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# 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 transforming energy systems around the globe. Such a shift has caused the power system to become a critical piece of infrastructure for the economic development of every nation on the planet. Therefore, guaranteeing its security is crucial, not only for energy purposes but also as a part of a national security strategy. This paper presents a multidimensional index developed to assess energy security of electrical systems in the long term. This tool, named the Power System Security Index (PSIx), 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, to measure its 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 is the case of Haiti.

**Keywords:** energy security; energy transitions; Latin America; power system; sustainability



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## 1. Introduction

Energy transitions are motivated, as stated by [1], by global efforts to efficiently increase competitiveness while respecting the environment and guaranteeing energy supply. The transitions are changing the way energy is produced, consumed, stored, and transmitted, not only by boosting the presence of renewable energy technologies but also by improving the system's flexibility through innovative infrastructure solutions, at the same time that enhancing energy productivity has become a state priority worldwide [2,3]. This new paradigm also presents new challenges, the security of energy supply being 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 concept of energy security is highly context-dependent and, consequently, differs significantly from one policymaker to another [5], requiring different authorities to determine their own approach to the concept for creating solutions for the procurement of energy supply in their respective populations. With the objective of maintaining 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-fuel reservoirs, but also in renewable energy potential. At the same time, some nations in the region do not possess strong economies, requiring them to undermine their electricity systems, independently of their possession—or lack—of fuels basins. Due to this diversity of circumstance, it is pertinent to evaluate how policies of different countries in the region are translated into improvements to energy security in their respective power systems.

As stated by [7], to be analytically helpful, a measure for evaluating energy security must be quantifiable. One instrument to do this is composed indexes, which are useful to identify benchmark performances and trends, focusing on particular issues and, by those means, setting policy priorities [8]. In the present document, the composed index developed by [9], named Power System Security Index (PSIx), is applied for the evaluation of different countries in the Latin America and Caribbean region. The developed tool consists of a multidimensional index aimed at evaluating policies regarding energy security in the power sector. Nevertheless, the instrument has been applied to one single country in different time frameworks. The path that every country in the region has determined for transitioning to a sustainable energy system is different, making it pertinent to analyze how each country is positioned in its own transition. The PSIx, which, as shown in Figure 1, has been constructed based on the framework of energy transitions, offers a common framework to evaluate development.

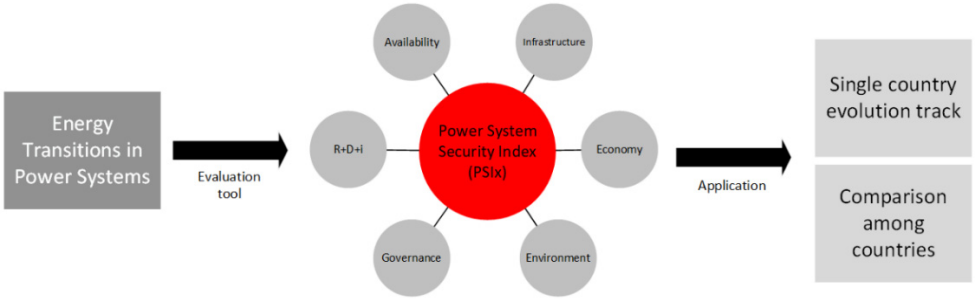


**Figure 1.** PSIx Approach [9].

The novelty of this paper lies in the application of the developed methodology, based on the PSIx, consisting of the evaluation of energy security policies of multifold economies in a given time frame, as Figure 1 shows, and its further use for the assessment of the case of Latin America. The suitability of the multidimensional index will be evaluated by executing a statistical analysis of different countries' development, as well as their comparison and ranking, according to their performance on achieving energy security in their respective power systems.

To achieve the abovementioned objectives, the present paper is organized into five sections. Section 2 describes the composed index. The third one describes mathematical model. In Section 4, the outcomes of the composed index application are presented and discussed. Finally, the respective conclusions are presented in Section 5.

## 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. How the index is structured 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.

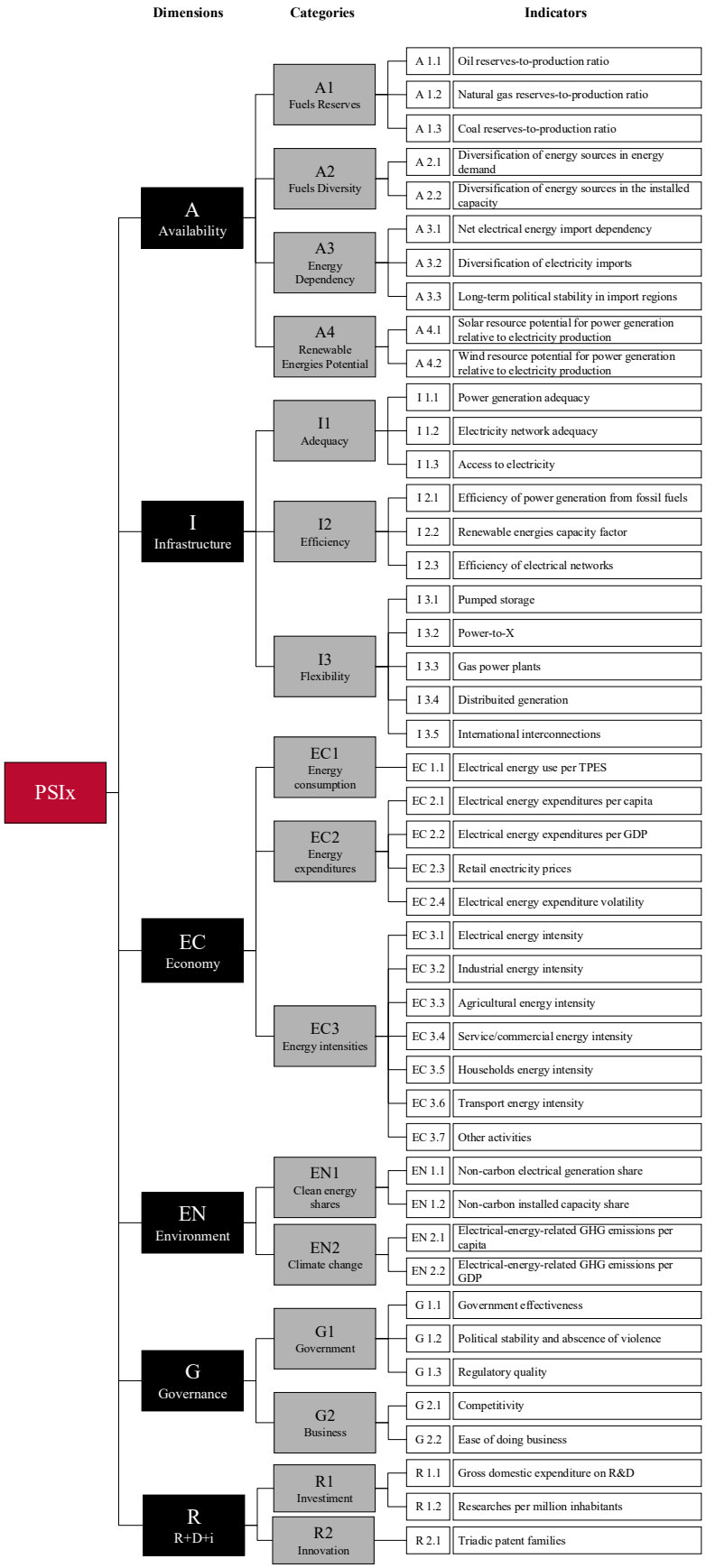


**Figure 2.** PSIx structure. Reprinted from ref. [9].

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 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 of the environmental dimension (EN) aim to measure the repercussions of energy-generation technologies on the environment, so that they do not represent a menace for sustainable development. Climate change has acquired a very high importance for energy policymakers during the current century, particularly greenhouse gas (GHG) emissions emitted into 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 for effectively planning infrastructure development to ensure long-term energy security [15]. They also pledge to establish lasting relationships with other countries, so it is possible to assure energy supplies in a politically stable scenario. On 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], assessing new technologies in the energy field, as well as the development of intellectual capital as a factor to assess risks on energy security.

The respective formulas and objectives of each indicator are summarized in Table A1 of Appendix A, while the corresponding description and units of formulas are presented in Table A2.

The source from which data was obtained for its analysis is the Latin America and the Caribbean Energy Information System, developed by the Latin America and the Caribbean Energy Organization [18], and the chosen year is the last one with a complete dataset, namely 2018.

## 3. Mathematical Model

The mathematical model consists of the imputation of missing data, normalization, a multivariate analysis, weighting, and aggregation. Although most of the model has been originally developed for the study of different economies and presented in this paper, the normalization process used here is the same as the one proposed by [9].

### *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 non-appearance 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; and 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, and 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 nonexistent.

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 the case of missing values, they are set to zero, 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 in the Caribbean. To achieve a more reliable imputation, the countries of the index have been divided into four categories, depending on the size of their economies and their geographical locations, 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, Paraguay, Uruguay, and Venezuela
C. Caribbean and the Guianas: Barbados, Cuba, Grenada, Guyana, Haiti, Jamaica, Dominican Republic, Suriname, and Trinidad and Tobago
D. Central America: Belize, Costa Rica, El Salvador, Honduras, Nicaragua, and Panama

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 a procedure leads to estimates similar to those found by weighting, provided the sampling weights are constant within weighting classes [19].

### 3.2. Multivariate Analysis

With the objective of assessing the underlying structure of the gathered data, a multivariate analysis was conducted. This approach is also helpful for assigning weights to the indicators, a crucial step for, according to [22], determining their influence within the index, as well as their trade-off values.

Among the different methodological techniques present in the literature, a data-driven approach was selected, since it depends entirely on the data themselves. A factorial analysis approach, specifically the principal component analysis, was chosen, since this statistical approximation allows the determination of interrelations among a great number of variables, at the same time as also allowing an explanation of their behavior in terms of their subjacent common dimensions [23]. For conducting the statistical analysis, Minitab® software was used (Minitab® and all other trademarks and logos for the Company's products and services are the exclusive property of Minitab, LLC. All other marks referenced remain the property of their respective owners. See minitab.com for more information).

The treated variables have been considered initially neither dependent nor independent from each other. Therefore and, according to [24], an interdependency study can be executed. As the methodology dictates, the statistical study must cover all the variables simultaneously, so an underlying structure can be identified for the whole set of indicators. For performing the principal components analysis, a covariance matrix of the

data was 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 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.

To determine the principal components of the data, the methodology proposed by [25] has been followed, in which the correlation matrix serves as the basis for such purpose. A principal component is defined as

$$\boldsymbol{z} = \boldsymbol{A}'\boldsymbol{x}^* \tag{1}$$

where $\boldsymbol{A}$ consists of columns formed by the eigenvectors of the correlation matrix, while $\boldsymbol{x}^*$ is composed by the arrangement of standardized variables. The objective of this approach is to identify the principal components of the standardize version of $\boldsymbol{x}^*$ with regard to $\boldsymbol{x}$, where $\boldsymbol{x}^*$ possesses the $j$th element $x_j/\sigma_{jj}^{1/2}$, $j = 1, 2, \ldots, p$, $x_j$ is the $j$th element of $\boldsymbol{x}$, and $\sigma_{jj}$ is the variance of $x_j$. Therefore, the covariance matrix for $\boldsymbol{x}^*$ is the correlation matrix for $\boldsymbol{x}$, and the principal components of $\boldsymbol{x}^*$ are determined by Equation (1).

For the selection of the factors to be considered to be relevant for a further analysis, and which give rise to the determination of principal components, an a priori criterion has been chosen, 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 shown in Table 2. They are 10 of the total sample of 44 values, which explain 91.2% of the variance of the dataset:

**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, as shown in Figure 3. The considerable high value of the first two components can be observed, while from the 15th value the curve presents practically a flat behavior.

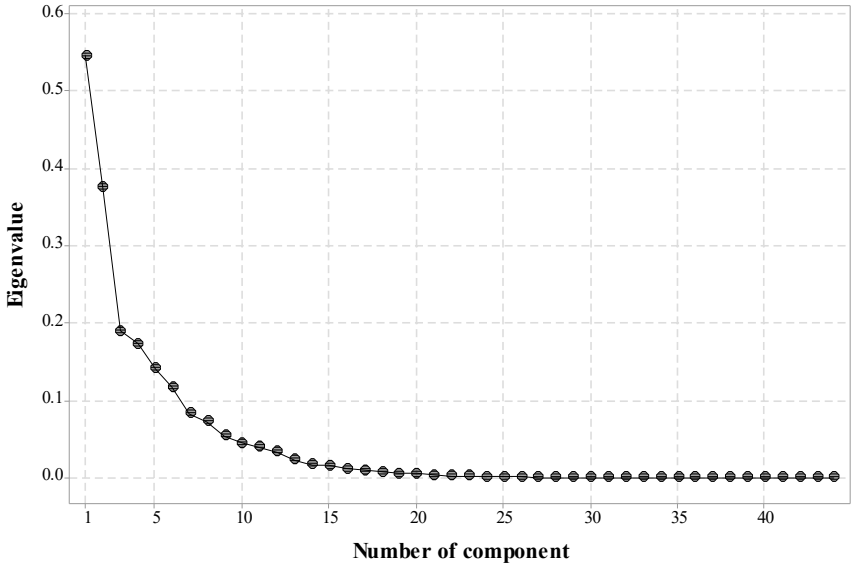


**Figure 3.** Data scree plot.

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 or eigenvectors. The load values higher than 0.25 are highlighted, as they are considered significant for each component.

**Table 3.** Eigenvectors for the first two principal 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 shows the loading plot of the data:

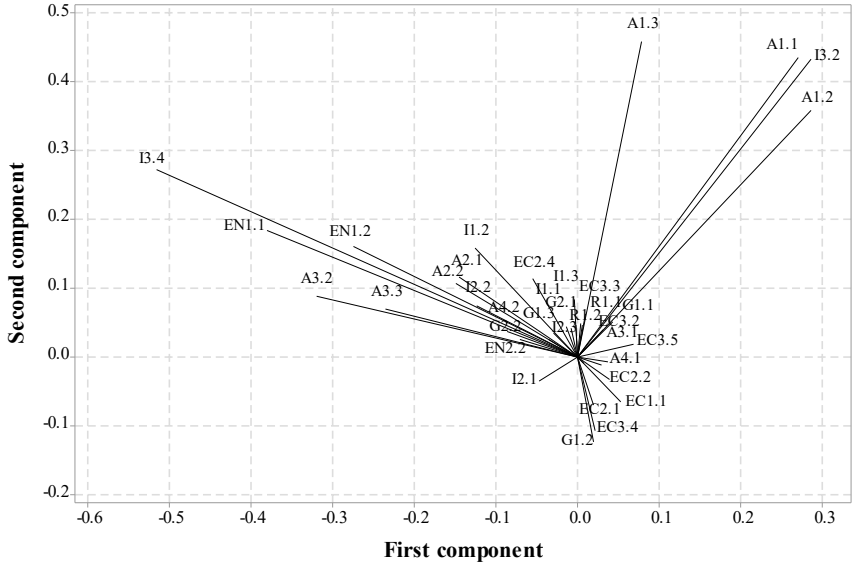


**Figure 4.** Loading plot for the first two principal components.

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. By contrast, 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 the larger the ratio of production of fossil fuels compared to the reserves, the lower the diversification of other sources of energy. PC2 has a considerable load of values corresponding to the infrastructure dimension, jointly with other availability indicators.

### *3.3. Weighting and Aggregation*

#### 3.3.1. 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 [26], it is necessary to establish a groundwork that assigns weights as importance coefficients to the indicators of the PSIx, so that 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 3.2 are 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 [27].

From the correlation matrix, also presented in Section 3.2, new intermediate composites have been obtained by selecting the indicator with the highest correlation to each significant factor, whose value is expressed by:

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

In which:
$j = 1, \ldots, m$: index indicators
$i$: analyzed country

$a_{ij}$: factor load for country $i$ of $j$ indicator
Therefore, the weight of each $j$th variable is obtained as follows:

$$w_j = \frac{\widetilde{w}_j \left( \frac{\sum_{k=1}^{m} a_{ik}^2}{\sum_{j=1}^{m-q} \sum_{k=1}^{m} a_{ik}^2} \right)}{\sum_{j=1}^{m} \widetilde{w}_j \left( \frac{\sum_{k=1}^{m} a_{ik}^2}{\sum_{j=1}^{m-q} \sum_{k=1}^{m} a_{ik}^2} \right)} \quad (3)$$

In which $q$ is the last significant factor to be considered for the analysis according to the scope described in Section 3. Table 4 shows the weights assigned to each indicator of the index according to the described methodology. As a result of such procedure, several indicators lack a significant value, with only 18 variables being considered to be significant. Furthermore, from the original six dimensions of the index, only three are 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) |
|---|---|---|---|---|---|---|
| Availability | A1.1 | 0.1247 | 0.0040 | 0.0005 | 0.0024 | 0.24 |
| | A1.2 | 0.3407 | 0.0370 | 0.0126 | 0.0604 | |
| | A1.3 | 0.2108 | 0.0910 | 0.0192 | 0.0918 | |
| | A3.1 | 0.1339 | 0.0020 | 0.0003 | 0.0013 | |
| | A3.2 | 0.2381 | 0.0710 | 0.0169 | 0.0809 | |
| Infrastructure | I2.1 | 0.1902 | 0.0010 | 0.0002 | 0.0009 | 0.44 |
| | I2.3 | 0.2634 | 0.0010 | 0.0003 | 0.0013 | |
| | I3.2 | 0.1964 | 0.0220 | 0.0043 | 0.0207 | |
| | I3.4 | 0.2664 | 0.2770 | 0.0874 | 0.4187 | |
| | | 0.2277 | 0.0600 | | | |
| Economy | EC1.1 | 0.1822 | 0.0170 | 0.0031 | 0.0148 | 0.32 |
| | 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 | |
| | EC3.2 | 0.1747 | 0.0050 | 0.0009 | 0.0044 | |
| | | 0.0180 | 0.0030 | | | |
| | 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 | |

#### 3.3.2. Aggregation

Although it is true that according to the impossibility theorem of [28], 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 use 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. Therefore, the use of a method is necessary which does not allow or restrain compensability according to the scope of the built index.

As stated by [24,29], for weights to be construed as importance coefficients, a non-compensatory framework 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 [22], 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:

$$\delta_{jj'} = \frac{1}{(1-\beta)} \tag{4}$$

From this expression, it is noticeable that the smaller the value of $\beta$, the smaller the allowed substitutability between indicators. Depending on if the values correspond to the same dimension or not, the value of $\beta$ is considered distinctly in the aggregation process. For intra-dimensional indicators, the value assigned to $\beta$ is set to 1, therefore $\delta \to \infty$, 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 $\beta$ is set to $-\infty$ and the elasticity of substitution $\delta$ is null.

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

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

## 4. Results and Discussion

The results obtained from the analysis are, as could be expected from a region with such diversity of countries in energy terms, quite divergent.

From Section 3, and with most of the variance in the data gathered, the score plot, shown in Figure 5, allows the clustering of the analyzed countries depending on their results. It can be observed that all the big economies in the continent, Group A according to the classification presented in Section 3.1, are located in the upper part of the graph, deducing, therefore, according to the principal components defined in Section 3.3, that their infrastructure is more developed than other countries, compared, for instance, with the case of the Caribbean countries and the Guianas. Central American countries can be easily grouped due to their close location in the plot; therefore, their energy security can be considered to be very alike. 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. The first of the characteristics, geographical location, plays a central role in determining the energy security of countries with a similar level of economic development, which is consistent with the geological basins of fuels and similar renewable energy potential.

The score of each country is determined by the multiplication of the performance on each dimension multiplied by its respective weight, as indicated in Table 5. The resulting outcomes from the evaluation of countries in 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.

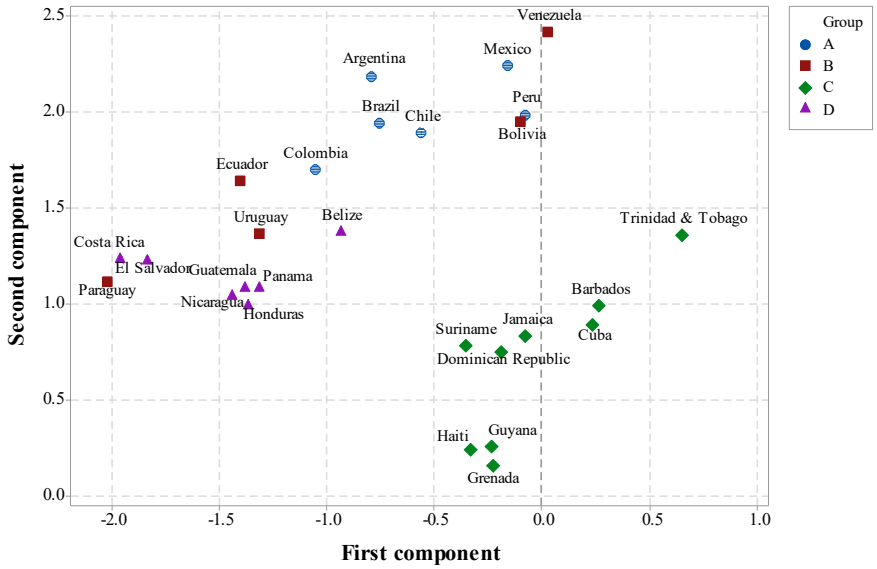


**Figure 5.** Score plot of the first two components.

**Table 5.** Dimensions grading system.

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

**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 and 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, even though 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 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-fuel reserves in its territory, has a feeble energy infrastructure and 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 it is deep, with Argentina, Colombia, Ecuador, Paraguay, Uruguay, and the Central American nations as the best performers in this dimension. No country has shown outstanding performance in the economic dimension; most have 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.

The results show a picture of the current situation of the region. As the path towards an energy transition of every country is defined by each nation state, also each state is also in charge of determining the priority dimension or dimensions it wants to focus on. Notwithstanding, the most efficient way to do it, at least mathematically and as explained in Section 3.3, is to improve the areas in which the country scores the lowest. Nevertheless, no one single dimension nor indicator should be considered to be completely irrelevant, since on they all, as a whole, rely on the possibility of succeeding in achieving a secure and sustainable energy system.

## 5. Conclusions

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

Latin America and the Caribbean is a very diverse region in energy terms, in which countries range from possessing the largest crude oil reserves in the world to extensive energy poverty; therefore, the analysis of its strategies on how efficient it is for procuring energy security is of outstanding usefulness for the enhancement of power systems on the continent.

The PSIx was conceived as a tool for policymakers 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 using a multidimensional approach, covering availability, infrastructure, economy, environment, government, and R + D + i spheres. Through the analysis of elements, the internal uniformity of the index has been verified, asserting that the tool measures the same characteristics, i.e., the 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. Through the study, it is confirmed that the PSIx is useful not only for tracking the development of a single country regarding its energy security, but it is also suitable for the study of multifold economies.

Three of the six dimensions are of statistical relevance, i.e., availability, infrastructure, and economy. It is 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 one, 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 performance. 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-fuel 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 to their economies lately.

The developed multidimensional index constitutes a tool addressed to help policymakers 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. Future work shall include the application of the index to other regions at a supranational level to assess the suitability of policies aimed to improve energy security, as well as the incorporation of more indicators aimed to achieve a sustainable energy system.

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## Appendix A

**Table A1.** Formulas and objectives of indicators [9].

| 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 | $EC3.5 = \frac{e_{c,4}}{pl}$ | Minimize |
| A4.1 | $A4.1 = \frac{e_{gen,p,s}}{e_{gen}}$ | Maximize | EC3.6 | $EC3.6 = \frac{e_{c,5}}{vh}$ | Minimize |

**Table A1.** *Cont.*

| ID | Formula | Objective | ID | Formula | Objective |
|---|---|---|---|---|---|
| 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 | | | |

EC3.5 consists of a proxy measure; household energy intensity is considered to be domestic electrical consumption per capita.

**Table A2.** PSIx variables [9].

| 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 |

**Table A2.** *Cont.*

| Variable | Description | Units | Variable | Description | Units |
|---|---|---|---|---|---|
| $e_{gen,f}$ | 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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