Integration of photovoltaic generation for large industrial consumers connected to distribution systems

Marco A. Toledo, Carlos Álvarez-Bel
Institute for Energy Engineering
Universitat Politècnica de València
Valencia, España
martoor@doctor.upv.es, calvarez@die.upv.es

J. X. Pachar, W.A. Quizhpi, Flavio A. Quizhpi
Carrera de Ingeniería Eléctrica
Universidad Politécnica Salesiana
Cuenca, Ecuador
jpachars@est.ups.edu.ec, wquizhpit@est.ups.edu.ec, fquizhpi@ups.edu.ec

***Abstract*—Technological advances in solar photovoltaic generation have considerably reduced equipment costs in new facilities, which is why this research focuses on determining the generation capacity through the use of existing infrastructure, solar radiation measurements and demand, to meet the demand for electrical energy through the application of forecasting models with the use of data analytics techniques and neural networks in order to determine the technical benefit in product quality, the reduction of demand peaks, mitigate transmission losses and provide greater reliability to the electrical system of the industry and utility.**

***Index Terms*—Distributed Generation, Load Profile, Photovoltaic Solar Radiation, Forecasting, Data Analytics.**

I. Nomenclature

DG: Distributed Generation.
SPV: Solar Photovoltaic.
PSH: Peak Solar Hour.
LC: Large Consumers.
EPS: Electric Power System.
EDS: Energy Distribution System.
ANN: Artificial Neural Networks.

II. Introduction

The electrical energy systems in its supply chain have kept the consumer in a passive state for decades, a constant that limits the management of their demand resources and the generation contribution that these could add to the Energy Distribution Systems (EDS). In recent years, these systems have taken on strategic importance since they are located close to demand, through a common connection point with the electrical distribution system, which is why they are studied in-depth to obtaining promising results published in compendia that standardize Distributed Generation (DG) [1], [2].

In Ecuador, the lack policies that govern the planning, operation of distributed generation and demand management systems, limit the grown of these technologies; furthermore, the electricity market is vertically integrated, are oligopolistic, where the generation, transmission, and distribution of energy belong from the state. Moreover, they grow in a disorderly way with projects of medium and small scale within the distribution networks [3]. In this sense, these research opens up a range of opportunities, in such a way that Large Consumers (LC) use their existing infrastructure to install and generate electricity in order to satisfy part or all of their demand within the stochasticity of generation, as indicated by the specialized literature reviewed in this research [4], [5].

The DG in Latin America is led in its great majority by multiple photovoltaic solar projects since its construction is more economical and easy to install; the countries in the region with the highest indicators in a photovoltaic solar generation are, Brazil with an installed capacity of 1.2 GW in 101,761 projects with a cut in 2019 and it is expected to reach 12 GW in 2027, the second country with the highest contribution is Chile, has solar projects below 10 MW connected to medium and low voltage distribution networks, has an installed capacity that exceeded 780 MW in 2019 and 1.2 GW of future capacity is expected to be included in 2025 [6] [7].

The ecuadorian electricity sector has carried out important works aimed at guaranteeing electricity supply, prioritizing the participation of renewable energies, especially hydroelectricity. In 2018 there were 8,826 MW of installed capacity, of which 59.84% correspond to renewable sources and 40.16% to non-renewable sources [8]. Currently, the country does not have a regulation that legislates the DG, it only has a regulation "ARCONEL 003/18 - Photovoltaic microgeneration for self-supply of final consumers of electrical energy", which allows residential regulated users to generate up to 100 kW for their consumption, while, for commercial and industrial rate customers, the generation limit is 500 KW under the same purpose [9], the settlement will be monthly through a net between the generation supply and the demand for electrical energy, without the surplus being recognized to the generator at its real cost.

It is important to consider that the cost of photovoltaic solar energy has come to compete with conventional technologies, which is why it is currently considered a great option to

This work was supported by Universitat Politècnica de València, Camino de Vera, s/n 46022 Valencia, Tel. (+34) 96 387 70 00 - Spain and the Universidad Politécnica Salesiana, Calle Vieja, Cuenca 010105 - Ecuador.

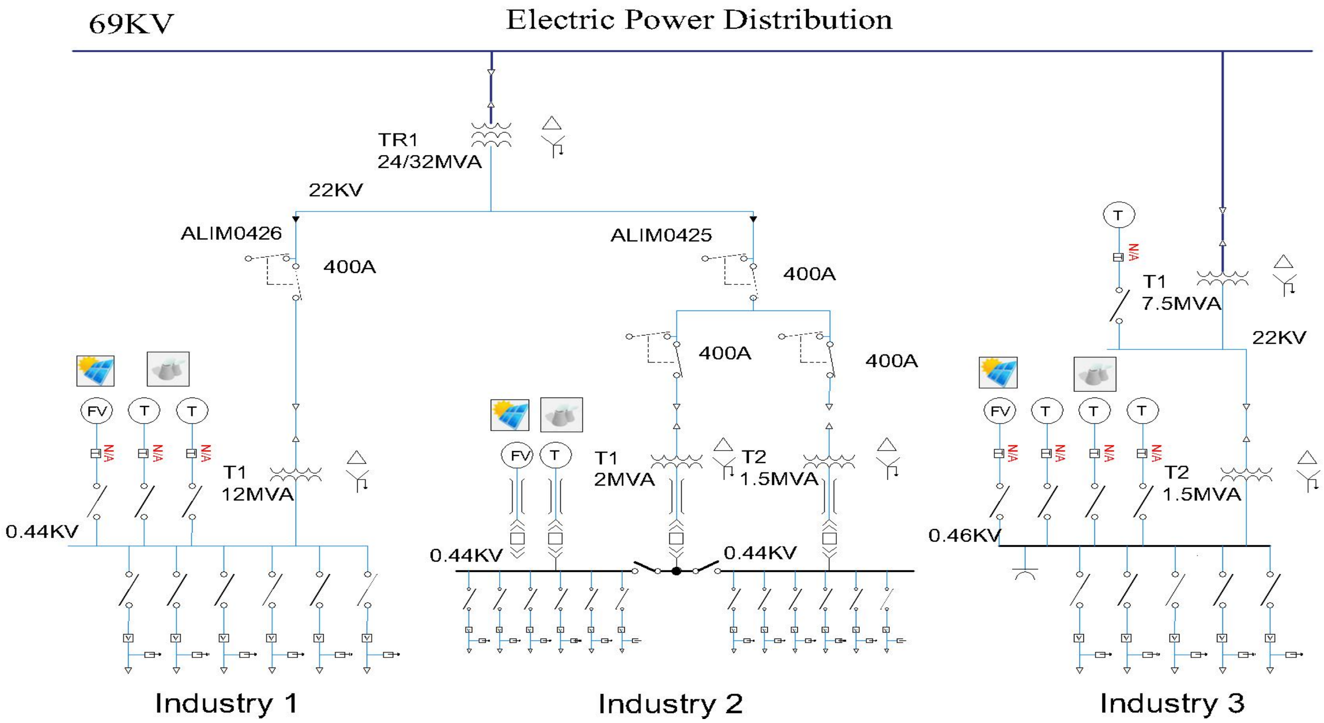

Fig. 1. Single-line diagram of the S/E of the Utility - Industry with Distributed Solar Photovoltaic Generation.

meet demand after a technical and economic analysis. For the year 2019, the global price of photovoltaic solar energy ranged between 0.05 and 0.21 USD/kWh [10], while energy, hydroelectric, and wind maintained prices that oscillated between 0.04 and 0.14 USD/kWh respectively, however, the regulatory conditions of the Ecuadorian electricity market create barriers to the expansion of these technologies [6], [11].

This investigation links the contribution that the DG of a large consumer maintains in the electrical system to satisfy its demand taking into account the uncertain conditions; the model uses data analytic techniques to forecast the demand and solar photovoltaic generation. The result contributes to the planning of the operation of the industrial processes, and it also benefits the distribution system, reducing the peaks of demand, mitigates transmission losses [12], [13], improves power quality, providing greater reliability to the electrical system upstream to the distribution substation [14], [15].

The one-line diagram of Fig. 1 describes a distribution express feeder that electrically feeds 3 industries, this considers the photovoltaic solar generation in the low voltage bus in each of the industries.

III. Problem Statement

The inclusion of DG brings great benefits, it also has drawbacks that must be resolved with the application of in-depth studies, as is the case of the analysis of the variability of natural resources, these are generally addressed from mathematics, statistics, techniques of data analysis, to find the optimal model and reduce the forecast error of the new magnitudes of irradiation and demand for electrical energy in the industrial sector. The stochasticity of the climatic variables has a direct impact on SPV generation and given this incidence, exist several problems on the electricity demand, and with the components of the electrical system, they are determining factors in the technical-economic analysis, both for the industry as Utility. In this way, this research focuses on generating a model that allows optimizing and forecasting renewable resources, as well as managing demand in industrial processes. This research uses measurements of more than three years of daily solar radiation in hourly intervals for the analysis and forecast of SPV generation, as well as the load profile of LC in the same time interval for forecasting demand. These models will have adjustments through data analytics techniques and artificial neural networks to reduce forecasting errors and contribute to the decision-making process for energy management, planning, operation, and dispatch in the industry. For the implementation of this methodology in the industrial sector, the risk must be assumed of: i) making the future benefit cover the investments required to carry out the implementation, ii) determining the generation capacity to cover a significant process in the company, iii) quantify the economic benefit from the partial reduction of electrical energy, iv) evaluate the technical parameters to minimize errors in the distribution systems.

IV. Insolation Measurement in the Industry Sector -Data Analytics in the Forecast of SPV and Electric Power Demand

The registered solar radiation in the place of the industry ceramic is captured by various meteorological monitoring stations [4]. This sector of the industry is located at 2°52'47" of latitude and 78°58'27" O longitude, the climatic variations are small, the maximum irradiation occurs in November, with 6,484 Wh/m^2 day, the average are in the order of 5,119 Wh/m^2 day of maximum direct insolation and 3,105 Wh/m^2 day of maximum diffuse insolation, the climate it is stable and spring throughout the year, reaching a minimum temperature of $8°C$ and a maximum of $25°C$ [16], [17].

To evaluate the potential of the solar photovoltaic system, used terrestrial data registered in the Google Map PRO program are related, and they are contrasted with the usable space of the industry through the development of the DG model for the industry [16]; Besides, the model considers different variables that make the calculations closer to reality, such as the shadow criterion, the angle of inclination, investor losses, among others [18].

The methodology begins by characterizing solar radiation as an income variable in the distributed generation model to satisfy a part or all of the demand for electrical energy in the industry; The variability of this resource and the uncertainty in the incidence of solar radiation on the industry is studied based on the analysis of statistical values and data analysis techniques, in such a way that they allow establishing appropriate criteria with the application of neural networks [12].

The neural network model is trained by a set of historical data of more than 3 years to determine the forecast patterns of photovoltaic solar generation through the solar incidence, and the dynamic pattern of the demand curve of industry, with the aim of adequate planning in the generation-demand balance.

A. Application of Artificial Neural Networks

This research uses the MATLAB interface as a tool to simulate the Neural Networks model through an input layer composed of 8 neurons and a hidden layer composed of 6 neurons, the variables correspond to information of year, month, day, and hour of more of three years of information, both on solar radiation and demand records, to obtain the appropriate model to forecast the demand for radiation and electricity. In the execution of the algorithm, the error must be less than 10% for the iterative process to stop, the model uses 80% training to achieve a forecast of 20%.

The activation function used in the RNA system is non-linear, specifically the so-called Tansing (Hyperbolic signal tangent), in terms of training it is supervised and uses the algorithm of reverse propagation or feedback (Backpropagation) with the differential activation function, thus the quadratic error is obtained in the output to be corrected.

The data in table I, correspond to the record of the variables taken directly from the average global solar radiation in periods of seconds and averaged over an interval of 1 hour in the years 2017, 2018, and 2019, this information comes from from the meteorological station located punctually in the study area.

TABLE I
DATA INPUT FOR ARTIFICIAL NEURAL NETWORK.

Year	**Month**	**Day**	**Hour**	**Energy kW/h**	**Radiation global W/m^2**
2017	1	1	6	840	0
2017	1	1	9	1059	176
2017	1	1	10	1057	205
2018	1	1	12	1243	847
-	-	-	-	-	-
2018	1	1	12	1190	847
2019	1	31	16	4378	688
2019	1	31	19	3459	123
2019	1	31	20	3298	0

V. ELECTRICITY GENERATION IN INDUSTRY

To determine the electrical power that an SPV system will contribute to the system to satisfy the electrical demand, it is necessary to take into account important factors that directly affect the system, for example, the configuration of the installation of the PV modules, these can be connected in series, parallel or combination, the installation will consider the fixed angle or the variation of the position, since generally, the front part of the panel must remain perpendicular to the solar radiation for greater uptake. Next, the process and calculation of different parameters considered in the buildings according to the location of the industries of this research are described.

A. PV potential per installation surface

Generally, industries in Latin America do not take advantage of their roofs or free spaces for the installation of photovoltaic solar systems, the DG methodology requires that the industry designate an area for the deployment of the SPV installation since this surface will directly determine the generation capacity of the system, that is, to have a greater SPV generation capacity it is necessary to have a large physical space (walls, ceilings, terrain), based on this criterion, the approximation of the number of PV panels on a given surface is calculated through:

$$N \approx \frac{S_{Installation}}{S_{Panel}} \tag{1}$$

Where:

N : number of panels on a given surface.
$S_{Installation}$: total area available for system installation.
S_{Panel} : area occupied by the PV panels.

Taking into consideration that the total capacity of the surface cannot be used due to the irregularity of the roofs of the industry and the structural resistance to support the solar panels, it is possible to define the number of panels that will be installed and the same time, determine the nominal capacity of the photovoltaic system.

B. Performance coefficient

It is the term used to establish the performance of the photovoltaic installation under real working conditions [15]. The following parameters are considered for the design:

$$PR(\%) = \eta(1 - L_{shades})(1 - L_{dirt})(1 - L_{inverter}) \quad (2)$$

Where:

PR : performance coefficient.
η : panel performance
L_{shades} : loss percentage in areas affected by shadows.
L_{dirt} : percentage loss to panel dust, mud or debris.
$L_{inverter}$: percentage of energy loss in the inverter module.

The energy generated by the SPV can be represented in terms of the nominal power of the integral system using the hypothetical criterion of full daily radiation or peak solar time by means of standard irradiation $1kW/m^2$) or in terms of radiation accumulation (annual, monthly, daily) of the ceramic industry [15], through:

$$E_{gen} = P_{peak} \cdot I(PSH) \cdot PR \quad (3)$$

Where:

E_{gen} : energy Generated - equivalent in PSH of the daily irradiation measured in kWh
P_{peak} : total installed photovoltaic power in kW.
$I(PSH)$: equivalent value in PSH of the daily irradiation in each hour.
PR : the coefficient of performance.

VI. Results of the Distributed Generation Application

The variables of solar radiation and electrical energy demand are the input for the application of the forecast model through artificial neural networks applied in the ceramic industry. This investigation, to protect the industry's information, will adopt the name of Industry 1, whose objective is to compare the operation of the algorithm and the results must contain errors of less than 10% in the generation and demand forecast to be admissible in this model.

Fig. 2 shows the result of the application of the Neural Network model, the behavior is similar to the current demand curve of Industry 1, highlighting the suspension of production in the last days of the year and the first 15 days of the following year, maintaining approximately 6 MW/h of electricity consumption.

Regarding the forecast of solar radiation, in Fig. 3, the result of the application of the neural network model of an input layer with 8 neurons and a hidden layer with 6 neurons can be seen, this determines the future radiation to estimate the generation capacity that the industry can produce, the

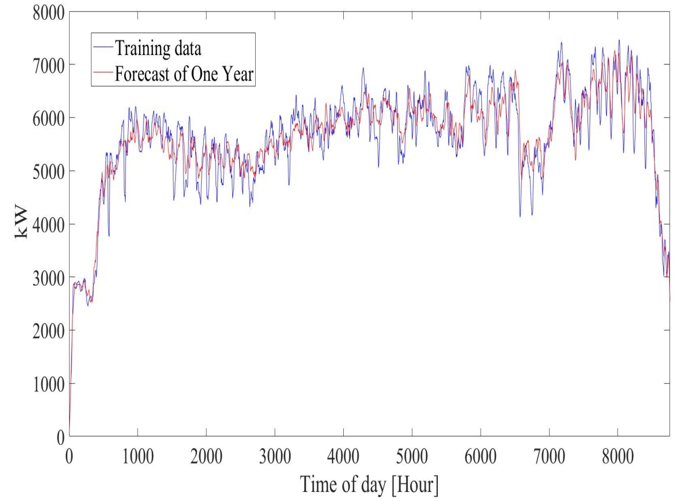

Fig. 2. Ceramic Industry Demand.

information resolution will be one hour, one day, one week and one year. In addition, this shows a behavior similar to the radiation curve affected by the climatic seasons of the year, however, the minimum regularity of 800 W of energy stands out.

The neural network generates a different result each time it is run, therefore, the absolute mean percentage error (MAPE) corresponds to the average value of 16.49% between the base and predicted data.

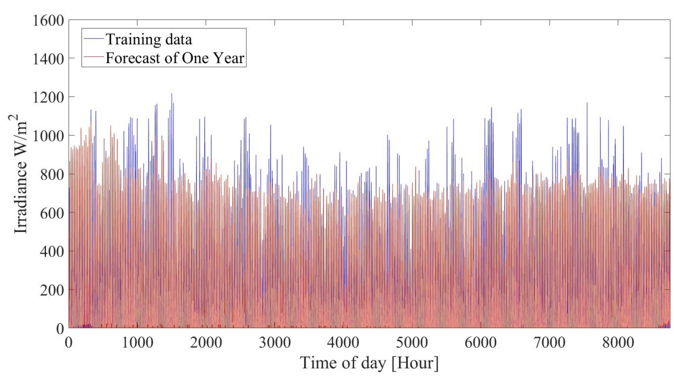

Fig. 3. Solar Radiation in the Ceramic Industry.

A. Combination of the Power Generation and Demand System

Once the results have been obtained with different intervals in the resolution, the industry begins the planning process, in such a way that it optimizes the generation based on the final use of energy, it is worth mentioning that this research does not consider the storage, therefore, the goal is to use 100% SPV generation to satisfy part of the demand. The model uses the netting method to calculate the hourly energy differentiation between the generation profile and the electricity demand profile, as can be seen in Fig. 4.

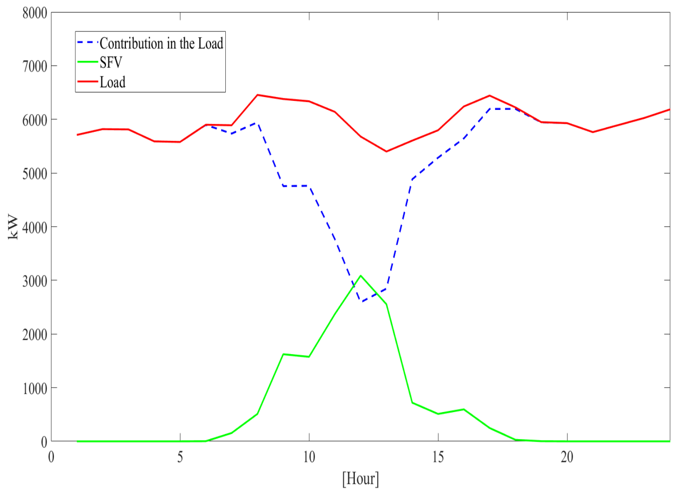

Fig. 4. Contribution of SPV Generation in the Electrical Demand of the Industry 1.

In the case of study, the SPV generation comes from an industry surface of 53.300m^2, the panels considered in the model have a nominal power of 250 W, from this analysis it is obtained that the model delivers a maximum system power of 6.879,67 kW and a maximum system energy per day of 377.738 kWh. Once the annual demand of the industry has been quantified, it is around 38.000 MWh/year, and the SPV generation under the evaluated conditions delivers around 11.000 MWh/year of energy.

B. Technical Analysis of Distributed Generation Photovoltaic in Distribution Systems

The input variables in the forecast model of demand and solar radiation, initially obtained a treatment through data analytics techniques, in this way the results of the technical conditions of the system, such as voltages, currents, powers, among other, that occur in the utility network, will be reliable for analysis [19], [20].

In the electricity markets, there are different software and algorithms for the analysis of electrical distribution systems. This research uses CYME commercial software, with which the operation of the distribution system is modeled considering real operating scenarios in the industry.

The **"Scenario 1"** uses the CYME "Load Distribution" model, this scenario does not consider the inclusion of solar photovoltaic generation in the industry [21]; while, **"Scenario 2"** it considers the inclusion of the SPV Generation in its maximum connected capacity in the industry's 22 KV bar with the one-year forecast.

The result in **"Scenario 1"**, allows obtaining the baseline of the technical characterization of the system, as indicated in table II.

The report of energy consumed and generated in the year of simulation, shows the losses of the different elements of the system, such as lines, cables, capacitance, transformers, and the total losses of the base system, as represented in table III.

TABLE II
TECHNICAL ANALYSIS OF BASE SYSTEM DEMAND.

Peak demand 18h00 - 22h00	7.827 kW
Maximum power demand	9.099 kVA
Minimum power demand	1.074 kVA
Maximum voltage	1 pu
Minimum voltaje	1 pu
Total annual losses	714.701 kWh

TABLE III
BASE SYSTEM LOAD FLOW RESULT.

Total sum of energy	MWh	Mvarh	MVAh
Total generation	0	0	0
Total load	48.294,33	23.390,01	53.660,36
Total capacitance	0	0,091	0,091
Lost on the line	0,862	2,409	2,559
Transformer losses	691,51	2.766,06	2.851,19
Total losses	692,37	2.768,47	2.853,75

The generation in the base system is at "zero", therefore for the industry, it absorbs all the demand from utility. In the same time interval (one year), the **"Scenario 2"**, includes the SPV generation, therefore, the response of the system changes its initial condition, as shown in table IV.

TABLE IV
LOAD FLOW RESULT INCLUDING DISTRIBUTED GENERATION IN THE INDUSTRY.

Total sum of energy	MWh	Mvarh	MVAh
Total generation	1.671,54	1.751,80	2.856,77
Total load	48.345,82	23.414,94	53.717,57
Total capacitance	0	0,091	0,091
Lost on the line	0,79	2,21	2,34
Transformer losses	639,64	2.558,59	2.637,33
Total losses	640,43	2.560,80	2.639,68

The total energy generated by the photovoltaic solar system is 1.671,54 MWh, this contribution has advantages in reducing losses of the line that are in the order of 7% and has an improvement of 5% in losses totals, the decrease in power consumption is 939 kVA, however, the peak power is not reduced since it occurs at night, and the voltage profile improves by ±3V.

Furthermore, in the scenarios presented, it is assumed that the prices offered locally for installation works of 16.508 solar panels on the useful surface of the roof of the ceramic industry (53.300 m^2), will present a monthly saving of 55.008 USD in the bill of payment of utility, this analysis was carried out with a useful life of the equipment of 25 years. Also, the current price of electricity is considered according to the tariff schedule of a regulated industrial consumer.

VII. Conclusions

A correct study of the location of the solar panels for the use of the photovoltaic solar resource by the industries makes it easier to estimate the generation capacity for self-consumption.

For the forecast of the values in the analysis, studies based on data mining were applied, in addition to the application of the artificial neural networks model to define an approach to the traditional model of energy demand and solar radiation profiles, where observes that in the experimental phase, there is a reduction of outliers, although these profiles follow the original pattern of the initial curves.

The simulation in the CYME program with the predicted SPV generation and energy demand profiles allows analyzing the technical benefits of the utilities. From the simulation results, the following stand out: the direct transmission line that feeds the industries does not contain an electrical power surge, thus reducing the possibility of failures in the electrical system.

Considering the second scenario, the SPV system releases part of the energy demand in the course of a few hours a day, giving industries the possibility of increasing their production without the need to affect energy demand.

Comparing the two scenarios, favorable results are seen in the system, such as a reduction in voltage drop and an improvement in system power losses by 2%, peak power consumption tends to decrease by 5% of the subsequent maximum value in a few hours a day, therefore, the model considers the direct use of the SPV generation without storage.

In the global results of the report, the comparison of the scenarios shows a difference of approximately 1% in the improvement of the system in terms of losses in the line, cables, and transformers, since all the electricity generation in the new system is delivered During the day, compared to the peak of demand in the industry produced at night, this contingency leads to change the processes of the industry, a situation not considered in this research.

References

[1] IEEE. Stand. 1547.2-2008, IEEE Standard for Interconnecting Distributed Resources with Electric Power Systems, no. April. 2009.

[2] Z. R. Vignol M., "TRANSMISSION NETWORKS OR DISTRIBUTED GENERATION" Proc. IASTED, Eur., 2001.

[3] F. Santamaria, C. L. Trujillo, and J. A. Hernandez, "A proposed index to evaluate the state of legislation fostering distributed generation in Latin America and the Caribbean" pp. 66–74, 2016, doi: 10.1016/j.tej.2016.02.007.

[4] X. Xu, C. Guan, and J. Jin, "Valuing the carbon assets of distributed photovoltaic generation in China", Energy Policy, pp. 374–382, 2018, doi: 10.1016/j.enpol.2018.06.046.

[5] M. A. Toledo, W. E. Macancela, F. F. Aucapiña, C. M. Álvarez, and D. X. Morales, "Forecast of solar radiation with the application of neural networks in rural zones of Ecuador", 2019 FISE-IEEE/CIGRE Conf. - Living Energy Transition, FISE/CIGRE 2019, no. December, 2019, doi: 10.1109/FISECIGRE48012.2019.8984995.

[6] Bnamericas, "El estado de la generación distribuida en Latinoamérica de cara a 2020", diciembre, 2019, Available: www.bnamericas.com/es/reportajes/el-estado-de-la-generacion-distribuida-en-latinoamerica-de-cara-a-2020.

[7] KPMG, "Impacto potencial de la nueva ley de generación distribuida en argentina a partir de fuentes renovables", pp. 1–14, 2018. Available:assets.kpmg/content/dam/kpmg/ar/pdf/posibles-impactos-de-la-ley-de-energia-distribuida.pdf

[8] MINISTERIO DE ENERGÍA Y RECURSOS NATURALES NO RENOVABLES, "Plan Maestro de Electricidad 2018-2027. Available:www.centrosur.gob.ec/wp-content/uploads/2020/01/Plan-Maestro-de-Electricidad.pdf.

[9] ARCONEL, "Codificacion Regulación No. 003/18., p. 41, 2018, Available: www.regulacionelectrica.gob.ec/regulaciones/".

[10] IRENA (2019), Renewable Power Generation Costs in 2018, p.41,2018, Available:www.irena.org/publications/2019/May/Renewable-power-generation-costs-in-2018.

[11] J. Valencia, "Generación Distribuida: Democratización de la energia eléctrica", Criterio Libr., Universidad Nacional de Colombia, Bogotá, D.C., pp. 105–112, 2008.

[12] J. Jurasz and P. Elia, "The potential of photovoltaic systems to reduce energy costs for office buildings in time-dependent and peak-load-dependent tariffs", Sustain. Cities Soc., vol. 44, no. July 2018, pp. 871–879, 2019, doi: 10.1016/j.scs.2018.10.048.

[13] S. Kamel, A. Selim, W. Ahmed, and F. Jurado, "Single- and multi-objective optimization for photovoltaic distributed generators implementation in probabilistic power flow algorithm", Electr. Eng., vol. 102, no. 1, pp. 331–347, 2020, doi: 10.1007/s00202-019-00878-7.

[14] F. A. Castillo Munoz, A. Aguila Tellez, and J. W. Gonzalez Sanchez, "Analysis of Stability of Tension and Losses of Electric Power in Distribution Networks with Distributed Generation", IEEE Lat. Am. Trans., vol. 14, no. 11, pp. 4491–4498, 2016, doi: 10.1109/TLA.2016.7795819.

[15] Y. He, Y. Pang, X. Li, and M. Zhang, "Dynamic subsidy model of photovoltaic distributed generation in China", Renew. Energy, vol. 118, pp. 555–564, 2018, doi: 10.1016/j.renene.2017.11.042.

[16] S. Zambrano-Asanza, E. F. Zalamea-León, E. A. Barragán-Escandón, and A. Parra-González, "Urban photovoltaic potential estimation based on architectural conditions, production-demand matching, storage and the incorporation of new eco-efficient loads", Renew. Energy, vol. 142, pp. 224–238, 2019, doi: 10.1016/j.renene.2019.03.105.

[17] CONELEC Consejo Nacional de Electricidad, "Atlas Solar Del Ecuador Con Fines De Generación Eléctrica", Corporación para la Investig. Energética, p. 51, 2008, Available: http://energia.org.ec/cie/wp-content/uploads/2017/09/AtlasSolar.pdf

[18] N. Martín-chivelet, "Photovoltaic potential and land-use estimation methodology", Energy, vol. 94, pp. 233–242, 2016, doi: 10.1016/j.energy.2015.10.108."

[19] L. F. Gaitán and J. D. Gomez, "Estudio del Impacto de la Generación Distribuida en Sistemas de Prueba IEEE", p. 159, 2017.

[20] F. A. Castillo Munoz, A. Aguila Tellez, and J. W. Gonzalez Sanchez, "Analysis of Stability of Tension and Losses of Electric Power in Distribution Networks with Distributed Generation", IEEE Lat. Am. Trans., vol. 14, no. 11, pp. 4491–4498, 2016, doi: 10.1109/TLA.2016.7795819.

[21] [1] V. Miskinis, E. Norvaisa, A. Galinis, and I. Konstantinaviciute, "Trends of distributed generation development in Lithuania", Energy Policy, vol. 39, no. 8, pp. 4656–4663, 2011, doi: 10.1016/j.enpol.2011.05.022.