

Review

Electricity Supply Regulations in South America: A Review of Regulatory Aspects

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Abstract: The quality of electricity is one of the most discussed issues in the regulatory context, structured by guidelines that allow the assessment of efficiency in electricity supply. Regarding electricity distribution systems, it is essential to highlight the aspects associated with the definition of continuity indicators to measure the service provided by the utilities. The parameters used to calculate the indicators are set by specific agencies in each country based on studies and their characteristics. With the growth in demand for electricity, debates associated with reducing greenhouse gas emissions in the atmosphere, and the increase in Distributed Energy Resources (DERs) connected to the grid, a new trend related to the energy supply is verified. Given these new scenarios, this paper presents a literature review in the regulatory field of existing distribution systems in South American countries. The research proposes to analyze, compare, and expose the current models to evaluate their methods and indicators, including a complete case study in Brazil. This paper seeks to illustrate and point out perspectives, challenges, and future perspectives through the collected and analyzed data.

Keywords: regulatory aspects; electrical power quality; current models; continuity indicators; electric power distribution systems; South America



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1. Introduction

Electricity access provides several benefits to society, since it benefits human development, reduces social inequality, stimulates industrialization, and allows global access to new technologies for health, communication, and education [1,2]. However, it should be noted that electricity supply in many developing countries could be rationed, limited, unstable, or characterized by poor quality [3].

The increasing of power demand requires special attention in terms of regulation, since consumers are substantially dependent on electricity, thus demanding a continuous and high-quality supply [4,5]. Meanwhile, in several countries, energy utilities are natural monopolies, and in this environment, economic regulation is the key to ensure cost efficiency and supply quality in the power distribution systems [6]. In general, this cost is usually based on benchmark models, which evaluate the utility performance and classifying it into a set of variables [7–9].

Regulatory agencies face a great challenge in finding a balance between the quality of supply and its costs, and surveys are usually applied to verify if the propensity to pay for quality improvement is compatible with the increase in costs incurred by the utility [10]. When discussions about service quality are brought up, it is possible to advance by proposing or updating existing evaluation criteria. Furthermore, such discussions aim

to highlight the regulatory limits and offer elements to rank utilities performance [11]. In particular, low power quality, as a consequence of interruptions in supply, can constitute a barrier to productive development, raising the costs, and aggravating the scenario when there are negative effects on the population's quality of life [12].

In this context, we propose reviewing the regulatory aspects of electric power quality in South American distribution systems. Since South America is a territory occupied by 12 countries, peculiarities such as culture, population, and habits, among other issues, could, directly and indirectly, affect how to model a power quality assessment. This type of study can enrich discussions about improving current models worldwide. The aim of the paper is to present, analyze, and compare regulatory models linked to the quality of service. Within these models, we seek to illustrate the indicators, their limits, and financial compensation, which are associated with the quality of electricity supply. Based on the research carried out, the aim is to point out challenges and future perspectives. It should be noted that the study period elaborated in this work covers laws and regulatory documents from 1964 to articles and information on service quality in 2022. Countries such as Argentina, Brazil, Chile, Colombia, Ecuador, and Uruguay have more current data, while Bolivia, Guyana, Paraguay, Peru, Suriname, and Venezuela present older information.

This paper is structured as follows. Section 2 presents an overview of the electricity distribution sector in South America. In Section 3, the fundamental issues assessed in regulatory models in South American countries are formalized. Section 4 summarizes the publicly available results of power quality performance of those countries. A Brazilian case study is presented in Section 5. Section 6 aims to discuss future directions for researches, and Section 7 ends with the main conclusions.

2. Overview of the Electricity Distribution Sector in South America

The regulatory aspects considered to evaluate power quality service directly affect the results of power systems performance. Among the inherent characteristics, it can be verified whether the service is public or private, how many utilities exist, and the influence of international companies. In addition to these points, it is worth highlighting issues related to the existence of service quality metrics, the level of consumer satisfaction, the amount of investments in the network, the profit achieved by the utilities, initiatives aimed at research, and the dissemination of data on the performance of distributors. The search for this information aims to obtain an overview of the electricity distribution sector in South America, to highlight similarities, differences, and peculiarities between the analyzed countries, focusing on the quality of electricity.

2.1. Argentina

In Argentina, the regulatory agency is the National Electricity Regulatory Entity (ENRE), which controls companies in this sector by requiring compliance with regulatory frameworks and concession contracts in the areas of generation, transmission, and distribution [13]. The country still has a set of provincial regulators, in addition to the federal regulator ENRE, which, although they have established their own regulations, are based on federal regulation. Tolerance values are different in each province, as there are different service markets, due to density characteristics, type of installations, and geography, among other factors [14].

Regarding the energy distribution system, Argentina is supplied by private and public companies, provincial entities, cooperatives, and other entities that provide services to final consumers, where the number of distributors is around 26 [15,16]. Electric power quality encompasses service aspects (frequency and duration of interruptions), products (voltage level and disturbances), and commercial (response times to connect new users, issuance of invoices, claims for billing errors, and restoration of supply due to non-payment) [17]. Every six months, duration and frequency indicators are updated, considering the information on contingencies related to the network typology and the commercial information of users [18].

2.2. Bolivia

The Electricity and Nuclear Technology Supervision Authority (AETN) is the main promoter of these energy inputs in Bolivia, whose mission is to control, supervise and regulate activities in the country [19]. As in Argentina, the Bolivian distribution sector is made up of public and private companies, and the country is made up of approximately seven distributors [16].

The Bolivian Electricity Sector Law, enacted on 21 December 1994 through Law N°1604 and its regulations, establishes a series of ordinances for the distribution companies of the public electricity service, related to the quality of the electricity service. In the same ordinance, the law defines by resolution the standard indicators of quality of service that distributors must meet. AETN has issued resolutions establishing the permissible limits and supply reliability indicators for distribution companies. Thus, they must meet supply quality criteria in terms of duration and frequency of interruptions, as well as product and commercial quality [20–22].

2.3. Brazil

In Brazil, the National Electric Energy Agency (ANEEL) is the autarchy under a special regime linked to the Ministry of Mines and Energy (MME), which is responsible for regulating the Brazilian electricity sector [23]. The distribution sector is composed of 60 distributors, which are both public and private [16]. The parameters associated with the quality of electricity are established in the Electricity Distribution Procedures in the National Electric System (PRODIST), in its module 8, where the guidelines relating to product, service, and commercial quality are presented [24].

The model linked to the definition of continuity indicators and limits for the quality of electricity in the Brazilian context is based on studies comparing the performance of energy distributors to defined goals [25,26]. Currently, the indicators and their limits are established by the methodology presented in Technical Note N°102/2014, which was presented at the ANEEL Public Hearing N°29/2014 [27]. The limits are considered for monthly, quarterly, and annual periods, which, if violated, imply the payment of financial compensation to the consumer units, by the utilities, and the calculation of the compensations is defined in module 8 of PRODIST [24].

2.4. Chile

Chile's Ministry of Energy represents the maximum collaboration organ of the President of the Republic with the energy sector. It is responsible for drawing up and coordinating plans, policies, and regulations for the sector, liaising with the President of the Republic from the National Energy Commission (CNE), the Superintendence of Electricity and Fuels (SEC), and the Chilean Nuclear Energy Commission (CChEN) [28–30].

The Chilean electricity distribution system is made up of 25 companies, all in the private sector [16]. The CNE establishes, through technical standards, the requirements associated with the quality of electricity and the process of compensation for violations in supply. The General Electric Services Law establishes the technical, safety, coordination, quality, information, and economic aspects of the sector. In particular, the main objective is to establish service quality standards for distribution systems with respect to product, supply, and commercial quality [31]. The CNE also defines the procedures, methodologies, and application conditions for the payment of compensation to end users for the unavailability of energy supply, in accordance with the provisions of article 72°-20 of the Law on the Regulation of Compensations [32].

2.5. Colombia

The regulation of the electricity sector in Colombia is linked to its regulatory agency, defined by the Energy and Gas Regulation Commission (CREG), which is dependent on the decisions of the Ministry of Mines and Energy (MME). The country is one of the cases in which regulatory institutions operate with independent funding, autonomous management,

and legislation separate from the rules that determine the civil service; however, they are subject to the administrative and formal approval of the Minister [30,33]. Among its functions, it is worth highlighting the regulation of monopolies in the provision of public services, promoting competition between public service providers, preparing bills to submit to the government's consideration and recommending the adoption of normative decrees that may be necessary [34].

There are 28 energy distribution companies in Colombia, which belong to the public and private sector [16]. Regarding the concept of quality, the CREG regulation establishes the categories of product, service and marketing quality, but for the distribution sector, only the category related to the service provided is addressed [35]. The regulatory methodology for assessing the quality of service is based on the assessment of average and individual quality indicators. In addition, continuity indicators are complemented with incentive and compensation mechanisms for the operator and users, and the Superintendency of Residential Public Services (SSPD) constantly monitors these indicators and ensures that they are within the limits defined by current regulations [36,37].

2.6. Ecuador

The Ecuadorian electricity sector is regulated by the Agency for the Regulation and Control of Energy and Non-Renewable Natural Resources (ARCERNNR), which was created in 2020 by the merger of several agencies, including the Electricity Regulation and Control Agency (ARCONEL) which carried out the actions aimed at energy quality [38]. ARCERNNR aims to control activities associated with public electric energy services and has as one of its objectives, to monitor non-renewable energies and natural resources for the benefit of economic development [39,40].

In the field of energy distribution, Ecuador has 11 companies associated with the public and private sectors [16]. The quality of electricity supply takes into account the product, technical, and commercial aspects [41]. The distribution service quality indices defined in the regulation include measurement and evaluation mechanisms, in addition to compliance with established limits [42].

2.7. Guyana

Guyana's electricity sector is regulated by the Guyana Energy Agency (GEA), which has as some of its functions monitoring the performance of the energy sector, disseminating information on management, developing energy policies, and conducting research associated with new energy sources [43,44]. Guyana Power & Light (GPL) is a public energy company, which is primarily and solely responsible for the areas of generation, transmission, and distribution of electricity for residential, commercial, and industrial customers in the country [45,46].

As far as the electricity distribution sector is concerned, the quality of supply has GPL as its main analysis organ, which is responsible for operating standards and performance targets. The company measures the quality of supply by regulating the voltage and frequency of the network, in addition to indicators of frequency and duration of interruptions [47].

2.8. Paraguay

The National Electricity Administration (ANDE) is an autonomous institution, decentralized from the public administration, which follows the regulations contained in Law N°966 and its subsequent expansion in Law N°976 [48]. One of the objectives of the institution is to design, build, and acquire works for the generation, transmission, and distribution of electric energy, including facilities and goods necessary for the normal operation of electric services in Paraguay [49,50].

The Paraguayan electricity distribution system assesses the quality of service through indicators of frequency and duration of interruptions [51]. The analysis of supply patterns

takes into account the set of technical, product, and commercial characteristics inherent to the criteria required by consumers and competent administration organs [52].

2.9. Peru

In Peru, the Supervisory Agency for Investment in Energy and Mining (Osinerghmin) is the organ body responsible for regulating and monitoring compliance with the legal provisions of companies in the electricity, hydrocarbons, and mining sectors [53]. The Ministry of Energy and Mines edited the norms for the development of activities in the areas of generation, transmission, distribution, and commercialization of electric energy, which have among them the Procedure N°686-2008-OS/CD, which aims to establish criteria aimed at technical service quality [54].

Peru has 23 companies in the electricity distribution sector, which are associated with both the private and public sector [16,55]. The Technical Standard for the Quality of Electrical Services (NTCSE), approved by the Supreme Decree N°020-1997-EM, establishes the minimum quality levels to be met in the country for urban areas, covering the areas of generation, transmission, and distribution of energy electricity, while Resolution N°016-02008-EM/DGE establishes the Technical Quality Standard for Rural Electric Services (NTCSER), associated with minimum levels of quality in rural areas [56,57]. Quality is evaluated in terms of the product (voltage, frequency and disturbances), supply (interruptions), commercial (treatment, attention, and measurement accuracy by customers), and public lighting [58].

2.10. Suriname

Suriname has the Ministry of Natural Resources and Energy, which is the organ responsible for the generation and distribution of electricity [59]. Among its attributions, the continuous availability of reliable and affordable electricity stands out. The ministry works together with Energy Companies Suriname (EBS), responsible for energy supply in urban areas, Electricity Supply Service (DEV), responsible for domestic electricity supply, among other institutions linked to water and mining [60].

Electricity distribution in Suriname is carried out only by EBS, which is also responsible for production and transmission and is a company belonging to the state [61]. With the passing by the Surinamese government of the Energy Authority of Suriname (EAS) Law and the Electricity Law in March 2016, the EBS underwent regulatory changes [62–64]. The quality of supply is evaluated by indicators of duration and frequency of interruptions [65].

2.11. Uruguay

In Uruguay, the Regulatory Unit for Energy and Water Services (URSEA), created by Law N°17,598 in 2002, sought to extend regulatory competencies beyond the electricity sector, which included petroleum-derived fuels, gas, drinking water, and sanitation [66,67]. The creation of URSEA complemented the activities previously carried out by the Electric Power Regulatory Unit (UREE), created in 1997 [68].

The Uruguayan energy distribution sector is associated with the national administration of Power Plants and Electric Transmissions (UTE), a public company that is also responsible for the activities of generation, transmission, and commercialization of electricity [69]. Distribution is controlled by the Regulation of Quality of Distribution of the Electric Power Service (RCDSEE), which is regulated by URSEA [70]. The quality of supply involves service (duration of interruptions), commercial aspects (cuts, re-connection, billing, and complaints), and product (voltage level). To measure these aspects, indicators that must meet defined goals are used. In case the targets are not met, compensation will be paid by the UTE as discounts to affected consumers [71].

2.12. Venezuela

Article 28 of the Organic Law of the Electricity Sector of Venezuela defines that the National Electric Corporation (CORPOELEC), an entity attached to the Minister of Popular Power for Electric Energy (MPPEE), is the provider of the regulation service in the electrical area and of its quality in the sectors of generation, transmission, distribution, and commercialization throughout the national territory [72,73]. It is up to CORPOELEC to determine the standards for measuring the quality of electrical service, including the recording of failures and the compensation to customers affected by them [74].

Venezuela's sole electricity distributor is CORPOELEC, an entity belonging to the public sector. Service quality is defined in articles 2 and 3 of the Quality Standards for the Electricity Distribution Service (NCSD), where the evaluation areas are divided into product quality (voltage wave level and disturbances), service (outages of the electrical flow according to frequency and duration), and commercial aspects (meeting users' requirements and claims) [75–77].

2.13. Summary of the 12 Countries

Through an overview of regulatory organs and electricity distributors in South American countries, both specific and similar characteristics are verified. Table 1 seeks to illustrate a summary of the main points observed in this section.

Table 1. Review of regulatory organs and distributors in South America.

Country	Regulatory Organ	Number of Utilities	Ownership of Utilities
Argentina	ENRE	26	mixed
Bolivia	AETN	07	mixed
Brazil	ANEEL	60	mixed
Chile	CNE	25	private
Colombia	CREG	28	mixed
Ecuador	ARCERNNR	11	mixed
Guyana	GEA	01	public
Paraguay	ANDE	01	public
Peru	Osinergmin	23	mixed
Suriname	EBS	01	public
Uruguay	URSEA	01	public
Venezuela	CORPOELEC	01	public

3. Regulatory Models in South America

In order to discuss the current metrics used to evaluate the power quality supply in all 12 countries, this section details the duration and frequency indicators proposed to analyze power supply interruptions, such as their current regulatory limits and the criteria used to estimate financial compensation to the consumers.

3.1. Duration and Frequency Indicators

Each country of South America presents a different regulatory model, and thus different names were found for indicators used to calculate the duration and frequency of power supply interruption as follows:

- Argentina [14]:
 - Total Interruption Time per Transformer (TTIT);
 - Total Interruption Time per Installed rated kVA (TTIK);
 - Average Frequency of Interruption by Transformer (FMIT);
 - Average Interruption Frequency per installed nominal kVA (FMIK).
- Bolivia [20]:
 - Total Interruption Time in LV (T_s);
 - Individual Total Time of Interruptions in MV and HV (T);
 - Average Interruption Frequency in LV (F_s);

- Individual Interruption Frequency in MV and HV (F).
- Brazil [14,24]:
 - Individual Interruption Duration per Consumer Unit or Connection Point (DIC);
 - Maximum Duration of Continuous Interruption per Consumer Unit or Connection Point (DMIC);
 - Duration of the Individual Interruption on a Critical Day per Consumer Unit or Connection Point (DICRI);
 - Equivalent Interruption Duration per Consumer Unit (DEC);
 - Individual Interruption Frequency per Consumer Unit or Connection Point (FIC);
 - Equivalent Interruption Frequency per Consumer Unit (FEC).
- Chile [31]:
 - Customer Interruption Time (TIC);
 - Individual Interruption Frequency per Consumer Unit or Connection Point (FIC).
- Colombia [14,78]:
 - Duration of Service Interruptions (DES);
 - System Average Interruption Duration Index (SAIDI);
 - Interruption Duration for the User (DIU);
 - Frequency of Service Interruptions (FES);
 - System Average Interruption Frequency Index (SAIFI);
 - User Interrupt Frequency (FIU).
- Ecuador [39,41,79]:
 - Total Interruption Time per installed rated kVA (TTIK);
 - Individual Interruption Duration per Consumer Unit or Connection Point (DIC);
 - Average Interruption Frequency per installed nominal kVA (FMIK);
 - Individual Interruption Frequency per Consumer Unit or Connection Point (FIC).
- Guyana [47]:
 - System Average Interruption Duration Index (SAIDI);
 - System Average Interruption Frequency Index (SAIFI).
- Paraguay [51]:
 - Equivalent Power Interruption Duration (DEP);
 - Equivalent Power Interruption Frequency (FEP).
- Peru [56–58]:
 - Total Weighted Duration of Interruptions per Client (D);
 - Individual Interruption Duration per Consumer Unit or Connection Point (DIC);
 - Total Number of Interruptions per Client per Semester (N);
 - Number of Interruptions per Consumer (NIC).
- Suriname [65]:
 - System Average Interruption Duration Index (SAIDI);
 - System Average Interruption Frequency Index (SAIFI).
- Uruguay [14,71]:
 - Total outage time of a consumer (T_{ci});
 - Maximum duration of interruption of a consumer (D_{max_i});
 - Total average time of interruption per consumer in a Group (T_{ca});
 - Interruption frequency of a consumer (F_{ci});
 - Average frequency of interruption per consumer in a Group (F_{ca}).
- Venezuela [75,76]:
 - Total Interruption Time for the User (TTIU);
 - Total Interruption Time per installed rated kVA (TTIK);
 - User Interrupt Frequency (FIU);
 - Average Interruption Frequency per installed nominal kVA (FMIK).

As expected, each indicator presents its regulatory limits, as discussed below.

3.2. Indicator limits

In Argentina, the Resolution ENRE N°527/1996 establishes the *Methodological Basis for Quality Control of the Technical Service*. In its sub-annex 4, referring to concession contracts, modified in 2017, the criteria for the indices are defined and their individual, global, and admissible limits [80].

The methodology to establish the limits is based on historical data of contingencies, network typology, and user information. ENRE monitors the indices as a national authority, such as North Distribution and Marketing Company (EDENOR), and South Distribution Company (EDESUR), through independent energy meters installed in the distribution system, with the limits being maintained in tariff periods of 5 years [18,81]. Table 2 illustrates the individual limits for each kind of customer, where small power demands are less than 10 kW, medium power demands are equal to or greater than 10 kW and less than 50 kW, and large power demands are equal to 50 kW or more [18].

Table 2. Individual continuity limits in Argentina.

Consumer Type	Duration Limit [Hours/Semester]	Frequency limit [Interruptions/Semester]
High-Voltage (HV) consumer	2	3
Medium-Voltage (MV) consumer	3	4
Low-Voltage (LV) consumer (big power demand)	6	6
LV consumer (medium and small power demands)	10	6

The continuity indicators in Bolivia must comply with the Electricity Distribution Quality Regulation (RCDE) provisions, considering both values of frequency and duration of the registered interruption. Thus, the control of indicators is carried out by collecting daily information through reports and monthly through the network databases [82].

The Bolivian distribution system is evaluated by the global continuity indicators, defined by T_s and F_s , which are analyzed in every six months for each LV consumer. In addition to the global indicators, there are individual continuity indicators T and F , aimed at MV and HV consumers. Therefore, Table 3 presents the values of the limits by voltage level and quality. It should be noted that Quality 1 and 2 refer to consumers in cities associated with the National Interconnected System with more than 10,000 consumers and fewer than 10,000 consumers, respectively, while Quality 3 is associated with a city or town with energy supply to from Isolated Integrated System [83].

Table 3. Global and individual limits of continuity in Bolivia.

Level	Type of System	Frequency (F_s) (Interruptions/Semester)	Time (T_s) Hours/Semester
LV consumer	Quality 1	7	6
	Quality 2	14	12
	Quality 3	30	35
MV consumer	Quality 1	7	12
	Quality 2	12	25
	Quality 3	20	35
HV	–	3	6

The Brazilian continuity indicators are defined through module 8 of PRODIST, created and developed the ANEEL. The methodology considered to calculate the limits for each utility is presented in Technical Note N°102/2014. As established in module 6 of PRODIST, each utility must send to ANEEL its Distributor Geographic Database (BDGD), from which the physical–electrical attributes will be extracted for use in defining the limits for the DEC and FEC indicators [84]. To establish the limits, the following procedure is performed [24]:

1. Selection of relevant attributes for comparative analysis;
2. Application of comparative analysis, based on selected attributes;
3. Calculation of limits for the DEC and FEC indicators, according to the performance of similar groups;
4. Analysis of the results by ANEEL for the definition of DEC and FEC limits.

In this way, the limits of collective indicators (DEC and FEC) are established in a specific resolution and made available for public consultation, according to the tariff review frequency. Regarding the limits of individual indicators (DIC, FIC, DMIC, and DICRI), the values are defined according to voltage level and consumer location, which are presented in Tables 1–5 of Annex 8.B of the module 8 of PRODIST. As a rule, the limits of individual duration indicators—DIC, FIC, DMIC, and DICR—are linked to the annual limit of the collective duration indicator (DEC). By the same token, frequency individual indicator FIC is linked to the annual limit of the FEC [24].

Chile presents TIC and FIC indicators for calculating power supply interruptions. Planned disconnections requested by the customer, force majeure events, and abnormal network status are considered into interruption analysis. Based on the technical standard for distribution energy service, the limits established in Tables 4 and 5 must not be exceeded for any customer during a period of 12 consecutive months. The density network is classified into different categories, using an index that represents the difficulty of delivering the distribution service in a given area. This index is based on the number of customers connected to the grid and the total length of the existing electrical lines [31].

Table 4. Limits expressed in hours for the TIC indicator in Chile during the year 2020.

Network Voltage	High Density Network	Medium Density Network	Low Density Network	Very Low Density Network
LV	9	10	14	18
MV	5	6	10	14

Table 5. Limits for the FIC indicator in Chile during the year 2020.

Network Voltage	High Density Network	Medium Density Network	Low Density Network	Very Low Density Network
LV	8	10	14	18
MV	6	7	8	12

Through Resolution n.070/1998, CREG introduced the specifications for the quality of electricity supply service in Colombia. This resolution includes the definition of DES and FES indicators. CREG, through Resolution n.97/2008 and more recently Resolution n.015/2018, inserted the average quality indicators SAIDI and SAIFI, in addition to the individual quality indicators DIU and FIU. Thus, it is possible to obtain information from other types of interruptions not covered by the first indicators, which are still used in the country by five utilities [78]. It is observed that these five companies still report the quality of service to customers through the DES and FES indicators, since they have not yet updated the measurement systems. Thus, they still do not meet the requirements established in Resolution n.015/2018, related to the calculation of SAIDI and SAIFI [78].

Regarding the limits associated with DES and FES indicators, the following aspects are highlighted:

- The evaluation of indicators is carried out quarterly;
- For the year 2020, the limit for DES was 48.4 hours, while for FES it was 52.3 interruptions;
- The analysis of indicators is carried out in four groups, which are defined by geographic location and number of inhabitants.

Colombian Resolution n.015/2018 establishes guidelines on the limits to be met and the incentive regime. It also establishes the calculation of compensation when the indicator

limits established for quality of service are exceeded [85]. The definition of limits for the average and individual indicators takes into account the following questions [78]:

- Average and individual quality indicators based on daily and monthly reports;
- The annual limits of the SAIDI and SAIFI indicators are calculated and established in separate resolutions;
- Depending on the performance of the indicators, incentives are applied to the annual income of the suppliers.

Table 6 presents the limits defined by the CREG for the SAIDI and SAIFI indicators from 2019 to 2022. Table 7 illustrates the limits for the DIU and FIU indicators, which take into account the limits of SAIDI and SAIFI, divided into five categories, with 1, 2 and 3 being associated with the multiple annual limits defined by the CREG; category 4 being related to users with more than 90 hours and/or interruptions; and category 5 being related to users with more than 360 hours and/or interruptions [78].

Table 6. Limits for SAIDI and SAIFI in Colombia.

Year	SAIDI [Hours]	SAIFI [Interruptions]
2019	35.0	45.1
2020	32.2	41.5
2021	29.6	38.2
2022	27.2	35.1

Table 7. Limits for DIU and FIU by category in Colombia for the year 2020.

Category	DIU (Inferior Limit)	DIU (Upper Limit)	FIU (Inferior Limit)	FIU (Upper Limit)
1	0.0	32.2	0.0	41.5
2	32.2	64.4	41.5	83.0
3	64.4	96.6	83.0	124.5
4	96.6	360.0	124.5	360.0
5	>360.0	>360.0	>360.0	>360.0

Ecuador's regulatory agency, ARCERNNR, has defined continuity limits for the global indicators TTIK and FMIK, as well as for individual indicators for MV and HV customers, associated with DIC and FIC. Resolution n.017/2020 of Regulation n.002/20 provides the limits of those indicators. Tables 8 and 9 present the limits for global and individual indicators, respectively, taking into account a validation period of 12 months [79].

Table 8. Continuity limits for global indicators in Ecuador.

Indicator	Network	High-Density Feeder	Low-Density Feeder
FMIK [interruptions]	6.0	7.0	9.5
TTIK [hours]	8.0	10.0	16.0

Table 9. Continuity limits for individual indicators in Ecuador.

Customer Type	FIC (Interruptions)	DIC (Hours)
High-Voltage consumer	6.0	8.0
Medium-Voltage consumer	8.0	10.0

In Peru, Osinergmin organization determines the continuity limits for duration and frequency indicators considering urban and rural areas. Threshold values are calculated for one semester control period and for each voltage level [56,57]. Tables 10 and 11 present the tolerance limits for continuity indicators in urban and rural areas, respectively, [58].

Table 10. Tolerance limits for indicators in Peru for urban areas.

Voltage Level	NIC (Interruptions)	DIC (Hours)
Very high/HV	2	4
MV	4	7
LV	6	10

Table 11. Tolerance limits for indicators in Peru for rural areas.

Voltage Level	NIC (Concentrated Rural) (Interruptions)	DIC (Concentrated Rural) (Hours)	NIC (Scattered Rural) (Interruptions)	DIC (Scattered Rural) (Hours)
MV	07	17	07	28
LV	10	25	10	40

In Uruguay, URSEA defines different limit values for the indicators, depending on the type of area, voltage level, and other characteristics of the service provided, such as the distance to the Sub Transmission (ST) power connection. Therefore, consumers connected in low voltage are classified into 42 groups, defined by geographic area and, later, within the same area, by density of sources connected in LV and MV. For MV, all consumers in the country are clustered into four groups, according to the density of supplies connected to MV. For the set of consumers connected to ST, these are grouped into two groups according to the distance to the power connection, being less than, equal to, or greater than 15 km [71,86]. The six-monthly limits in force, defined for each indicator and grouping, are shown in Table 12.

Table 12. Continuity limits by grouping in Uruguay.

Indicator	Urban High Density (LV)	Urban High Density (MV)	Urban Medium Density (LV)	Urban Medium Density (MV)	Low Density Urban (LV)	Low Density Urban (MV)	Rural (LV)	Rural (MV)	Distance ≤15 km from ST	Distance >15 km from ST
T_{c_a} (hours)	3.6	2.5	9.9	6.8	18	14	36	28	3	8
F_{c_a} (interruptions)	1.8	1.5	4.5	4	8	7	14	11	1.5	4
T_{c_i} (hours)	16	9	25	20	37	31	77	58	9	20
F_{c_i} (interruptions)	7	5	12	10	18	16	33	24	3	9
D_{max_i} (hours)	10	8	10	10	10	10	14	14	8	8

In Venezuela, indicators are calculated for internal (fault attributed to a distributor) and external (fault attributed to an electricity service provider that is not a distributor) causes, with different limits for each. The limits allowed for external causes are one quarterly interruption and one quarterly hour. On the other hand, the limits allowed for internal causes depend on the voltage level, as shown in Table 13 [75].

In addition to the FIU and TTIU indicators, there are also the TTIK and FMIK indicators for the low voltage level, which consider interruptions per installed kVA. In this case, the limits allowed for external causes are three semester interruptions and two semester hours. On the other hand, the limits allowed for internal causes depend on the voltage level, as shown in Table 14 [75].

Table 13. Tolerance limits for indicators in Venezuela by voltage level.

Voltage level	FIU (LV) (Interruptions)	TTIU (LV) (Hours)	FIU (MV) (Interruptions)	TTIU (MV) (Hours)	FIU (HV) (Interruptions)	TTIU (HV) (Hours)
Very high	2	2	1	1	1	1
HV	2	4	1	2	1	1
MV	4	4	2	2	2	2
LV	4	4	2	2	2	2
Very low	6	6	3	3	2	2

Table 14. Tolerance limits for indicators in Venezuela per installed kVA.

Voltage Level	FMIK (Interruptions)	TTIK (Hours)
Very High	2	2
HV	2	3
MV	3	3
LV	3	4
Very low	4	4

Based on the review and documents associated with the regulation of electricity supply in South American countries, presented in this section, it is possible to perceive some similarities and differences in the calculation of the indices. Among these, the classifications by voltage level [18,24,31,56,57,71,75,79,83,84,86], type of system [24,71,83,84,86], density of consumers [31,78,83], categories [24,31,78,84], and location [24,56,57,71,78,84,86] are worth highlighting. Finally, as one can see, information was not found for *Guyana, Paraguay, or Suriname*.

3.3. Financial Compensation

When the limits of the indicators defined in the previous subsection are exceeded, there are regulations that determine how consumers must be financially compensated. The following is a discussion of these aspects for each country in South America.

In Argentina, the time for calculating the indicators is every six months. If a user is affected by power outages longer than 3 minutes, which exceed the limits established in terms of duration and/or frequency for the respective semester, they will receive a credit on the invoice from the distributor [18,81]. The compensation amount is proportional to the energy not supplied in the analyzed semester (excluding major events), where the compensation is carried out by the tariff category of each customer, as shown in Table 15 [18].

Table 15. Value of energy not supplied in Argentina.

Client Type	Cost of Energy Not Supplied (US\$/kWh)
MV and HV rates	2.71
LV rates (small demands)	2.27
Residential and public lighting rates	1.40

The AETN of *Bolivia* applies reductions in utilities' remuneration, proportional to the amount of not supplied energy, calculated in accordance with the provisions of article n.45 of the RCDE. The cost of energy not supplied must be 7 times the base price of energy in the National Interconnected System, as established in Annex 5, sub-item 5.2 of the RCDE. In this way, the amounts of reductions in the utilities' remuneration are returned to the consumers affected by power outages longer than 3 minutes [82,83].

In Brazil, ANEEL establishes financial compensation through individual indicators, in module 8 of PRODIST. According to the module, in the case of violation of individual continuity limits, compensation must be made in credit on the consumer's invoice within 2 months after the calculation period. In cases where the amount of compensation exceeds the invoiced amount, excess credit must be carried out on the next billing. In addition, for the purpose of possible violations, the following situations are considered [24]:

- The minimum amount of compensation must be BRL 0.01 (one cent of the real);

- The amount of compensation must be limited to 18 times the VRC (base monetary value for calculating the compensation in the current month);
- When it exceeds the limit of two or more individual indicators (DIC, FIC, and DMIC) in the same calculation period, the indicator with the highest monetary compensation is considered;
- When a violation of the DICRI indicator occurs, the compensation must be carried out without prejudice to the compensation for violation of the DIC, FIC, and DMIC indicators;
- The utility must adopt a single billing cycle reference used in the calculation of the VRC for the month in which the indicator is calculated.

The CNE establishes the payment of compensation to customers for the interruption of energy supply in Chile, when the duration of the interruption exceeds 3 minutes. The technical standard on unavailability of supply and compensation defines the general provisions on the payment of compensation, supply quality requirements, and procedures for determining compensation. It should be noted that the indices of unavailability of supply are calculated for a control period corresponding of 12 consecutive months, immediately prior to the control month [32]. The standard takes into account the following points:

- Origin of payment of compensation;
- Outage rates and standards;
- Determination of energy not supplied and compensation amount;
- Allocation of payment of compensations.

CREG Resolution n.015/2018 establishes guidelines related to compensation for the violation of the limits of continuity indicators in Colombia. Among the aspects used in the methodology for calculating and paying consumers, the following stand out [85]:

- Classification and exclusion of events;
- Individual quality levels;
- Reference indicators and minimum quality required;
- Requirements and information for the application of the incentives and compensation regime.

ARCERNNR establishes compensation measures for non-compliance with service quality limits in Ecuador, according to the specifications of Resolution n.017/2020 of Regulation n.002/20. Violations for not providing electricity are divided into partial and repeated. Regarding partial violations of global and individual indicators, a sanction of 20 unified basic salaries is imposed on the utility, referring to the year in which the violation occurred per indicator exceeded and per affected customer, in the case of individual indicators. In addition, the utility must take corrective actions within 120 days of notification of violation. In the annual evaluation, if poor indicators persist, there will be a sanction of 30 unified basic salaries, and the utility must also carry out corrective actions within 120 days. If partial violations continue to occur after 120 days, sanctions of 40 unified basic salaries per indicator and per customer may be imposed, and the utility must carry out corrective actions within the established period [79].

In the Peruvian context, compensation is defined for the continuity limits not met for urban and rural areas by the norms of Osinergmin [56,57]. For both zones, the following criteria are considered for the payment of compensation:

- Power theoretically not provided and energy recorded in the semester;
- Number of interruptions per customer in the analyzed semester;
- Total cumulative duration of outages;
- Unitary compensation for breach in the quality of supply in the amount of 0.35 USD/kWh;
- Magnitude factor of supply quality indicators;
- Compensation received by the end customer or utility.

URSEA defines compensation for breach of continuity in *Uruguay* proportional to the deviation from the limit and the average monthly billing of the affected user. The calculation of compensation is defined in section “Quality of the Technical Service”-Title III “Compensation to Users”, Articles 23 to 27 of the RCDSEE [71,86]. Compensations consider the following points:

- When the limits of the Tc_a and Fc_a indicators are exceeded, the value corresponding to the compensations for the two indicators will be calculated and the greater of them will be applied;
- It will be calculated and applied in the same way when the limits of the Tc_i and Fc_i indicators are violated;
- Compensation for exceeding the $Dmax_i$ indicator will always be applied, regardless of the result of other indicators in the same period;
- Compensation will be implemented through discounts on the invoice of affected consumers;
- When the compensation exceeds the amount of the first invoice on which the discount is made, the remaining balance must be deducted from the next invoices, limited to a maximum amount, until the compensation is completed.

In Venezuela, non-compliance with quality limits results in the application of sanctions by the regulator in accordance with the provisions of the Organic Law of the Electricity Service. Sanctions for quality deviation of the technical service are applied regardless of the root cause being of an internal or external nature [75]. For calculation of the sanction to be applied in bolivars (VEF) and payment to each affected user, the following aspects are taken into account:

- Amount of energy not supplied and average price of energy expressed in VEF/kWh;
- Multiplier factor, according to the nature of the infraction, classified into first, occasional, or repeated;
- User billing for the last 3 months at the end of the control period expressed in Bs;
- Total energy billed to the user in the last 3 months at the end of the control period, expressed in kWh.

In view of the financial compensation models presented, some similarities and differences can be observed in the criteria adopted for penalties and reimbursement to affected customers. The determination of minimum values, energy not supplied, reference values per calculation period, multiplier factors, and user billing are some of the variables used to calculate the compensation values. Just as no defined limit values were found for Guyana, Paraguay, or Suriname, no criteria for financial compensation were identified.

4. Performance Results

In order to identify the impact of current regulations on the quality of service provided by utilities, some performance results in each analyzed country will be presented below.

According to ENRE’s 2020 annual report, companies with national jurisdiction in Argentina, EDENOR and EDESUR, between 1997 and 2020, were responsible for the application of 39% and 61% of the compensation, respectively, [81]. Table 16 illustrates the compensation values from 2016 to 2020.

Table 16. Annual compensation expressed in *Argentine* pesos for EDENOR and EDESUR.

Year	EDENOR	EDESUR
2016	73,050,236	88,166,229
2017	118,979,332	244,985,018
2018	444,332,458	364,712,301
2019	239,649,596	460,882,653
2020	204,870,778	526,344,375

In Brazil, as illustrated in Figure 1, the value of continuity compensation paid directly to consumers increased, from a value of BRL 634 million in 2020 to BRL 718 million in 2021. The amount of offsets also increased slightly, from 79.49 million to 79.97 million [87].

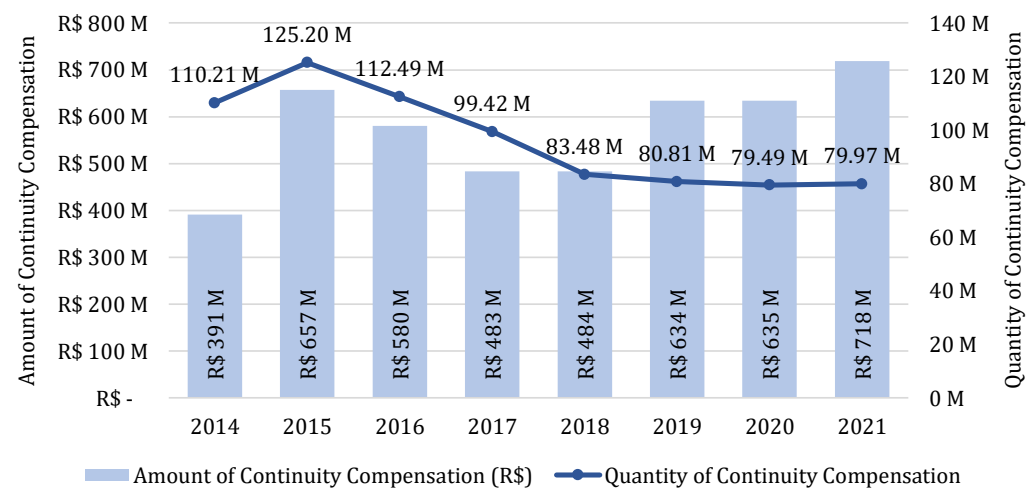


Figure 1. Compensation in Brazil paid directly to consumers.

In Figure 2, the SAIDI indicator was used to assess interruptions in Chile, due to internal causes (responsibility of the utilities), external causes (unauthorized interruptions in the transmission and/or generation systems), or even forces majeures. The utilities report the different interruptions to the SEC and perform a first classification, giving rise to the SAIDI indicator [88]. It should be noted that, between 2012 and 2020, most of the interruptions were of internal origin, followed by forces majeures and external causes.

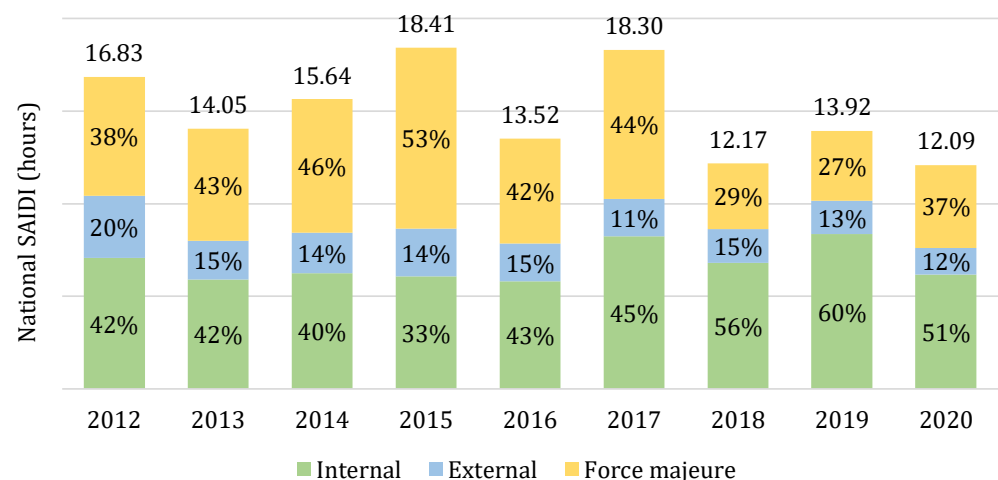


Figure 2. Duration of interruptions in hours in Chile.

In Colombia, the SSPD presents the values of SAIDI and SAIFI indicators for some utilities, as shown in Figures 3 and 4, respectively, for the years 2018 and 2019 [89]. The SAIFI indicator is more affected than the SAIDI, as there are more distributors that exceed the average frequency values.

Through information available in the Ecuadorian electrical panorama from 2019 to 2022, the values calculated for the FMK and TTIK indicators are listed in Table 17 [38,90,91]. Through these, it is observed that there has been an improvement in the quality of service over the last few years.

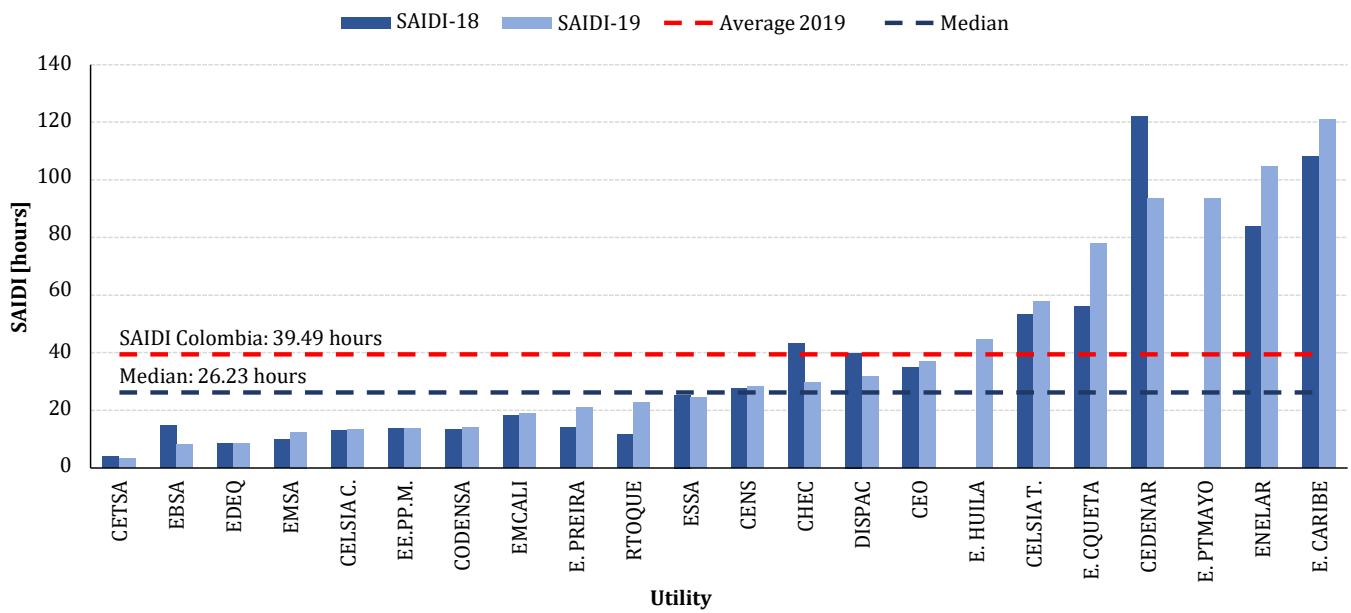


Figure 3. SAIDI indicator calculated in Colombia.

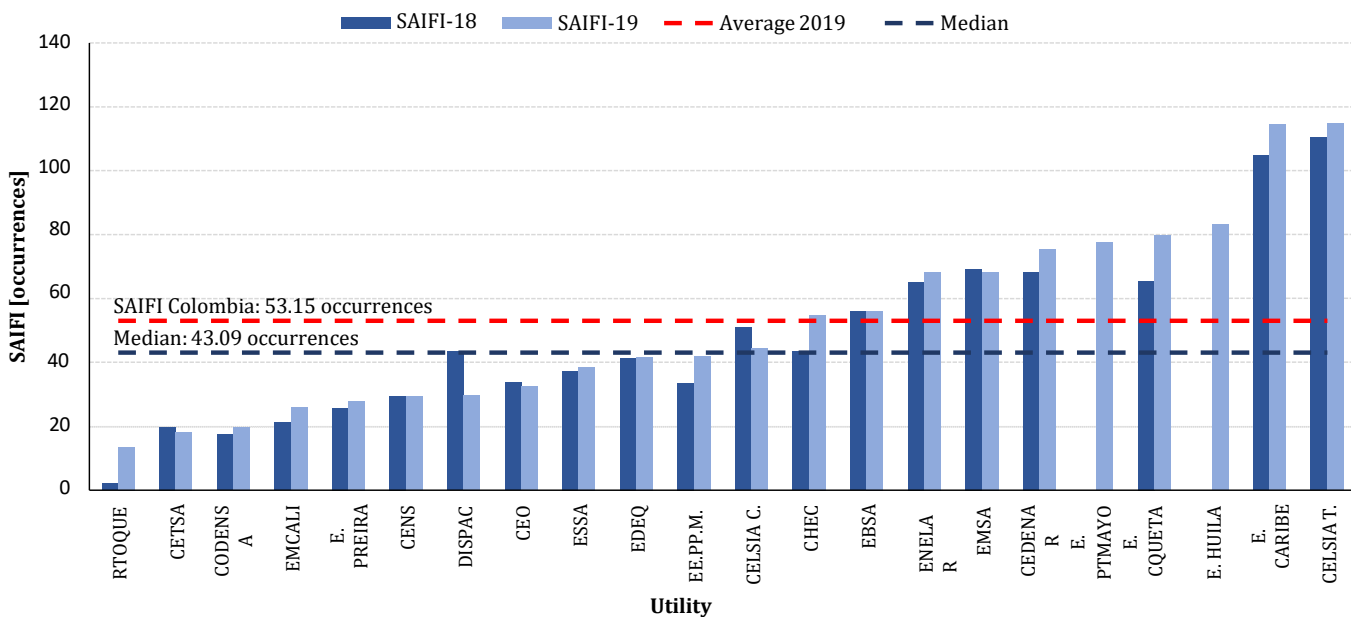


Figure 4. SAIFI indicator calculated in Colombia.

Table 17. FMIK and TTIK indicators calculated in Ecuador.

Indicator	2018	2019	2020	2021
FMIK	7.60	6.15	6.05	4.85
TTIK	10.09	7.63	7.66	5.90

Figure 5 shows the semiannual evolution of compensation applied to utilities for exceeding continuity limits for high- (S1) and medium- (S2) density urban distribution systems in Peru. The amounts do not consider the recalculation of indemnities associated with force majeure requests that are generated after the date of delivery of the reports, nor those associated with denials of loads [92].

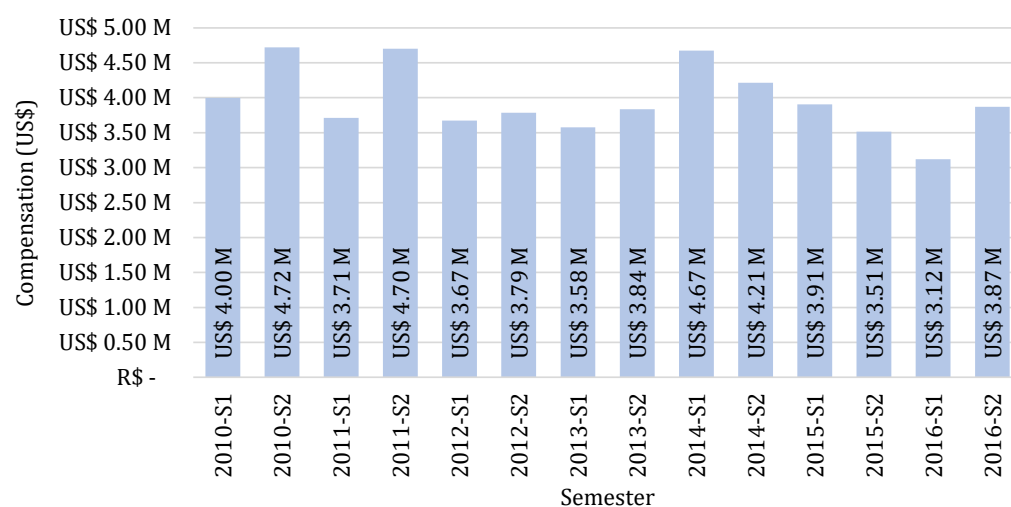


Figure 5. Semiannual evolution of compensation for poor quality in Peru.

Figures 6 and 7 present the values calculated for continuity indicators in Uruguay, considering in a single grouping all consumers in the country, disaggregating into urban and rural connected to LV or MV and consumers directly connected to ST [71]. Thus, it appears that consumer groups located in rural areas are more affected by supply interruptions.

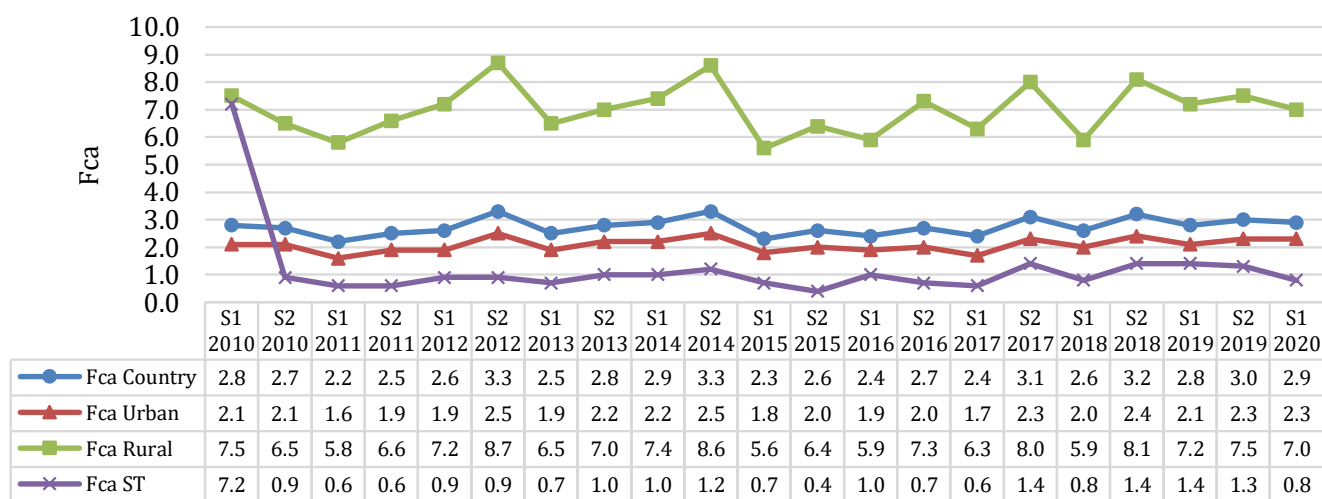


Figure 6. Semiannual F_{ca} from Uruguay from 2010 to 2020.

In the set of results presented, the performances of Guyana, Paraguay, and Suriname were not considered, as the specifications defined in Section 3 were not found. In addition, relevant databases were not found for Bolivia and Venezuela, relating to established indicators and/or information on reimbursements to customers for violating service quality limits.

From the performance results presented, it was found in general that the major problem is related to the interruption duration, although some countries have major problems with the frequency. Regarding the duration and frequency of interruptions, it was observed that Uruguay presented the best results and Colombia the worst. The highest compensation values are from Brazil, followed by Argentina, given the size of their territory and power electrical systems. In terms of types of areas covered by distribution networks, rural areas tend to have higher duration and frequency rates than urban areas.

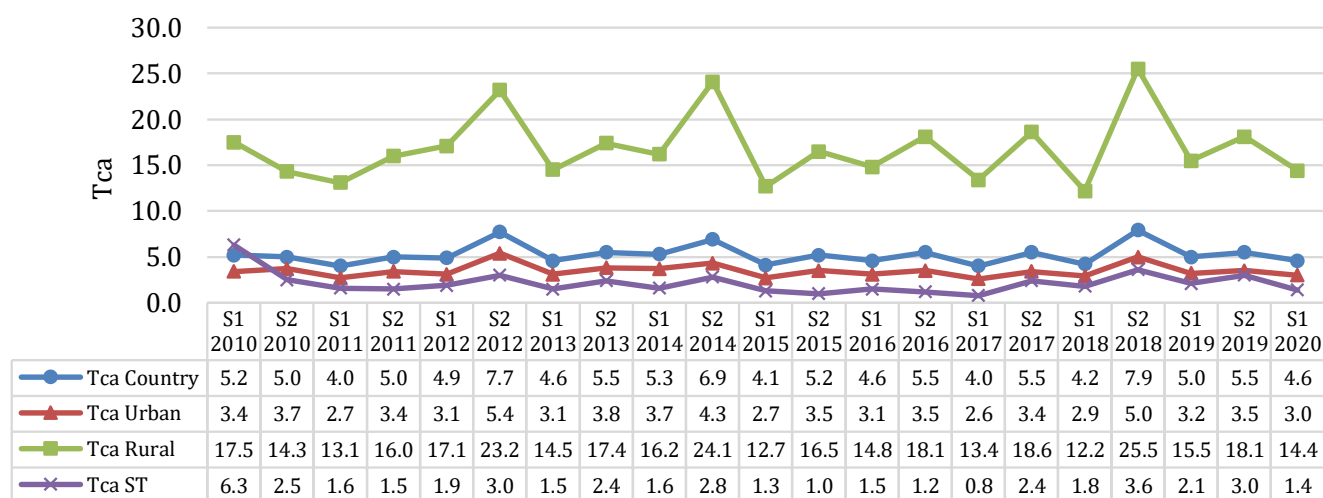


Figure 7. Semiannual Tca from Uruguay from 2010 to 2020.

5. A Case Study: Brazil

By specifying the main aspects used in the methods of evaluating the quality of service, presented in the previous sections, it is possible to verify the existence of regulatory mechanisms in South America. In this section, a case study carried out in Brazil is presented, covering the process of selecting attributes, clustering the sets, defining the limits for the indicators and analyzing two sets for a distributor in the southern region of the country.

For a better understanding of this method, the following terms are defined:

- *Attribute*: represents one of the characteristics of a set that allows analyzing similarities between other sets;
- *Set*: is formed by a certain number of consumer units and defined by the distribution substation;
- *Cluster*: through the attributes, the sets are grouped by the a clustering method, which seeks to gather the most similar sets, giving rise to a cluster.

5.1. Selection of Attributes

The attribute selection process published by ANEEL in Technical Note n.102/2014 consists of seven steps, illustrated in Figure 8 and described in this subsection:

- **Step 1:** Acquisition of a complete database including 146 attributes of 2610 sets of utilities, as defined in Public Consultations n. 043/2009 and n. 008/2010. This consolidated database allows one to verify the information about utilities, sets, attributes, and average values of the collective indicators. To assess the impact of socioeconomic attributes on the model, analyses were performed, first considering 11 socioeconomic attributes listed in Technical Note n. 102/2014. Socioeconomic variables are associated with factors such as social status, income, basic sanitation, subnormal households, housing infrastructure, municipal development, access to water supply, garbage collection service, and violence. Then, a second analysis was performed disregarding socioeconomic aspects. In addition, given the difficulty of obtaining information, the problems of standardizing the way of sending, the intersection of databases, and high correlations, more than 70 attributes were excluded in Step 1;
- **Step 2:** Realization of Pearson and Spearman correlation analyses between the attributes and the average values of DEC and FEC (considering the years from 2011 to 2013). ANEEL considers a minimum correlation of 0.20, in the module, for the attribute to remain in the following analysis. As a result, 69 attributes were selected for DEC and 67 for FEC.

- **Step 3:** Assessment of the socioeconomic impact in the selection of attributes. This step intersects with the problem in two distinct streams, with the blue stream representing the model with all attributes, and the green stream representing the model without the 11 socioeconomic attributes. Before the regression analysis was performed, the data were normalized, aiming at a more uniform distribution. As the original data distribution differs from the normal distribution, the natural logarithm was applied to obtain linearity. Data normalization was performed using the following expression [27]:

$$X_T = \ln(1 + X), \quad (1)$$

where X_T represents the transformed variable and X the original variable. It can be seen that in (1) that the variable is added with 1 inside the argument in order to avoid numerical problems in cases where the variable is zero. Considering that certain sets do not present data for all attributes, it becomes necessary to remove these sets from the next step of the process, as some software identifies empty data as zero, which can result in problems in the selection of attributes;

- **Step 4:** Perform a linear regression by the Stepwise method for sets that do not have empty data, where the attributes are inserted step-by-step in the model, according to their additional contribution. Eventually, with the inclusion of a new variable, a previously inserted variable may no longer be significant and is removed from the model. The significance criterion adopted by ANEEL is 1% for the variable to enter or leave the model. Then, to obtain attributes with little correlation with each other, a Multicollinearity analysis is performed using the statistical measure called Variance Inflation Factor (VIF) as a metric. The attribute with the highest VIF is discarded from the regression, which is performed again with the attributes that were not excluded. This process of regression and analysis of the VIF is carried out until all attributes have a VIF lower than five. The entire process described in this step is carried out for DEC and FEC, with and without socioeconomic attributes;
- **Step 5:** Repeat the process of Step 4, but with the attributes selected in the previous step. In addition, the behavior of socioeconomic attributes is evaluated;
- **Step 6:** Decision on whether to include socioeconomic variables. From the models obtained for DEC and FEC, considering or not the socioeconomic attributes, it is observed that the more complete models present a higher value of the accumulated coefficient of determination (R^2 of the model). Despite this, it should be noted that most of the socioeconomic attributes available by the municipality have a low data-update rate, which may result in distortions in the analyses. Therefore, observing the difficulty of updating socioeconomic data, the model without the socioeconomic variables for DEC and FEC is chosen;
- **Step 7:** Evaluation of the partial coefficient of determination partial R^2 , from the model without socioeconomic attributes. ANEEL adopted the value of 2% for the partial R^2 for the DEC and FEC. This value was chosen after verifying that from the sixth to the seventh attribute, the value of the partial R^2 drops to less than half. Thus, we decided to use only the six most important attributes for the two models. It is noteworthy that, of the six attributes chosen, five are common to both indicators.

After the seven steps, ANEEL defines the most representative attributes for DEC and FEC indicators. The difference found for the attributes, when the models for collective indicators are compared, is that the DEC calculation considers the number of industrial consumer units (NUC_IND), and FEC calculation considers the number of commercial consumer units (NUC_COM). Table 18 presents the selected attributes at the end of the described process.

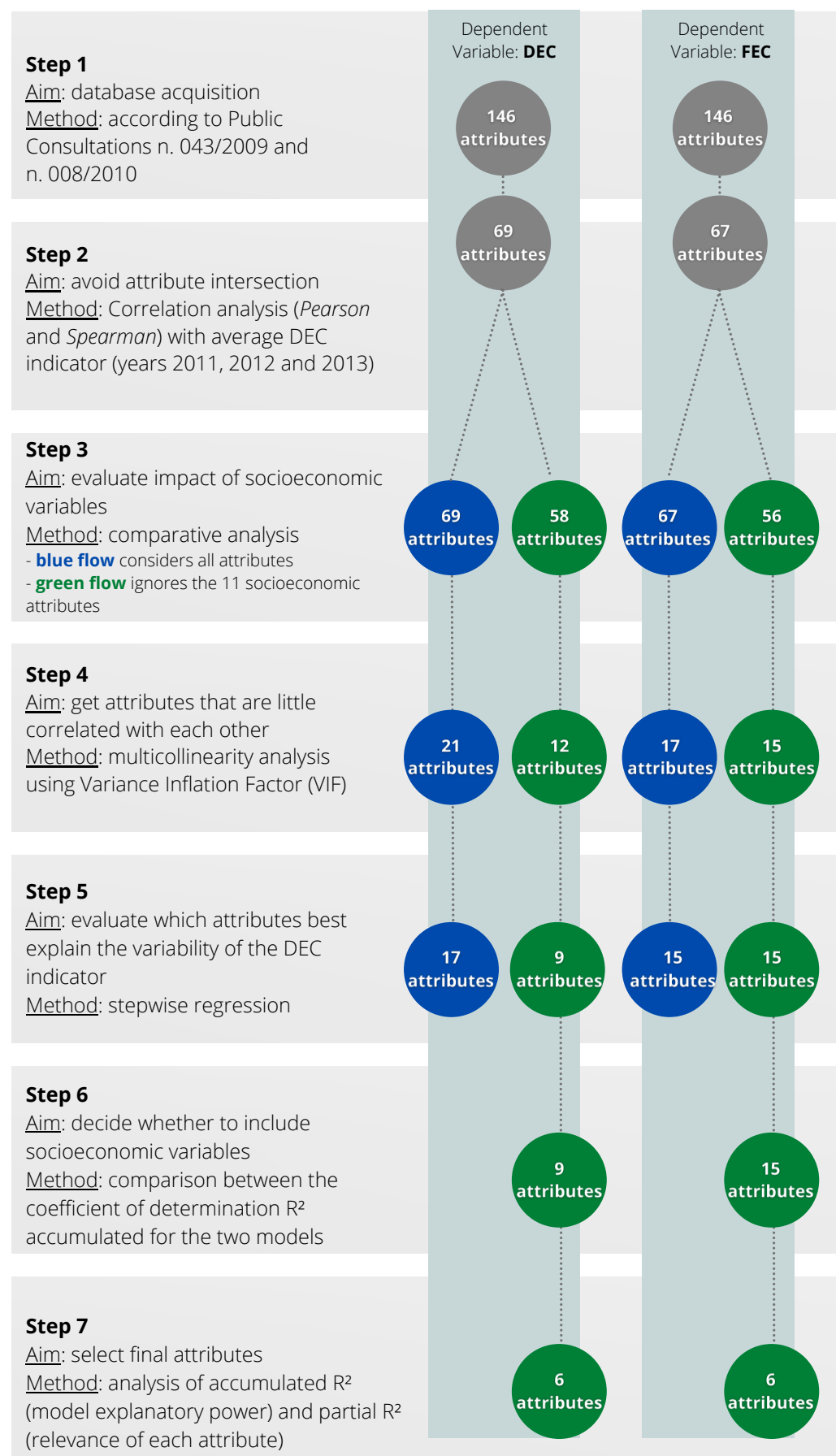


Figure 8. Main steps of the attribute selection process adopted by ANEEL in Brazil.

Table 18. Selected attributes for DEC and FEC in Brazil.

Attribute	Description
PC_NUC_AD	Percentage of number of consumer units in areas of high density (%)
PC_VRAM	Percentage of area with high or medium remaining vegetation (%)
PC_ERMT_3F	Percentage of three-phase MV networks (%)
PLUV	Average annual rainfall (mm)
CM_NUC_RES	Average consumption per consumer unit of the residential class (MWh)
NUC_IND	Number of industrial class consumer units
NUC_COM	Number of commercial class consumer units

5.2. Clustering of Sets

ANEEL employs the dynamic method for grouping sets. As published in Technical Note n.121/2016, this process aims to compare each set with others, looking for similarities. The method is applied separately for the DEC and FEC indicators, due to the existence of a distinct attribute between the indicators [93].

Initially, the method removes the effects of measurement scale of each attribute through normalizing each indicator. The normalization used is the Score Z, which aims to transform each variable into a new variable with zero mean and unit standard deviation, according to [93]:

$$x_{il} = \frac{x_{il}^* - m_l}{s_l}, i = 1, \dots, N; l = 1, \dots, d, \quad (2)$$

where x_{il}^* is the original data, m_l is the sample mean and s_l is the sample standard deviation.

The dynamic method uses the Euclidean distance as a measure of similarity, given by [93]:

$$D(\mathbf{x}_i, \mathbf{x}_j) = \left(\sum_{l=1}^d |x_{il} - x_{jl}|^2 \right)^{1/2} \quad (3)$$

where $\mathbf{x}_i$ and $\mathbf{x}_j$ are objects (in this case, the consumer units sets) of a data array with d dimensions (where $d = 6$, the total attributes used per indicator).

Based on these definitions, the distance from each set to all sets in Brazil is calculated. It is noteworthy that the aerial and underground sets are separated in the comparison stage; that is, aerial sets are only compared with aerial sets and underground sets with underground sets.

From the values of the calculated distances, a matrix is structured, of size n , which is the number of sets. After this step, it is possible to order the distances from each set to the others, thus obtaining the closest sets to each analysis set.

The next step consists in establishing how many sets it needs to compare each set of consumer units with. For this criterion, ANEEL adopted the 100 closest sets, provided that a limit of homogeneity between them is respected. The definition of this limit was performed by the quantity called percentage heterogeneity, calculated according to (4). Through statistical analyses, the value of 20% was defined as the heterogeneity limit for an adequate comparison between sets [93].

$$Heterogeneity_i^P = \frac{\max(Dist_i^j)}{3 \times \sqrt{k}} \quad (4)$$

where P indicates that the result of the equation is on a hundredths basis, i is the index of the reference set, j is the set next to the set i , $Dist_i^j$ is the Euclidean distance from the set i to the set j , n is the number of sets similar to the set i , and k is the number of attributes.

When the calculated heterogeneity value exceeds 20%, the most distant set is removed from the analysis, and the heterogeneity is recalculated. Thus, ANEEL adopted 50 sets as a minimum and 100 sets as maximum of comparable sets. Furthermore, it should be noted that if the heterogeneity value remains above 20% when 50 sets are reached, the method does not remove any more sets from the cluster. Therefore, for this scenario, the comparison was not ideal, and the set under analysis was classified as heterogeneous.

The heterogeneous sets are evaluated by the metric called Score ANI, which seeks to define whether the set has more favorable characteristics than the sets in its cluster.

5.3. Definition of Indicators Limits

The definition of threshold values for the DEC and FEC indicators is based on the technique called *yardstick competition* [93]. Through this technique, ANEEL establishes the reference value for each cluster, which will define the objective limit to be reached by the set under analysis. Table 19 presents the percentile adopted in the clustering to define the objective limit, divided by type of set.

Table 19. Percentile adopted by type of set.

Set Type	Percentile (%)
Aerial interconnected	20
Isolated aerial	50
Underground	50

It is worth noting that the percentile is obtained by ordering the sets according to the average of the performances observed by the indicators calculated, considering the last 3 calendar years available. As an example, in a cluster with 100 sets, the 20th percentile will be the value of the indicator obtained by the 20th place (from the best to the worst performance) among the sets. The calculation of set position, whose performance represents the desired percentile, is given by [93]:

$$Position = \text{int}((N_{SimiSet} - 1) \times Percentile + 1) \quad (5)$$

where $N_{SimiSet}$ is the number of similar sets in the cluster.

The period defined for a set to reach the objective limit is initially 8 years. However, with each tariff revision, the limits are updated. Considering that the frequency of each distributor's tariff review can vary from 3 to 5 years, the initial years of the trajectory are used. This trajectory is linear, starting from the current limit of the set and reaching the objective limit in 8 years, according to (6) [93]. It should be noted that if the objective limit is greater than the initial limit, (7) is used, maintaining the initial limit until the end of the tariff period [93].

$$Limit^t = Limit^0 - t \left(\frac{Limit^0 - Limit^{objective}}{T} \right), \text{ if } Limit^0 > Limit^{objective}, \quad (6)$$

$$Limit^t = Limit^0, \text{ if } Limit^0 \leq Limit^{objective}, \quad (7)$$

where T is the transition period (considered 8 years), t is the year in which the limit is calculated, $Limit^t$ is the limit to be calculated for the year T , $Limit^0$ is the last limit already established for the set (current limit), and $Limit^{objective}$ is the limit obtained by applying the percentile (objective limit).

5.4. Analysis of Sets

In this subsection, an analysis will be made of the best and worst aerial set, based on average DEC, of a utility in the southern region of Brazil, according to data made available by ANEEL for the year 2021. This case study aimed to evaluate different aspects through the establishment of bubble graphs, in which it is possible to identify the x and y axes as the average FEC and DEC scale, respectively. The bubble size, on the other hand, varied according to the physical–electrical attribute in question.

In this case study, we also propose illustrating the geographic location of the set of interest, together with the location of the sets that make up the cluster it is part of. Table 20 presents the best and the worst set, based on the values obtained for average DEC.

Table 20. Best and worst set (aerial networks) based on average DEC.

Set Name	Average DEC
Porto Alegre 1	4.88 hours
Pedro Osório	67.12 hours

The results obtained for set *Porto Alegre 1* are depicted in Figures 9 and 10. As one can see in Figure 9, the clustering process (described in Section 5.2), where the interest set was *Porto Alegre 1*, resulted in a cluster with 100 sets. This bubble chart was made by setting the results of “NUC_IND attribute”. It should be noted that the bubble size increases according to the representativeness of industrial consumer units contained in the set. Furthermore, three colors were used to highlight different aspects: (i) green bubbles represent the similar sets belonging to the utility in the southern region, (ii) red bubbles represent similar sets of other Brazilian utilities, and (iii) the blue bubble represents the reference set, which establishes the DEC limit for this cluster (of 100 sets). It is clear from Figure 9 that the set of *Porto Alegre 1* has DEC and FEC performances higher than most sets of the cluster. As one can see, the number of industrial customers is not crucial to explain this behavior once the bubbles have similar sizes.

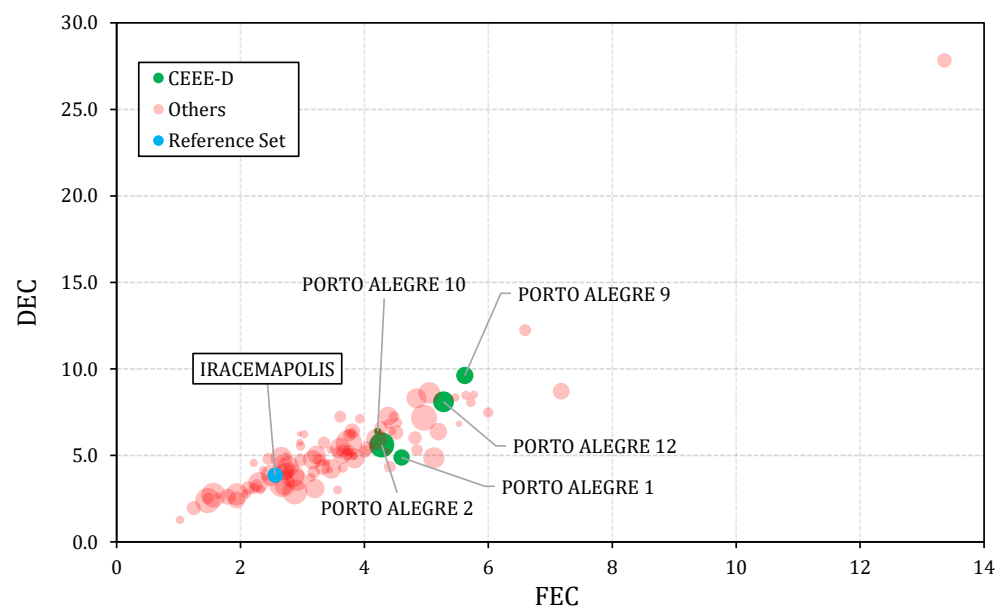


Figure 9. Impact of the NUC_IND attribute on DEC and FEC performance for the cluster of *Porto Alegre 1* set.

Figure 10 shows the geographic location of the sets belonging to the cluster of the *Porto Alegre 1* set, which is located in the south of Brazil. Considering that the clustering process was carried out with all the sets in Brazil, an interesting result was observed: when analyzed statistically in terms of the attributes listed in Table 18, this set presents a characteristic behavior of sets in the Brazilian Southeast.



Figure 10. Geographic location of all 100 sets of cluster belonging to the *Porto Alegre* set.

The same analysis was performed for the *Pedro Osório* set, resulting in Figures 11 and 12. Thus, Figure 11 illustrates the bubble chart obtained for the cluster of *Pedro Osório* set. Additionally, Figure 12 shows the geographic location of the sets belonging to this cluster, where there is a dispersion of most clusters within the country compared to Figure 10.

From the comparison between the bubble charts for the best and worst set of interest, that is, *Porto Alegre 1* and *Pedro Osório*, respectively, the following results were observed:

- In relation to attributes NUC_IND and PC_ERMT_3F, the set with the best performance for the average DEC presented a higher number of larger bubbles in its cluster. This indicates a higher industrial concentration and percentage of three-phase MV networks in the similar sets;
- When analyzing the attribute PC_VRAM, the set with the worst performance for the average DEC presented a higher number of larger bubbles in its cluster. Thus, indicating a higher concentration of high or average remaining vegetation in similar sets;
- In terms of geographic location, the best performing set was clustered into a cluster with sets concentrated in the Brazilian Southeast. However, the set with the worst performance integrates a cluster with more dispersed sets.

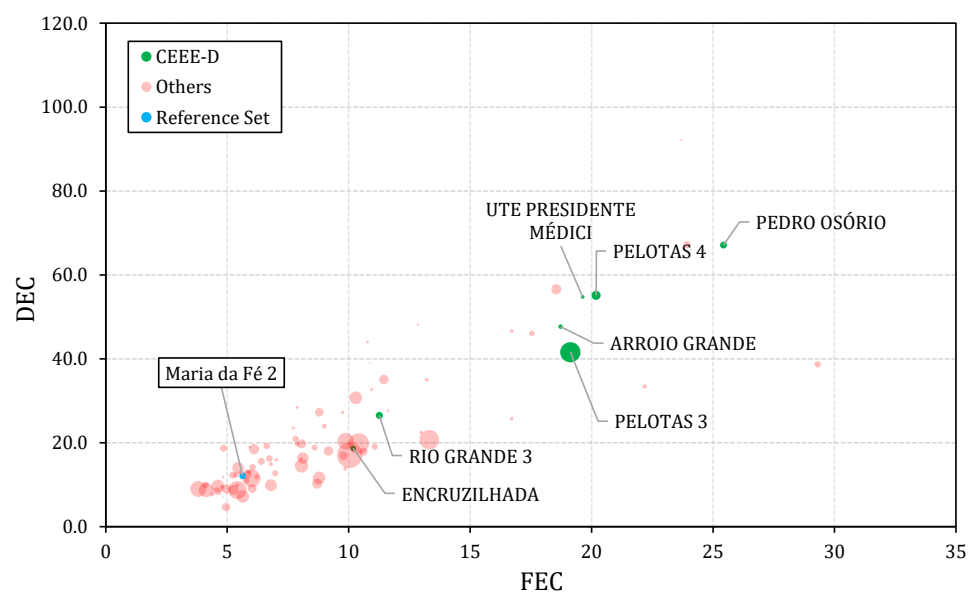


Figure 11. Impact of NUC_IND attribute on DEC and FEC performance for Pedro Osório cluster.

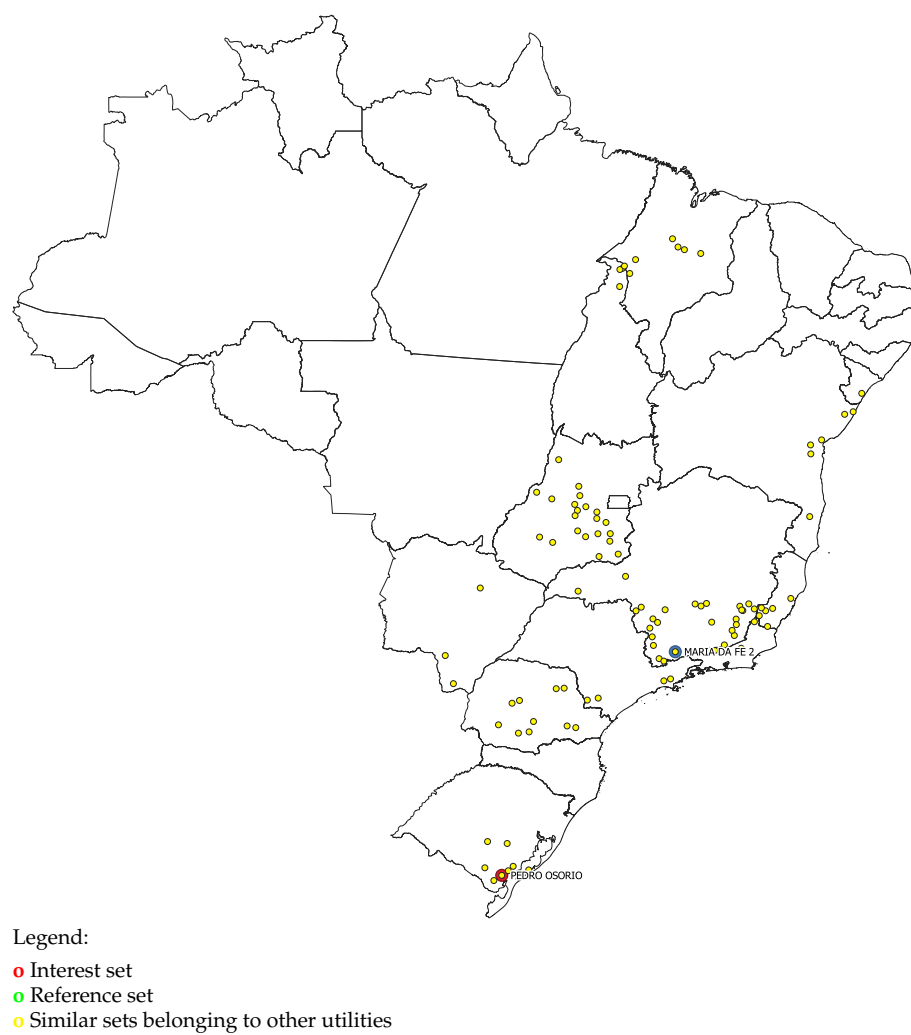


Figure 12. Geographic location of all 100 sets of cluster belonging to the *Pedro Osório* set.

6. Future Directions

The growing search for new forms of electric energy generation, along with the growing concern with the global environmental crises, the international pressure for greater energy efficiency and the transition to sources with lower emission of greenhouse gases, constitute the current and future reality for meeting the demand for electricity [94].

In 2020, even with economic problems stemming from COVID-19 lockdowns, the addition of DERs, such as wind and solar, increased at the fastest pace in two decades. Furthermore, the sale of electric vehicles set new records, favoring the emergence of a new energy economy, driven by political actions and innovative technologies [95].

In this context, this review paper addressed the evaluation of regulatory models in South American countries, allowing us to verify that there are investments directed to DERs. However, there are still no variables related to the DERs and the role of prosumers to evaluate the quality of electricity, as well as to define the limits of continuity indicators. In this way, it is understood that the inclusion of DERs and the prosumers in regulatory models is an important research gap [96–100]. In the future, by inserting this parameter into the model, it will be possible to improve the analysis of service quality in distribution systems. Especially in the context of managing information in a Smart Grids environment [101–106].

In the Brazilian context, a strongly influence was observed by which many attributes were selected in the analysis (as presented in Section 5). For this reason, a Research and Development (R&D) project developed in Brazil with ANEEL concluded that the use of a single attribute associated with the density of consumer units would be more relevant for the evaluation of DEC and FEC limits [107]. Therefore, the definition of attributes and their quantity are aspects to be evaluated, enabling the simplification of methods and the analysis of variables associated with DERs, which constitutes a challenge to be explored.

7. Conclusions

Methods to evaluate the quality of electricity supply seek to establish metrics that help regulatory agencies to monitor the performance of different utilities, especially because each utility differs in terms of operating its distribution networks, the number of customers, the coverage territory, the distance from the substation, and many other issues. Regarding the evaluation metrics, the continuity indicators, their limits, calculation, and compensation paid for violation of non-supplied energy, different models were verified, which were developed through variables with consolidated databases. Given these factors, this review paper presents the main regulatory aspects for the quality of electricity in distribution systems in South America, illustrating similarities and differences in their guidelines.

In all the countries analyzed, it was possible to identify the existence of norms associated with the quality of electric energy, containing specifications regarding the indicators of duration and frequency of interruptions. Most regulatory agencies in the electricity sector in South America employ supply quality analysis for product, technical, and commercial aspects. This demonstrates initiatives aimed at improving the supply of electricity demand. The prevalence of ownership of distributors is mixed; that is, they are composed of companies in the public and private sector, with Guyana, Paraguay, Suriname, Uruguay, and Venezuela having distributors only in the public sector and Chile having companies in the private sector in its entirety.

In the regulatory models analyzed, indicators of the duration and frequency of interruptions were observed, directed by transformer, nominal installed power, individual, collective, and by grouping. In addition, the definition of limits for these indicators took into account aspects such as voltage level, type of system according to country-specific classification, density of clients served, coverage zones, and distance from the ST. The calculation of financial compensation is defined by multiple variables, which include tariffs by voltage level, cost of energy not supplied, base price of energy in the analyzed period, and energy billed, among other parameters attributed to the amount paid to consumers.

Aiming to exemplify a detailed analysis of the impact of the attributes considered in the model, a Brazilian case study was presented. It is important to note that no publicly available databases were found for defining indicator thresholds, financial compensation models, and performance results for all 12 countries. This shows that there is no consolidated database or public access to the results for all South American countries. In relation to the results found, it was possible to verify an increase in compensation paid in Argentina, Brazil, and Peru, while for the indicators found, there was a reduction in Chile and Ecuador, an increase in Colombia, and stability in Uruguay, over of the last decade.

The case study in Brazil illustrated the application of ANEEL's current model to define the limits for continuity indicators, covering the analysis of the best and worst sets for a utility in the southern region of the country. The analysis of the sets sought to map the geographic location of the sets of each cluster in order to interpret possible patterns in the clustering. Furthermore, the representation of results, using bubble charts, allowed us to evaluate the dispersion and the relationship of different aspects of the sets of each cluster. Such results are extremely important in planners' decision making.

After the evaluation of the regulatory aspects of the quality of supply for the countries of South America, the future directions illustrated current points that have a growing tendency to participate in the definition of service quality. The DERs associated with the smart grids play a decisive role in the construction of new models to evaluate the performance of effectively meeting the demand for electricity.

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Abbreviations

The following abbreviations are used in this manuscript:

AETN	<i>Autoridad de Fiscalización de Electricidad y Tecnología Nuclear</i>
ANDE	<i>Administración Nacional de Electricidad</i>
ANEEL	<i>Agência Nacional de Energia Elétrica</i>
ARCERNR	<i>Agencia de Regulación y Control de Energía y Recursos Naturales no Renovables</i>
ARCONEL	<i>Agencia de Regulación y Control de Electricidad</i>
BDGD	<i>Base de Dados Geográfica da Distribuidora</i>
CChEN	<i>Comisión Chilena de Energía Nuclear</i>
CELESC	<i>Centrais Elétricas de Santa Catarina</i>

CM_NUC_RES	<i>Consumo médio por unidade consumidora da classe residencial</i>
CNE	<i>Comisión Nacional de Energía</i>
CORPOELEC	<i>Corporación Eléctrica Nacional</i>
CREG	<i>Comisión de Regulación de Energía y Gas</i>
D	<i>Duración Total Ponderada de Interrupciones por Cliente</i>
DEC	<i>Duração Equivalente de Interrupção por Unidade Consumidora</i>
DEP	<i>Duración Equivalente de Interrupción por Potencia</i>
DERs	<i>Distributed Energy Resources</i>
DES	<i>Duración de las Interrupciones del Servicio</i>
DEV	<i>Dienst Electriciteits Voorziening</i>
DIC	<i>Duração de Interrupção Individual por Unidade Consumidora ou por Ponto de Conexão</i>
DICRI	<i>Duração da Interrupção Individual ocorrida em Dia Crítico por Unidade Consumidora ou por Ponto de Conexão</i>
DIU	<i>Duración de Interrupción para el Usuario</i>
Dmax _i	<i>Duración máxima de interrupción de un consumidor</i>
DMIC	<i>Duração Máxima de Interrupção Contínua por Unidade Consumidora ou por Ponto de Conexão</i>
EAS	<i>Energie Autoriteit van Suriname</i>
EBS	<i>Energie Bedrijven Suriname</i>
EDENOR	<i>Empresa Distribuidora y Comercializadora Norte</i>
EDESUR	<i>Empresa Distribuidora Sur</i>
ENRE	<i>Ente Nacional Regulador de la Electricidad</i>
F	<i>Frecuencia Individual de Interrupción en MT y AT</i>
F _s	<i>Frecuencia Media de Interrupción en BT</i>
Fc _a	<i>Frecuencia media de interrupción por consumidor en un Agrupamiento</i>
Fc _i	<i>Frecuencia de interrupción de un consumidor</i>
FEC	<i>Frequência Equivalente de Interrupção por Unidade Consumidora</i>
FEP	<i>Frecuencia Equivalente de Interrupción por Potencia</i>
FES	<i>Frecuencia de las Interrupciones del Servicio</i>
FIC	<i>Frequência de Interrupção Individual por Unidade Consumidora ou por Ponto de Conexão</i>
FIU	<i>Frecuencia de Interrupción para el Usuario</i>
FMIK	<i>Frecuencia Media de Interrupción por kVA nominal instalado</i>
FMIT	<i>Frecuencia Media de Interrupción por Transformador</i>
GEA	<i>Guyana Energy Agency</i>
GPL	<i>Guyana Power & Light</i>
HV	<i>High Voltage</i>
kVA	<i>kilovolt-ampere</i>
kWh	<i>kilowatt-hour</i>
LV	<i>Low Voltage</i>
MME	<i>Ministério de Minas e Energia / Ministerio de Minas y Energía</i>
MPPEE	<i>Ministro del Poder Popular para la Energía Eléctrica</i>
MV	<i>Medium Voltage</i>
MWh	<i>Megawatt-hour</i>
N	<i>Número Total de Interrupciones por Cliente por Semestre</i>
NIC	<i>Número de Interrupciones por Consumidor</i>
NCSD	<i>Normas de Calidad del Servicio de Distribución de Electricidad</i>
NTCSE	<i>Norma Técnica de Calidad de los Servicios Eléctricos</i>
NTCSER	<i>Norma Técnica de Calidad para los Servicios Eléctricos Rurales</i>
NUC_COM	<i>Número de unidades consumidoras da classe comercial</i>
NUC_IND	<i>Número de unidades consumidoras da classe industrial</i>
Osinerghmin	<i>Organismo Supervisor de la Inversión en Energía y Minería</i>
PC_ERMT_3F	<i>Percentual de redes MT trifásicas</i>
PC_NUC_AD	<i>Percentual de número de unidades consumidoras em áreas de alta densidade</i>
PC_VRAM	<i>Percentual de área com vegetação remanescente alta ou média</i>
PLUV	<i>Precipitação pluviométrica média anual</i>
PRODIST	<i>Procedimentos de Distribuição de Energia Eléctrica no Sistema Eléctrico Nacional</i>

RCDE	Reglamento de Calidad de Distribución de Electricidad
RCDSEE	Reglamento de Calidad de Distribución del Servicio de Energía Eléctrica
SAIDI	System Average Interruption Duration Index
SAIFI	System Average Interruption Frequency Index
SEC	Superintendencia de Electricidad y Combustibles
SG	Smart Grids
SSPD	Superintendencia de Servicios Públicos Domiciliarios
ST	Sub-transmission
T	Tiempo Total Individual de las Interrupciones en MT y AT
T_s	Tiempo Total de Interrupción en BT
T_{ca}	Tiempo medio total de interrupción por consumidor en un Agrupamiento
T_{ci}	Tiempo total de interrupción de un consumidor
TIC	Tiempo de Interrupciones por Consumidor
TTIK	Tiempo Total de Interrupción por kVA nominal instalado
TTIT	Tiempo Total de Interrupción por Transformador
TTIU	Tiempo Total de Interrupción para el Usuario
UREE	Unidad Reguladora de la Energía Eléctrica
URSEA	Unidad Reguladora de Servicios de Energía y Agua
UTE	Usinas y Transmisiones Eléctricas
VIF	Variance Inflation Factor

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