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Composed Index for the Evaluation of the Energy Security of Power Systems: Application to the Case of Argentina

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Abstract: Energy transitions' trend towards sustainable systems has prompted energy systems to shift from being fossil-fuel-based to rely on renewable energy. These transitions have led the power system to occupy the center of modern infrastructures, so assuring its security has become a priority for policy makers. This work presents a tool based on a multidimensional index, the Power System Security Index (PSIx), for the evaluation of policies affecting the security of the supply of electrical energy. The developed frame is applied to the current power system of Argentina, and it is compared to the system in year 2002. Availability of resources and infrastructure are the strengths of the country, while economic, governability, and research, development and innovation spheres leave room for improvement. The further incorporation of more economies to the study would substantially enrich the statistical analysis of the results.

Keywords: energy security; energy transition; power system; sustainability

1. Introduction

Security of energy supply is a matter of utmost importance for the efficient functioning of an economy [1]. Energy transitions, as a new regime, are reshaping the global energy system. They are driven by international efforts to efficiently increase competitiveness while respecting the environment and guaranteeing the supply of energy [2].

Each nation establishes its own path for the shift of its current energy system, depending on its own circumstances, needs, possibilities, and interests. Nevertheless, it is indubitable that the main target economies are seeking is to achieve sustainability in the supply of energy [3]. This pursuit includes measures such as boosting the integration of renewable energy sources, expanding the presence of unconventional-fossil-fuel power plants, and expanding international interconnections and energy storage as efforts to increase flexibility of the energy system, jointly with enhancing energy productivity [4,5]. All these actions make up a new paradigm that the energy system is immersed in, making it imperative to guarantee the supply of energy under new conditions.

Due to its flexibility and versatility, electricity has heavily extended its presence in the global energy matrix, whose final energy consumption increased 215% between 1990 and 2016 [6]. Moreover, thanks to the integration of renewable energies, electricity occupies a central role for decarbonizing the energy system [7]. Therefore, ensuring the reliability of the crucial power system infrastructure is essential for the development of modern societies, not only in terms of energy but also as part of a national economic strategy [8–10].

The concept of security of energy supply is highly context-dependent [11] and differs significantly from one policy maker to another. Governments around the globe determine their own approach for ensuring the security of their energy systems; consequently, they conduct policies and strategies in diverse priority lines that can cover areas from energy poverty to climate change [12]. Specific circumstances of a country, its level of economic development, and the reliability of its energy system, along with risk perceptions and prevailing geopolitical issues, are the factors that set up the frame in which energy security is defined [13].

In order to be analytically helpful, a measure of energy security has to be quantifiable [14]. Composed indexes are useful to identify benchmark performances and trends focused on particular issues and, by those means, to set policy priorities [15].

A composed index, named the Power System Security Index (PSIx), is presented in this work and proposed for use in the evaluation of policies concerning energy security in the power sector. This tool consists of a multidimensional index comprised by six dimensions, each of them possessing in turn several indicators grouped in diverse categories. Subsequently, the tool is applied to the study of the Argentinean power sector so energy security in this system can be evaluated and discussed.

This paper is structured as follows: Section 2 provides a review of the available literature on energy security. The dimensions that shape the index are listed and described in Section 3, along with details regarding the normalization process. Section 4 provides insight into the current power sector in Argentina. Section 5 presents the results of the evaluation of the Argentinian energy sector according to the tool. In Section 6, the outcomes of the composed index application are presented and discussed. Finally, conclusions are provided in Section 7.

2. Literature Review on Energy Security

2.1. The Concept of Energy Security

The concept of energy security became globally meaningful in the 20th century. It was originally related to oil supply, but nowadays it has been widely broadened to cover not only the supply of different forms of energy but also additional topics ranging from energy poverty to climate change [12].

Even without a globally accepted definition for energy security [11], the term has acquired an indubitable relevance among policy makers and has become one of the main targets of energy policy [1,16]. Internationally, enhancement of energy security has become a key objective of the European Union in its common energy policies [17]; its improvement is a priority action within the National Security Strategy of the United States of America [18], and it constitutes a guiding vector for structuring China's energy system according to its 2016–2020 strategy [19].

The International Energy Agency defines energy security as "the uninterrupted physical availability at a price which is affordable, while respecting environmental concerns" [20]. However, inasmuch as the concept of energy security is highly context-dependent [13], the establishment of suitable boundaries is necessary for its proper study according to the desired scope. Such boundaries are framed by specific circumstances of a country, its level of economic development, and the reliability of its energy system, along with risk perceptions and the prevailing geopolitical issues [13].

Despite the fact that the security of energy systems could be threatened by natural, accidental, or human-engineered malicious causes or actions, as summarized in [21], for this paper, energy security will be covered from a long-term perspective at a national level. That is, energy security will be covered in relation to state policies focused on assuring a longstanding supply of energy and particularly, according to [22], its influence on resilience, vulnerability, economic dependency, and political affectability. Energy security will be understood, as proposed by [23], as the sustainable supply of energy.

Energy transitions around the globe have enabled power systems to gain a level of utmost importance in the political agenda and to become the center of modern infrastructures [24]. Electricity occupies the second most widely consumed final energy form in the world, and it is the one with the largest proportional expansion in this century [25]. Hence, the energy security of the power system is crucial for achieving sustainable development of an economy, with this being the basis for the outcome of the present work.

2.2. Literature Review

Composite indicators, when referring to countries' development, allow a relatively easy and illustrative comparison of large amounts of data in a synthetic way. They consist of a set of individual indicators arranged into a single index on the basis of an underlying model [26].

Specifically for the case of energy security, manifold indicators allow a broader understanding of the concept and are indispensable for its measurement [1,27]. Indicators are useful instruments for identifying trends and drawing attention to particular issues, either among different countries or in different time frames [26]; as such, they are of particular relevance for the study of security of energy supply.

In order to achieve a reliable energy security measurement tool design, it is essential that the indicators shaping it follow minimum quality standards that ensure the trustworthiness and coherency of the composed index. Indicators are entitled to go beyond basic statistics and to contribute to a broader understanding of the main treated issues [28].

Within a composite indicator, dimensions constitute the highest hierarchical level of analysis [26]. The dimensions group different indicators and point out the scope of the variables that they measure. The indicators assigned to each dimension within the index must fulfill the following criteria:

- Analytical soundness: Chosen indicators must pertinently measure a significant condition according to the index scope.
- Measurability: Objective assessment must be possible for values of the treated variable.
- Robustness: The data source must be reputable, well-recognized, and authoritative.
- Accessibility: The data must be publicly available.
- Updatability: Historical data must be able to be replaced with new data outlooks.
- Timeliness: The time between the data becoming available and the phenomenon it describes happening must be as short as possible.
- Coherence: The same methodologies, concepts, and definitions must be applied both over time and across countries.
- Consistency: Data should come from a single, common, unique source to the extent possible.

Several composed indicators focused on studying energy security have been constructed; some of the most widespread indexes in the literature are summarized in [1,13,29,30]. The indicators that have been reviewed for the construction of the proposed index in this paper are presented in Table 1. As the table shows, they generally deal with primary energy security of supply; as a result, they are unsuitable for specifically evaluating energy security in the power system. Due to the growing significance of the power sector, the present situation calls for the development of an index that focuses on the security of the supply of electrical energy.

Table 1. Reviewed studies on energy security.

Author/Institution	Name of Indicator/Index	Energy Source	Dimensions	No. of Indicators
Asia Pacific Energy Research Centre	Energy Security Indicators	Primary Energy	Availability; accessibility; acceptability; affordability	16
International Atomic Energy Agency	Energy Indicators for Sustainable Development	Primary Energy	Social; economic; environmental	31
World Energy Council	World Energy Trilemma Index	Primary Energy	Energy security; energy equity; environmental sustainability	35
Global Energy Institute	International Index of Energy Security Risk	Primary Energy	Global fuels; fuel imports; energy expenditures; price and market volatility; energy use intensity; electric power sector; transportations sector; environmental; R&D	29
Sovacool and Mukherjee	Energy Security Index	Primary Energy	Availability; affordability; technology development and efficiency; environmental sustainability; regulation and governance	20
Martchamadol and Kumar	Aggregated Energy Security Performance Indicator	Primary Energy	Social; economic; environmental	25
Kruyt et al.	Security of Supply Indicators	Primary Energy	Availability; accessibility; acceptability; affordability	22
Scheepers et al.	Supply/Demand index	Primary Energy	Essential energy demand needs; primary energy sources; energy conversions and transport	19
Jansen et al.	Long-term energy security indicators	Primary Energy	Diversification of energy sources in the energy supply; diversification of imports with respect to imported energy sources; long-term political stability in import regions; the resource base in regions of origin	4

For designing and structuring the proposed tool, recommendations presented in the Handbook on Constructed Composite Indicators (a guide developed by the OECD [26] for helping to compare and rank countries' performance in diverse areas) have been followed, such as industrial competitiveness and sustainable development. The suggested steps in the handbook that will be covered in this work are the development of a theoretical framework, data selection, imputation of missing data, normalization, and visualization of results. These steps, applied for the construction of the tool, are developed in Section 3 of this document.

3. Methodology

3.1. PSIx Structure

Due to the polysemic nature of the energy security concept [14], it can be covered from different approaches, which leads energy security to possess different defining factors that depend on the specific analysis to be conducted [31].

For this work, according to the definition stated in Section 2.1, six dimensions will characterize the energy security concept, namely availability; infrastructure; economy; environment; governance; and research, development, and innovation (R+D+i). In turn, each one of these dimensions possesses multifold indicators that are grouped into different categories. The structure of the PSIx is presented in Figure 1, where the dimensions, categories, and indicators are shown. Each dimension, category, and indicator possess an alphanumeric code identifying it.

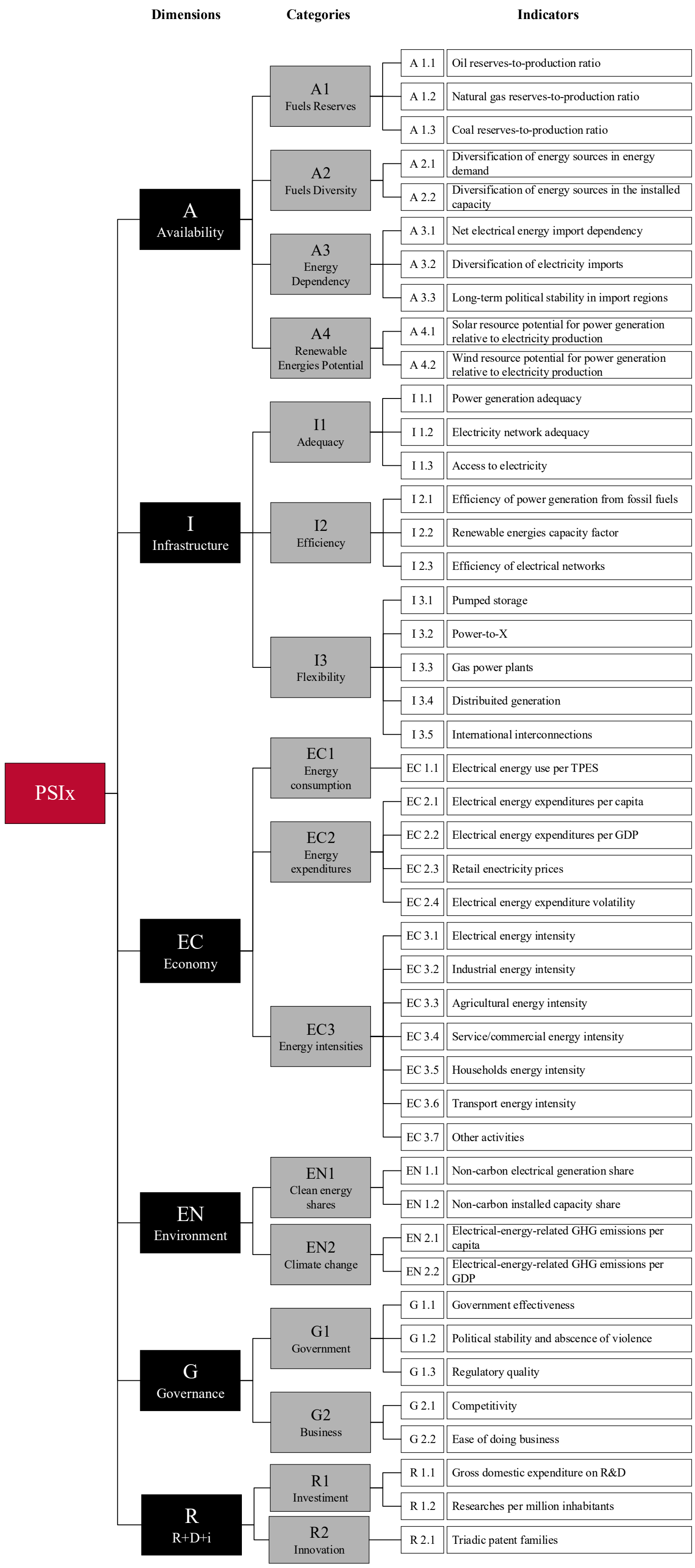

Figure 1. Power System Security Index (PSIx) structure.

3.1.1. Availability (A)

Availability is the dimension that appears the most in literature [1], and it is directly related to energy independence [32]. It refers to the geological existence of an energy resource within a determined area, as well as the degree of its replacement by alternative energy resources [33,34]. Moreover, this dimension covers the promotion of diversified energy technologies and energy sources [32]. Four categories constitute the availability dimension, namely fuel reserves, fuel diversity, energy dependency, and renewable energy potential:

- Fuel reserves (A1): This category covers the existence of a certain type of fuel relative to its production within national borders. This measure indicates the remaining years of the fuel at current production levels, as proposed by [1]. Since this category deals with the depletion rates of energy fuels, only conventional ones are included in it.
- Fuel diversity (A2): This category covers how different types of fuels are integrated in the electrical energy matrix, both in terms of installed capacity and consumed energy. Both conventional and renewable technologies are included in this category.
- Energy dependency (A3): The extent to which a country relies on alien sources to fulfill its energy needs is examined under this category. This series of measures is particularly important due to the fact that low reliability on energy import and a high diversity of energy import regions mean a lower risk for energy security [35].
- Renewable energy potential (A4): Under this category, the electricity production potential of solar and wind energy sources is measured.

3.1.2. Infrastructure (I)

This dimension measures the reliability of the power system, understood as the ability to access energy resources in order to provide a stable and uninterrupted supply of electrical energy; in some studies, it is referred to as accessibility [1,36]. Three categories make up the infrastructure dimension, namely adequacy, efficiency, and flexibility:

- Adequacy (I1): This category covers the sufficiency of power generation plants and electrical networks in guaranteeing access to electrical energy to the population. Additionally, the population with access to that energy is included.
- Efficiency (I2): This category deals with power generation plants as well as electrical networks, evaluating how these facilities are able to achieve their maximum productivity in providing electrical energy supply.
- Flexibility (I3): This category includes measures to allow the power system to cope with variability of generation and demand so that the system stays resilient, one of the greatest challenges the energy sector faces globally [37]. Flexibility encompasses energy storage, interconnections, and distributed generation facilities.

3.1.3. Economy (EC)

The economic dimension, or affordability, is intended to measure the price of energy for a series of technologies [34]. Its relevance resides in the fact that volatility and high energy prices have strong repercussions on the economy, the competitiveness of industries, and the balance of trade [35]. In this dimension, energy consumption, expenditures, and energy intensities are covered:

- Energy consumption (EC1): This category, along with the others, is focused on electrical energy. This measure is contrasted with the total primary energy consumption at the national level.
- Energy expenditures (EC2): This category includes measurements of how much is paid for electrical energy supply, which are contrasted to national income as well as the volatility of the prices of electrical energy.

- Energy intensities (EC3): This category is used as a proxy measure to indicate the efficiency of a country, considering the economic growth generated per unit of used energy. It will be, as proposed by [28], divided into sectors in order to have a benchmark of energy efficiency. This category is a particularly relevant issue for the scope if this work, since efficiency helps to improve energy security by reducing energy needs due to favorable changes in energy technologies, systems, and practices [13].

3.1.4. Environment (EN)

The impact on the environment, particularly in terms of GHG emissions, has become of great importance for energy policy makers in this century. This tendency has been translated into strict restrictions on conventional energy technologies, which has spurred several countries to transform their power systems. In this context, the aspects of the environmental dimension are intended to measure the repercussion of technologies on the environment to ensure that they do not represent a menace for sustainable development. Electricity shares of non-carbon sources and emissions associated with climate change are the categories of this dimension:

- Electricity shares (EN1): This category covers the share of non-carbon power plants in the total installed capacity on a national basis, as well as the share of their generation in the national production.
- Climate change (EN2): This category deals with GHG emissions per capita and per GDP as a measure of environmental impact of energy-related activities.

3.1.5. Governance (G)

Governments are responsible for effectively planning infrastructure development in order to ensure long-term energy security [13]. In addition, governments pledge to establish lasting relationships with other countries, making it possible to ensure the security of energy supplies in a politically stable scenario and representing another reason to consider governance as a fundamental component of energy security. Government and business environment shape this dimension:

- Government (G1): This category covers data related to governmental development. It includes the performance of the government, the political stability it produces, its regulatory quality, and its ability to ensure the absence of violence; all of these measures are necessary for the proper functioning of the energy system.
- Business (G2): This category considers the economic environment of the country since investments are the lifeblood of the energy system [38].

3.1.6. Research, Development, and Innovation (R)

Research, development, and innovation (R+D+i) play a central role in energy security since these improve the capacity to adapt and respond to disruption challenges [32]. This dimension has the aim of, as proposed by [39], measuring new energy technologies and the development of intellectual capital as a factor to assess energy security risks. The categories composing this dimension are investment and innovation:

- Investment (R1): This category is dimensioned by the variables of gross domestic expenditure on R+D+i and the proportional number of researchers in respect to the population.
- Innovation (R2): This category uses the triadic patent families of a country as a proxy variable to measure the innovation level of the country on an annual basis.

Appendix A presents the formulas and the objectives of each indicator, as well as the source from which information was obtained for the case of Argentina. Appendix B describes the variables contained in the indicators' formulas, jointly with their corresponding units.

3.2. Mathematical Model

As indicators use different measurement units and scales, it is necessary to create a frame that allows adding them up in the PSIx [13,30]. The application of the composed index will be carried out through gathering and subsequently comparing large amounts of data of different natures and from different sources, containing information which ranges from fossil fuel reserves to expenditures on R+D+i. Hence, it is necessary the establishment of rules that allow a precise management of such information.

3.2.1. Normalization

In order to make the values comparable in this work, two different forms of normalization are used depending on the nature of the variable to be measured: distance to a reference and historical evaluation. Both used formulas are mathematically identical, but they differ in terms of the definition of their denominators:

- Distance to a reference: The first normalization technique to be applied in the index consists of measuring the distance to a base value of an indicator. This distance can be applied either to a maximum or minimum figure, depending on the nature 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. Equation (1) illustrates this approach:

$$I_{qc}^{t} = \frac{x_{qc}^{t}}{x_{qb}^{t}} \tag{1}$$

  where 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} to the maximum value given by x_{qb}^{t}. Indicators scored under this method are those belonging to the A, I, EN, G, and R dimensions.

- Historical evaluation: The second normalization scope will be used to evaluate historical data, mainly related to economic indicators; this measurement will be performed through percentage of annual differences over years. This technique is described as follows:

$$I_{qc}^{t} = \frac{x_{qc}^{t}}{x_{qc}^{t_0}} \tag{2}$$

  where the normalized value of the qth indicator I_{qc}^{t} is given by the ratio of the indicator x_{qc}^{t} to the value of the same country but a different time, t_0. Indicators contained in the EC dimension are evaluated according to this second scope.

Within the availability dimension, reserves-to-production maximum ratios were established by the median value of international ratios in order to neglect extreme values. The maximum diversification of sources is obtained by assuming optimal conditions in the power system.

Adequacy values in the infrastructure dimension are taken from [40] and are set as 20% over the peak demand values. Efficiency in power plants and transmission lines is reflected directly as a percentage in the index.

The factors belonging to the economic dimension are evaluated by historical data. For establishing a time basis that serves as a benchmark for this dimension, the year 2002 was chosen. During this year, as detailed in Section 6, values corresponding to the most severe financial crisis in Argentina in its recent history are reflected. Taking this year as a basis establishes a common starting point for the evaluation of the development of the country in energy-related matters.

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

The data used in the governance dimension come from sources which present them as percentages, already measuring the performance of the nation within its different categories.

The R+D+i category's maximum values are obtained from the world-leading country for each indicator under this dimension.

The minimum value of each indicator is set to 0, while the maximum value is considered to be the unit, as well as the most desirable value for each indicator. In the case that the objective of an indicator is its minimization, according to what is indicated in Appendix A and in order to keep the value of 1 as the target, the value of this particular indicator is subtracted from one; therefore, it is ensured that the unit is the desired and maximum value in both cases, maximization and minimization. For the specific case of the EC dimension, the base year will be considered to be the unit, in order to track the performance of the country from this benchmark.

3.2.2. Weighting and Aggregation

The benchmarking frame developed by the normalization method makes it so that the weights of the indicators, as stated by [26], have a significant effect on the overall composite indicator. The selected model for the PSIx is the equal weight model, consisting of assigning the same value to the weight of each variable within the index. Since dimensions and categories possess different numbers of indicators, their weights are also different: A accounts for 22.22%, I for 24.4%, EC for 26.67%, EN for 8.89%, G for 11.11%, and R for 6.67% of the total weight of the composed index.

Two approaches have been applied for the aggregation of variables. The first one is a non-compensatory aggregation technique among indicators of different categories; this in order to avoid compensability of indicators belonging to categories of distinct dimensions. The second approach is taught to be applied to indicators within a specific category, and it consists of the geometric aggregation described by Equation (3):

$$CI_c = \prod_{q=1}^{Q} x_{q,c}^{w_q} \tag{3}$$

where $q = 1, \ldots, Q$ are the series of indicators $x_{q,c}^{w_q}$ with the assigned weight w_q and belonging to the same category. This method, geometrical aggregation, aims to incentive the enhancement of indicators with particularly low scores [26], a desirable characteristic for ensuring the security of energy systems.

4. The Case of Argentina

Argentina is the barycenter of the electrical market in the Southern Cone [41]. The current Argentinean electrical system depends heavily on hydrocarbons, but the country intends to reshape it through the fulfillment of ambitious targets, particularly the expansion of renewable energy sources and their decentralized integration to the electrical grid, as well as the implementation of several efficiency measures.

The last decade of the 20th century was characterized by favorable conditions for new power installations in Argentina, which include availability of natural resources, mature technology, a suitable regulatory frame, and a friendly macroeconomic environment [42]. These conditions drove the energy matrix of the country to become more dependent on thermal energy plants, particularly those using natural gas as fuel, relegating nuclear and renewable energies to a place of lesser importance. Moreover, one of the most severe economic crises in recent Argentinian history took place between years 2001 and 2002, leading to an abrupt change in energy consumption, all within a frame established by a government regime with an abruptly different outlook towards energy production compared to that of the one presided by Mauricio Macri.

The austral country has plenty of fossil and renewable energy resources suitable to be exploited, both conventional and unconventional ones. Argentina possesses very important proven reservoirs of fossil fuels, namely 2017 million barrels of oil and 355 billion cubic meters of natural gas [43], placing the country as one of the leaders in the Latin America in terms of energy potential.

Natural gas is the pillar of the Argentinean energy system; as such, the country intends to expand its gas ducts, both nationally and internationally, in order to increase its capabilities of gas trade. Additionally, the federal government, in cooperation with the local governments, plans to develop unconventional gas field projects, which will importantly increase the country's availability of this fuel [44]. This dependence of the country on natural gas leaves an important area of improvement for enhancing diversification of the energy system.

Argentina has electrical interconnections with most of its neighbors, besides several binational hydropower plants. In 2017, the country exported 69.2 GWh, of which 69.1 GWh went to Brazil; the rest was exported to Chile. Electrical imports amounted to 733.9 GWh, from which 474.0 GWh were imported from Uruguay, 153.6 GWh from Brazil, 70.4 GWh from Paraguay, and 36.9 GWh from Chile [45].

The country possesses very advantageous conditions for the development of renewable energy installations, particularly solar and wind power plants. The southern part of the country has some of the better wind power densities in the continent for electricity production, while the solar irradiation in the northeast is ideal for generation of electricity from photovoltaic installations.

According to the standards proposed by [40], the infrastructure of the electrical system is considered to be adequate, both in terms of the installed capacity and the electrical network; its efficiency is similar to other countries in the region [46]. Moreover, the country has implemented the necessary measures to achieve a very high percentage of people with access to electricity: 98.79% [46].

Driven by the local energy transition, particularly by the introduction of renewable energies and their non-homogenous nature, it is fundamentally necessary to enhance the flexibility of the power system. Several measures can be implemented for this purpose, such as energy storage, power-to-x, the expansion of gas-fueled power plants, the broadening of distributed generation, and the reinforcement of national and international interconnections.

Argentina has a strong presence of gas-fueled power plants, including plants based on combined cycle, turbo-gas, and turbo-vapor technologies. Besides natural gas, most of the installed plants allow the use of fuel oil or gas oil for electricity generation, increasing the system's flexibility even further. As previously stated, international electrical interconnections play an important role in the day-to-day supply of electricity in the country. Thus, the Argentinean power system's flexibility is strong, but there is still room for improvement in a high renewable energy penetration scenario.

The Argentinean federal administration is committed to improving the efficiency of energy consumption; with this aim, it has created a series of programs with which it is expected that the country will reduce its final energy consumption by 5.9% by the year 2025, compared to the current tendency [44].

Economically, the country has gone through adverse conditions during the last decades. The current level of inflation is 43.7% [47], and the GDP is expected to contract by 1.82% in 2019 [48]. The complicated economic situation is extended to the prices of energy, which have increased jointly with increases in the costs of energy production, directly associated to foreign currencies. Despite the economic stumble, energy intensities have had a mixed development. Agricultural, commercial, and transport sectors have improved compared to the year 2009, while industrial, household, and other activities have decreased their electrical energy productivity.

The current federal government addresses the promotion of renewable energies in the country as a strategic objective for mitigating climate change and improving the nation's energy security [49]. In this context, the government has issued the long-term target of achieving a level of 20% of electrical energy consumption coming from renewable sources by 2025 [50]; the government is also committed to promoting distributed generation of energy produced from renewable sources and its integration to the electrical network [51].

The governance and business environment dimensions are, in general and according to international entities (such as [52,53]), large areas of opportunity in the country. The middling development in these dimensions is not endemic for Argentina, but it is a common trend in the region. Political stability, control of corruption, and government effectiveness are some aspects that the country needs to improve in order to create an adequate environment that attracts investments and boosts the national economy in general and the energy industry in particular.

Finally, R+D+i in Argentina are currently in disadvantageous conditions, partially due to economic reasons which have shrunk their advancement, but also because they have not been established as priorities under the recent administrations. Just like the dimensions of governability and business environment, the country could improve R+D+i in order to create favorable conditions for attracting investment and get qualified personnel for the development and implementation of energy projects, which would, in turn, translate into improvements of national energy security.

5. Results

The outcomes of each of the indicators after applying the PSIx tool to the case of Argentina are summarized in Tables 2 and 3. Following the background described in Section 3.2.1, the year 2002 was chosen as a reference for contrasting the current status of the security of the power system of the country and for tracking its development.

Table 2. Outcome of indicators in the Argentinean case.

Dimension	Category	ID	Indicator	2002	2017	Change
Availability	Fuel reserves	A1.1	Oil reserves-to-production ratio	0.41	0.47	16.01%
		A1.2	Natural gas reserves-to-production ratio	0.65	0.54	−17.07%
		A1.3	Coal reserves-to-production ratio	1.00	1.00	0.00%
	Fuel diversity	A2.1	Diversification of energy sources in electrical energy demand	0.44	0.37	−15.27%
		A2.2	Diversification of energy sources in the electrical installed capacity	0.38	0.40	5.33%
	Energy dependency	A3.1	Net electrical energy import dependency	0.90	0.93	3.27%
		A3.2	Diversification of electricity imports	0.31	0.71	128.19%
		A3.3	Long-term political stability in import regions	0.21	0.55	157.38%
	Renewable energy potential	A4.1	Solar resource potential for power generation relative to electricity production	1.00	1.00	0.00%
		A4.2	Wind resource potential for power generation relative to electricity production	1.00	1.00	0.00%
Infrastructure	Adequacy	I1.1	Power generation adequacy	1.00	1.00	0.00%
		I1.2	Electricity network adequacy	0.71	0.87	21.93%
		I1.3	Access to electricity (% of population)	0.96	0.99	2.79%
	Efficiency	I2.1	Efficiency of power generation from fossil fuels	0.65	0.68	4.62%
		I2.2	Renewable energy capacity factor	0.36	0.42	16.09%
		I2.3	Efficiency of electrical networks	0.85	0.85	0.14%
	Flexibility	I3.1	Pumped storage	1.00	1.00	0.00%
		I3.2	Power-to-X	0.00	0.27	100.00%
		I3.3	Gas power plants	1.00	1.00	0.00%
		I3.4	Distributed generation	0.00	0.18	100.00%
		I3.5	International interconnections	1.00	1.00	0.00%
Economy	Energy consumption	EC1.1	Electrical energy use per total primary energy consumption	1.00	1.00	0.00%
	Energy expenditures	EC2.1	Electrical energy expenditures per capita	1.00	1.00	0.00%
		EC2.2	Electrical energy expenditures per GDP	1.00	1.00	0.00%
		EC2.3	Retail electricity prices	0.55	0.66	19.24%
		EC2.4	Electrical energy prices volatility	0.34	0.96	180.36%
	Energy intensities	EC3.1	Electrical energy intensity	1.00	1.00	0.00%
		EC3.2	Industrial energy intensities	1.00	1.00	0.00%
		EC3.3	Agricultural energy intensities	1.00	0.56	−43.54%
		EC3.4	Service/commercial energy intensities	1.00	1.00	0.00%
		EC3.5	Household energy intensities	1.00	0.55	−45.07%
		EC3.6	Transport energy intensities	1.00	1.00	0.00%
		EC3.7	Other activities	1.00	1.00	0.00%
Environment	Electricity shares	EN1.1	Non-carbon electrical energy production share	0.56	0.35	−37.47%
		EN1.2	Non-carbon installed capacity share	0.45	0.37	−17.92%
	Climate change	EN2.1	Electrical-energy-related GHG emissions per capita	1.00	1.00	−0.06% [1]
		EN2.2	Electrical-energy-related GHG emissions per GDP	1.00	1.00	0.00%

Table 2. *Cont.*

Dimension	Category	ID	Indicator	2002	2017	Change
Governance	Government	G1.1	Government effectiveness	0.47	0.60	25.64%
		G1.2	Political stability and absence of violence/terrorism	0.22	0.53	140.00%
		G1.3	Regulatory quality	0.19	0.41	113.26%
	Business	G2.1	Competitiveness index	0.31	0.57	87.43%
		G2.2	Ease of doing business index	0.58	0.58	0.22%
R+D+i	Investment	R1.1	Gross domestic expenditure on R&D	0.09	0.13	47.28%
		R1.2	Researchers per million inhabitants (per 1000 employed)	0.12	0.18	49.30%
	Innovation	R2.1	Triadic patent families	0.00	0.00	17.78%

[1] Changes are not shown in the indicator due to decimal places.

Table 3. PSIx score in the Argentinian case.

ID	Category	2002	2017	Change	ID	Dimension	Weight	2002	2017	Change	Score 2002	Score 2017
A1	Fuel reserves	0.26	0.25	−3.79%	A	Availability	0.22	0.00	0.01	420.73%	0.29	0.02
A2	Fuel diversity	0.17	0.15	−10.75%								
A3	Energy dependency	0.06	0.36	506.48%								
A4	Renewable energy potential	1.00	1.00	0.00%								
I1	Adequacy	0.68	0.86	25.33%	I	Infrastructure	0.24	0.14	0.21	52.42%		
I2	Efficiency	0.20	0.24	21.62%								
I3	Flexibility	0.00	0.05	100.00%								
EC1	Energy consumption	1.00	1.00	0.00%	EC	Economy	0.27	1.00	0.02	−98.36%		
EC2	Energy expenditures	1.00	0.05	−94.71%								
EC3	Energy intensities	1.00	0.31	−68.98%								
EN1	Electricity shares	0.25	0.13	−48.68%	EN	Environment	0.09	0.25	0.13	−48.71%		
EN2	Climate change	1.00	1.00	−0.06%								
G1	Government	0.02	0.13	543.06%	G	Governance	0.11	0.00	0.04	1108.02%		
G2	Business	0.18	0.33	87.86%								
R1	Investment	0.01	0.02	119.88%	R	R+D+i	0.07	0.00	0.00	158.99%		
R2	Innovation	0.00	0.00	17.78%								

In Table 2, the quantitative results of the indicators are reflected, as is their change between the years 2002 and 2017. Table 3 shows the results for categories and dimensions of the index, also contrasting the evolution of the country in the selected time frame, as well as the corresponding weights of the dimensions and the PSIx scores.

Argentina shows mixed values in the different covered dimensions, categories, and individual variables.

In terms of the indicators, the largest improvements are observed in A3.2 and A3.3 (both related diversification of imports), I3.4, and G1.2 and G1.3 (both related to governability). On the other hand, EC2.3, EC2.1, and EC3.5 are the indicators that present the largest setbacks in the analyzed time frame for Argentina.

The category with the largest improvement is G1, which is followed by A3, Meanwhile, EC2 is the category with the weakest development.

In dimensions, the country clearly scores higher in areas such G and A, with important improvements also seen in I and R. In contrast, EC and EN are the dimensions that present a negative behavior for the country during the covered time.

6. Discussion

Within the A dimension and thanks to its large energy resources, the country presents an outstanding development. Both fossil fuel basins and renewable energy potential remarkably strengthen the energy security of Argentina. In spite of notable outcome numbers for the diversification of energy sources, this is an area in which the country could make greater improvements. This is due to its dependence on natural gas for electricity generation, which shrinks its diversity of fuels for electricity production. The abundance of energy resources also translates to a low dependency on electrical energy imports. The country presents an outstanding result for renewable energy potential thanks to its very favorable conditions for solar and wind sources.

Both installed capacity and the electric transport network are adequate for the country's energy needs according to the standards proposed by [40], which is also reflected in the high percentage of the population with access to electrical energy. Power plants and of electrical networks present appropriate levels of efficiency when compared to other countries in the region. Moreover, adequacy and efficiency of the electrical infrastructure have been improved during the covered time frame. On the other hand, the flexibility of the system can still be boosted by deploying power-to-x installations and increasing distributed generation, a measure that the current government is already working on through different public policies. Gas-fueled power plants have been included in the PDIx as sources of flexibility in the power system as a specific indicator, not only because they are highly compatible with renewable energy sources, but also because such plants currently generate most of the electricity in Argentina; consequentially, the electricity market price is determined by the behavior of the natural gas price. In a further stage of development, more sources could be incorporated.

The economy dimension is the one which has suffered the greatest shrinkages. One of the main reasons that explain this situation is that prices of electricity in Argentina are suffering a constant increase caused by subsidy cuts, at a time when national GDP has not been increased considerably, leading indicators of expenditures on electricity to suffer an important downturn. Energy intensities, in general, also show a setback, which is partially also due to the contraction of the national GDP, unable to be overcome by efficiency measures conducted to reduce energy consumption. Exemptions to this tendency are industrial, commercial, and transport energy intensities.

Since the energy mix is dominated by natural gas and hydropower plants, GHG emissions of the country are relatively low compared to those of other expanding economies. Nevertheless, the expansion of gas-fueled power plants translates to more emissions than those associated to the use of renewable technologies. In this context, a 15% reduction of GHG emissions in a business-as-usual scenario towards 2030 is the current national objective, and that reduction can be augmented to a 30% reduction if necessary foreign aid is provided to the country [54].

Argentina's governability is placed in an improvable position, since it scores 0.6, 0.5, and 0.4 in the government effectiveness, political stability, and regulatory quality indicators, respectively. It is notable, however, that the country has achieved enormous progress in each category, improving by 26%, 140%, and 123% in the government effectiveness, political stability, and regulatory quality indicators, respectively, compared to year 2002 [52]. This has allowed the country to present an increase of 1108.02% in the G dimension. It should be noted that the geometric aggregation system gives more importance to improvements on weak indicators, which is a reason that allows the country to have such a high score in governance. It must be noted that the Argentinian case is atypical. In 2002, the country was in an unprecedented political transition, in which several people occupied the presidency within a few days; besides the resulting external debt, this brought the country to a peak of governance instability, a situation that was overcome by 2017.

The business environment of Argentina also represents an area for improvement, since the country scores 57.7 out of 100 in the Global Competitiveness Index [53] and 58.8 out of 100 in the Ease of Doing Business Ranking [55].

For the year 2016, the country expended 0.53% of its GDP expenditures on R+D+i, reported 3.0 researchers per 1000 employed people, and summed 10.9 triadic patent families [48]. Despite the fact that these numbers position Argentina over its neighboring countries in the R dimension, internationally the country can still improve in this matter.

The strengths and weaknesses of Argentina are therefore clear, while its large energy resources and solid infrastructure represent its most valuable assets in energy terms, the economic and governability spheres are the largest areas of opportunity of the country.

Despite the fact that the PSIx has been thought of as a tool applicable to different economies, some limitations have been identified for achieving such purpose under certain circumstances. The selected method of equal weights assigns the same importance to all the indicators and therefore establishes the same importance to categories with a large number of variables, which might be translated into a disequilibrium among dimensions. Benchmark values for determining maximum values in the A dimension represent room for improvement in the index design, since these values have been selected arbitrarily. Furthermore, for different economies, some dimensions or categories could be of particular interest for their national energy security, but such conditions have not been considered in the present study.

7. Conclusions

Different nations around the world tend to adapt their systems according to their own needs, interests, and possibilities. Nevertheless, there are trends that extend to all regions in the planet, with energy transitions being the most transcendent one taking place in the today's energy field. The central measures of this transformational shift for energy systems include their decarbonization and the efficient use—and production—of energy, which have driven the power system to become a key infrastructure in modern nations. Therefore, ensuring the security of the supply of electrical energy is crucial for achieving sustainable development.

With the aim of proposing a framework addressed to help policy makers in their task of issuing strategies focused on reaching sustainable development through energy security enhancement, an evaluation tool, based on a composite indicator, has been developed and presented in this work. PSIx offers the possibility to assess energy security in the power system from a multidimensional approach, covering the spheres of availability, infrastructure, economy, environment, government, and R+D+i. These dimensions, to which several indicators are assigned and are, in turn, grouped into different categories, allow the identification of areas where the country in question develops well, and areas where room for improvement exists. By these means, the PSIx constitutes a comprehensive frame in which strategies aimed to enhance energy security in the power system can be evaluated according to their effectiveness for achieving that purpose.

As a developing economy with plenty of natural resources, albeit passing through an adverse economic situation, Argentina performs particularly well in the availability and infrastructure dimensions, helped by its abundant indigenous energy resources as well as a diversified and interconnected electrical system. The economic dimension is the weakest point of the country since, due to the contraction of the GDP, national energy productivity has been harmed in several areas, being unable to improve it despite the implemented efficiency measures. Governance and R+D+i are areas in which Argentina has been weakly developing, making it necessary to enhance them in order to attract financing for fulfilling energy projects that facilitate the national energy transition.

The current federal administration of Argentina has the aim of transforming the national energy system while boosting the usage of local sources. Despite the economic obstacles, the local energy transition towards a greener and more secure system continues, representing a key objective in the overall goal of sustainable development. Considering that the country is at a political crossroad, it is of fundamental importance for it to keep its achievements in energy policy on track.

Future work will include a statistical analysis incorporating more economies to the index to allow the correlations among indicators to be identified and the covered countries to be ranked according to their effectiveness in ensuring energy security in their electrical systems.

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Appendix A

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

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

Appendix B

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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