western Europe and East Asia, Eurasia—including Russia and its 12 former satellites—plays an important role in ensuring the ES of Asia and Europe. However, the region's strong energy supply is unfortunately overshadowed by its poor performance in energy delivery; consequently, the index of $\overline{SESD}$ is -0.035, ranking sixth among the nine regions. This result implies that the infrastructure in Eurasia is inefficient to generate power and deliver the electricity. Meanwhile, the index of $\overline{SEUD}$ is

0.020, ranking the region fourth among the regions, but the regional economy's high dependence on conventional fossil fuels remains a potential challenge for Eurasia, thus the $\overline{E\_S}$ index is −0.037, the second lowest among the nine regions. Among the countries in Eurasia, Latvia and Lithuania are in the Good (I) group, with better performances on all three dimensions than the rest of the region (see Fig. 8). Unlike the first two countries, Georgia is in Good (II) group, with weak SPED index, reflecting the country's political transition the country is going through. The overall ES performance of Russia is limited by the weak SEUD performance, especially the low environmental sustainability. By contrast, for Estonia, the SESD continues to be a challenging dimension that limits its overall ES performances. Therefore, these two countries are classified as Limited (I) and Limited (II), respectively. For Uzbekistan, Azerbaijan, and Kazakhstan, the three countries in Weak (I) group, SESD is the only dimension that slightly enhances their overall ES performances, whereas Kyrgyz Republic and Tajikistan classified as Weak (II) have a good performance in SEUD. The five remaining countries are classified as Poor because they underperform in all three dimensions.

The Middle East plays a vital role in the global energy industry, as it holds an estimated 66% of the world's oil and 45% of the world's natural gas reserves [62]. Despite its vast strategic oil and natural gas reserves, the region's triangular profile is relatively balanced (see Fig. 7), but it is limited by its SEUD performance. The regional $\overline{ESI_{tot}}$ is 0.092 (see Table 6), ranking fifth among the regions. This mediocre ranking can be explained in part by the very limited diversity among the region's sources of electricity generation and energy supply, its high economic dependence on energy exports, and its fossil fuel consumption. In concrete terms, the region's good level of energy production is offset by its underperformance in diversifying its energy supply mix and electricity generation portfolio. In fact, the average of SESD sub-index is surprisingly low (0.068), ranking fourth among the regions. Supported by very affordable gasoline, the region performs well in energy equity but poorly in environmental sustainability. The index for environmental sustainability is −0.125, the lowest among the nine regions. Consequently, the SEUD sub-index is just 0.003. Qatar, Kuwait, and United Arab Emirates outperform their regional peers (see Fig. 8), falling into the Good (I) group, with better performances in all three dimensions. Four countries, including Iraq, Iran, Saudi Arabia, and Oman are assigned to the Limited (I) group because they underperform in the SEUD, whereas Bahrain is classified as Limited (II). Classified as either Weak or Poor, the five remaining countries in the Middle East struggle to progress in all three dimensions.

Along with its rapid economic development in manufacturing and tourism, Central America faces a growing energy supply threat due to its increasing reliance on energy imports; therefore, the index of $\overline{Sup}$ is just −0.107 (see Table 6), the lowest among the regions. Consequently, the average of SESD sub-index is −0.037, ranking eighth among the regions. In addition, the regional use of fossil fuels for transportation and electricity generation is increasing, and the use of wood fuel—primarily for cooking—is also unsustainably high. These developments result in rising CO_2 emissions and lead to a low SEUD sub-index. Contextually, the region's performance remains weak on SPED. As a result, the region balances the three competing sides of the ES triangular profile well, despite weak performance on all three dimensions (see Fig. 7). At the national level, 14 Central American countries are assigned to six groups (see Fig. 8). Among them, Costa Rica performs good on all dimensions, which is a member of Good (I) category, while El Salvador and Belize are categorized as Good (II) due to their relatively good SESD and SEUD performances, but weak SPED performance. Trinidad and Tobago belongs to Limited (I) group due to the low energy supply. In addition, Honduras, Guatemala, Nicaragua, and Panama are assigned to the Weak (I) group because their good performance on SESD and poor performances on both SEUD and SPED, while Dominica and Barbados are classified as Weak (III) due to their underperformances on SESD and SEUD. The four remaining countries in this region are classified as Poor because they underperform in all three dimensions.

South America performs well on ES, with an $\overline{ESI_{tot}}$ is 0.140 (see Table 6). Because the region includes mostly middle- and lower-income countries, the competing dimensions of ES performance are unbalanced: the region exhibits good SESD and SEUD performances but struggles with a political-economic environment that lacks strength and stability (see Fig. 7). South America is an energy-rich region with large oil and gas deposits and great natural endowments of exploitable renewable energy. In particular, the rapid development and widespread use of hydropower has improved the region's balanced performance in both SESD and SEUD, turning the region into the world's top performer in the environmental sustainability component. Among the 11 countries in South America, Uruguay is the region's top ES performer, falling within the Good (I) group (see Fig. 8), while Colombia and Brazil are classified as Good (II). Three countries—Chile, Peru, and Bolivia—are assigned to the Limited (I) group, which have an excellent performance on SESD, and weak performances on SEUD and SPED due to high levels of energy and emission intensity. In addition, Venezuela, Ecuador and Argentina are classified as Weak (I) due to their poor performances on SEUD and SPED. By contrast, Paraguay's SEUD performance greatly outpaces its SESD performance, with almost 100% of electricity generation issuing from hydropower. Suriname is assigned to the Poor group due to its underperformance on all three dimensions. Europe has a good ES performance, with an $\overline{ESI_{tot}}$ of 0.350 (see Table 6), ranking second among the nine regions. Although most European countries are net energy importers and lack large natural fossil fuel deposits, the region manages to be relatively energy-secure due to controlled energy consumption growth and conscious efforts to diversify its energy supply and electricity generation portfolios. Overall, Europe balances the three dimensional security very well, especially in SEUD (see Fig. 7), driven mainly by a combination of continued deindustrialisation, greater energy efficiency, and the use of more renewable energy. The average of SEUD sub-index is 0.115, the highest of the nine regions. For the 35 European countries in this study, Norway is the only country out of the 162 countries in the sample to achieve an Excellent balance score (see Fig. 8), while 13 Western European countries and 3 Eastern European countries (the Slovak Republic, Slovenia, and Croatia) are classified as Good (I) due to good performance on all dimensions. Turkey is a member of Good (II) group because of underperformance on SPED. Seven countries are categorized as Limited due to their relatively weak SESD or SEUD performances. Among them, three Eastern European countries show an imbalance that tilts towards the SESD, while they struggle to minimize their environmental impact. By contrast, four Western European countries perform well on SEUD and struggle to provide energy supply security. The eight European countries have Weak ES performances. Kosovo, Romania and Montenegro are categorized as Weak (I) due to good performance on SESD, and underperformances on SEUD and SPED, while Albania is a member of Weak (II) group. The four countries, including Hungary, Poland, Cyprus and Malta, belong to Weak (III) group. Bosnia and Herzegovina, and Macedonia are classified as Poor because of their underperformances in all three dimensions.

In this study, Oceania includes Australia, New Zealand, and Papua New Guinea. Similar to North America, despite Oceania's high score on $\overline{ESI_{tot}}$, the index is 0.314 (see Table 6), ranking third among the nine regions. The triangular profile shows a weak SEUD performance relative to those in the other dimensions due to a lower use of energy and related activities (see Fig. 7). Both Australia and New Zealand have mature, post-industrial economies, strong political-social strength, and large natural endowments, thus they are part of the Good group due to their balanced performance in all three dimensions (see Fig. 8). Papua New Guinea is a net energy exporter, and like other typically fossil-fuelled and less-developed economies—it shows poor SEUD and SPED performances, and good performance on SESD. This imbalance puts Papua New Guinea in the Weak (I) group.

The top ES performer, North America, has an $\overline{ESI_{tot}}$ of 0.628 (see Table 6). This region is relatively self-sufficient, as all three countries—Canada, the United States, and Mexico—have large natural endowments of oil, natural gas, coal, and hydropower potential. The average of SESD sub-index is 0.336, the highest among the regions. SEUD is their weakest energy dimension due to these countries' high levels of energy and emission intensity and a higher reliance on energy-intensive resource development industries relative to those of most industrialised countries (see Fig. 7). At the country level, both Canada and the United States have mature, post-industrial economies, and their triangular profiles show a Good balance (see Fig. 8), while Mexico is a modern, fast-growing industrial economy with a weak energy system.

5. Conclusions and policy implications

We propose an ES index for 162 countries using an accounting framework that considers the integrated application of subjective and objective weight allocation simultaneously, SOWA. Unlike most ES frameworks in the literature, BSM that highlights how well a country manages the trade-offs among the three competing dimensions is introduced. The benefits of using this scoring system include interpretability, non-linear scaling, and a reduced decisive effort for a specific dimension. This approach is found to be viable by comparing our findings with the WEC's report results. This study contributes to the literature by proposing a new evaluation approach to depict global distribution patterns of national ES.

At least three interconnected conclusions can be drawn from this research and be applied to obtain policy alternatives. First, countries still struggle to develop a comprehensively secure energy system, with only one country out of 162 achieving an Excellent score and 37 countries achieving a Good score, accounting for approximately one-fourth of the sampled countries. Second, the degree of dispersion is greatest in SESD, followed by SEUD, indicating that the striking disparities in countries' capacities to enhance energy supply stability and improve environmental sustainability is the main concern for these countries' policymakers. Third, the geographic disparities in the performance of national ES are very significant. The countries in the Excellent and Good groups are concentrated in Western Europe, which has the world's only Excellent country and 17 of the 37 Good countries. The Limited countries are concentrated in Europe, Middle East and Asia, which account for over 67% of the sampled countries in this category. Most of the Weak and Poor groups comprise developing countries and the world's least developed countries in Africa.

These findings indicate the need to develop a differentiated energy policy system that is credible and capable of addressing overarching sustainability restrictions and operationalizing long-term objectives into effective mechanisms for steering and coordinating their implementation. To this end, we offer the following proposals.

The development of domestic energy sectors could help countries in Africa and Asia begin the journey towards economic growth and social development. However, due to poverty, illiteracy, inadequate basic life necessities, and a lack of the fundamental facilities and systems needed to promote the region's development, energy equity is the key restrictive component. Governments should thus develop institutional frameworks and domestic financial markets to support investment in the exploitation of energy resources and the construction of energy infrastructures. In addition, given the regions' economic growth, social development, and growing populations, energy investment—especially in renewable energy—is needed on an unprecedented scale. Policymakers in Africa and Asia urgently need to focus on restoring energy markets and attracting a great deal of investment to increase the use and exploitation of renewable energy.

Eurasia's vast oil and gas holdings are undeniably an advantage in ensuring ES; however, the region's great challenge lies in the inefficiency and high emissions of existing power generation and grids, even in the process of oil-refining installations, as well as final consumption, which leads to poor environmental sustainability. Power-generating facilities should be modernized through the introduction of cutting-edge technologies that will not only ensure domestic supply but also enable countries to reduce the emissions caused by energy consumption. Policymakers should therefore develop a favourable investment climate and attract investment in the production of energy resources that can be exported to global markets and in the improvement of energy efficiency and environmental sustainability for domestic consumption. As in Eurasia, countries in the Middle East are also seriously challenged by high energy and CO_2 emission intensities due to their heavy reliance on fossil fuels. Governments should thus promote a switch away from traditional fossil fuels and diversify the energy supply to decarbonize electricity generation. They may also attempt to import advanced technologies such as carbon capture, utilization, and storage (CCUS) tools. Diversifying the economy and reducing its dependence on hydrocarbons is another important way to improve energy system performance.

Central American countries should seek to diversify their channels of energy cooperation with foreign partners to enhance energy supply stability and reliability, as they face mounting challenges from surging energy demand, geopolitical risks, and price volatility. Central American governments should also increase investment in the exploitation of renewable energy resources to accelerate the transition of energy mixtures to more low-carbon energy systems. As in Central America, most economies in South America are still developing and being challenged by growing energy demand. Although these countries are endowed with numerous powerful rivers, energy shortfalls caused by droughts have led to ES concerns. To mitigate the risks associated with hydroelectric power generation, governments in these countries should increase the share of non-hydropower renewable energy, such as solar and wind energy.

Due to Europe's heavy reliance on energy imports, rising electricity and gasoline prices are a concern for many European countries. Policymakers have to craft the right market structures and support and implement prudent, forward-looking energy policies based on strategies that exploit local and renewable energy resources to ensure energy reliability. Although both North America and Oceania perform better in terms of overall ES, they lag behind Europe and South America in SEUD—especially in environmental sustainability—as they rely heavily on energy production for energy exports, transportation, and heavy industries. Government efforts to reduce CO_2 emissions in the energy sector should focus on energy-efficiency improvements—on both the supply and the demand side—and the development of lower carbon energy solutions, such as carbon capture and storage technologies. North America and Oceania should also change their regulations governing coal-fired power plants and increase their use of natural gas and renewable and clean energy in power generation.

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