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Hosting capacity and optimal sizing: a Colombian case of study

Capacidad de alojamiento y dimensionamiento óptimo: caso de estudio colombiano

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Abstract

The global energy transition has driven the adoption of renewable generation resources in distribution networks worldwide. This shift has presented new operational challenges for these networks. One such challenge involves determining the ideal sizing of these resources and the hosting capacity of the distribution networks to maximize their potential to enhance technical parameters within the system. This article proposes strategies to optimize the generation capacity and the selection of nodes in Colombian distribution networks, prioritizing nodes of lower voltage to improve reliability and continuity of supply. Specific methodologies are developed due to the passive and radial nature of these networks.

Keywords: distributed generation; variable generation; technical-economic analysis; hosting capacity; technical simulation.

Resumen

La transición energética ha facilitado la integración de recursos de generación renovable en las redes de distribución a nivel mundial. Sin embargo, esta transición ha presentado nuevos desafíos operativos para estas redes. Uno de estos desafíos implica determinar el tamaño óptimo de estos recursos y la capacidad de alojamiento de las redes de distribución, con el objetivo de maximizar su potencial para mejorar los parámetros técnicos del sistema. Para abordar este tema, este artículo propone estrategias para optimizar la capacidad de generación y la selección de nodos en redes de distribución colombianas, priorizando los nodos de menor voltaje para mejorar continuidad del suministro. Se desarrollan metodologías específicas debido a la naturaleza pasiva y radial de estas redes.

Palabras clave: generación distribuida; generación variable; análisis técnico-económico; capacidad de alojamiento; simulación técnica.

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1. Introduction

In 2015, the United Nations adopted the Sustainable Development Goals (SDGs) to be achieved by 2030 [1]. Among these goals, two stand out, goal number seven (7): "Affordable and non-polluting energy," and goal number eleven (11): "Cities and human settlements inclusive, safe, resilient, and sustainable." Colombia has focused on diversifying its national energy matrix by incorporating non-conventional renewable sources and expanding electricity coverage to remote and vulnerable areas. The target is to increase the installed generation capacity with non-conventional renewable energy from 22.4 MW in 2018 to 1500 MW by 2030 [2], [3]. The Paris Agreement (PA), accepted in 2015, is the first universal and legally binding agreement on climate change. It plays a crucial role in achieving the SDGs and provides a roadmap to mitigate climate change and limit global temperature increases below two degrees Celsius (2°C) [4]. Decarbonization is essential in fulfilling the PA and SDGs [5]. Colombia faces the challenges of climate change and coal usage, given the presence of one of the world's largest open-pit coal mines used for electricity generation [6]. Transitioning to electrical power generation from renewable sources is an intuitive approach to decarbonization [7].

The Mining Energy Planning Unit (UPME) in Colombia proposes ideas and a roadmap for the country's energy sector through the national energy plan. Various non-conventional renewable generation technologies have been tested and identified as viable options for integration into the national energy matrix, potentially leading to significant reductions in greenhouse gas emissions [8]. The Colombian government from the UPME and the Department of National Planning has presented projections on the integration of Non-Conventional Sources of Renewable Energy (FNCER by its Spanish initials), starting from the energy potential, going through the study of the technologies suitable to be implemented in the country and reaching the analysis of the technical and regulatory barriers that the introduction of these technologies would face [9], [10], [11]. Law 1715 of 2014 plays a significant role in promoting the development and use of unconventional sources of electrical energy [12].

With the integration of renewable energy sources in electricity generation, new challenges have arisen, making it necessary to create or improve control and operation strategies of distribution systems, always aiming to maintain and even upgrade the reliability and continuity of the electricity supply. The intermittent nature of renewable resources, dependent on climatic conditions, complicates the design of effective electrical systems. When designing systems with unconventional alternative energy sources, the project's geographical location and available renewable resources are essential considerations [13], [14], [15]. For projecting a system that includes unconventional alternative energy sources, the project's geographical location must be considered, in addition to the renewable resources that can be used in the area [16], [17]. Colombia's geographical location and diverse relief offer abundant renewable resource potential. In this sense, biomass is used predominantly in rural areas, geothermal energy shows promise, wind energy is available onshore and offshore, and solar photovoltaic energy has significant potential, particularly along the Atlantic and Pacific Coasts, with higher solar radiation than the global average and even surpassing that of Germany, a leader in solar energy [9], [18], [19].

Hosting capacity refers to the maximum amount of distributed generation that can be installed on the system without compromising its performance [20]. In other words, it represents the upper limit of renewable generation that can be added without jeopardizing the stability and quality of the power supply in the distribution network. The estimation of hosting capacity at each system node takes into account technical and operational factors. In addition, we can find various articles proposing techniques for determining hosting capacity alongside mathematical analyses, data processing, and numerical methodologies. For instance, one study presented a framework for estimating accommodation capacity, taking into account net load deviation, it thereby overcomes the abrupt net load deviation for the economic accommodation of variable renewable energies obtaining results for which the proposed net load filter exhibited excellent performance in capturing the net load deviation without distorting the conventional performance index [21]. Moreover, there are other documents that not only focus on optimization methods but also evaluate photovoltaic systems for distributed generation, for example, the methods for quantifying the solar PV hosting capacity of low voltage distribution grids. Three fundamentally different methods are considered: deterministic, stochastic, time series [22]. An approach based on a coordinated management scheme of control devices in distribution systems is also proposed, i.e transformer taps and VAr sources. It also considers the promising electrical vehicles with their stochastic nature and comprehensive model [23]. In addition, a document mentions the operation of radial distribution networks and the method with which they can be addressed, a constructive model for hosting capacity determination. Based on geometrical understanding, hosting capacity solutions are constructed sequentially according to realistic constraints so that the optimal solution can be reserved even with a non-convex model [24]. Articles por research papers discuss the diverse advantages and disadvantages of distributed generation systems, as well as the evolving definitions of operators and energy markets in the context of increasing hosting capacity [25].

This paper presents a study on distributed generation in Colombia. Firstly, the project's location is selected based on its potential for photovoltaic solar energy and the demand composition [26], [27]. Next, the system sizing is determined using the HOMER Pro simulation software, which identifies the optimal sizing of the generation units, recommended energy resources in the area, economic variables for investment and system operation, and the selection of equipment and devices that will compose the architecture of the integrated renewable generation system. Subsequently, a technical analysis using the DIgSILENT Power Factory software simulates the integration of the renewable generation system into a distribution network, assessing technical implications and identifying the ideal integration location based on hosting capacity, a crucial factor in the study.

2. Methodology

Figure 1 shows the methodology used in this study. The analysis was divided into two phases corresponding to (1) the technical-economic analysis of the case study, (2) The technical analysis of the results obtained in the first phase on an extended time horizon.

The purpose of this research is the analysis and dimensioning of an optimal distributed variable generation system to be integrated into a typical distribution network; the process is developed with the support of the specialized simulation software DIgSILENT Power Factory and HOMER Pro.

2.1. Phase 1: Dimensioning of the optimal participation of variable generation resources (initial technical-economic analysis)

This phase is subdivided into three stages, and the result is a series of technical and economic variables that must be used in phase two

2.1.1. Data collection and selection

A literature review is executed to identify the current panorama of the optimal dimensioning of distributed generation systems with non-conventional renewable resources. Next, the variables of interest to conduct the fundamental calculations and simulations in the development of the research are determined, so the technical information associated with the demand for electrical energy to be modeled is acquired from the database of the national dispatch center XM, obtaining a demand profile of real data for the selected study area.

The data related to primary energy resources as well as other environmental conditions of interest in this research are acquired from the HOMER Pro specialized software library which is linked to the NASA database; this data is compared and validated with the information published by IDEAM about the energy potential in different areas of Colombia.

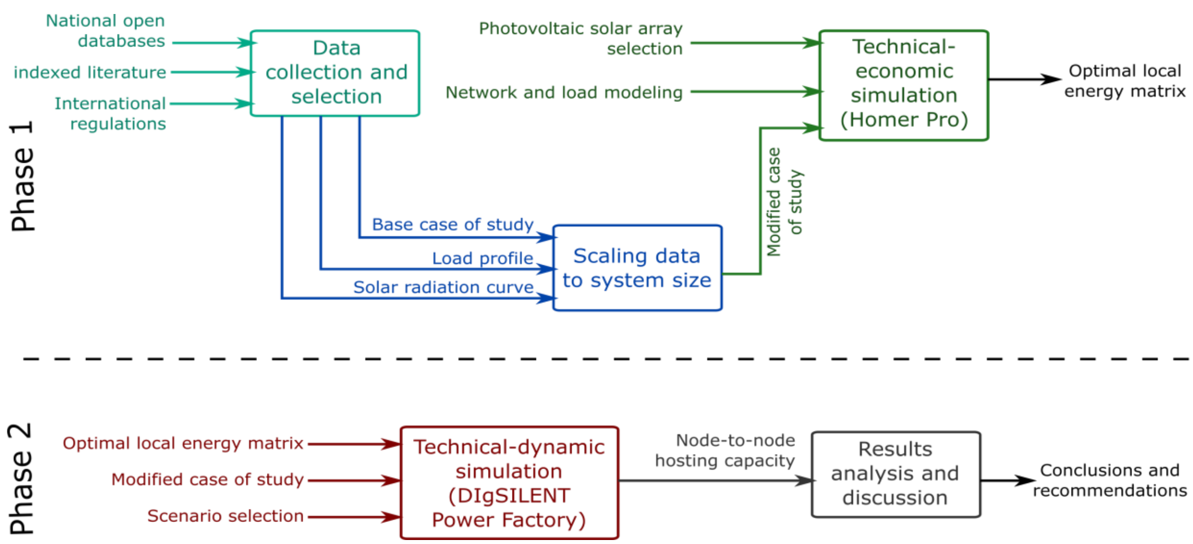

Figure 1. Methodology followed in the development of the research. Source: Own Compilation.

Also, aspects of international regulations were considered, which highlights the need to establish limits for the inclusion of variable generation in each network to avoid the formation of unintentional islands, overloads of equipment of the electric power system, changes in the design of protections due to variations in the fault current and the modifications of the voltage and quality of the power.

2.1.2. Scaling the data to system size

The information and technical data acquired must be scaled to the conditions of the selected case of study, this process is necessary to achieve the modeling and simulation of the events of interest; thus, the data collected on the previous stage (solar radiation and load profile) is scaled to the size of the selected base case of study, which would allow coupling the results obtained from the technical-economic analysis of the next stage, to the technical simulation that will be performed in the next phase.

2.1.3. Technical-economic simulation (HOMER pro)

This The data collected and previously scaled together with the technical-economic information requested by the simulation software allow the modeling of the distributed generation system in HOMER Pro, software in which the simulation of the designed network is carried out.

HOMER Pro requires two types of variables, technical and economic. The technical variables include: the geographical location of the project, environmental variables associated with the location, duration of the project, whether it will be isolated or connected to the grid, efficiency of the elements of the solar array, durability, voltage level, among others, these data are obtained from some providers of solar arrays, where their products comply with national regulations. The economic variables include: inflation rate, fixed costs, variable costs, and the type of currency to be used, these data are obtained from the Bank of the Republic, the Department of National Planning, and other indexed literature. The result obtained from this stage is the optimal value of the local energy matrix that can be integrated into the simulated distribution network.

2.2. Phase 2: Obtaining the hosting capacity of the system (final technical analysis)

Based on the load profile (Figure 2) that was scaled in Phase 1 and the matrix resulting from the technical-economic analysis conducted in the software HOMER Pro. This phase is a compound of two stages, the technical-dynamic simulation and a discussion and analysis of the results.

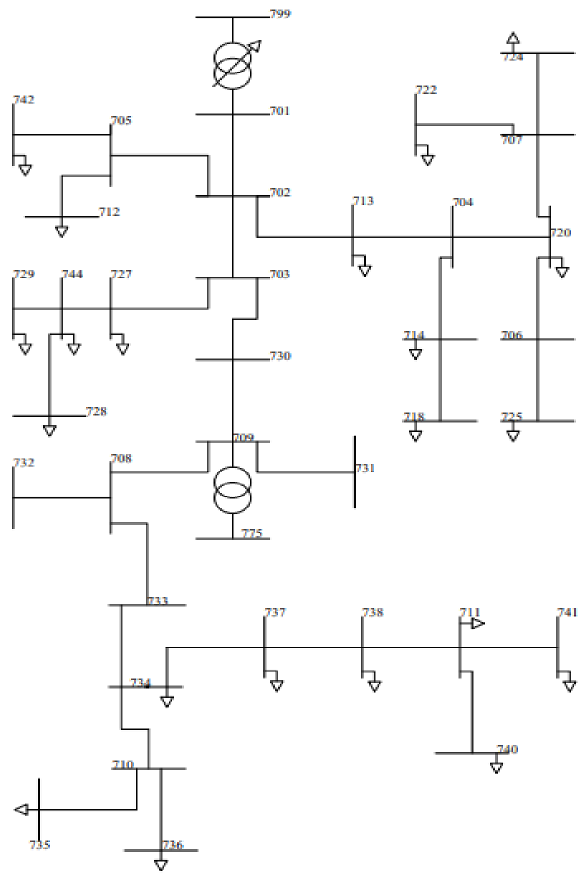

Figure 2. One-line diagram of the selected base case study (IEEE 37 node test feeder). Source: Own compilation based on [28].

2.2.1. Technical-dynamic simulation (DIgSILENT)

Based on the results obtained in HOMER Pro, such as the optimal distribution generation capacity to be integrated into the selected distribution network, a dynamic simulation is performed in DIgSILENT Power Factory to analyze the behavior of the technical variables of the power system when installing distributed generation, so, the modified case of study of the typical radial distribution network is modeled in DIgSILENT Power Factory and the optimal solar array obtained from the previous stage is integrated; initially, the generation capacity of this array will be equal to the HOMER Pro optimal suggestion; thus linking HOMER Pro and DIgSILENT Power Factory. In this stage, it is possible to perform different tests such as installing the total solar generation in a single node, to distributing it in "n" nodes, all this to obtain a greater level of detail in the behavior of the distribution network against the incursion of renewable energy. Finally, a convenient distribution of the optimal generation capacity obtained in the previous phase, in the different nodes of the network, is determined; this is accomplished by identifying the dynamic behavior of the technical variables of the system by modeling different capacities in each node of the system, monitoring the stability and voltage quality in every node of the network.

3. Case of study

The Bocagrande sector, located in Cartagena city, was chosen as the reference place for obtaining the daily load profile curve and the daily average solar radiation curve. This location was selected due to the availability of data and the presence of residential users together with a considerable percentage of commercial and industrial users. The load profile curve considered in this paper is shown in Figure 3, it was built up by calculating the average load curve of the weekdays and weekends, for the year 2019. In this chart, the residential, commercial, and industrial users are cluster.

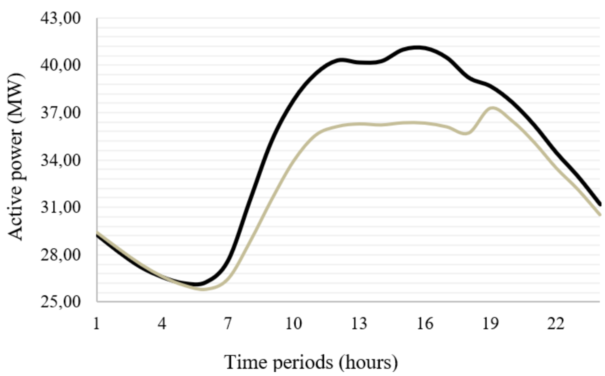

Figure 3. Demand curve in MW for the city of Cartagena for the 24 periods of the day, for weekdays (black line) and for weekends (gray line). Source: Own compilation based on XM data.

Finally, the photovoltaic solar arrangement is selected, which is composed of the photovoltaic solar module (Table 1), as well as the inverter to be used throughout the project, this process was carried out by researching catalogs of companies that offer this type of equipment for photovoltaic solar generation applications In Colombia, after conducting this search, the RETIE certified equipment with the following characteristics is selected.

3.1. Phase 1: Dimensioning of the optimal participation of variable generation resources (initial technical-economic analysis)

From loads of the selected distribution network, a scale factor is obtained that allows to reflect the behavior of the demand profile shown in Figure 3, with the load originally installed in each of the nodes of the IEEE 37 node test feeder. Once the data has been scaled, and after entering the data of the modified case of study, a technical-economic simulation is performed in HOMER Pro. The following obtained results summarizes the information of the system architecture of the winning case (Table 2) with the optimal sizing of the photovoltaic solar panels and the inverter system to be integrated on the grid.

Table 1. Characteristics of the equipment selected for the photovoltaic solar array

	Inverter	**Solar Panel**
Name	Fronius Primo 10 kVA (208/240) V	Talensun TP672P-330
Nominal Voltage	665 V_{CD} / 208-240 V_{AC}	37,7 V
Nominal Power	10 kW	0,33 kW
Frequency	45 Hz – 66 Hz	
Efficiency	96 % - 97,9 %	17 %
Max. Current	51 [A] / 41,6 [A] – 48,1 [A]	15 [A]

Source: Own compilation based on HOMER Pro data.

Table 2. Sizing of the winning case study of the technical-economic analysis in Homer Pro

	Solar panel-Tal330	**Inverter – Fron9.995**
Capacity (kW)	7785	3724
kWh/year	15742503	
Average Output (kW)		1252
Architecture		

Source: Own compilation.

Furthermore, the inverter in its stable state will not deliver energy to the grid greater than its nominal capacity. The last will generate energy not supplied to the system, which can be recognized when comparing Figure 4 (shown above) with Figure 5, where the power generated by the solar panels is displayed (Figure 4), and the output of the inversion system, limited by the capacity of this equipment is shown (Figure 5).

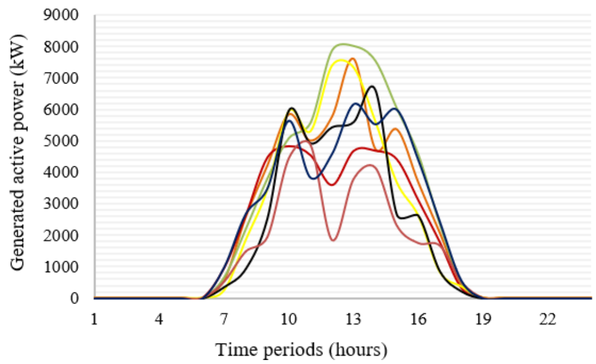

Figure 4. Average solar generation units' curves in kW/h for Monday (green line), Tuesday (red line), Wednesday (gray line), Thursday (yellow line), Friday (black line), Saturday (orange line) and Sunday (blue line). Source: Own compilation based on HOMER Pro data.

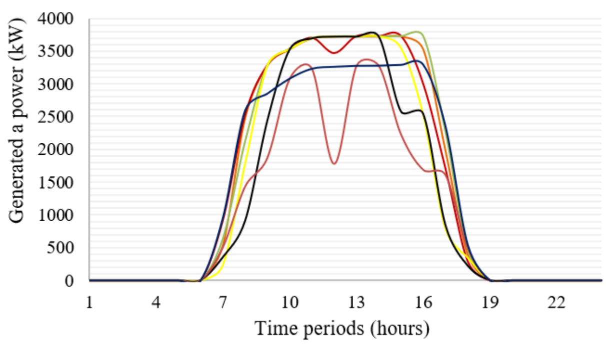

Figure 5. Average solar generation inverters curves in kW/m² for Monday (green line), Tuesday (red line), Wednesday (gray line), Thursday (yellow line), Friday (black line), Saturday (orange line) and Sunday (blue line). Source: Own compilation based on HOMER Pro.

3.2. Phase 2: Obtaining the hosting capacity of the system (final technical analysis)

After obtaining the optimal sizing of the photovoltaic solar distributed generation system to be integrated into the system, a technical analysis is performed in DIgSILENT Power Factory software, to identify the hosting capacity of each system's nodes, as a mechanism for decision making to determine the ideal location for connecting the assets.

The hosting capacity of each node of the system is estimated through a dynamic simulation of a typical day of operation of the system, with the connection of a subtly oversized solar photovoltaic generation unit to the analyzed node. When the node voltage exceeds the overvoltage limit of the system (1.05 p.u.) the inverter power output is verified, and this power value is considered as the node's hosting capacity. It is relevant to bear in mind that the situation above described occurs approximately between 11:00 a.m. and 2:00 p.m. since at this time there will be an output of photovoltaic solar generation that is close to the daily maximum, and there will be a high-power demand (which will make the voltage profile present low values at that moment).

However, it is also necessary to take into account that the hosting capacity obtained with the previous method may be greater than the actual hosting capacity of the node, because so far we are only considering the voltage as a parameter of decision, and yet we have not considered the ampacity of the lines that communicate to this node with the rest of the system, since this capacity limits the current that in steady-state can flow through the grid. Therefore, it is necessary to obtain not only the hosting capacity by voltage but also to calculate the hosting capacity limited by the current in said node, compare these two values and take the lowest one as the hosting capacity of the node in which distributed generation in been connected, this can be seen in Figure 6.

Figure 6 shows the process of determining the hosting capacity for one of the nodes of the system. First, the overvoltage limit (1.05 p.u.) and the current limit of the lines adjacent to said node (150 A) are established. Then, it is developed a dynamic simulation, for a 24-hour horizon of the network's behavior with the connection of a photovoltaic solar plant to said node. The distributed generation injected when each operating limit is exceeded is verified, i.e., in the example, for node 736 the housing capacity per voltage is 2001 kW, while the one per current is 1447 kW. Finally, the lowest value is selected as the hosting capacity for the analyzed node (1447 kW in the case of node 736).

Thus, the hosting capacity for all the nodes of the IEEE 37 nodes study case was calculated. This process was developed by analyzing the behavior of the technical variables of the system when installing photovoltaic solar generation in each node. This analysis allows us to determine the places with the highest hosting capacity, which are exhibit in Table 3, and the nodes of the system that, because of their technical characteristics, limit the hosting capacity to lower levels, as shown in Table 4. The hosting capacity of each node of the system varies according to its location, directly influenced by the radial topology of the system, the current carried by the lines, and the voltage level of each node.

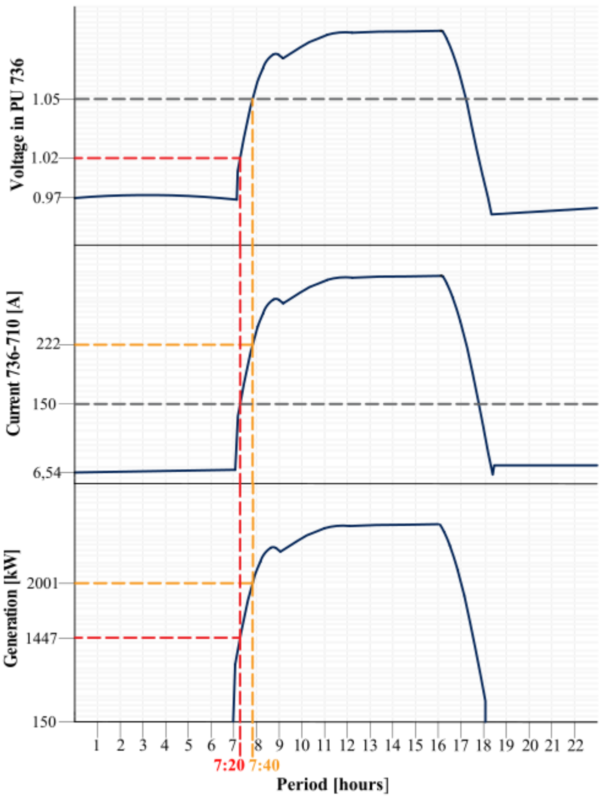

Figure 6. Node 736 hosting capacity determination chart considering the overvoltage limit and the ampacity of the adjacent lines. Source: Own compilation.

Table 3. Nodes with greater hosting capacity

System's node	Hosting capacity
702	6071
703	5191
730	3133

Source: Own compilation.

Table 4. Nodes with lower hosting capacity

System's node	Hosting capacity
712	1429
718	1432
732	1380

Source: Own compilation.

Based on the hosting capacity of each of the nodes and their technical characteristics, the points in which the solar generation installation is most feasible are identified, dividing the output power that HOMER Pro produces into equal parts, as shown in Table 5.

Table 5. Photovoltaic solar generation capacity to install in each of the selected nodes

System's node	741	736	724	737	728
Power capacity (kW)	372.4	372.4	372.4	372.4	372.4

System's node	718	742	731	702	725	Total
Power capacity (kW)	372.4	372.4	372.4	372.4	372.4	3724

Source: Own compilation.

The feasibility of connecting the distributed generation in these nodes is because they are the nodes with the lowest network voltages, approaching and in some cases below the limit operate allowed (0.95 p.u.).

At this point, it is not being considered that the installation of a distributed generation unit in one bus of the system affects the hosting capacity of the surrounding nodes. So, when performing the simulation under the conditions described in Table 5, although the integration of these units improves the voltage in some nodes of the system, the current limit is exceeded in several lines, thus compromising the supply's continuity.

Consequently, the strategy to integrate these ten (10) distributed generators in the system is modified. So far, the nodes with the lowest voltage levels and that represent critical points in the network are candidate nodes to install generation. So, to the bus with the lowest voltage, a 372.4 kW solar photovoltaic plant is connected after verifying that the hosting capacity determined for this node is higher than the one to be installed. Then, the hosting capacity estimation is performed again for all the system's nodes, and the new node with the lowest voltage is identified. The afore-mentioned process is re-executed until the 3724 kilowatts are successfully integrated, always observing that the voltage and current levels do not exceed the technical limits and do not represent a risk for the continuity of supply. Table 6 presents the nodes in which the optimal generation capacity was finally distributed.

Table 6. Photovoltaic solar generation capacity to install in the most suitable identified nodes

System's node	741	740	711	738	737
Power capacity (kW)	372.4	372.4	372.4	372.4	372.4

System's node	736	735	710	734	733	Total
Power capacity (kW)	372.4	372.4	372.4	372.4	372.4	3724

Source: Own compilation.

After installing distributed generation in the strategic nodes, an improvement can be observed in the voltage levels of the busbars of the IEEE 37 node test feeder (Table 7). Thus, contributing to a reduction of the Joule effects, showing that the installation of distributed generation in an optimal way favors the behavior of the system.

Table 7. Per Unit voltage in the nodes in which the installation of distributed generation was proposed, before (original voltage) and after (modified voltage) the installation of photovoltaic solar generation assets

System's node	741	740	711	738	737
Original voltage [p.u]	0,962	0,962	0,962	0,963	0,964
Modified voltage [p.u]	1,01	1,01	1,01	1,01	1,01

System's node	736	735	710	734	733
Original voltage [p.u]	0,964	0,965	0,966	0,967	0,971
Modified voltage [p.u]	1,01	1,01	1,01	1,01	1,01

Source: Own compilation.

4. Conclusions

This paper presents a methodology for determining the optimal generation capacity that can be integrated into a selected distribution network and identifying the most suitable nodes for successfully incorporating this capacity. For instance, based on the results obtained, it becomes evident that nodes with lower voltage levels, which also serve as critical points in the network, are potential candidates for installing generation capacity. The objective is to ensure that integrating these assets improves various technical parameters within the system, subsequently enhancing supply continuity and reliability. It was observed that traditional methods for estimating the optimal capacity and placement of distributed generation units within electrical power systems are not entirely applicable to typical Colombian distribution networks. The last is primarily due to their passive and radial characteristics, necessitating the development of new methodologies to facilitate the successful integration of such assets at the distribution level.

The use of the proposed mechanism allows for the amplification of the effects of variable generation on voltage quality at the network nodes without compromising user connections. Furthermore, the methodology ensures that distributed generation units' inclusion will not lead to network congestion, as it considers the current limits of all system lines as a decision parameter.

The hosting capacity varies based on the considered decision variables for its calculation. Additionally, this estimation helps to determine the appropriate generation capacity to be installed at specific nodes within the system, and it also provides strategic insights for identifying areas within the system where performance enhancements can be achieved, contributing to a more resilient and efficient distribution network.

5. Recommendations

Based on the findings presented in this research article, a comprehensive understanding emerges regarding the determination of optimal generation capacity and the identification of suitable nodes for the integration of distributed generation assets within a specific distribution network. These results have important implications, as they model technical variables within the system, thereby enhancing the continuity and reliability of energy supply while addressing limitations inherent in traditional estimation methods. Furthermore, it is crucial to emphasize the increased housing capacity, which enables the fulfillment of the escalating energy demand by ensuring sufficient electrical infrastructure to cater to the energy needs of consumers, households, businesses, and industries. This expanded capacity also facilitates the support and seamless integration of renewable energy sources as part of an energy transition aimed at improving network resilience and reliability. Consequently, this approach ensures a stable and efficient supply of electricity to consumers, while simultaneously adapting to future energy requirements and contributing to sustainable development goals.

However, the determination of optimal resource locations and the enhancement of system hosting capacity face certain limitations. Traditional methods are not entirely suitable for typical distribution networks in Colombia due to their passive and radial nature, resulting in limited flexibility and connectivity. This is primarily due to technical and capacity constraints within the existing electrical infrastructure, necessitating investments, and network modernization. Furthermore, it is crucial to emphasize the issue of network congestion, particularly concerning the current limitations of all system lines, as overloading the network must be avoided.

The examination of research findings not only enables reflection but also catalyzes further exploration in the field. In this regard, it is worthwhile to consider future investigations that concentrate on the advancement of alternative estimation techniques tailored to overcome the inherent limitations of Colombian passive and radial distribution networks. It would be advantageous to explore stochastic, deterministic, and time series methods for estimating housing capacity [22], as these approaches have the potential to yield more precise and accurate results. Such endeavors would enhance the overall quality of estimations and contribute to a deeper understanding of the subject matter.

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Autor Contributions

D. A. González-Sotto: Formal Analysis, Methodology, Resources, Visualization, Writing -Review and Editing. C. Arango-Lemoine: Data Curation, Project Administration, Validation. D. López-García: Conceptualization, Data Curation, Funding Acquisition, Writing Original Draft. A. Arango-Manrique: Conceptualization, Funding Acquisition, Methodology, Resources, Supervision, Writing Original Draft, Writing -Review and Editing.

All authors have read and agree to the published version of manuscript.

Conflicts of Interest

The authors declare no conflict of interest.

Institutional Review Board Statement

Not applicable.

Informed Consent Statement

Not applicable.

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