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Article

Composed Index for the Evaluation of Energy Security in Power Systems within the frame of Energy Transitions – The case of Latin America and the Caribbean

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Abstract: Energy transitions are reshaping the global energy system. Such shift has taken the power system to become a critical infrastructure for achieving economic development of every nation in the planet, therefore, guaranteeing its security is crucial, not only for energy purposes but as a part of a national security strategy. This paper presents a multi-dimensional index developed to assess energy security of electrical systems in the long term. This tool, named Power System Security Index (PSIx), and which has been previously used for the evaluation of a country in two different time frames, is applied to evaluate the member countries of the Latin American Energy Organization, located within the Latin America and the Caribbean region, in order to measure their performance on energy security. Mixed results were obtained from the analysis, with clear top performers in the region such as Argentina, while there are others with broad areas of opportunity, as it is the case of Haiti.

Keywords: Energy Security; Energy Transitions; Latin America; Power System; Sustainability

1. Introduction

Energy transitions are driven by international efforts to increase competitiveness efficiently, while respecting the environment and guaranteeing the supply of energy [1]. They are reshaping the global energy system, not only by boosting the presence of renewable energy technologies, but also by improving the system's flexibility through innovative infrastructure solutions, at the time that enhancing energy productivity has become a state priority worldwide [2,3]. This new paradigm presents also new challenges, being the security of energy supply an utmost important matter for the efficient functioning of modern economies [4].

Despite its importance and its wide presence in different national energy strategies, the energy security's concept is highly context-dependent and, consequently, differs significantly from one policy maker to another [5], taking different authorities to determine their own approach of the concept for creating solutions for the procurement of energy supply to their respective populations. With the objective of maintaining a uniformity of the concept and for the development of the present paper, the definition proposed by [6] has been taken on board, i.e. energy security is understood as the sustainable supply of energy.

Latin America is an energy rich region, not only in fossil fuels reservoirs, but also in renewable energies potential. At the same time, some nations in the region do not possess strong economies, taking them to undermine their electricity systems, independently of their possession -or lack- of fuels basins. Due to this diversity of circumstances, it results pertinent to evaluate how policies of different countries in the region are translated into improvements on energy security in their respective power systems.

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As stated by [7], for being analytically helpful, a measure for evaluating energy security must be quantifiable. One instrument to do so are composed indexes, which are useful to identify benchmark performances and trends, focusing on particular issues and, by those means, to set policy priorities [8]. In the present document, the composed index developed by [9], and named Power System Security Index (PSIx), is applied for the evaluation of different countries in the Latin America and the Caribbean region. The developed tool consists of a multidimensional index aimed to evaluate policies regarding energy security in the power sector. Nevertheless, the instrument has been applied to one single country in different time frameworks. It is the aim of this paper to evaluate the suitability of the application of this tool for the evaluation of multifold economies, as Figure 1 shows, by comparing and ranking them according to their performance on achieving energy security in their respective electrical systems.

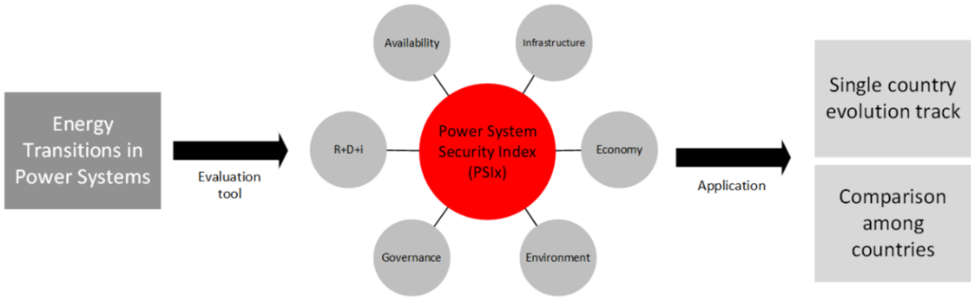

Figure 1. PSIx Approach [9]

This paper includes five chapters. Chapter two describes the composed index. The third one describes mathematical model. In chapter four the outcomes of the composed index application are presented and discussed. Finally, conclusions are presented in chapter nine.

2. PSIx

The dimensions included in the PSIx for the characterization of energy security are availability, infrastructure, economy, environment, governance and research, development and innovation (R+D+i). Each one of these six dimensions possesses multifold indicators grouped, in turn, into different categories. The structure of the PSIx is presented in Figure 2, in which dimensions, categories and indicators are shown, each of them possessing an alphanumeric code for easing its identification throughout the document.

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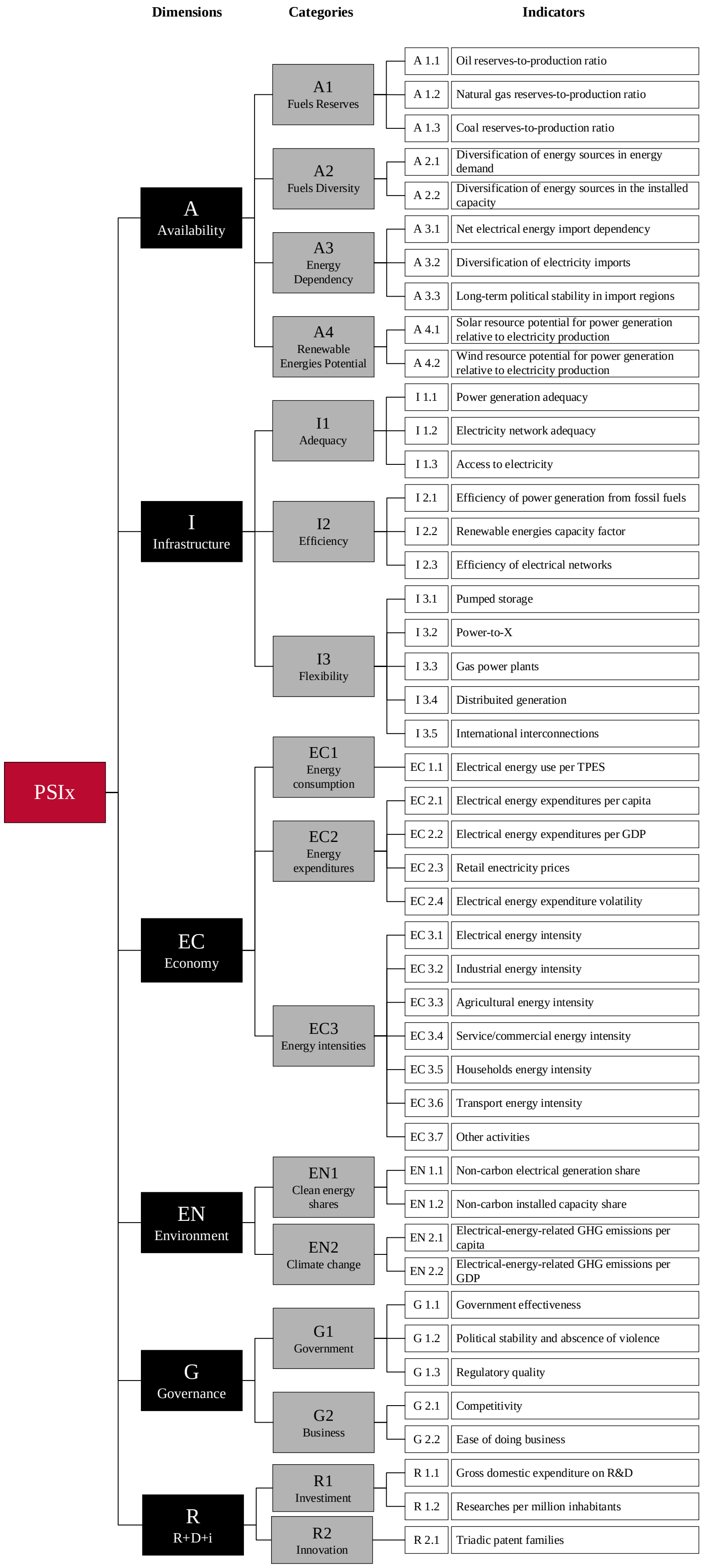

Figure 2. PSIx structure [9]

The dimension of availability (A) is directly related to energy independence [10]. It evaluates the geological presence of energy resources within a determined area, as well as the degree of their replacement by alternative energy resources [11,12]. The dimension also evaluates the diversification of energy technologies and sources for fulfilling the energy needs of a specific region.

The infrastructure dimension (I), also known as accessibility [4,13], evaluates the ability to access energy resources in order to provide a stable and uninterrupted supply of electrical energy, i.e. the reliability of the power system.

The economy dimension (EC), also called affordability, measures energy prices as well as their volatility, since, as stated by [14], these two factors have a great influence on the overall economy, as well as on industrial competitivity and trade balance.

The indicators conforming of the environmental dimension (EN) are aimed to measure the repercussion of energy generation technologies on the environment, so they do not represent a menace for sustainable development. Climate change has acquired a very high importance for energy policy makers during the current century, particularly GHG emissions emitted to the atmosphere, as proxy measures of the pollution of human activities. This tendency has been translated into strict restrictions to conventional energy technologies, which has spurred several countries to transform their power systems towards more sustainable models.

Governments are responsible entities of effectively planning infrastructure development in order to ensure long-term energy security [15]. They are, as well, pledge to establish lasting relationships with other countries, so it is possible to assure energy supplies in a political-stable scenario. By their part, there are also the competent bodies for creating an attractive environment for attracting investments, which are lifeblood of the energy system [16].

Finally, research, development and innovation (R+D+i) play a central role for the enhancement of energy security, since they improve the capacity to adapt and respond to disruption challenges through innovation [10]. The R+D+i dimension (R) has the aim of, as proposed by [17], assess new technologies in the energy field, as well as the development of intellectual capital as a factor to assess risks on energy security.

The main source for obtaining information about the countries' energy systems is the Latin America and the Caribbean Energy Information System, developed by the Latin America and the Caribbean Energy Organization [18].

3. Mathematical model

3.1. Imputation of missing data

Some economies, particularly the smallest ones, have not provided complete datasets on energy information, either to international entities or through their own responsible authorities, which is translated into missing values for the indicators within the composed index. Therefore, it is necessary to complete these values by means of a suitable analytical method.

As defined by [19], missing data are unobservable values, which, if observed, would have a meaningful implication in the analysis. According to [20], there are three types of missing values depending on their predictability of not-appearing in the studied dataset, i.e. missing completely at random (MCAR), missing at random (MAR) and not missing at random (NMAR). MCAR values are independent of the variable of interest or any other observed variable; MAR values are independent of the variable of interest, but other variables in the dataset condition their missingness while, by their part, NMAR values are dependent on the missing data.

The indicators containing missing values are I1.2, I3.1, I3.3, EC2.4, EC3.3, EC3.6, EC3.7, G2.1, R1.1, R1.2, R2.1. Two indicators possess NMAR values, since the availability of data is scarce for every country, not only those gathered by international institutions, but also those collected by each responsible national entity. These indicators are I3.1 and I3.3. It is inferred that these values are unavailable in most cases due to, precisely, the scarcity of data. Moreover, these indicators are relatively new compared to the rest of them, and policies of the covered countries do not consider them as priorities yet, therefore, their measurement at national level is, in most cases, rather low or inexistent.

For the NMAR values present in the index, an implicit modeling method has been selected for completing the corresponding datasets, i.e. hot deck imputation. This method is used to impute missing values within a data matrix by using available values from the same matrix with similar figures [21]. The countries are considered to have a similar behavior in the deployment of power-to-x and distributed generation installations. For these two specific indicators, in case of missing values, they are set to cero, considering, therefore, that the measured value is negligible for its study.

The rest of the indicators with missing values correspond, in general, to small economies, particularly to those located in the Caribbean. In order to achieve a more reliable imputation, the countries of the index have been divided in four categories, depending on the size of their economies and their geographical locations, this with the purpose of considering them more equal in energy terms. These categories are:

A. Big continental economies: Argentina, Brazil, Chile, Colombia, Mexico and Peru
B. Small continental economies: Bolivia, Ecuador, Guatemala, Uruguay and Venezuela
C. Caribbean and the Guianas: Barbados, Cuba, Grenada, Guyana, Haiti, Jamaica, Dominican Republic, Suriname and Trinidad & Tobago
D. Central America: Belize, Costa Rica, El Salvador, Honduras, Nicaragua and Panama

In order to impute the missing values of indicators, an explicit method, based on a formal statistical model, was selected, specifically the unconditional mean imputation method. This approach consists of the substitution of missing values by means of the sample series. Consequently, such procedure leads to estimates similar to those found by weighting, provided the sampling weights are constant within weighting classes [19].

3.2. Normalization

Regardless of their units and scales and with the target of render the variables comparable, it is necessary to determine a normalization method for the gathered data, which is done through the design of a frame that allows the addition of their values within the composite index [15,22]. For that purpose, two different strategies have been followed in this work, depending on the nature of the measured variables, i.e. distance to a reference and historical evaluation. Mathematically, both approaches are the same, nevertheless, their denominator is determined in a different way.

Distance-to-a-reference is the first of the methods, and it consists of measuring the numerical distance to a base value of an indicator's series. This distance can be applied either to a maximum or minimum figure, depending on the attributes of the indicator in each situation; a maximum value is intended to be reached in cases such as population with access to electricity, while a minimum value is desirable in, for instance, electrical import dependency. This approach is described by equation 1:

$$I_{qc}^{t} = \frac{x_{qc}^{t}}{x_{qb}^{t}} \quad (1)$$

The normalized value of the qth indicator I_{qc}^{t}, associated to a c country at a t time, is given by the ratio of the indicator x_{qc}^{t} compared to the maximum value given by x_{qb}^{t}. Dimensions scored under this method are availability, infrastructure, environment, governance and R+D+i.

The historical evaluation scope has been applied for the evaluation of time-based data, specifically for the indicators contained in the economic dimension. Their development assessment is performed through a percentage of annual differences over a stablished time-series. Such technique is described by equation 2:

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$$I_{qc}^{t} = \frac{x_{qc}^{t}}{x_{qc}^{t_0}} \quad (2)$$

In this case, normalized value of the qth indicator I_{qc}^{t}, is given by the ratio of the indicator x_{qc}^{t} compared to the value of the same country but a different time, t_0. The indicators belonging to the economy dimension follow this normalization technique.

Reserves-to-production maximum ratios, presented in the A dimension, have been determined by the median value of international ratios, so extreme values could be neglected. The maximum diversification of sources is gotten by assuming optimal conditions in the power system.

Adequacy values in the infrastructure dimension are gotten from those proposed by [23], which are 20% over the peak demand values. By its part, efficiency in power plants and transmission lines is reflected directly as a percentage in the index.

For establishing a time basis that serves as a benchmark for the economic dimension, year 2009 was chosen. During this year the values of the latest international financial crisis are reflected, in which global economies were affected significantly and synchronously [24]. Taking this year as a basis for the economic dimension, entails a common starting point for different economies to measure their development in energy-related matters.

A GHG-emissions-free scenario has been considered to be the ideal one, as well as one whose whole energy comes from renewable sources, this in the line with the definition of energy security described in section **Error! Reference source not found.**.

For the environmental dimension, a GHG-emissions-free and 100% renewable energy system is considered the ideal system to be reached.

By their part, the maximum values contained in the R+D+i dimension are obtained from the world's leader country of each indicator.

For every indicator of the PSIx, its minimum value is set to zero, while their maximum value is considered to be the unit and the most desirable value. In the case that the objective of an indicator is its minimization, in order to keep the value of one as the target, the obtained value of this particular indicator is subtracted from the unit; therefore, it is ensured that one is the maximum value in both cases, maximization and minimization. The objective of every indicator, as well as its corresponding formula, are presented in Table A1.

3.3. Multivariate analysis

With the objective of assessing the underlying structure of the gathered data, a multivariate analysis has been conducted. This approach is also helpful for assigning weights to the indicators, a crucial step for, according to [25], determining their influence within the index, as well as their trade-off values.

Among the different methodological techniques present in literature, a data-driven approach has been selected, since it depends entirely on the data themselves. A factorial analysis approach, specifically the principal component analysis, has been chosen, since this statistical approximation allows the determination of interrelations among a great number of variables, at the time that it also allows to explain their behavior in terms of their subjacent common dimensions [26].

The treated variables have not been considered initially neither dependent nor independent from each other, therefore and, according to [27], an interdependency study can be executed. As the methodology dictates, the statistical study must cover all the variables simultaneously, so an underlying structure and can be identified for the whole set of indicators. For performing the principal components analysis, a covariance matrix of the data has been employed, containing 44 indicators for the 27 analyzed countries within the composed index.

For analyzing the correlations of the indicators, an item analysis was performed and the most significant values of the resulting correlation matrix is shown in Table 1. The matrix confirms the existence of a subjacent structure among the gathered data. In the

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table the most significant correlations among the variables, those equal to or above 0.70, are highlighted.

Table 1. Correlation matrix showing the most significant correlations among variables

	A1.3	A2.1	A3.2	I1.1	I1.3	I2.2	I3.1	I3.3	I3.4	EN1.1	EN2.1	G1.1	G1.3	G2.1	R1.1
A2.2	0.16	**0.97**													
A3.3	0.00	0.11	**1.00**												
I1.3	0.24	0.03	0.20	**0.83**											
I2.3	0.03	0.13	0.00	0.69	**0.73**	0.10									
I3.3	0.53	0.07	0.28	-0.04	0.12	-0.01	**0.82**								
EC1.1	-0.21	-0.22	-0.18	**-0.76**	-0.63	-0.12	-0.19	-0.15	-0.24						
EN1.1	0.06	0.51	0.45	0.11	0.20	**0.76**	-0.15	-0.12	**0.75**						
EN1.2	0.20	0.33	0.45	0.11	0.12	**0.70**	-0.07	-0.01	0.64	**0.90**					
EN2.2	-0.04	0.33	0.44	-0.16	0.02	0.45	-0.05	0.02	0.64	**0.75**	**0.71**				
G1.3	0.14	0.07	-0.09	0.36	0.41	0.03	0.04	0.01	0.05	0.15	-0.20	**0.78**			
G2.1	0.30	0.23	0.02	0.51	0.63	0.19	0.16	0.14	0.25	0.29	-0.13	**0.76**	**0.80**		
G2.2	0.02	0.21	0.16	0.41	0.45	0.13	0.02	0.06	0.30	0.24	0.04	0.69	**0.79**	**0.87**	
R1.1	**0.78**	0.17	0.00	0.09	0.21	0.15	0.47	0.56	0.05	0.09	-0.04	0.30	0.38	0.53	
R1.2	**0.74**	0.14	0.08	0.06	0.19	0.16	0.64	**0.72**	0.10	0.09	-0.01	0.28	0.30	0.43	**0.95**

With the purpose of evaluating the internal consistency of the analyzed data, the Cronbach's alpha parameter was employed and, since its value overpasses the benchmark of 0.7, specifically 0.7347, it is considered that the analyzed data measures the same characteristic, namely energy security in the power system, in the case of the present study.

For the selection of the factors to be considered as relevant for a further analysis, an a-priori criterion has been determined, i.e. it will be considered that those factors that contribute for explaining 90% of the variance of the data are those that will be kept.

After the execution of the principal component analysis, the variance values of the principal components with a considerable influence were obtained and they are sown in

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Table **2**. They are 10 of the total sample of 44 values, which explain 91.2% of the variance of the dataset:

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Table 2. Values of the factors of the covariance matrix

Factor	Eigenvalue	Proportion	Accumulated
1	0.54515	0.277	0.277
2	0.37498	0.191	0.468
3	0.18972	0.097	0.565
4	0.17292	0.088	0.653
5	0.14021	0.071	0.724
6	0.11698	0.06	0.783
7	0.08296	0.042	0.826
8	0.07199	0.037	0.862
9	0.0537	0.027	0.889
10	0.04414	0.022	0.912

The scree plot of the total number of factors vs. their corresponding eigenvalues in a descending order is shown in Figure 3. It can be observed the considerable high value of the first two components, while from the 15th value the curve presents practically a flat behavior.

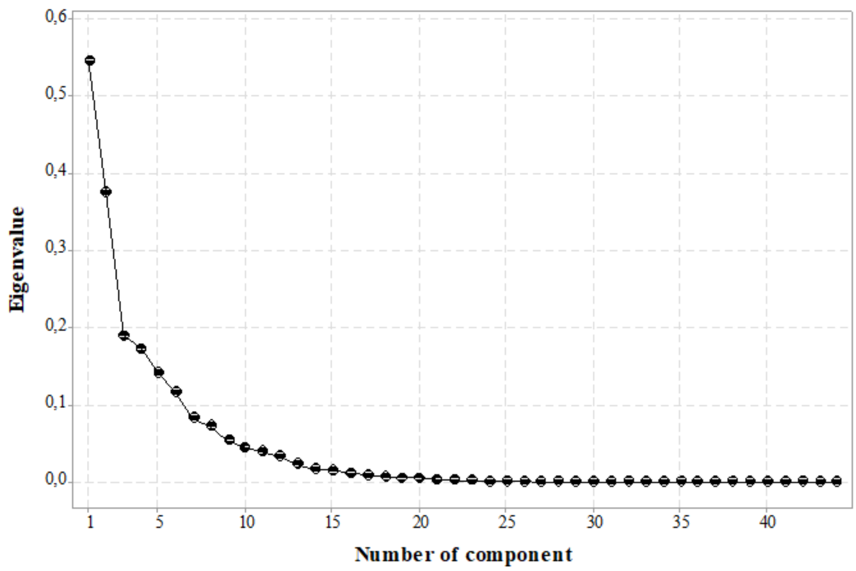

Figure 3. Data scree plot

The first two principal components, named PC1 and PC2 and which account for 46.8% of the total variance in the data, are presented in

Table **3**, jointly with the PSIx variables and the corresponding factorial loads. The load values higher than 0.25 are highlighted, as they are considered significant for each component.

Table 3. Principal components analysis for the first two components

Variable	PC1	PC2	Variable	PC1	PC2	Variable	PC1	PC2	Variable	PC1	PC2
A1.1	**0.27**	**0.44**	I1.2	-0.13	0.16	EC2.2	0.04	-0.03	EN1.2	**-0.28**	0.16
A1.2	**0.29**	**0.36**	I1.3	-0.01	0.08	EC2.3	0.01	-0.01	EN2.1	0.00	0.00
A1.3	0.08	**0.46**	I2.1	-0.05	-0.04	EC2.4	-0.06	0.11	EN2.2	-0.07	0.03
A2.1	-0.15	0.12	I2.2	-0.12	0.07	EC3.1	0.00	0.00	G1.1	0.04	0.05
A2.2	-0.15	0.11	I2.3	0.00	0.05	EC3.2	0.03	0.04	G1.2	0.02	-0.12
A3.1	0.04	-0.01	I3.1	0.00	0.00	EC3.3	0.01	0.06	G1.3	-0.03	0.03
A3.2	**-0.32**	0.09	I3.2	**0.29**	**0.43**	EC3.4	0.02	-0.11	G2.1	-0.01	0.04
A3.3	**-0.24**	0.07	I3.3	0.00	0.00	EC3.5	0.07	0.02	G2.2	-0.04	0.02
A4.1	0.03	-0.01	I3.4	**-0.52**	**0.27**	EC3.6	0.00	0.00	R1.1	0.01	0.05
A4.2	-0.09	0.04	EC1.1	0.05	-0.07	EC3.7	0.00	0.00	R1.2	0.00	0.05
I1.1	-0.01	0.04	EC2.1	0.02	-0.07	EN1.1	**-0.38**	0.18	R2.1	0.00	0.00

To picture these results graphically, Figure 4 is shows the loading plot of the data:

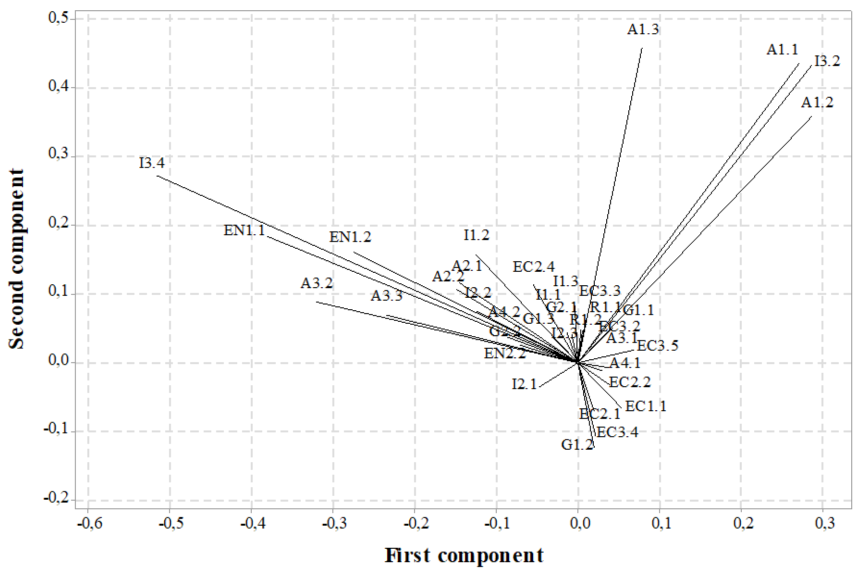

Figure 4. Loading plot for the first two principal components

PC1 has a large positive influence of loads coming from variables belonging to the availability dimension, particularly A1.1 and A1.2, which measure reserves-to-production ratios of oil and gas fuels, respectively. Therefore, it can be inferred that this component is an indicator related the availability of energy sources. On the contrary, indicators I3.4 of international electrical interconnections, and availability indicators related to the diversification of sources have a strong negative load in the component. It can be deduced that while the larger the ratio of production of fossil fuels compared to the reserves, the lower the diversification of other sources of energy. By its part, PC2 has a considerable load of values corresponding to the infrastructure dimension, jointly with other availability indicators.

3.4. Weighting and aggregation

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3.4.1. Weighting

Despite the fact that the relative importance of different indicators for sustainable energy development vary from country to country, depending on country-specific conditions, national energy priorities, sustainability development criteria and their inherent objectives [28], it is necessary to establish a groundwork that assigns weights as importance coefficients to the indicators of the PSIx, so the analyzed countries can be evaluated, compared and ranked within a common framework.

A data-driven approach has been determined for assigning weights to the PSIx indicators. For that aim, the outcomes obtained through the principal component analysis in section **Error! Reference source not found.**, result highly advantageous, since they offer a statistical approach for comparing the variables of the index and, since a large amount of data is being analyzed, the risk of double-weighting the indicators of the index is avoided [29].

From the correlation matrix, also presented in section **Error! Reference source not found.**, new intermediate composites have been obtained by selecting the indicator with the highest correlation to each significant factor, whose value is expressed equation 3:

$$\widetilde{w}_j = arg\max_i \left(\frac{a_{ij}^2}{\sum_{k=1}^{m} a_{ik}^2} \right) \tag{3}$$

In which:

j = 1, ..., m: index indicators

i: analyzed country

a_{ij}: factor load for country i of j indicator

Therefore, the weight of each jth variable is obtained as follows:

$$w_j = \frac{\widetilde{w}_j \left(\frac{\sum_{k=1}^{m} a_{ik}^2}{\sum_{j=1}^{m-q} \sum_{k=1}^{m} a_{ik}^2} \right)}{\sum_{j=1}^{m} \widetilde{w}_j \left(\frac{\sum_{k=1}^{m} a_{ik}^2}{\sum_{j=1}^{m-q} \sum_{k=1}^{m} a_{ik}^2} \right)} \tag{4}$$

In which q is the last significant factor to be considered for the analysis according to the scope described in section 3.

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Table 4. Weights assigned to each indicator shows the weights assigned to each indicator of the index according to the described methodology. As a result of such procedure, several indicators lack of a significant value, with only 18 variables being considered as significant. Furthermore, from the original six dimensions of the index, only three result of statistical interest, which are Availability, Infrastructure and Economy, summarizing a weight of 0.24, 0.44 and 0.32, respectively.

Table 4. Weights assigned to each indicator

Dimension	Variable	Domain weight	Weight of the respective factor	Weight score (ωi)	Resulting weight (Σωi=1)	Dimension weight (Σωi=1)
	A1.1	0.1247	0.0040	0.0005	0.0024	
	A1.2	0.3407	0.0370	0.0126	0.0604	
Availability	A1.3	0.2108	0.0910	0.0192	0.0918	0.24
	A3.1	0.1339	0.0020	0.0003	0.0013	
	A3.2	0.2381	0.0710	0.0169	0.0809	
	I2.1	0.1902	0.0010	0.0002	0.0009	
	I2.3	0.2634	0.0010	0.0003	0.0013	
Infrastructure	I3.2	0.1964	0.0220	0.0043	0.0207	0.44
	I3.4	0.2664 0.2277	0.2770 0.0600	0.0874	0.4187	
	EC1.1	0.1822	0.0170	0.0031	0.0148	
	EC2.1	0.2477	0.0710	0.0176	0.0842	
	EC2.2	0.3906	0.0420	0.0164	0.0786	
	EC2.3	0.2854	0.0080	0.0023	0.0109	
	EC2.4	0.2246	0.0270	0.0061	0.0290	
Economy	EC3.2	0.1747 0.0180	0.0050 0.0030	0.0009	0.0044	0.32
	EC3.3	0.5825	0.0170	0.0099	0.0474	
	EC3.4	0.3893	0.0200	0.0078	0.0373	
	EC3.5	0.5186	0.0060	0.0031	0.0149	

3.4.2. Aggregation

While it is true that, according to the impossibility theorem of [30], there does not exist a perfect aggregation method, it is necessary design a frame that fits the needs of the desired scope for the PSIx application. In this process, the utilization of rules implying additive or multiplicative principles, i.e. linear or geometric aggregation methods, could be possible. Even though, the use of any of these techniques implies that weights become able to be substituted by themselves, meaning that a poor development on one variable might be compensated by an over standing development in another one. The compensability property leads linear and geometric aggregation methods to minimize the importance of the associated indicators. It is, thus, necessary the use of a method which does not allow or restrain compensability according to the scope of the built index.

As stated by [27,31], for weights to be construed as importance coefficients, a non-compensatory frame must be adopted in the aggregation process. The non-compensatory multi-criteria approach (MCA), is the selected method, since it restrains compensability by setting arrangements between two or more legitimate goals.

The elasticity of substitution between indicators j and j', understood, according to [25], as how much one variable has to give up of one achievement to get an extra unit of a second indicator while keeping the level of energy security, is expressed by:

$$\delta_{jj'} = \frac{1}{(1-\beta)} \tag{5}$$

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From this expression, it is noticeable that the smaller the value of β, the smaller the allowed substitutability between indicators. Depending on if the values correspond to the same dimension or not, the value of β is considered distinctly in the aggregation process. For intra-dimensional indicators, the value assigned to β is set to 1, therefore $\delta \rightarrow \infty$, meaning that all the indicators of one particular dimension are completely substitutable with each other. On the other hand, it is desired that the possibility of substitutions among indicators of different dimensions is zero, so β is set to $-\infty$ and the elasticity of substitution δ is null.

With the purpose of assigning scores to each dimension, the following one-digit classification has been stablished:

Table 5. Dimensions grading system

Performance	Grade
X > 90	1
80 ≤X< 90	2
70 ≤ X< 80	3
60 ≤ X< 70	4
50 ≤ X< 60	5
40 ≤ X< 50	6
30 ≤ X< 40	7
20 ≤ X< 30	8
10 ≤ X< 20	9
X< 10	0

The score on each dimension is determined by evaluating the development of each individual country. Since there is no inter-dimensional substitutability, there will be a grade for each relevant dimension within the index.

4. Results and discussion

From section 3 and with most of the variance in the data gathered, the score plot, shown in Figure 5, allows to cluster the analyzed countries depending on their results. It can be observed that all the big economies in the continent, the A group according to the classification presented in section 3.1, are located in the upper part of the graph, deducing, therefore, that their infrastructure is more developed than other countries, compared, for instance, with the case of the Caribbean countries and the Guianas. By their part, Central American countries can be easily grouped due to their closeness in the plot; hence, their energy security, according to the first two principal components, can be considered to be very alike to each other. The plot shows that the geographical location of the covered countries does have a strong influence on the development of their power systems, as well as the size of the respective economies.

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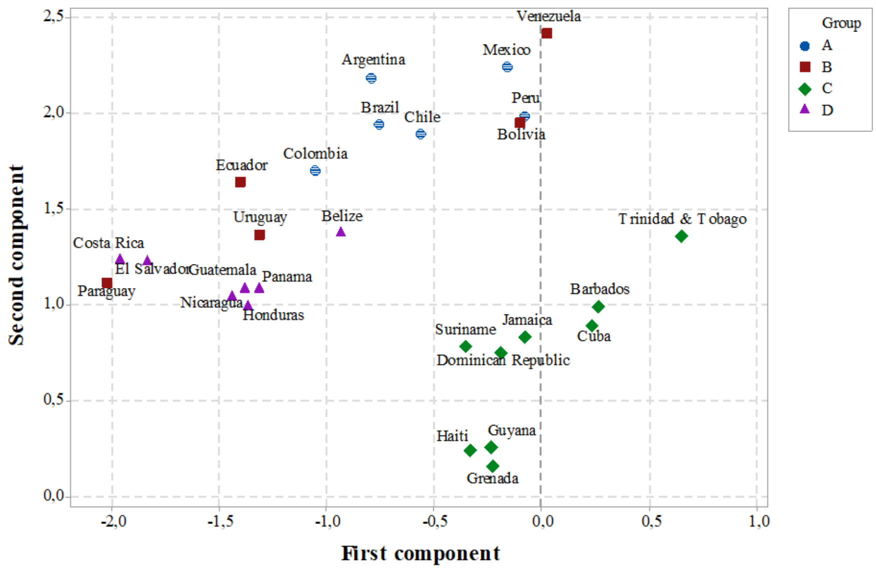

Figure 5. Score plot of the first two components

The resulting outcomes from the evaluation of countries in the Latin America and the Caribbean region, are summarized in Table 6, where the results of each dimension are shown, as well as the overall score of the index. The score of each country is determined by the multiplication of the performance on each dimension times its respective weight, as indicated in Table 5.

Table 6. Resulting scores of the composed index for countries of Latin American and the Caribbean

		A	I	EC	Score			A	I	EC	Score
1st	Argentina	3	1	0	0.67	15th	Mexico	5	5	0	0.40
2nd	Ecuador	7	1	0	0.58	16th	Venezuela	4	7	0	0.33
3rd	Costa Rica	8	1	8	0.55	17th	Peru	8	8	8	0.24
4th	El Salvador	7	1	0	0.54	18th	Brazil	5	0	0	0.24
5th	Paraguay	7	1	0	0.54	19th	Trinidad & Tobago	8	0	8	0.15
6th	Colombia	7	1	0	0.54	20th	Cuba	8	0	8	0.15
7th	Panama	0	1	8	0.50	21st	Barbados	0	0	8	0.13
8th	Nicaragua	0	1	0	0.49	22nd	Grenada	0	0	8	0.07
9th	Bolivia	8	2	0	0.49	23rd	Guyana	0	0	8	0.07
10th	Uruguay	0	1	0	0.48	24th	Suriname	0	0	0	0.06
11th	Honduras	0	1	0	0.47	25th	Dominican Republic	0	0	0	0.04
12th	Guatemala	0	1	0	0.47	26th	Jamaica	0	0	0	0.04
13th	Chile	6	4	8	0.45	27th	Haiti	0	0	0	0.03
14th	Belize	0	1	0	0.44						

It can be observed that the countries within the region have mixed values in their energy security performance. The country with the highest overall score is Argentina, mainly due to its performance on infrastructure and availability dimensions, and despite the fact that it does not have an outstanding development in the economic dimension. Indeed, the country has very important reserves of fossil fuels, it has a noticeable energy self-sufficiency and, additionally, its electrical interconnections provide an important flexibility capacity to the Argentinean power system. On the other hand, Haiti is the country with more areas of improvement, being weak in all the three evaluated dimensions; the Caribbean country has no fossil fuels in its territory, has a feeble energy infrastructure and it possesses a fragile and inefficient economy.

By dimension, most of the studied countries have an improvable behavior in availability, with Venezuela, Argentina, Brazil and Mexico being the countries best positioned, in this order. In infrastructure, the gap among countries with relatively good energy infrastructure and those lacking of it is deep, with Argentina, Colombia, Ecuador, Paraguay, Uruguay and the Central American nations as the best performers in this dimension. By its part, no country has shown an outstanding performance in the economic dimension, on the contrary, most of them have a mediocre behavior; Barbados, Chile, Costa Rica, Cuba, Grenada, Guyana, Panama, Peru and Trinidad and Tobago are the countries that performed the best in this dimension.

5. Conclusions

Energy transitions are reshaping the global energy system, taking electricity to occupy a predominant role in modern infrastructures. This new paradigm represents also new challenges, and among them, guaranteeing energy security of the power system has become a priority for policy makers. The path that each nation adopts in this line depend on its own needs, interests and possibilities, therefore, there does not exist a single approach on energy security, but a series of divergent strategies.

Latin America and the Caribbean is a very diverse region in energy terms, in which countries range from one possessing the largest crude oil reserves in the world, to others with an extensive energy poverty, hence, the analysis of their strategies on how efficient they are for procuring energy security results of an outstanding usefulness for the enhancement of power systems in the continent.

The PSIx was conceived as a tool for policy makers for issuing strategies focused on reaching sustainable development through energy security enhancement. The tool offers the possibility to assess energy security in the power system from a multidimensional approach, covering availability, infrastructure, economy, environment, government and R+D+i spheres. Through the conduction of an analysis of elements, the internal uniformity of the index has been verified, so it is asserted that the tool measures the same characteristic i.e. energy security performance of a nation. The composed index constitutes, therefore, a comprehensive frame in which strategies addressed to enhance energy security in the power system can be evaluated, according to their effectiveness for achieving that purpose.

Three of the six dimensions result of statistical relevance i.e. availability, infrastructure and economy. It results pertinent to notice that this does not mean that the rest of the dimensions are not important for energy security, but that variance of data among countries is explained mostly by those dimensions considered statistically significant.

The evaluated countries, as expected, perform very distinctly in the relevant dimensions of the index. Countries that possess considerable fuel reservoirs have higher evaluation results in the energy availability dimension. There exists a wide division between countries with an adequate electrical infrastructure and those that lack of it, mainly due to the existence of international interconnections and the presence of gas-fueled power plants, which, additionally, are measures that greatly enhance the flexibility of the electrical network. No country presents distinguished results on the economic dimension, on the contrary, they all have rather lackluster performances. The country with the highest overall score is Argentina, with 0.67 points, followed by Ecuador and Paraguay with 0.58 and 0.54 points, respectively. The first two countries, Argentina and Ecuador, have important fossil fuels reservoirs, while Paraguay is a net electricity exporter thanks to its large hydropower plants. These three countries are very well interconnected with their neighbors, and Ecuador and Paraguay have experienced important improvements on their economies lately.

The developed multi-dimensional index constitutes a tool addressed to help policy makers to assess energy security strategies in the power system. Through its application in the case of Latin America and the Caribbean, and after the subsequent statistical analysis, it can be confirmed that this tool can, by means of the betterment of energy security, help national systems to reach sustainable development.

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Appendix A

Table A1. Formulas and objectives of indicators

ID	Formula	Objective	ID	Formula	Objective
A1.1	$A1.1 = \frac{r_a}{s_a}$	Maximize	EC2.2	$EC2.2 = \frac{x_e}{GDP}$	Minimize
A1.2	$A1.2 = \frac{r_b}{s_b}$	Maximize	EC2.3	$EC2.3 = \frac{c_e}{e_u}$	Minimize
A1.3	$A1.3 = \frac{r_c}{s_c}$	Maximize	EC2.4	$EC2.4 = \frac{x_e - x_{e-1}}{GDP}$	Minimize
A2.1	$A2.1 = -\sum_i (p_i \ln p_i)$	Maximize	EC3.1	$EC3.1 = \frac{e_c}{GDP}$	Minimize
A2.2	$A2.2 = -\sum_i (q_i \ln q_i)$	Maximize	EC3.2	$EC3.2 = \frac{e_{c,1}}{GDP_1}$	Minimize
A3.1	$A3.1 = \frac{e_z}{e_y}$	Minimize	EC3.3	$EC3.3 = \frac{e_{c,2}}{GDP_2}$	Minimize
A3.2	$A3.2 = -\sum_k (r_k \ln r_k)$	Maximize	EC3.4	$EC3.4 = \frac{e_{c,3}}{GDP_3}$	Minimize
A3.3	$A3.3 = -\sum_i (c_{3,i} p_i \ln p_i)$	Maximize	EC3.5[1]	$EC3.5 = \frac{e_{c,4}}{pl}$	Minimize
A4.1	$A4.1 = \frac{e_{gen,p,s}}{e_{gen}}$	Maximize	EC3.6	$EC3.6 = \frac{e_{c,5}}{vh}$	Minimize
A4.2	$A4.2 = \frac{e_{gen,p,w}}{e_{gen}}$	Maximize	EC3.7	$EC3.6 = \frac{e_{c,o}}{GDP_o}$	Minimize
I1.1	$I1.1 = \frac{P}{D_{peak}}$	Maximize	EN1.1	$EN1.1 = \frac{e_r}{e_p}$	Maximize
I1.2	$I1.2 = \frac{P_{trans}}{D_{peak}}$	Maximize	EN1.2	$EN1.2 = \frac{P_r}{P}$	Maximize
I1.3	$I1.3 = \frac{pl_e}{pl}$	Maximize	EN2.1	$EN2.1 = \frac{GHG}{pl}$	Minimize
I2.1	$I2.1 = \frac{e_{gen,f}}{e_{gen,f,max}}$	Maximize	EN2.2	$EN2.2 = \frac{GHG}{GDP}$	Minimize
I2.2	$I2.2 = \frac{e_{gen,r}}{e_{gen,r,max}}$	Maximize	G1.1	Direct value	Maximize
I2.3	$I2.3 = \frac{e_l}{e_c}$	Maximize	G1.2	Direct value	Maximize
I3.1	$I3.1 = \frac{S_{pump}}{P}$	Maximize	G1.3	Direct value	Maximize
I3.2	$I3.2 = \frac{PtX}{P}$	Maximize	G2.1	Direct value	Maximize
I3.3	$I3.3 = \frac{P_{gas}}{P}$	Maximize	G2.2	Direct value	Maximize
I3.4	$I3.4 = \frac{P_{dis}}{P}$	Maximize	R1.1	Direct value	Maximize
I3.5	$I3.5 = \frac{L_{int}}{P}$	Maximize	R1.2	Direct value	Maximize
EC1.1	$EC1.1 = \frac{e_c}{TPES}$	Maximize	R2.1	Direct value	Maximize
EC2.1	$EC2.1 = \frac{x_e}{pl}$	Minimize			

[1] Proxy measure. Household energy intensity is considered to be domestic electrical consumption per capita.

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Appendix B

Table B1. PSIx variables

Variable	Description	Units	Variable	Description	Units
r_a	Crude oil reserves	b	e_l	Electricity supplied to the power lines	kWh
s_a	Crude oil production	b	e_c	Electricity consumption	kWh
r_b	Natural gas reserves	cu m	PtX	Power-to-X installed capacity	MW
s_b	Natural gas production	cu m	P_{gas}	Installed capacity of gas-fired power plants	MW
r_c	Coal reserves	ton	P_{dist}	Installed capacity of distributed generation facilities	MW
s_c	Coal production	ton	L_{int}	International interconnections	MW
p_i	Share of energy source *i* in the total electricity generation matrix	-	$TPES$	Total primary energy supply	MWh
q_i	Share of energy source *i* in the total installed capacity matrix	-	x_e	Electrical energy expenditures	USD
e_z	Net imported electricity	kWh	GDP	Gross domestic product	USD
e_y	Net consumed electricity	kWh	$e_{c,1}$	Electricity consumption by industrial activities	kWh
r_k	Share of electrical energy imported from k region	%	GDP_1	Gross domestic product of industrial activities	USD
c_3	Correction factor for pi, political stability	-	$e_{c,2}$	Electricity consumption by agricultural activities	kWh
e_{gen}	Total electricity generation	kWh	GDP_2	Gross domestic consumption of agricultural activities	USD
$e_{gen,p,s}$	Potential for power generation from solar sources	MW	$e_{c,3}$	Electricity consumption by service/commercial activities	kWh
$e_{gen,p,w}$	Potential for power generation from wind sources	MW	GDP_3	Gross domestic product of service/commercial activities	USD
P	Power generation capacity	MW	$e_{c,4}$	Household electricity consumption	kWh
D_{peak}	Peak demand	MW	$e_{c,5}$	Electricity consumption by transport	kWh
pl	Total population	people	vh	Number of vehicles	-
pl_e	Population with access to electricity	people	$e_{c,o}$	Electricity consumption by other activities	kWh
$e_{gen,f}$	Produced electricity from fossil-fuel-based installations	kWh	GDP_o	Gross domestic product of other activities	USD
$e_{gen,f,max}$	Maximum possible produced electricity from fossil-fuel-based installations	kWh	c_e	Cost of electricity	USD/kWh
$e_{gen,r}$	Produced electricity from renewable energy installations	kWh	e_u	Electrical energy unit	kWh
$e_{gen,r,max}$	Maximum possible produced electricity from renewable energy installations	kWh	e_r	Electricity produced by renewable sources	kWh
S_{pump}	Pumped-storage capacity	MW	e_p	Electricity production	kWh
$e_{gen,max}$	Maximum generation energy	kWh	P_r	Installed capacity of renewable energy facilities	MW
P_{trans}	Transformers power	MW	GHG	Greenhouse gases emissions	ton

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