Energy Security: Multidimensional Analysis for South American Countries

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Abstract- Among public policies, energy security has gained interest in recent years. Energy security seeks to guarantee continuous energy availability maintaining affordable prices and low environmental impacts. This issue has been widely studied by developed countries since energy has played a vital role in countries' development. On the other hand, literature only shows a few works related to energy security applied to South American countries. Accordingly, this work aims to evaluate the energy security of nine South American countries using an Energy Security Index (ESI) initially conceived. To develop this ESI, three dimensions have been considered such as energy supply and delivery (SDD), energy equity (EED), and environmental sustainability (ESD). The indicators of each dimension have been previously chosen and their indices computed using equal weights. A normalization process has been next performed to scale raw data. A K-means clustering algorithm has been then applied to the dimensions of each country to find similarities between them. Finally, the qualitative results obtained in this work have been compared with previous studies.

Keywords Energy security index, k-means clustering, energy policy, multidimensional analysis.

1. Introduction

The 1970s energy crisis highlighted the vulnerability of industrialized countries to oil prices shocks. Since then, countries have been discussing and prioritizing energy security in their energy policies. Energy security is essential for different agents such as policy-makers, industry, business and the community in general whose quality of life depends on an uninterrupted supply of energy [1]. Note that developed countries have established management models to monitor energy security levels; for example, the International Energy Agency (IEA) has developed the Nexus Approach to water-energy-food security [3] and the World Economic Forum (WEF) has established a methodology called Energy Architecture Performance Index [4] to analyze national energy systems.

Establishing a single definition of energy security is a complicated task due to its multidimensional nature that includes technical, economic, social, environmental and geopolitical aspects. Note that the simplest definition of energy security is to adequate supply of energy at a reasonable cost [5]. Moreover, the IEA defines energy security as the uninterrupted availability of energy sources at an affordable price [6]. The WEF describes it as the degree to which energy architectures are at risk of an impact and whether suitable access to energy is provided for all sectors of the population [4]. Meanwhile, the United Nations Development Program (UNDP) establishes energy security as the availability of energy at all times and in various forms, in sufficient quantities, and at reasonable prices [7].

In previous works, an evaluation of energy security considering external (security of energy supply from abroad) and internal dimensions (security of national energy infrastructures) was performed by Bompard et al. [8] using a methodology initially proposed. The methodology was applied to the Italian case regarding different geopolitical scenarios. The results showed that this methodology provided an effective way of making decisions in presence of geopolitical risks and adverse events. Besides, a new evaluation technique called Subjective & Objective Weight Allocation (SOWA) to assess global national energy security was developed by Wang and Zhou [9]. They evaluated 162 countries using data from 2014. The results highlighted the necessity to develop a differentiated energy policy system that is capable of addressing general sustainability constraints. Zhang et al. [10] evaluated the Energy security index (ESI) regarding various dimensions such as availability and diversity, affordability and equality, technology and efficiency, environmental sustainability, and governance and innovation. 30 Chinese provinces were taken into account in the evaluation using data from 2013. Radovanović et al. [11] defined a new ESI using six different indicators. They assessed 28 European countries for the period 1990–2012. The proposed ESI differs from others in the way environmental and social aspects are included. Additionally, a study to assess the sustainability performance of 30 European countries using the Differential Multi-Criteria Analysis (DMCA) technique was carried out by Antanasijević et al. [12]. This technique was applied over the period 2004-2014 to determine the sustainability progress of the countries.

More recently, Du et al. [13] proposed an ESI that included 16 indicators within the dimensions of energy production, energy consumption and environment. 30 countries were classified into five categories representing, for example, low energy security (China and India) and high and diversified energy security (Norway). Besides, trends in energy security for Estonia, Latvia and Lithuania using data from 2008 and 2012 were analyzed by Zeng et al. [14]. They used the ESI indicators corresponding to the European Union energy policy. The results showed that Latvia maintained the highest level of energy security. Similarly, Obadi and Korček [5] analyzed energy security of 26 European Union countries using different dimensions such as energy and economic efficiency, affordability, physical availability, and environmental stewardship. The energy efficiency and environmental stewardship dimensions showed signs of growing cohesion between the countries. However, the countries that improved their energy security relied primarily on their affordability dimension.

A universal multidimensional ESI consisting of four dimensions was developed by Li et al. [15]. They compared the evolution of indices for 19 countries of the G20. The results highlighted that ESIs of the countries analyzed were increasing during the period studied. The countries presenting better ESIs were mainly concentrated on the Americas and Europe. Furthermore, Moghim and Garna [16] studied the vulnerability to natural and anthropogenic hazards of 141 countries using six environmental indicators. The results confirmed that resilience was dependent on location, with Estonia and Ethiopia being the most and the least resilient countries, respectively. Note that the tendency to include environmental and sustainable developments when evaluating energy security has been increasing in recent years [13]. On the other hand, the scientific literature only shows a few studies related to energy security applied to South American countries.

Scientific literature demonstrates that many indices were quantified for European, Asian and North American countries. Meanwhile, indices for South American countries were under-reported. Therefore, a comprehensive energy security assessment of South American countries seems necessary to guarantee a reliable and environmentally friendly energy supply that supports their economic development [17].

The energy policies have to be adjusted according to future prospects to ensure the support and development of society [18]. In this way, the incorporation of renewable energy sources in the grid generation mix can benefit the energy security [19]. Note that electricity is an important component of human life [20]. International and national policies generally encourage decarbonization through low-carbon power generation and improved energy efficiency. Thus, the energy transition would only be effective through the greater integration of renewable energies [21-24].

Accordingly, this study aims to assess the energy security of nine South American countries. Three dimensions such as energy supply and delivery (SDD), energy equity (EED), and environmental sustainability (ESD) are considered to build an ESI. The indicators of each dimension are chosen and their indices are calculated using equal weights. A normalization process is next carried out to scale raw data. A K-means clustering algorithm is additionally used to find similarities between the dimensions of each country analyzed. The countries included in this study are Argentina, Bolivia, Brazil, Chile, Colombia, Ecuador, Peru, Paraguay and Uruguay. Venezuela is not included in this study due to lack of data. The ESI is calculated for the years 2010, 2012, 2014 and 2016. Consequently, the methodology developed is presented in Section 2. Next, Section 3 depicts the results obtained. Finally, the main conclusions are presented in Section 4.

2. Methodology

2.1. Dimensions and indicators

An initial analysis to identify indicators used in ESI computations is performed. Therefore, several articles published between 2017 and 2018 have been selected for analysis. 217 indicators have been identified in this analysis. Similar indicators have been next grouped. Finally, the indicators have been chosen based on their repeatability. The dimensions and their indicators used here are shown in Table 1. A description of each dimension is presented below.

2.1.1. Energy Supply–Delivery Dimension (SDD)

Energy supply is related to the capacity of a country to supply its internal energy demand. One key to the energy supply is to produce its own fuel. This means having proved reserves to guarantee fuel production for a given period. If a country has no resources or has a high production cost, to import fuel from another country would be the best option. Fuel imports, however, generate dependency and increase the risk of not guaranteeing the supply. Some fuels such as oil are affected by political or economic scenarios worldwide. Thus, researchers and policy-makers consider self-sufficiency as another key to energy supply. Since countries use different fuels, it is necessary to know how this affects their ESI. The diversity of energy supply (Table 1) explains this relationship.

Table 1. Indicators of the energy security dimensions

Indicator	Unit
Energy supply–delivery dimension (SDD)	
Proved reserves of Oil and Natural Gas	Millions of tons of oil equivalent
Self-sufficiency	Percentage
Diversity of energy supply	-
Diversity of electricity generation	-
Energy consumption per capita	TJ/population
Energy access, quality and affordability (EED)	
Access to clean cooking	Percentage
Electricity access	Percentage
Electricity prices	US$ per liter
Gasoline and diesel prices	US$ per liter
Quality of electricity supply	-
Environmental sustainability (ESD)	
Air pollution	Micrograms per cubic meter
Carbon intensity	kg CO2 per $
Energy intensity	MJ per $
Share of non-fossil fuel of total primary energy supply	Percentage
Share of renewable electricity generation of total electricity generation	Percentage

Energy delivery is also related to efficiencies of final energy consumption and primary energy supply. The main energy losses in power systems are attributed to the electricity generation and final consumption sectors. Each technology used in power systems has different efficiency and operational characteristics. In particular, thermal technologies only show efficiencies from 35% to 55% when they convert primary energy into electricity. Technologies based on renewable energies present lower efficiency than thermal technologies, but technological diversity in power systems provides flexibility and improves energy security. On the other hand, energy consumption is not easy to quantify. Particularly, energy consumption values are not correctly measured or estimated in South American countries. Nevertheless, an indicator such as energy consumption per capita can be used as an alternative to energy consumption. Low values of energy consumption per capita improve the ESI.

2.1.2. Energy Equity Dimension (EED)

Energy equity assesses energy's accessibility and affordability within a country or region [25]. Indicators used in this dimension are related to the accessibility of population accessibility to different types of energy such as gasoline, oil and electricity, and the affordability of energy supply in order to bring benefits like clean cooking and development in rural areas [26]. All countries have to guarantee access to energy satisfying household needs, commercial activities and industrial requirements, maintaining affordable energy prices for the population. The indicators used in this dimension are listed in Table 1.

2.1.3. Environmental Sustainability Dimension (ESD)

This dimension is related to preservation and protection of natural resources for future generations [27], i.e., environmental sustainability is a condition of balance and resilience that allows society to satisfy its needs without exceeding the capacity of ecosystems to regenerate resources or reducing biological diversity [28].

Although energy security has traditionally been treated separately from environmental sustainability, the relationship between them has recently been recognized and discussed [29]. Environmental sustainability is also linked to energy use, as energy systems produce greenhouse gas (GHG) emissions that contribute to global warming [30]. The growing awareness of global GHG emissions and local air pollutants has been one of the drivers to integrate energy security and environmental sustainability [31]. Note that air pollution refers to substances in the atmosphere that has negative impacts on the health of people and ecosystems [16].

2.2. Energy Security Index (ESI) Calculation

2.2.1. Normalization

Due to different scales of indicators, an initial treatment is necessary to adjust their values to a common scale, so a normalization strategy where a range between -1 and 1 is considered. The indicators are normalized as follows,

$$I_{ijk} = 2\left(\frac{x_{ijk} - x_{ij,min}}{x_{ij,max} - x_{ij,min}}\right) - 1 \tag{1}$$

where i, j and k represent the dimension, the indicator and the year of evaluation, respectively. x_{ijk} represents the indicator without normalization and I_{ijk} is the normalized indicator. $x_{ij,max}$ and $x_{ij,min}$ are the maximum and minimum values of the indicator I, respectively.

Note that indicator values close to 1 are favorable for the energy security of the countries. Conversely, values close to -1 reduce the energy security.

2.2.2. Weighting and aggregation

For this study, equal weights are considered. All indicators are added to their respective dimension as,

$$D_{SDD,k} = \sum_{j=1}^{n} I_{1jk} \tag{2}$$

$$D_{EED,k} = \sum_{j=1}^{n} I_{2jk} \tag{3}$$

$$D_{ESD,k} = \sum_{j=1}^{n} I_{3jk} \tag{4}$$

where DSD_k, DEE_k and DES_k are the values of energy supply–delivery, energy equity, and environmental sustainability dimensions, respectively, for year k. These values are then aggregated to ESI in an additive way.

2.2.3. Energy Security Index (ESI)

The energy security index (ESI) for each country is determined by Eq. (5).

$$ESI_k = D_{SDD,k} + D_{EDD,k} + D_{ESD,k} \tag{5}$$

2.3. Cluster analysis using k-means algorithm

Clustering is a type of unsupervised machine learning algorithm that can be used to analyze data. The main goal is to find natural groups (clusters) in the data that have similar characteristics [32]. When we cluster observations, we want the observations in the same group to be similar and those observations in other groups to be different. In particular, k-means clustering is the simplest and most widely used clustering method for splitting a dataset into a set of k groups. The details of the algorithm are described in [32]. The main idea is that the k-means algorithm groups countries based on their energy security indicators.

3. Results and discussion

3.1. Dimensions and indicators

To compute the indicators related to energy supply and delivery, data obtained from the IEA [33] have been used. The data needed to calculate the indicators related to energy access, quality and affordability, and environmental sustainability indicators have been directly extracted from the World Bank [34] and Our World in Data [35]. Note that data from 1990 to 2016 had been initially analyzed, but ESI has been only computed for the years 2010, 2012, 2014 and 2016, as complete data on the indicators is only available in these years. The maximum and minimum values of each indicator listed in Table 1 are found in data extracted from 1990 to 2016. All indicators are normalized using Eq. (1), whereas Eq. (2-4) are then used to compute the values of each dimension.

3.1.1. Supply and Delivery Dimension (SDD)

The results for SSD are shown in Table 2. It can be pointed out that Colombia has obtained an excellent performance in all the years evaluated. This is attributed to the fact that less than 10% of its internal energy supply was imported. Colombia exports oil and coal to other countries which that excellent performance can be related to. Meanwhile, natural gas and biofuels are produced internally to cover their demand. Besides, electricity generation in Colombia comes mainly from hydroelectric power and natural gas, which benefits the electricity generation diversity indicator. In addition, energy consumption per capita in this country is one of the lowest in the region.

Bolivia, Brazil, and Peru show good performance in this dimension because these countries import fuels to supply their internal demand. Regarding the energy supply diversity indicator, they maintain a good behaviour. Meanwhile, Bolivia only presents a high value of the electricity generation diversity indicator. On the other hand, a low performance of final consumption per capita has been obtained by Brazil. Argentina, Chile, Ecuador, Paraguay, and Uruguay present limited performance. Noticeable differences have found in this group. For example, Chile imports 72% of the energy needed to satisfy its internal energy demand. Argentina, Chile, Paraguay and Uruguay have had the highest values for final energy consumption per capita in South America.

Table 2. Supply and delivery dimension (SDD) results.

Country	2010	2012	2014	2016
Argentina	0.192	0.144	0.126	0.124
Bolivia	0.500	0.442	0.428	0.408
Brazil	0.354	0.323	0.309	0.364
Chile	-0.114	-0.046	-0.079	-0.101
Colombia	0.771	0.684	0.685	0.696
Ecuador	0.130	0.201	0.115	0.222
Paraguay	0.095	0.076	0.077	-0.011
Peru	0.534	0.499	0.511	0.438
Uruguay	0.003	-0.058	0.016	0.066

3.1.2. Energy Equity Dimension (EED)

The results for this dimension are shown in Table 3. Ecuador has obtained the best result mainly due to its relatively low prices for gasoline and oil, and its high percentage of the population that has had access to electricity since 2010. Note that this percentage has been growing since 2010. Conversely, Paraguay has had the worst performance during years analyzed. This is attributed to low values of its indicators of access to electricity and electricity quality. Note also that gasoline and oil prices in Paraguay are close to the average value for the region, but this fact does not contribute enough to the final value of this dimension. Argentina, Paraguay and Uruguay present similar values of EED in 2016. These values are lower than those shown by Brazil and Peru, which have obtained values close to the average for the region. Brazil has had a slight improvement in EDD through the years analyzed.

3.1.3. Environmental Sustainability Dimension (ESD)

The results for ESD are presented in Table 4. As seen in Table 4, most South American countries show negative ESD. Colombia and Peru have experienced a positive evolution over the years from 2010 to 2016. Uruguay has presented low values of SDD and EED dimensions, but it can be considered an eco-friendly country because it shows the highest ESD value compared to other South American countries. In contrast, Bolivia has obtained the worst ESD value. Besides, Brazil and Peru can be considered neutral environmental sustainability countries because their ESD values are close to zero.

Table 3. Energy equity dimension (EED) results.

Country	2010	2012	2014	2016
Argentina	0.488	0.261	0.192	0.395
Bolivia	0.562	0.547	0.563	0.651
Brazil	0.354	0.435	0.416	0.504
Chile	0.534	0.387	0.435	0.718
Colombia	0.408	0.387	0.492	0.694
Ecuador	0.741	0.766	0.802	0.809
Paraguay	0.153	-0.023	0.091	0.330
Peru	0.209	0.103	0.241	0.475
Uruguay	0.382	0.146	0.224	0.408

Table 4. Environmental sustainability dimension (ESD) results.

Country	2010	2012	2014	2016
Argentina	-0.355	-0.380	-0.355	-0.375
Bolivia	-0.696	-0.735	-0.761	-0.724
Brazil	0.197	0.157	0.060	0.162
Chile	-0.426	-0.476	-0.305	-0.363
Colombia	0.218	0.328	0.254	0.258
Ecuador	-0.413	-0.258	-0.282	-0.130
Paraguay	0.691	0.722	0.793	0.668
Peru	-0.112	-0.139	-0.089	-0.063
Uruguay	0.659	0.434	0.756	0.765

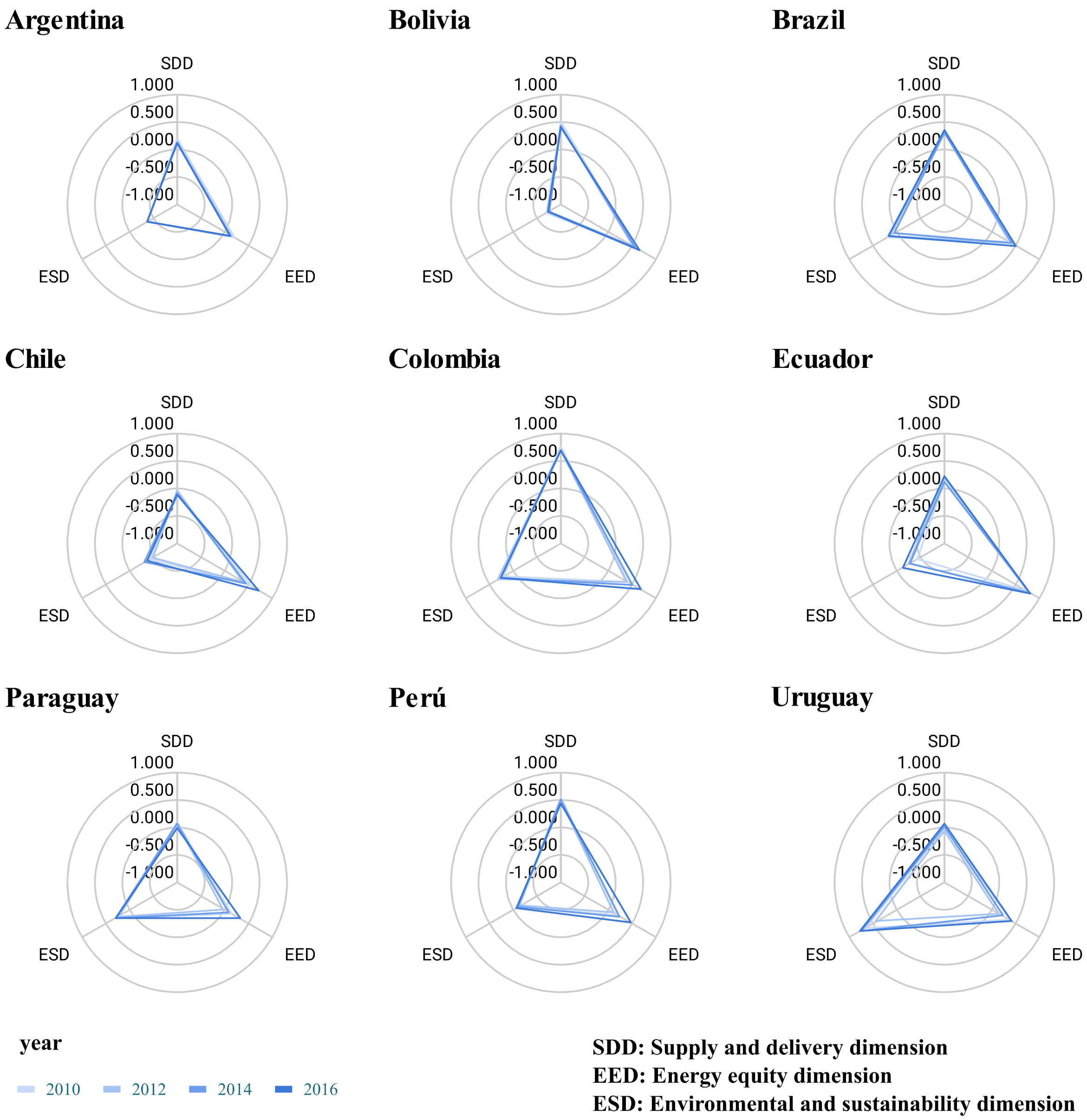

Fig. 1. Profiles of each dimension by country

3.2. Energy Security Index

ESI has been computed applying Eq. (5) and the results are shown in Table 5. As seen in Table 5, Argentina, Bolivia, Chile, and Paraguay has obtained a limited performance until 2014, but improvements in their ESIs are depicted for 2016. Note that Paraguay has the lowest ESI value in South America, i.e., its energy security is the weakest. Conversely, Bolivia, Chile, Colombia and Ecuador have a good performance being Chile and Ecuador the countries with the best energy security among the South American countries.

Table 5. Energy Security Index (ESI) values.

Country	2010	2012	2014	2016
Argentina	0.488	0.261	0.192	0.395
Bolivia	0.562	0.547	0.563	0.651
Brazil	0.354	0.435	0.416	0.504
Chile	0.534	0.387	0.435	0.718
Colombia	0.408	0.387	0.492	0.694
Ecuador	0.741	0.766	0.802	0.809
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Additionally, Fig. 1 has been constructed based on the values of each ESI dimension. As seen in Fig. 1, Argentina, Bolivia and Brazil have shown similarities in energy policy represented by their dimensions, but the difference in the development of each country could be attributed to the way their policies had been implemented. It is clear that ESD has the lowest priority in the energy policy of these countries. Similar to the aforementioned countries, Colombia and Peru show equivalent policies, but different magnitude of actions performed to reach their targets. Paraguay presents similar values in SSD and ESD, and its EED value has grown between 2010 and 2016 because Paraguay has been driving actions to improve accessibility and affordability of energy.

Ecuador, which has the best value in EED, presents similar values in the three indicators. Note that Ecuador has presented the second-best ESD which means this country has made actions in terms of environmental sustainability to guarantee its energy security. Chile has a similar policy to Ecuador, but Chile's ESD is far below Ecuador's one. On the other hand, Uruguay is the only country in the region that shows a high ESD value.

3.3. Cluster analysis

The k-means algorithm used to find similarities between the countries is applied to average ESI values. The normalized values of each dimension are used as variables in the clustering, i.e., SDD, EED, ESD. Note that it is necessary to specify the number of clusters (k) to use this algorithm. Therefore, an initial analysis using different k values from 2 to 5 has been performed. The results of this analysis are depicted in Fig. 2 The average silhouette approach measures the quality of a clustering, that is, it determines how well each object lies within its cluster [32]. Note that a high average silhouette width means a useful clustering. Thus, the silhouette approach has been then applied to obtain the optimal number of clusters. It has been found that four clusters maximize average silhouette values.

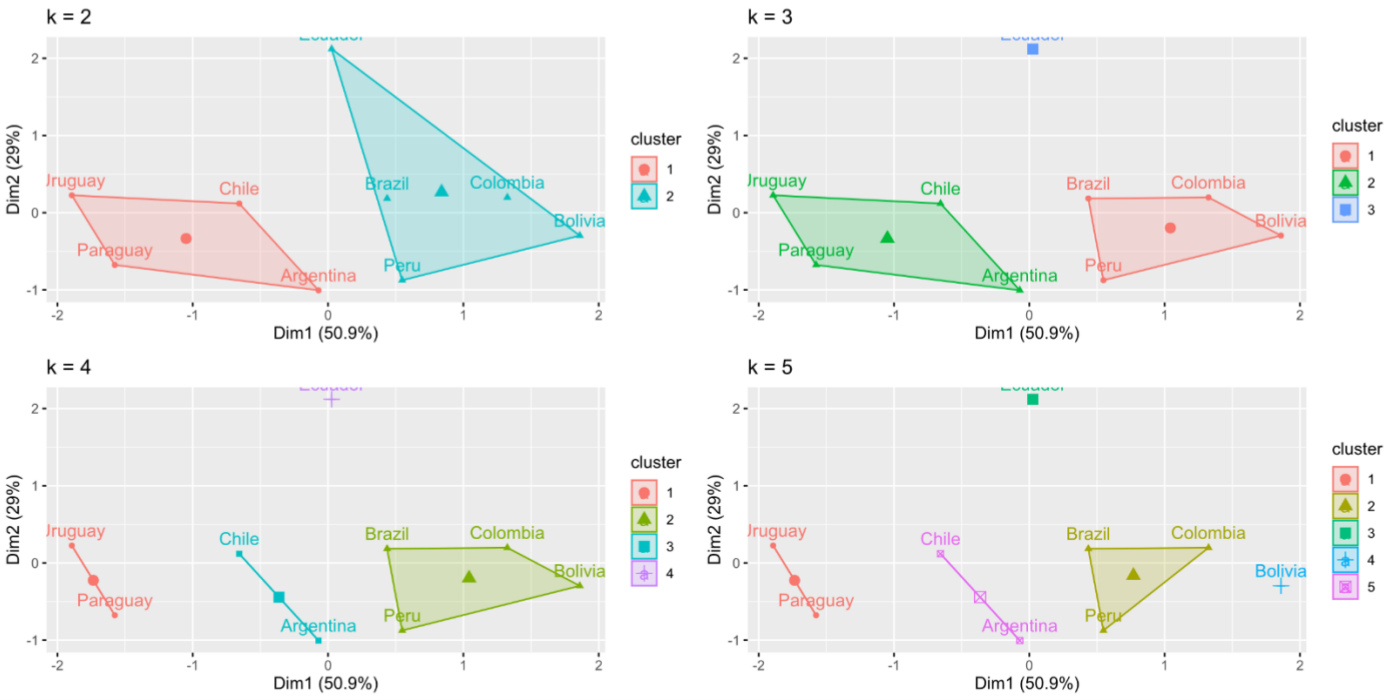

Fig. 2. Clustering treatment applied to average ESI values

Finally, a three-dimensional representation of the indices and clustering is shown in Fig. 3. The first cluster, related to Ecuador, has obtained limited performance in SDD, excellent performance in EED and good performance in ESD. Chile and Argentina are considered within the second cluster. This cluster has limited performance in SDD, good performance in EED, and limited to weak performance in ESD. The third cluster regards Uruguay and Paraguay, which have obtained limited performance in SDD, limited to good performance in EED, and good to excellent performance in ESD. The fourth cluster is related to Bolivia, Brazil, Colombia, and Peru, which have shown good to excellent performance in SDD, good to excellent performance in EED, and limited to poor performance in ESD.

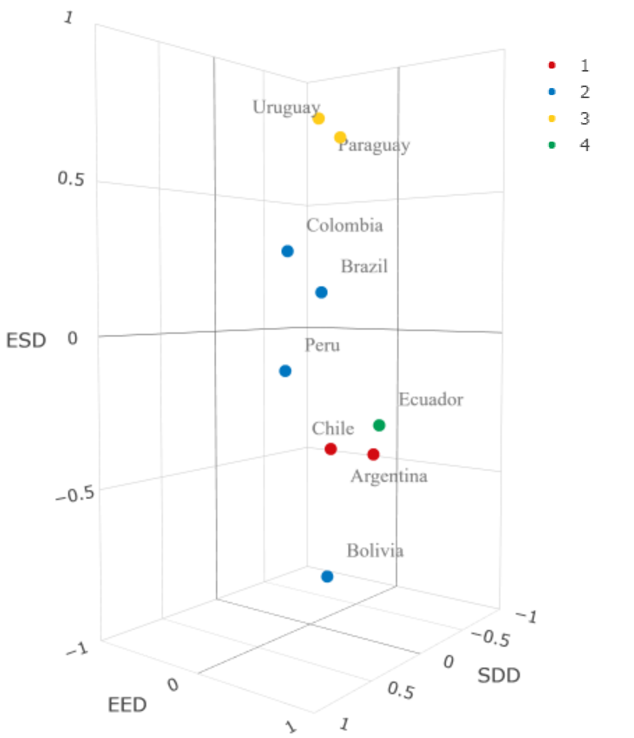

Fig. 2. Classification of South American countries with respect to ESI

3.4. Inter-study comparison

A comparison between the qualitative results of this work and other studies has been carried out. The results are summarized in Table 6. The studies performed by Wang and Zhou [9], WEF [4] and WEC [25] have been accounted for. Note that this work is identified as Approach in this table. As seen in Table 6, WEC and WEF report 7 and 5 countries are Excellent, respectively. Meanwhile, Wang has determined that 4 countries are Weak based on their energy security. Only Bolivia has been qualified in the same way for all studies analyzed.

Table 6. Inter-study comparison.

Country	Approach	Wang[9]	WEF[14]	WEC[25]
Argentina	Limited	Weak	Good	Excellent
Bolivia	Limited	Limited	Limited	Limited
Brazil	Good	Good	Excellent	Excellent
Chile	Limited	Limited	Good	Excellent
Colombia	Good	Good	Excellent	Excellent
Ecuador	Good	Weak	Limited	Excellent
Paraguay	Good	Weak	Good	Limited
Peru	Good	Limited	Excellent	Excellent
Uruguay	Good	Good	Excellent	Excellent

4. Conclusion

This study evaluates the ESI for nine South American countries using two methods, such as scoring and clustering. First, a traditional score method based on normalization and weighting has been used. The main advantage of this method is related to the ease of interpretation and simplicity of calculation. On the other hand, this method is sensitive to the way indicators are added and the choice of the weights, which make the ESI results can change completely when these parameters change. The clustering method based on k-means is then used to find similarities in energy policy of the countries. This last method could be viable to determine the level of energy transition of the countries. Note that this method does not require weighting and it does not generate a ranking as the scoring method. The evaluation of the nine South American countries shows remarkable differences among the results of each one. This finding points out the necessity of developing a different energy policy for each South American country.

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