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Article

Efficiency of the Ecuadorian electricity sector measured through the Dea-Network model

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Abstract: The Ecuadorian electricity sector encompasses generation, transmission, distribution and sales. Since the change of the Constitution in Ecuador in 2008, the sector has opted to employ a centralized model. The present research aims to measure the efficiency level of the Ecuadorian electricity sector during the period 2012–2021, using a DEA-NETWORK methodology, which allows examining and integrating each of the phases defined above through intermediate inputs, which are inputs in subsequent phases and outputs of some other phases. These intermediate inputs are essential for analyzing efficiency from a global view of the system. For research purposes, the Ecuadorian electricity sector was divided into 9 planning zones. The results revealed that the efficiency of zones 6 and 8 had the greatest impact on the overall efficiency of the Ecuadorian electricity sector during the period 2012–2015. On the other hand, the distribution phase is the most efficient with an index of 0.9605, followed by sales with an index of 0.6251. It is also concluded that the most inefficient phases are generation and transmission, thus verifying the problems caused by the use of a centralized model.

Keywords: efficiency; Dea-Network; generation; transformation; distribution; sales

1. Introduction

The trending subjects of business today differ greatly from the past. Previously there was too much focus on profits with much business literature focusing on the drivers of economic performance, which can lead to a neglect of the environment (Ngo, 2021). Research studies have shown that more than three thousand international corporations cause over two trillion dollars in negative social and environmental impacts each year (Dai et al., 2021; Sutherland et al., 2016). The problem of environmental pollution has attracted increasingly widespread attention, and problems such as air pollution, wastewater discharges, and climate warming need to be urgently solved (An et al., 2022). Therefore, realizing a double-win situation between environmental protection and economic development is a hot issue in the modern scientific community, and also a conflict that countries around the world are desperate to resolve (Peng et al., 2020; Zhang et al., 2022). Enterprises in modern society should concentrate not only on economic achievement but also on environmental performance.

According to Mohsin et al. (2021) 70% of the world's energy consumption is attributed to China (28.98%), the United States (17.97%) and India (6.47%); energy consumption has increased due to increasing industrialization and globalization caused by high population and economic growth. According to Tiep et al. (2021), the consumption of electricity in China increased by 7.80%, for this reason the access of private producers to the market was increasing. (Susanty et al., 2022) Indonesia is expected to be one of the 4 large economies in 2050, and since 2000 the demand for electricity has grown by 6% each year.

According to CAF (2013) energy losses are a costly phenomenon, especially in Latin America, being those associated with electricity the highest in the world and representing approximately 14% of total production, so the challenge is to obtain the same benefit from current consumption using fewer resources. Each percentage point equates to nearly $500 million wasted each year due to technical (such as mechanical constraints) and non-technical (such as traffic congestion) reasons. These inefficiencies in energy transformation and distribution can be addressed through energy efficiency policies.

For the particular case of Ecuador, the total amount of electricity production increased by 41.08% from 2012 to 2021; in the latter year a total of 32,570.68 GWh was produced, including 32,206.88 GWh of own production and 363.80 GWh of imported electricity.

As in Latin America, electricity losses in the Ecuadorian system are also significant; 13.06% of the electricity available in the system is lost. The value has not changed much in the last 10 years, with a percentage loss of 13.6% in 2012, when 18,720.95 GWh were produced, decreasing slightly in 2017 (11.4%) and 2018 (11.3) (Agencia de Regulación y Control de Energía y Recursos Naturales No Renovables, 2021).

The constant losses of electric energy translate into system inefficiencies even more if they are public companies, which represent a cost both in terms of welfare and monetary resources for the countries and particularly in economies with high budgetary restrictions such as the case of Ecuador; that is why we seek to determine the factors that affect the processes of generation, transformation and distribution of electric energy, identifying the inefficiencies of the system and its opportunities for improvement.

2. Literature review

Measuring overall or economic efficiency can be assessed to both energy producing and consuming companies, and the entire electricity system in general so Xie et al. (2012) and Liu and Wang (2015) point out. On the other hand, Jamasb et al. (2017) propose reforms that achieve lasting benefits that are aligned to meet the objectives of economic efficiency in the electricity sector of developing countries. Authors such as Diaz (2018), Halkos and Polemis (2018), Wu et al. (2018) and Zhang et al. (2018), highlight in their research that, both in emerging economies and developed countries, they have the need to measure the economic efficiency of their electric power systems, for such reason, they agree that the overall efficiency must exceed 0.5, comprising the scale from 0 to 1, for an electricity system to be efficient. However, Petridis et al. (2019) and Alizadeh et al. (2019) highlight the energy losses found in the energy distribution processes. Alasinrin et al. (2020) and Cardoso et al. (2020) state that the increase in electricity demand can cause large energy losses, as some utilities do not support the specific distribution loads.

While Poupeau (2020) mentions that the authorities keep the electric power system excessively controlled, Mousavizadeh et al. (2020) demonstrate that, in the study conducted between the two stages, the DEA-Network model can provide accurate estimates of efficiency costs. In addition, Almeida (2020), Tavassoli et al. (2020) and Ouyang and Yang (2020) identified that through the application of DEA-Network model, there is an increased inefficiency due to increased demand in power systems, for example, one of the distribution companies in Iran achieved an efficiency of 0.8487, but another one obtained a score of 0.4667 which makes it inefficient, so the application of this model can also provide policy makers with more detailed results than the single process method. This model is implemented to estimate the efficiency of the whole system that includes production, transfer and circulation among the companies that make up the sector, seeking the optimization of the outputs involved in the process (Cong et al., 2021; Gharizadeh et al., 2021; Maradin et al., 2021). Sustainability in energy system transition requires that economic efficiency is high, and if not, corrective or boosting measures are applied respectively (Aldieri et al., 2021; Mohsin et al., 2021).

The model described above highlights a specification in several investigations, since the intermediate inputs serve as outputs for the new phases of the production, transformation, distribution and commercialization process of electricity companies, for this reason, energy inefficiency is perceived when electricity wastes increase, and in the face of the growing demand for electricity makes the system not optimal (Dolsak et al., 2022; Sun and Huang, 2021; Susanty et al., 2022; Tiep et al., 2021; Wang et al., 2021). Finally, an economic or global efficiency is needed within the electricity system since this is a fundamental factor for the production processes of companies and also for household consumption, for such reason, it is sought that this system has the lowest possible loss of electrical energy (Lan et al., 2022; Medeiros et al., 2022; Wei et al., 2022; Zhao et al., 2022).

2.1. Ecuadorian electricity sector

The Ecuadorian electric sector in 2021 obtained generation levels of 8,734.4 MW of nominal power and 8,100.68 MW of effective power according to the Atlas of the Ecuadorian Electric Sector, 2021. On the other hand, it is necessary to indicate that there was a total of 555 generating, self-generating and distributing companies with generation that contributed with energy production.

On the other hand, it was possible to calculate that the nominal power in the year 2021 reached 8734.41 MW; of which 5308.27 MW representing 60.77 % of the total, these values correspond to plants with renewable energy sources. In addition, the remaining 39.23 % are of the 3426.14 MW belonging to non-renewable energy plants.

Among the renewable energy sources for electricity generation are: hydro, biomass, photovoltaic, wind and biogas. The most representative source of reproduction was hydroelectric, with an installed capacity of 5,106.85 MW or 96.21% of the national total, followed by biomass with 2.72%, photovoltaic with 0.52%, wind with 0.40% and biogas with 0.16%. The plants that provide renewable energy sources are located in 2 provinces on the coast, 9 in the highlands and 4 in the Amazon region.

On the other hand, the generation plants with non-renewable energy sources that consider the use of fossil fuels, i.e., those derived from oil and natural gas, registered a nominal power reached of 3426.14 MW. There are three sources which are: internal combustion engines MCI that generated 2020.67 MW, turbogas plants with 943.85 MW and finally turbo-steam plants with 461.63 MW respectively. Additionally, the renewable nominal power in isolated systems reached 13.90 MW, while the non-renewable type registered a total of 1362.67 MW installed in the Ecuadorian Amazon.

In accordance with the 257,215.30 km^2 of Ecuador's territorial area, the distribution units are represented as follows: 11 business units belonging to Empresa Eléctrica Pública Estratégica Corporación Nacional de Electricidad (CNEL EP) and 9 to electric utilities. Finally, it is worth mentioning that the gross electric energy production in Ecuador was 32,206.88 Gwh and the national demand reached 21,248.40 Gwh, distributed in 19,791.80 Gwh of the Public Electric Energy Service (SPEE) and 1456.60 Gwh to the General Public Lighting Service (SAPG).

2.2. Electricity markets

In the international context, the aim is to increase efficiency levels in the electricity industry. In recent years it has become normalized to move from vertically integrated monopolies to perfect markets. Consequently, this process has been visualized under regulations and restructuring to privatize the sector; however, the policies applied in each country have been different, which has allowed the generation of new markets with specific characteristics and requirements.

According to Bazan (2011), the so-called models of the reformed electricity system have been identified, including the monopoly model, single buyer, centralized, decentralized and wholesale models.

2.3. Monopolistic model

The research conducted by Flores and Santos (2015) defines the electricity sector as a natural monopoly due to the indication that efficiency levels increased with size, i.e., presenting strong economies of scale. In addition, Joskow (2003) points out that the model is managed with minimum cost criteria, in accordance with the advantages offered by the coordination of generation, transmission, distribution and commercialization of energy.

Therefore, the monopolistic model in the electricity sector maintains the participation ratio solely and exclusively in a single company. Under this scenario, there is no free market competition, since the monopolistic entity is the sole supplier of electricity to consumers. In effect, consumers feel uncertainty due to price fixing, on the other hand, this organization lacks incentives to improve its efficiency and subsequently limits itself to participate in innovation processes for the industry.

2.4. Single buyer model

Based on Díaz (2009) the single buyer model is identified as a monopsony, that is, an exclusive buyer, in this case the local electric company, maintains energy acquisitions with the available plants, so that there is only competition in generation. In turn, Molina (2017) states that this model does not allow a competitive tariff for the final consumer, due to the fact that the sole buyer trades long-term contracts with generators and distributors. However, Kirschen and Strbac (2004) mention that this model under a competitive bidding mechanism allows receiving the cheapest offers for the construction of new capacity.

Based on the above, it can be stated that this model maintains an organizational structure in which only one entity, usually a government agency, has the exclusive responsibility for acquiring the electricity generated in its entirety within a specific area.

2.5. Centralized model

For the centralized model of the electricity market Liera, Gutiérrez and Tovar (2011) state that operations in the system are governed by a detailed optimization of generation resources, therefore, they are intertwined in a pool with the objective of satisfying the electricity demand in the most profitable way, preserving the visible restrictions within the electricity grid.

On the other hand, optimization refers to the allocation of generation units, where it is obtained which units have to be synchronized and at which power levels they should operate. Consequently, a system operator supervises this process, managing the operation of the transmission and commercialization phase. Thus, in this model, the generators propose offers to the pool, visualizing cost functions and operational restrictions (Wilson, 2001).

Therefore, once the unit allocation problem is solved, the pool calculates various price components, including the marginal price of the phase, which determines the price of active power and is structured so that the generation organizations recover their total costs.

2.6. Decentralized model

Decentralized models emerged with the purpose of establishing a more transparent energy trading mechanism in response to criticisms of the complexity and information requirements of the centralized model (Wilson, 2001). In a decentralized model, market activities are separated from power system operations. In early examples, such as the California market, there were two operators: the market operator (MO) and the independent system operator (ISO). The Power Exchange (PX) acted as the market operator, receiving single bids from suppliers and consumers one day in advance for the purchase and sale of active power. For each hour, the PX organized the bids to form supply/demand curves, the intersection of which defined the unit allocation and the market spot price. After the auction, the PX transmitted the accepted power to the ISO, which evaluated its viability from a transmission network perspective.

In this type of market Hogan (2005) states that the supply strategies of generation companies must be designed to recover costs and comply with the operating restrictions of their units.

3. Methodology

The method applied is the hypothetical-deductive method, due to the fact that empirical background of studies that show the efficiency of the electric sector in different regions of the world is gathered, in addition, the deductive method is applied since the expected results in the electric system of Ecuador may show variations in the levels of efficiency that would not be optimal.

In the words of Hernández et al. (2010), the hypothetical-deductive method is based on deductive logic, which is referred to as the reasoning process that starts from the general to the specific, that is, it begins from a theory or general principle, and in turn hypotheses are formulated and empirical tests are carried out to check the validity of the hypotheses.

This research assumes a quantitative approach, because it incorporates data on generation, transformation, distribution and consumption of the Ecuadorian electricity sector; at the same time, it is non-experimental and descriptive. It is descriptive because it analyzes the behavior of the variables (inputs-outputs) that affect the efficiency of the Ecuadorian electricity sector.

The research design is non-experimental because there is no manipulation of the variables, as the study develops naturally, in addition, the research problem will be solved as it happens in reality. In turn, the study is complemented with secondary sources of information, such data come from the Agency for Regulation and Control of Energy and Non-Renewable Natural Resources (2021), an institution related to the research work.

The population is considered to be the historical data of the variables analyzed during the period 2012–2021. The sample covers the 9 planning zones of Ecuador considered below in **Table 1**:

Table 1. DMU's of the SEE efficiency study.

DMU	Planning Zone	Member provinces
01	Zone 1	Esmeraldas Carchi Imbabura Sucumbíos
02	Zone 2	Pichincha (except Quito canton) Napo Orellana
03	Zone 3	Pastaza Cotopaxi Tungurahua Chimborazo
04	Zone 4	Manabí Santo Domingo de los Tsáchilas
05	Zone 5	Guayas (except the cantons of Guayaquil, Durán and Samborondón) Los Ríos Santa Elena Bolívar Galápagos

Table 1. (*Continued*).

DMU	Planning Zone	Member provinces
06	Zone 6	Azuay Cañar Morona Santiago
07	Zone 7	El Oro Loja Zamora Chinchipe
08	Zone 8	Cantón Guayaquil Cantón Durán Cantón Samborondón
09	Zone 9	Distrito Metropolitano de Quito

Note: The table shows the different information of the 9 planning zones of Ecuador according to SENPLADES (2010).

For the electric power generation process, the companies shown in **Table 2** will be taken into account, based on the GEO PORTAL of the Ecuadorian electric system:

Table 2. Electricity generating companies.

Company	Province of location
Agroazucar	Cañar
Altgenotec	Guayas
Brineforcorp	Manabí
Cbsenergy	Carchi
CELEC-Coca Codo Sinclair	Imbabura
CELEC-Coca Codo Sinclair	Napo
CELEC-Electroguayas	Guayas
CELEC-Electroguayas	Santa Elena
CELEC-Gensur	Loja
CELEC-Gensur	Zamora Chinchipe
CELEC-Hidroagoyán	Tungurahua
CELEC-Hidroazogues	Cañar
CELEC-Hidronación	Guayas
CELEC-Hidronación	Los Ríos
CELEC-Hidrotapi	Pichincha
CELEC-Sur	Azuay
CELEC-Termoesmeraldas	Esmeraldas
CELEC-Termogas Machala	El Oro
CELEC-Termomanabí	Manabí
CELEC-Termopichincha	Pichincha
Elecaustro	Azuay
Electrisol	Pichincha
ElitEnergy	Napo

Table 2. (*Continued*).

Company	Province of location
EMAC-BGP	Azuay
Enersol	Manabí
Epfotovoltaica	Cotopaxi
EPMAPS	Pichincha
Gasgreen	Pichincha
Generoca	Guayas
Gonzanergy	Loja
Gransolar	Imbabura
HidroImbabura	Imbabura
Hidrosibimbe	Los Ríos
Hidrosierra	Tungurahua
Hidrosigchos	Cotopaxi
Hidrotambo	Bolívar
Hidrotavalo	Imbabura
Hidrovictoria	Napo
I.M. Mejía	Pichincha
Intervisa Trade	Guayas
IPNEGAL	Pichincha
Lojaenergy	Loja
Municipio Cantón Espejo	Carchi
Renova Loja	Loja
Sanersol	El Oro
Sansau	Guayas
Saracaysol	El Oro
SERMAA EP	Imbabura
Solchacras	El Oro
Solhuaqui	El Oro
Solsantonio	El Oro
Solsantos	El Oro
Surenergy	Loja
Valsolar	Imbabura
Widtecsa	Guayas

Note. Based on Agencia de Regulación y Control de Energía y Recursos Naturales No Renovables (2021).

On the other hand, **Figure 1** shows the scope and types of transmission lines that exist in the Ecuadorian electrical system:

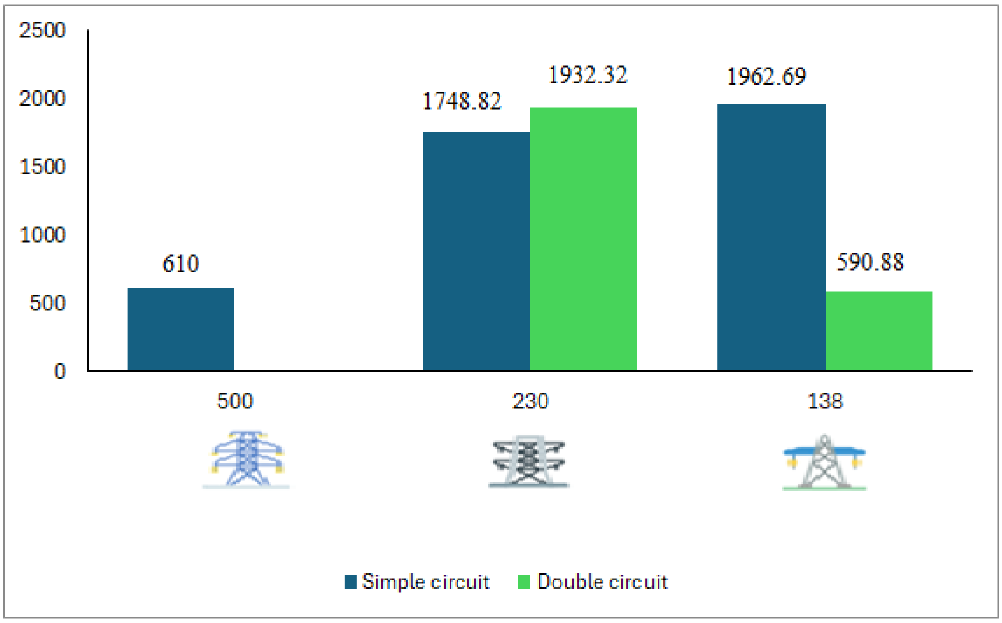

Figure 1. Length of transmission lines (km), by circuit type and voltage level.

Note: Information gathered from the atlas 2021 of the Ecuadorian electricity sector.

Finally, **Table 3** shows the companies that participate in the energy distribution process in the Ecuadorian electricity system:

Table 3. Electricity distribution companies in the Ecuadorian electricity system.

Company	**Province of location**
CNEL-Sucumbíos	Sucumbíos
CNEL-Esmeraldas	Esmeraldas
CNEL-Santo Domingo	Santo Domingo
CNEL-Manabí	Manabí
CNEL-Guayas Los Ríos	Guayas
CNEL-El Oro	El Oro
CNEL-Sta. Elena	Santa Elena
CNEL- Milagro	Guayas
CNEL-Bolívar	Bolívar
CNEL-Los Ríos	Los Ríos
CNEL-Guayaquil	Guayas
E.E. Ambato	Tungurahua
E.E. Centro Sur	Azuay
E.E. Sur	Loja
E.E. Quito	Pichincha
E.E. Norte	Carchi
E.E. Galápagos	Galápagos
E.E. Riobamba	Chimborazo
E.E Cotopaxi	Cotopaxi
E.E Azogues	Cañar

Note: Information obtained from the atlas 2021 of the Ecuadorian electricity sector.

To understand the efficiency of the Ecuadorian electricity sector, its key processes are broken down in **Table 4**, which presents the inputs and outputs that define each stage, from generation to the final sale of energy.

Table 4. Factors influencing the efficiency of the Ecuadorian electricity sector.

Processes	Inputs (x)		Outputs (y)	
F1 Generation	a^1	Installed generating capacity (MW)		
		Electricity generating units (#)		
Output (Intermediate input) →			b^1	Electrical energy generated (GWh)
F2 Transmission	a^2	Transmission Lines (Km)		
Output (Intermediate input) →			b^2	Electrical energy transmitted (GWh)
F3 Distribution	a^3	Electrical energy received in distribution (MW)		
		Electric power distribution units (#)		
Output (Intermediate input) →			b^3	Distributed electric energy (GWh)
F4 Sales	a^4	Number of employees of the distribution companies (#)		
Output (Output) →			b^4	Electrical energy sold (GWh)

Note: The table shows the inputs, inputs (intermediate) and outputs that affect the efficiency of the Ecuadorian electricity sector. Period 2012–2021.

In addition, **Table 5** presents the mathematical model used for the efficiency analysis based on the DEA-Network methodology. This model is designed to evaluate the performance of the different entities within the Ecuadorian electricity sector by considering both the inputs and outputs across interconnected phases.

The DEA-NETWORK model is called static, and can be used to measure performance over time, the comparative static model takes technology and inputs as fixed and exogenous in each period, however, technical change can occur over time. This idea has been used to model productivity change in a DEA framework. In terms of (Färe and Grosskopf, 2000) this model maintains a set of technologies or sub-processes with common characteristics, while retaining linear constraints.

Four nodes can be seen in the model. The first $\alpha^1({}_0^1a)$, is given by (a) to (c). The second one $\alpha^2({}_0^2a, {}_1^2b,)$, consists of the expressions (d) to (h). The third α^3 $({}_0^3a, {}_2^3b, {}_3^4b,)$ with expressions (i) to (h) and the last $\alpha^4({}_0^4a, {}_2^4b, {}_3^4b, {}_4^4b,)$ given by (m) to (q).

It can be seen that the mathematical model maintains intermediate products and assigned inputs. It must be considered that a product is intermediate in the production process if it is produced and consumed, i.e., it is both an output and an input, within the network and that not all intermediate goods are necessarily demanded or consumed within the network; since they can also be presented as final outputs.

Finally, the outputs produced by subprocesses $\boldsymbol{i}$ is delivered to node j by ${}_i^jb$.On the other hand, it can be observed that the production of node 1 generates an intermediate product output denoted as ${}_1^2b$, this phase does not keep any intermediate product as input. Node 2 or phase 2 collects as intermediate input ${}_1^2b$ coming from phase 1 and in turn, generates the output${}_2^3b$, without producing any final output. Likewise, node 3 receives the intermediate input b from node 2 to node 3, producing the output b from node 3 to node 4, which is sent to node 4. Finally, phase 4 produces the final output b from node 4 to the output node. In general, each of the phases receives an exogenous input denoted by ${}^{1}_{0}a,\ {}^{2}_{0}a,\ a\ and\ {}^{4}_{0}a$, respectively, as mentioned in the constraint posed at the beginning of this analysis.

Table 5. DEA-Network mathematical model for the efficiency analysis of the Ecuadorian electricity sector.

Phase	Sequence	Equation/Description
Phase 1:	a	${}^{2}_{1}b_p \le \sum_{k=1}^{k} z_k^1\, {}^{2}_{1}b_{kp}, p = 1, \dots, P^1,$
	b	$\sum_{k=1}^{k} z_k^1\, {}^{2}_{1}a_{kq} \le {}^{1}_{0}a_q, q = 1, \dots, Q,$
	c	$z_k^1 \ge 0, k = 1, \dots, K$
Phase 2:	d	${}^{3}_{2}b_p \le \sum_{k=1}^{k} z_k^2\, {}^{3}_{2}b_{kp}, p = 1, \dots, P^2,$
	e	$\sum_{k=1}^{k} z_k^2\, {}^{2}_{0}a_{kq} \le {}^{2}_{0}a_q, q = 1, \dots, Q,$
	f	$\sum_{k=1}^{k} z_k^2\, {}^{2}_{1}b_{kp} \le {}^{2}_{0}b_p, p = 1, \dots, P^1,$
	g	$z_k^2 \ge 0, k = 1, \dots, K$
Phase 3:	h	${}^{4}_{3}b_p \le \sum_{k=1}^{k} z_k^3\, {}^{4}_{3}b_{kp}, p = 1, \dots, P^3$
	i	$\sum_{k=1}^{k} z_k^3\, {}^{3}_{0}a_{kq} \le {}^{2}_{0}a_q, q = 1, \dots, Q,$
	j	$\sum_{k=1}^{k} z_k^3\, {}^{3}_{2}b_{kp} \le {}^{3}_{2}b_p, p = 1, \dots, P^2,$
	k	$z_k^3 \ge 0, k = 1, \dots, K$
Phase 4:	l	${}^{5}_{4}b_p \le \sum_{k=1}^{k} z_k^4\, {}^{5}_{4}b_{kp}, p = 1, \dots, P^4$
	m	$\sum_{k=1}^{k} z_k^4\, {}^{4}_{0}a_{kq} \le {}^{4}_{0}a_q, q = 1, \dots, Q,$
	n	$\sum_{k=1}^{k} z_k^4\, {}^{4}_{3}b_{kp} \le {}^{4}_{3}b_p, p = 1, \dots, P^3,$
	o	$z_k^4 \ge 0, k = 1, \dots, K$
Distribution of exogenous inputs	p	${}^{1}_{0}a_q + {}^{2}_{0}a_q + {}^{3}_{0}a_q + {}^{4}_{0}a_q + \le a_q, n = 1, \dots, Q$
Calculation of overall system efficiency	q	$\frac{F_1 + F_2 + F_3 + F_4}{4} = K \le 1$

Note: Own elaboration based on Färe and Grosskopf (2000) and Moreno et al. (2015).

4. Results and discussion

The efficiency of a firm can be presented through a production function, which denotes the maximum achievable output value as various combinations of inputs interact, on the other hand, the calculation of an efficiency index is essential to observe which organizations are on the production frontier and which are far from it (Diaz, 2018).

Consequently, the resulting efficiency indexes are presented for each of the phases that make up the Ecuadorian electrical system. It should be emphasized that an index equal to 1 shows the maximum level of efficiency achievable; on the other hand, when this indicator is less than 1, it indicates the possibility of improvement compared to other units analyzed. At the moment of obtaining the global efficiency, a new frontier is established in which the intermediate inputs registered in each phase are considered and are paramount.

4.1. Efficiency in the generation phase

Throughout the period 2015–2021, planning zones 5 and 6 were those that carried out the most efficient practices in the Generation process, that is, with the respective electric energy generated and with the correct allocation of resources such as the installed generation capacity (MW) and the electricity generating units that zones 5 and 6 had. On the other hand, zone 1 was the most inefficient region within the generation process recorded in this period.

The efficiency indexes resulting from the generation phase, presented above (**Table 6**), have been calculated in relation to the value of inputs, corresponding to the installed plant capacity and generating units, and as output to the energy generated, the latter were considered as the main factors that have affected the efficiency of the generation process of the Ecuadorian electricity system throughout the period 2015–2021.

Table 6. Generation efficiency ratios 2015–2021.

Year								
DMU	**2015**	**2016**	**2017**	**2018**	**2019**	**2020**	**2021**	**Average**
Z01	0.0176	0.1757	0.1218	0.0887	0.0283	0.0076	0.0112	0.0644
Z02	0.2186	0.2186	0.4939	0.4654	0.4150	0.5186	0.5067	0.4053
Z03	0.5694	0.5694	0.7139	0.6113	0.6462	0.6827	0.7630	0.6508
Z04	0.0014	0.0014	0.0017	0.3325	0.2277	0.2812	0.2466	0.1561
Z05	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000
Z06	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000
Z07	0.0052	0.5199	0.5879	0.4203	0.4586	0.5650	0.5087	0.4379
Z08	0.1748	0.1748	0.2899	0.3650	0.2477	0.2221	0.1724	0.2352
Z09	0.3295	0.3295	0.2106	0.2270	0.2438	0.3301	0.2361	0.2724
Average	0.3685	0.4433	0.4911	0.5011	0.4741	0.5119	0.4939	

Note: Own elaboration.

It is evident that the most inefficient zone is zone 1, with an average of 740.37 MW in installed capacity and 89 generating companies on average has generated

696.99 GWh, its inefficiency is demonstrated because with a large number of companies it is not able to produce what other zones with fewer companies and less installed capacity in generation do.

As for zone 5, one of the most efficient zones, with 263.49 MW of installed capacity and 19.28 companies on average it has generated 2437.14 GWh, during the period 2015–2021. On the other hand, in zone 6 it should be noted that the company CELEC-Hidropaute is one of the largest companies in the country in terms of electricity generation, competing directly with the company CELEC-Cocacodosinclair. It should also be noted that this zone with 2,085.16 MW in installed capacity and 16.85 generating companies on average results in 8,771.38 GWh of electricity generated by this zone during the period 2015–2021.

4.2. Efficiency in the transmission phase

According to the period 2015–2021, the only completely efficient zone is number 8, this was the one that best performed its activities in the electric power transmission phase, in addition, it maintained a correct allocation of resources such as high transmission lines. In a sense of inefficiency, zone 2 is visualized, which will be described in detail later on.

The indexes shown in the transmission phase, presented in **Table 7**, were calculated through the intermediate input, which helps to interrelate the generation process with the transmission phase, the input transmission lines and the output, represented by the transmitted energy; these have been considered for the present study, as the factors that affect the efficiency of the transmission phase of the Ecuadorian electrical system throughout the period 2015–2021.

Table 7. Transmission efficiency ratios 2015–2021.

Year								
DMU	**2015**	**2016**	**2017**	**2018**	**2019**	**2020**	**2021**	**Average**
Z01	0.2436	0.1840	0.2624	0.4551	0.9385	1.0000	1.0000	0.5834
Z02	0.1505	0.0882	0.0849	0.0842	0.0753	0.0243	0.1133	0.0887
Z03	0.2058	0.2094	0.1995	0.2250	0.2001	0.2224	0.2008	0.2090
Z04	1.0000	1.0000	1.0000	0.9590	1.0000	0.8871	0.8355	0.9545
Z05	0.2737	0.2782	0.3093	0.4135	0.3781	0.3417	0.3712	0.3380
Z06	0.1951	0.1698	0.1640	0.1490	0.1394	0.1465	0.1393	0.1576
Z07	0.1782	0.1559	0.1843	0.2333	0.2450	0.2076	0.2204	0.2035
Z08	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000
Z09	0.7406	0.7358	1.0000	1.0000	0.9711	0.7390	0.8505	0.8624
Average	0.4431	0.4246	0.4672	0.5021	0.5497	0.5076	0.5257	

Note: Own elaboration.

Zone 8 participated throughout the period 2015–2021 with 1266.85 GWh of energy generated as input-intermediate, 303.38 kilometers of transmission lines, these inputs generated as output 960 MW, it should be emphasized that these values are calculated on average among the entire study period.

Zone 2 being the most inefficient in the transmission phase, awarded 5,366.51

GWh of generated electric energy, this variable is considered as an intermediate input, as input of the phase the zone registers 153.14 kilometers of electric energy transmission lines and finally in transmitted electric energy it maintains a value of 32.27 GWh, all these values are calculated in an average over the period 2015–2021.

4.3. Efficiency in the distribution phase

Throughout the period 2015–2021, zones 2 and 8 were those that performed the best efficiency practices in the Distribution phase, this with respect to the electric energy they distributed and the successful allocation of inputs such as transmitted electric energy (input-intermediate), electric energy received in distribution (GWh) and electric energy distribution units.

In **Table 8** shows that the average index of all zones over the period 2015–2021 is found to be 0.9605 which shows that this index is widely close to unity, i.e., the efficiency of the distribution process is evident.

Table 8. Distribution efficiency indexes 2015–2021.

Year								
DMU	**2015**	**2016**	**2017**	**2018**	**2019**	**2020**	**2021**	**Average**
Z01	0.8986	0.8974	0.8858	1.0000	1.0000	0.9760	0.9781	0.9480
Z02	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000
Z03	0.9561	0.9508	0.9203	0.9179	0.8854	0.9135	0.9998	0.9348
Z04	0.9177	0.8849	0.9072	0.9230	0.9033	0.9093	0.9563	0.9145
Z05	1.0000	0.9287	0.8859	0.8753	0.8734	1.0000	0.9010	0.9235
Z06	1.0000	1.0000	1.0000	1.0000	0.9960	1.0000	1.0000	0.9994
Z07	0.9685	0.9771	0.9526	0.9739	0.9517	1.0000	0.6624	0.9266
Z08	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000
Z09	1.0000	0.9833	1.0000	1.0000	1.0000	1.0000	1.0000	0.9976
Average	0.9712	0.9580	0.9502	0.9656	0.9566	0.9776	0.9442	

Note: Own elaboration.

Zone 2 through an input-intermediate which was the transmitted electric energy registering 32.27 MW; 234.12 GWh of electric energy received in distribution and electric energy distribution unit was able to distribute 201.28 GWh, on average during the research period.

On the other hand, zone number 8 with the input-intermediate which was the transmitted electric power with 960 MW; and with the inputs as the electric power received in distribution which obtained 5,633.13 GWh and an electric power distribution company was able to distribute 4,698.48 GWh on average during the period 2015–2021.

4.4. Efficiency in the sales phase

Throughout the period 2015–2021, zone 8 was the one that carried out the best efficiency practices in the sales phase, this with respect to the electric energy they sold and the correct allocation of resources such as the number of workers in each of the distribution companies (National Electric Energy Corporations and the Electric

Companies).

The efficiency indexes resulting from the sales process, presented previously in **Table 9**, have been determined in relation to the value of the intermediate input, which was the distributed energy, which intertwines the distribution process with the sales of electric energy, also the input, number of employees and the output represented by the energy sold or demanded by the final consumers; they have been considered for the present study, as the main factors that have affected the efficiency in the sales process in the Ecuadorian electric system throughout the period 2015–2021.

Table 9. Sales efficiency ratios 2015–2021.

Year								
DMU	**2015**	**2016**	**2017**	**2018**	**2019**	**2020**	**2021**	**Average**
Z01	0.5669	0.5595	0.5689	0.4625	0.5269	1.0000	0.4869	0.5959
Z02	0.7135	0.6996	0.6963	0.6756	0.6445	0.4721	0.6077	0.6442
Z03	0.6730	0.6581	0.6616	0.6401	0.5747	0.7913	0.5367	0.6479
Z04	0.6722	0.6597	0.6614	0.6363	0.5973	0.4422	0.5568	0.6037
Z05	0.2330	0.2254	0.2306	0.2363	0.2031	0.1396	0.1775	0.2065
Z06	0.7528	0.7447	0.7402	0.7762	0.6820	0.4507	0.6373	0.6834
Z07	0.6280	0.6131	0.6086	0.6158	0.5489	0.3830	0.8033	0.6001
Z08	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000
Z09	0.7140	0.6996	0.6963	0.6755	0.6445	0.4713	0.6077	0.6441
Average	0.6615	0.6511	0.6515	0.6354	0.6024	0.5722	0.6016	

Note: Own elaboration.

The most efficient zone and that performed in the best way the activities in the sales phase was number 8 with an efficiency level equal to 1, obtained 4698.48 GWh in distributed energy as intermediate input, 1622 employees as input and as output sold 7127.68 GWh, it is pertinent to note that all these values are calculated on average over the period 2015–2021.

The zone with the highest levels of inefficiency was number 5 which recorded an efficiency level of 0.2065. This zone evidences in that the intermediate input which is the distributed electric energy was 3712.52 GWh, as input which was the number of employees it is observed that they were 2335, and as output it is appreciated 1196.42 GWh of electric energy sold, all the aforementioned data are calculated on average over the study period.

It is said that in the sales process the next zone that shows inefficiency was number 1, since it registers an index of 0.5959, that is, compared to the other zones of the Ecuadorian electrical system it does not exceed the barrier of the index of 0.6000, and that on average zones 2, 4, 6, 7 and 9 register an index of 0.6372, which in relation to zone 5 performs better the activities in the sales process.

4.5. Global efficiency

Global efficiency is an analysis that links each of the phases that make up the Ecuadorian electrical system: generation, transmission, distribution and sales. In general, the zone that maintains a value close to 1 and would demonstrate higher efficiency indexes would be number 8, and the inefficient zone within the Ecuadorian electric system during the 2015–2021 period corresponds to number 2. **Table 10** presents the overall efficiency ratios for the indicated period.

Table 10. overall efficiency ratios 2015–2021.

Year								
DMU	**2015**	**2016**	**2017**	**2018**	**2019**	**2020**	**2021**	**Average**
Z01	0.4317	0.4541	0.4597	0.5016	0.6234	0.7459	0.6190	0.5479
Z02	0.5207	0.5016	0.5688	0.5563	0.5337	0.5037	0.5569	0.5345
Z03	0.6011	0.5969	0.6238	0.5986	0.5766	0.6524	0.6251	0.6106
Z04	0.6479	0.6365	0.6426	0.7127	0.6821	0.6299	0.6488	0.6572
Z05	0.6267	0.6081	0.6065	0.6313	0.6136	0.6203	0.6124	0.6170
Z06	0.7370	0.7286	0.7260	0.7313	0.7044	0.6493	0.6942	0.7101
Z07	0.4450	0.5665	0.5833	0.5608	0.5510	0.5389	0.5487	0.5420
Z08	0.7937	0.7937	0.8225	0.8412	0.8119	0.8055	0.7931	0.8088
Z09	0.6960	0.6870	0.7267	0.7256	0.7149	0.6351	0.6736	0.6941
Average	0.6111	0.6192	0.6400	0.6510	0.6457	0.6424	0.6413	

Note: Own elaboration.

The efficiency index in the zone shows an upward trend; however, in the year 2021 there is a drop in this index and the average efficiency of this zone is 0.5479. On the other hand, zone 2 maintains a variable behavior, but without dropping below the 0.5000 barrier. In addition, zone 3 has achieved an average efficiency value of 0.6106 throughout the study period.

Zone 4 has a peak where the efficiency reached its highest level in 2018, registering a value of 0.7127, being the highest of the whole period. Zone 5 surpasses the 0.6000 frontier as it registers an average value of 0.6172 during the period 2012–2021. Zone 6 in particular is shown as the second most efficient as it registers a value of 0.7101 during the period under study. Zone 7 registers an index of 0.5472, placing it above zones 1 and 2, respectively. Zone 8, as mentioned above, is the most efficient within the Ecuadorian electrical system, registering a value of 0.8088, and finally, zone 9 shows an index of 0.6941 of global efficiency.

5. Discussion

In relation to the study conducted by Liu and Wang (2015) where they measure the level of efficiency in 30 regions of China, the research shows that the overall efficiency levels in the north of this country are below 0.5000, but the eastern zones are close to unity, i.e., they show significant efficiency. In the Ecuadorian electricity sector, a totally different behavior occurs, since the efficiency level in the planning zones exceeds the 0.5000 barrier; four zones are between 0.6000 and 0.6999; zone 6 obtained 0.7101 and zone number 8 resulted with an index of 0.8088, that is, the last zone is the only one that is closer to unity, but does not exceed the 0.9000 barrier. Both studies use the DEA-Network model, and the results show in which zones or regions corrective measures can be applied for improvement in the electricity sector of both nations.

Comparing the study of Diaz (2018) Efficiency of the Mexican Electricity Sector 2008–2015 an application of the DEA NETWORK model, where four nodes are considered within the system; according to generation, the installed generation capacity and the electricity generating units are considered as inputs and as output and intermediate input the generated electric energy. On the other hand, in the transmission node, the energy received in transmission and the transmission lines are considered as inputs, and the transmitted electric energy is considered as output and intermediate input. For the distribution node the inputs were the electric energy received in distribution, the distribution lines and the transformation capacity, and as output and intermediate input the distributed electric energy, and finally in the sales node the inputs were the electric energy received in sales and the number of employees and as output the electric energy sold, the combination of these factors resulted in an average efficiency index of 0.8698.

On the other hand, for the Ecuadorian electricity sector, the generation phase considers as inputs the installed generation capacity and the electricity generating units and as output and intermediate input the electricity generated; for the transmission phase, the transmission lines are considered as the only input and as output and intermediate input the electricity transmitted; on the other hand, for the distribution phase, the inputs are the electricity received in distribution and the electricity distribution units, and as output and intermediate input the electricity distributed, for the distribution section the inputs were the electric energy received in distribution and the electric energy distribution units and as output and intermediate input the distributed electric energy, finally for the sales phase the input was considered as the number of employees of the distributors and as output the electric energy sold, the combination of these factors generated an average global efficiency index of 0.6358 for the period 2015–2021.

According to the research conducted by Tavassoli et al. (2020) where they apply a DEA-Network methodology to measure the overall efficiency level of the Iranian electric system, they have provided efficiency levels in the generation system of 0.3318, in electric power transmission 0.6349 and in distribution 0.7156. With respect to the study conducted to measure the efficiency in the Ecuadorian electricity sector period 2015–2021, 4 phases have been considered; generation with an efficiency level of 0.4691, transmission 0.4886, distribution 0.9605 and including to the study the sales phase with an efficiency index of 0.6251. Considering the comparison that both Iran and Ecuador are considered developing economies, the application of activities within the electrical system is carried out more efficiently by Ecuador.

Based on Alizadeh et al. (2020) and considering their research on the global efficiency measurement of Iran’s electricity sector through a dynamic DEA-Network model, which establishes a global summation of the efficiency of each system, in this case generation, transmission and distribution of each province of this nation, an overall efficiency in the year 2017 of 0.780 is obtained; 2018 of 0.726 and 2019 of 0.677. In relation to the research conducted for the Ecuadorian electricity sector and considering the indexes of 2017 with 0.6400; 2018 with 0.6510 and 2019 with 0.6457, it is assumed that the best performed practices were in the nation of Iran for this period.

6. Conclusions

This paper concludes that the study of the Ecuadorian electricity sector period 2012–2021 did not have the necessary data to complete the years 2012, 2013 and 2014 due to the uniformity in the presentation of statistical series imposed by the Agency for Regulation and Control of Renewable Resources based on Article 15 where it mentions the duties and powers of the organization, which comes into force from 16 January 2015, for this reason, the period 2015–2021 was considered for the study.

The Ecuadorian electricity sector, distributed in 9 planning zones, has four phases: generation, transmission, distribution and sales. The average efficiency level for the generation node was 0.4691, in transmission 0.4886, in distribution 0.9605 and finally in sales 0.6251. It can be seen that the phase with the highest level of efficiency is the electricity distribution process.

Finally, the use of data envelopment analysis by networks (DEA-Network) allowed determining the overall efficiency level for the Ecuadorian electricity sector during the period 2015–2021, according to a dynamic analysis based on a weighted sum of the efficiency of each phase and thus determine the overall efficiency of the entire sector. Thus, the average efficiency of the entire sector and in relation to the study period was 0.6358, which shows that the Ecuadorian electricity sector is moderately efficient and highlights the electricity losses identified in the problem of this research.

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