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Review

Optimal Integration of Photovoltaic Systems in Distribution Networks from a Technical, Financial, and Environmental Perspective

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Abstract: Due to the increasing demand for electricity around the world, different technologies have been developed to ensure the sustainability of each and every process involved in its production, transmission, and consumption. In addition to ensuring energy sustainability, these technologies seek to improve some of the characteristics of power systems and, in doing so, make them efficient from a financial, technical, and environmental perspective. In particular, solar photovoltaic (PV) technology is one of the power generation technologies that has had the most influence and development in recent years due to its easy implementation and low maintenance costs. Additionally, since PV systems can be located close to the load, power losses during distribution and transmission can be significantly reduced. However, in order to maximize the financial, technical, and environmental variables involved in the operation of an electrical system, a PV power generation project must guarantee the proper location and sizing of the generation sources. In the specialized literature, different studies have employed mathematical methods to determine the optimal location and size of generation sources. These methods model the operation of electrical systems and provide potential analysis scenarios following the deployment of solar PV units. The majority of such studies, however, do not assess the quality and repeatability of the solutions in short processing times. In light of this, the purpose of this study is to review the literature and contributions made in the field.

Keywords: sustainability; generation; photovoltaic solar energy; power losses; location; sizing; mathematical methods; repeatability

1. Introduction

As a result of the recent excessive population growth and the associated demand for electricity, power generation and distribution systems are playing a crucial role in the sustainable development of our modern society. However, although there are currently a variety of systems to satisfy our basic power demands, their inefficiency and potential environmental impacts have raised serious concerns. Therefore, several industries across the globe have concentrated their efforts on developing cleaner and more efficient power generation technologies to meet both our present and future energy needs [1,2].

Conventional power generation and distribution systems have long contributed to the development of our society and are quite reliable. However, given that the stability of the current electrical system has been threatened by the sharp increase in power demand, network operators have been forced to explore new possibilities to meet future energy needs. Some of the main limitations of conventional power systems are related to their efficiency and low implementation in geographically difficult-to-reach areas [3]. Concerning efficiency, one of their biggest problems is that since the energy is produced far from the end user, power systems suffer energy losses during transmission and distribution. Moreover, because they are not often deployed in difficult-to-reach areas, many communities are compelled to use nonrenewable energy sources, which raises energy costs and increases greenhouse gas (GHG) emissions [4].

Due to the above, there is currently a pressing need to integrate nonconventional energy sources into electrical systems. This integration would help enhance the technical, financial, and environmental conditions of existing networks, improve access to electricity in remote areas, and reduce the reliance on highly polluting energy sources such as fuel and diesel. In this regard, the purpose of this study is to identify the key problems and challenges regarding the integration of distributed generation (DG) systems into distribution networks. Additionally, we will review the contributions made by different authors in the field. Figure 1 shows the distribution of the subject areas with the most related publications, and Figure 2 depicts the recent increase in the number of studies on the topic.

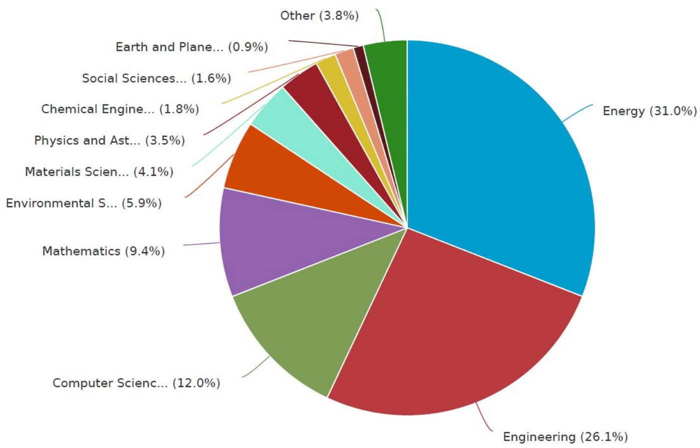

Figure 1. Related publications per subject area.

Analyzing the participation percent of the thematic addressed in this research in the different subject areas exploring in the literature, illustrated in Figure 1, it can be appreciated that most important participation corresponds to the areas of energy, engineering and computer sciences—which were considered as a focus of this work, by demonstrating in this way the importance and relevance of this manuscript. Furthermore, with respect to the importance of the integration of photovoltaic distributed generators in electrical distribution grids, Figure 2 showed an increase in the last decade, with a total of 42 works published in the current year. This figure showed stable behavior until 2005. However, with the entry into force of the Kyoto protocol in that same year, the interest in research projects that reduce CO_2 emissions and increase the implementation of renewable resources in the conventional electrical systems has increased considerably. Then, the Paris agreement signed at the end of 2016 gave a new boost to the planning of energy projects based on renewable resources with a view to reducing emissions. It is also necessary to consider that, during the years 2020 and 2021, many research laboratories were closed as a result of the pandemic, and this situation could have impacted the production of research articles on the topic addressed; as could be appreciated in Figure 2. This highlights the importance of exploring this thematic in the main indices studied in the literature: technical, financial and environmental indicators.

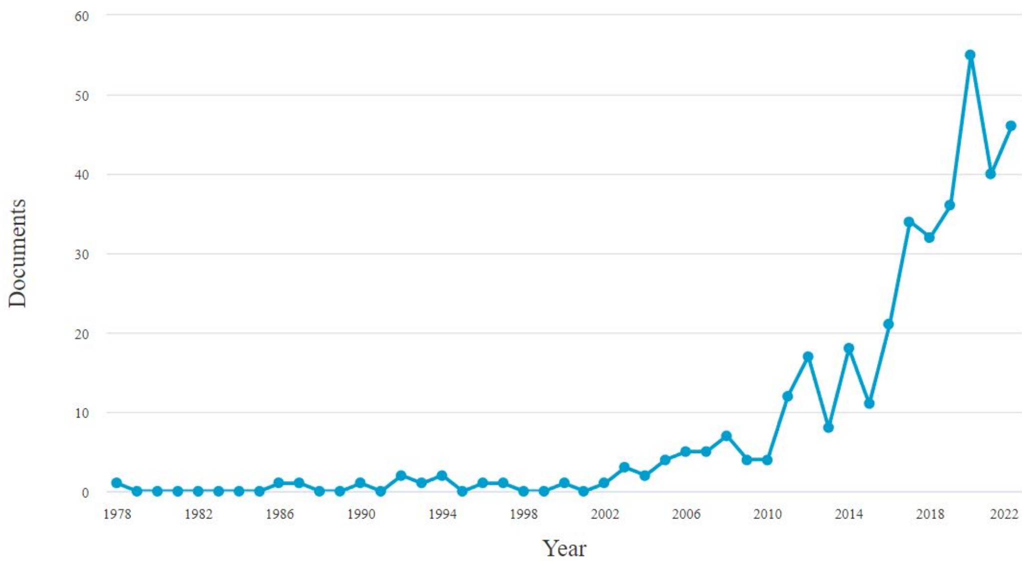

Figure 2. Related publications per year.

2. Distributed Generation Systems in Power Distribution Networks

Given the importance of mitigating the shortcomings of conventional power systems and satisfying the growing energy demand, researchers and the energy sector have worked on identifying such shortcomings and devising solutions to make existing systems more efficient, reliable, and environmentally friendly [5,6].

In terms of efficiency and reliability, one of the primary problems with conventional power systems is that the energy source is far from the end user, which results in energy losses during distribution and transmission. This, however, could be avoided if energy were produced closer to the load, and this is where DG systems play a fundamental role, due to their proximity to the end user [7]. In DG systems, power generation technologies are integrated into conventional networks, and the source is placed as close to the load as possible, which lowers the costs of producing, purchasing, and transporting energy and enables a more active network management [8]. Importantly, a proper DG implementation could enhance the operating characteristics of distribution networks. It could, for instance, improve voltage profiles, minimize line congestion, and reduce CO_2 emissions [9].

Considering the relevance of this type of power generation system, the following section examines the technologies that were used for distributed generation.

3. Types of Technologies Used for Distributed Generation

Even though DG systems can use both renewable and nonrenewable energy sources, their implementation should be associated with sustainable, profitable, and, most importantly, environmentally sound generation technologies, due to the benefits that these bring [10]. The choice of generation technology depends on multiple factors, and the success of its implementation will be determined by how well this choice was made, as well as by the topographic and meteorological characteristics of the area where this resource will be used [11–13]. Below, we describe some of the most popular renewable energy technologies.

3.1. Wind Turbines

Various regions in the world have a huge potential for producing electricity from wind power, primarily because of geographical factors that create air flows, which wind turbines harness to transform kinetic energy into electrical energy [14]. These systems were initially installed close to major consumption centers in certain countries. However, given the rapid industrialization and the need for new solutions to support conventional power systems, wind farms started to be built, even in places far from the end user and with power being directly injected into the transmission system [15].

Countries such as China, the United States, and Germany have worked on developing this type of technology and have designed policies that promote the adoption of more environmentally friendly energies. In Colombia, the Mining and Energy Planning Unit (UPME, by its Spanish acronym) is the entity in charge of regulating the usage of nonconventional energy sources [16].

Wind energy technologies require open spaces with constant air flows, which does not make it quite attractive for distributed generation applications. Nonetheless, they have been widely employed in areas with suitable topographic and meteorological characteristics.

3.2. Small-Scale Hydropower Plants

Small-scale hydropower plants use the kinetic energy produced from the mechanical movement caused by the flow of water to generate electricity. Although there is no consensus on their power capacity—the average power they produce does not exceed 20 MW—it is clear that these systems differ significantly from large hydropower plants in terms of generation capacity. Despite being a good option for distributed generation applications, their efficiency is not the highest compared to other technologies [17]. This paper has focused on small-scale hydro-power plants only, since our study applies to distribution systems, which include distributed generation sources that are generally smaller compared to the plants connected to the electric power transmission systems.

3.3. Photovoltaic Panels

Photovoltaic (PV) panels use solar radiation to produce electricity. These have been widely accepted due to their easy implementation and low maintenance costs. For decades, several production sectors have created different materials and procedures that have made this technology accessible to a large portion of the population [18]. Furthermore, the financial incentives that encourage the use of this technology have increased in recent years in several countries throughout the world [16,19]. PV panels are the most extensively used technology for distributed generation, as they are highly efficient, offer a great cost–benefit ratio, and emit less CO_2.

4. Location and Sizing of Distributed Generators in Distribution Networks

As mentioned previously, the purpose of integrating renewable energy sources (e.g., PV panels) into distribution networks—as close to the end user as possible—is to improve their technical, financial, and environmental conditions. Given their easy implementation and the tropical and warm weather in countries such as Colombia, these energy sources can be deployed in hard-to-reach areas. However, even though these technologies have many advantages over conventional generation methods, special consideration must be given to their sizing and location in electrical systems. This is because the success of their implementation will depend on the proper planning and arrangement of each element involved in the process [9,20]. Besides their proper location and sizing, choosing the right technology is also crucial; all of which will lead to the best outcomes. In countries such as Colombia, for instance, PV panels are always one of the preferred choices for power generation.

For the optimal location and sizing of PV DGs, it is important to know the main characteristics of conventional distribution networks. In addition, it is necessary to collect data on weather conditions and identify the technical requirements of the DGs and the way they will be integrated into the network. Figure 3 presents the proposed methodology for the optimal location and sizing of DGs in distribution networks.

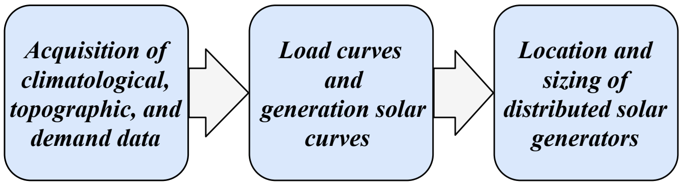

Figure 3. Stages of a project for the optimal location and sizing of distributed generators in distribution networks.

4.1. Acquisition of Data on the Climate, Topography, and Power Demand in the Region Under Study

To properly plan a DG project (optimal location and sizing of DGs), it is necessary to be aware of certain characteristics of the case study that might have a considerable impact on how each step of the project develops. For instance, since PV panels depend on solar radiation, data on the climate of the region under study are key to determining the system's power capacity and efficiency [11]. Additionally, data on the topography of the region must be collected to evaluate, after modeling, whether the system can be implemented. The reason for this is that if there were any limitations regarding the previously selected locations for the DGs, the efficiency of the DG system, as designed, could be significantly impacted. Likewise, as the success of a DG system based on PV panels largely depends on how efficient its design is, it is imperative to know the power demand in the region under study, so that each component may be properly sized [21].

When defining technical and operational aspects, it is also important to know the system's energy consumption profile, as successful DG integration hinges on supplying the right amount of power to the system nodes, which is dependent on the overall power demand. Such an energy consumption profile makes it possible to define the system's performance and power demand and thus design mathematical models based on trends and evaluate performance over fixed time intervals. As with the power generation curves, the choice of the period of analysis will be determined by the needs of the network operator or owner.

In the specialized literature, numerous techniques are employed to estimate energy consumption, including regression models [22], the Box–Jenkins method [23], econometric models, and intelligent techniques such as neural networks [24] and machine learning [25]. All these techniques require high-quality data (such as socioeconomic stratum, historical data on power consumption, and climate conditions of the region under analysis) to accurately represent a system's actual behavior and mathematically model it. In recent years, authors in the field have favored approaches that help reduce processing times and improve estimation accuracy [26].

If no actual data or energy consumption curves are available, power demand can be estimated using the nominal powers of users and the hours of usage of the electrical devices [27]. However, since this strategy is highly susceptible to human error and requires the devices' usage scheme, the chances of generating curves that are more accurate may be significantly reduced. Moreover, because of the volume of data and analysis that it requires, it is a lengthy and extremely rigorous process. In the literature, it is also common to find power demand tables, which are provided by the network operators of each region and represent the estimated power consumption behavior of users in various socioeconomic strata. This strategy is one of the most frequently used by network operators [28].

Importantly, the positive impacts of DG projects on the technical, financial, and environmental aspects of networks will always depend on the use of precise information. This information helps construct representative mathematical models to propose high-quality solutions to the problem of optimally locating and sizing DGs in electrical networks.

4.2. PV Power Generation and Load Curves

Data on power generation and load demand are key when designing operation strategies for an electrical system. In the case of distributed generation based on renewable energy sources, it is crucial to know the generation and load profiles of each source present in the system. The reason for this is that the generation curves of renewable energy sources are typically very variable and heavily influenced by the geographic and meteorological conditions of the region where the electrical system is located.

Power generation curves can be modeled via prediction methods [29], which take into account the energy resources available in the region under study. These curves are vital for determining whether a DG system can produce the required power. They can be estimated using data on the nominal power of the generation system and the solar radiation and temperature of the region under analysis. Load curves, for their part, are often modeled using historical power consumption data managed by network operators; however, in the absence of such data, they can also be obtained via deterministic or stochastic models. In deterministic models, power consumption is estimated by using the power consumed by the users' equipment connected to the system [30]. In stochastic models, power consumption is analyzed over a specific time period (usually months or years) to generate curves that represent the best consumption probability [31]. With enough and adequate data, it is possible to estimate power generation and, using this information, perform analyses to improve the technical and financial efficiency of the generation system by optimally sizing and locating the chosen devices.

The energy potential of different regions around the world has been described in technical reports. In Colombia, for instance, the UPME is the entity responsible for promoting the creation of reports containing this specific information. There is a report on the water potential of the country's various regions (the hydropower atlas) [13], as well as on their solar radiation potential (the solar and ultraviolet radiation and ozone atlas) [11] and wind conditions (the wind atlas) [12]. However, as these data can vary over time due to topographic and meteorological factors, this type of report can only be used to obtain approximate generation profiles. Therefore, when employing renewable DGs, on-site measurements should be conducted to avoid doing calculations using inaccurate generation estimates. Importantly, in order to make a project profitable, every little detail counts.

In the specialized literature, several techniques have been proposed to evaluate the energy potential of different renewable energy sources. These techniques typically rely on historical data or on-site measurements to obtain power generation estimates. Techniques based on statistical and stochastic data, artificial intelligence [32], and Big Data [33] have gained traction in recent years. The choice of the appropriate technique will depend on the required estimation accuracy and the period of analysis will be determined by the needs of the network operator or owner. In any case, the chosen technique must accurately represent the generation profile of the region under analysis; this in order to assess the impact of DG integration on the project's technical, financial, and environmental aspects. If no historical data are available or on-site measurements cannot be made, the aforementioned generation curves may be an acceptable alternative in terms of accuracy.

4.3. Location and Sizing of Distributed Generators

In this stage, which is key to assessing the system's efficiency, the data collected from the previous two stages are employed to create a design that meets the basic goals of distributed generation in terms of energy-economic efficiency. Importantly, to make this type of initiative profitable and efficient, DGs need to be optimally located and sized.

Even though DGs emerged as a solution to some of the issues that conventional power systems face, they have several disadvantages associated with the complexity of the medium in which they must be installed. Since the successful operation of a distribution network depends on a variety of technical and operational factors, DGs must considerably improve its operating parameters while also ensuring a swift return on investment. According to Hernández et al. [34], the main drawbacks of distributed generation include the fact that it may lead to an increased intermittency of the service, fail to properly coordinate protections (which are designed for unidirectional flows but are exposed to bidirectional flows due to the nature of distributed generation), and cause a higher congestion in electrical networks with high voltage variations. Nonetheless, by properly sizing and locating DGs, these drawbacks can be overcome.

The optimal integration of distributed energy resources into electrical networks can be represented by means of a master–slave methodology (see Figure 4). In this methodology, the master stage is in charge of selecting the appropriate DGs and locating them in the network, and the slave stage is responsible for determining their right size using an Optimal Power Flow (OPF) technique or optimal sizing strategy. The primary goal of these techniques and strategies is to find the most suitable power configuration based on an objective function which has been previously mathematically modeled. In other words, they aim to estimate the impact of a potential DG integration and operation over a given time period. An objective function, which can be single- or multi-objective and whose focus will depend on the needs of the network owner, is just a criterion represented through variables that describe a system's behavior.

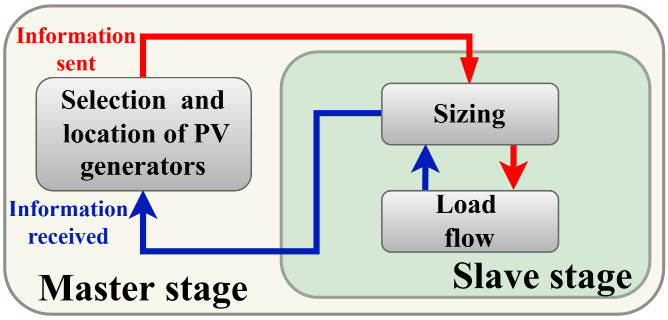

Figure 4. Master–slave methodology for the optimal integration of distributed generators into electrical networks.

Importantly, for each power configuration defined by the OPF method, a load flow analysis must be conducted to determine its impact on the objective function and constraints of the problem, as shown in Figure 4. Such load or power flow analysis requires data on the power delivered by each DG, the power demanded by users, and the system's technical parameters to compute the voltages at each node for a permanent regime, as well as the active and reactive power flows in each component of the system (lines, transformers, reactances, and capacitors) [35]. Through the load flow analysis, the system's operating conditions can be verified, which is performed in two stages. In the first stage, the complex voltages at each system node are determined. To that end, a system of nonlinear equations must be developed considering the system variables and solved using numerical approaches due to the nonlinearity of the problem. In the second stage, the active and reactive power flows, as well as the power losses in each component of the system, are calculated using the data obtained in the first stage [36].

Different methods to solve the load flow problem have been reported in the specialized literature, with the Gauss–Seidel and Newton–Raphson methods [37,38] being the most popular. The Gauss–Seidel method, which employs complex numbers, is an iterative approach to solving linear equations. When used to solve the load flow problem, its complexity increases as the number of nodes to be evaluated in the system increases [39]. It is easy to implement because it directly works with complex numbers; however, since its processing time increases as the number of nodes increases (larger system), its convergence is fairly slow [35,40]. The Newton–Raphson method, for its part, uses an algorithm to find approximations to the zeros or roots of a real function. Additionally, it determines a function's maximum or minimum using the zero of the first derivative [41]. Given that its original formulation is considerably more complete, this method is more efficient than the Gauss–Seidel method in terms of processing time and the number of iterations needed to solve the equations. However, when used for radial distribution networks, it turns out to be less efficient because it often requires the inversion of high-dimensional matrices, which extends processing times [35,42,43].

In recent years, novel approaches that guarantee convergence to the solution in shorter processing times have been proposed to solve the load flow problem. Clearly, given the large number of load flow analyses that must be performed when solving a planning problem such as that addressed in this paper, processing times become quite important.

4.4. Available Literature on the Subject

The increasing demand for electricity around the world has sparked tremendous interest in the deployment of renewable energy technologies. These technologies offer a number of financial benefits over conventional energy sources while also being substantially more environmentally friendly [8]. For example, DGs based on renewable energy sources have emerged as a solution to the majority of the technical, operational, financial, and environmental problems of conventional power systems [44] (e.g., power losses, violations of the acceptable voltage limits, line loadability, and high operating costs). However, if DGs are not properly integrated into distribution networks, these problems can be exacerbated rather than solved.

The key to a successful DG integration lies in choosing the right method for such a task. For instance, various studies in the specialized literature have employed mathematical optimization methods to find the optimal technical and operational conditions while also improving the project's financial and environmental aspects. In essence, these methods help analyze the impact of DG integration on a network's operating characteristics and thus adjust certain variables to make its operation more efficient [45,46].

Mathematical optimization models include an objective function, which defines the focus of the solution [47]. Objective functions are used to define parameters that produce the effects linked to the intended goal, which may be associated with the technical, financial, and environmental aspects affected by the operation of the network. Among the parameters impacted by power injection by DG systems, the technical ones drew the greatest attention. In fact, most studies in the specialized literature use the improvement in the system's technical and operational conditions as the objective function. Another goal pursued by several authors is the reduction in the network's operating costs, which is crucial for making energy projects financially feasible. Although the environmental issue has received little attention, it cuts across the technical and financial ones. Clearly, if low-emission renewable energy sources are integrated into power systems, the GHG emissions of the latter will be reduced, and they will become environmentally friendly. Importantly, the single- or multi-objective nature of the objective functions used to represent the network's indicators will determine the solution's elements of interest [46,48]. Multi-objective functions, in particular, are made up of combinations of conflicting goals such as the reduction in operating and investment costs, the minimization of power losses and investment costs, and the reduction in energy purchase costs and CO_2 emissions [49].

Some studies in the specialized literature have employed analytical, numerical, heuristic, metaheuristic, and hybrid methodologies to optimally integrate DGs into electrical networks [49]. Analytical techniques use a mathematical model with a straightforward numerical solution to represent the operation of the system. Since they are typically implemented using computational tools and rarely analyze the impact on voltage profiles, special care must be taken to ensure that the permitted voltage limits are not exceeded in accordance with the regulations of each region [50]. Numerical approaches, which might be direct or indirect, are best suited for low-complexity problems. The most popular ones include dynamic programming [51], linear and nonlinear programming [52,53], stochastic programming [54], and integer programming [55]. Heuristic and metaheuristic methods produce high-quality solutions with low computational effort (processing time and memory usage) [47], with bio-inspired algorithms such as the genetic algorithm [56], particle swarm optimization [57], and the ant lion optimizer [58] standing out among these techniques. Finally, hybrid methodologies combine the methods previously mentioned to solve the master and slave stages of the DG integration problem, and this is why they are widely used in the literature [59].

Below, we present and describe some of the studies that use the aforementioned solution methodologies. Such studies were classified based on the focus considered in the objective function, which may be technical, financial, or environmental.

4.4.1. Technical Focus

Since DG deployment is influenced by the technical aspects under which distribution networks operate, an objective function seeking to optimize their technical and operational conditions will positively impact the goal of optimally sizing and locating DGs.

In the specialized literature, there is a clear strong tendency to develop methodologies aimed at enhancing a system's technical and operational conditions, which is why this area has seen significant progress in recent years. The problem of optimally locating and sizing distributed energy resources —in which both their integration and operation are evaluated—is often solved using mathematical optimization techniques, whose goal is to improve certain technical aspects associated with the system' energy efficiency (e.g., line loadability, violations of acceptable voltage profiles, and power losses) [45,46]. The following are some of the most relevant publications in the field that focus on technical aspects:

- By integrating a single DG into a distribution network, the authors of [60] presented a methodology for optimally locating and sizing DGs. The objective function they considered was the reduction in the power losses associated with energy distribution and transmission, for which they developed a sensitivity loss factor based on the system's equivalent current injection. Their proposed analytical method for radial systems avoids using operations with admittance, impedance, or a Jacobian matrix with a single power flow and is quite similar to the classical grid search algorithm based on successive load flows. Furthermore, besides being easy to implement, its accuracy is higher than that of other analytical techniques. Its effectiveness was tested in the 12-, 34-, and 69-node test systems, and it achieved power loss reductions ranging from 45.41 to 59.09%. Likewise, after comparing its performance with Acharya's method [61], the authors reported significant reductions in processing times. Finally, because the objective function focused on optimizing the system's technical and operational conditions, it is not possible to determine how the obtained improvements impact the system's financial and environmental characteristics.
- In [62], the authors proposed a technique for optimally sizing and locating DGs, with the objective function being the reduction in power losses. In comparison to other studies reported in the literature, the authors obtained exceptional results using the mixed-integer second-order cone programming (MI-SOCP) model, whose performance was tested in the 33- and 69-node test systems. Being an exact technique, their proposed model produces very good quality solutions (zero standard deviation) at shorter processing times. Additionally, by evaluating several time frames, it makes it possible to find the system's global optimum. To do so, it uses computational tools that allow the code to be modified in accordance with the stated requirements (MATLAB). The authors, however, only examined technical and operational aspects and their impact on power losses but failed to consider the financial and environmental gains of the proposed solutions. Furthermore, the use of specialized software raises the cost and complexity of the solutions and, in some cases, requires processing input and output data for the software being used.
- The authors of [63] presented an analytical method for optimally locating and sizing DGs, which employs analytical expressions based on the change of the active and reactive components of the currents to reduce actual and reactive power losses in radial distribution networks. This method evaluates the active and reactive power at each node and uses this information to select the nodes with the biggest positive impact on the system. It can be used to locate one or more DGs and has been proven to considerably improve voltage profiles. Its effectiveness was tested in the 33- and 69-node test systems, and the solution it provided was modeled using MATLAB. According to the results, it achieved power loss reductions ranging from 69.55 to 89.89%.

The authors' approach, however, does not allow us to assess the processing times or the quality of the obtained solutions. Furthermore, the solutions only addressed technical aspects, ignoring the financial and environmental issues, which may have been employed as a supplement to the proposed methodology.

- In [64], the authors proposed an efficient analytical (EA) technique aimed at minimizing power losses in distribution networks. With this technique, various types and numbers of DGs with different generation capacities can be integrated into power systems. Moreover, it makes it possible to calculate the best power factor for each DG and, along with the OPF method, efficiently address the system constraints. Its effectiveness was tested in the 33- and 69-node test systems, yielding, among the best results, power loss reductions of 65.5% and 71.5%, respectively. When compared to other methods, it was faster and more precise and produced high-quality solutions in terms of finding the most suitable location and size for each case under analysis. Although the authors examined the technical aspects and their impact on the system's power losses, they failed to assess the financial and environmental effects of DG integration.
- The authors of [65] presented a methodology whose objective function is the improvement in the technical and operational conditions of power systems with existing DGs. The proposed methodology uses a convex approximation of the alternating current power flow equations for the reconfiguration of distribution networks. To do so, it concentrates on managing active and reactive power, as well as controlling the current using system-intervening components (switches). The mathematical optimization model adopted linear disjunctive formulations and was developed using the general algebraic modeling system (GAMS). The proposed methodology was tested in the 34-, 70-, and 135-node test systems under various generation–consumption scenarios. According to the results, it managed to reduce processing times, the computational burden (by lowering the search space), and power losses. Nonetheless, the solutions' scope only allows its technical and financial impacts to be estimated, without taking into account its environmental implications. Additionally, since the proposed methodology employs commercial software, it comes with the drawbacks mentioned earlier.
- In an effort to reduce power losses, the authors of [66] proposed a numerical model that uses the primal-dual interior point (PDIP) method to solve nonlinear OPF problems. The main goal of their proposed model is to find the optimal location and size for the DGs and thus optimize the technical and operational conditions of power systems. The proposed model was tested in the 10- and 42-node radial distribution systems, and, based on the results of the simulations performed in MATLAB, it was found to significantly reduce power losses. According to the authors, their proposed model is superior to other methods reported in the literature. They, however, did not specify which other methods they analyzed to come to this conclusion. Furthermore, their findings do not make it possible to assess the solution's quality and repeatability and processing times. Finally, since this methodology focuses on technical and financial aspects, it fails to assess the environmental impacts of DG integration.
- In [67], the authors presented a heuristic solution to the power flow problem, which uses the improvement in the two technical and operational conditions of the system (improved voltage profiles and lower power losses) as the objective function. Based on an analysis of the system's steady-state conditions, DGs are placed at the nodes with the highest variation in voltage profiles, which minimizes the power losses and enhances such profiles. The proposed methodology was tested in the 90-node test system, and although the results showed a reduction in the system's power losses, the authors failed to compare their numerical results with those of other approaches. Furthermore, due to variations in the convergence results, processing times cannot be estimated. Moreover, because the solutions focus on technical aspects, the financial benefits or environmental implications of DG integration cannot be evaluated.

- The authors of [68] proposed a method for the optimal location and sizing of DGs, in which the mixed-integer nonlinear problem (MINLP) is solved in two stages. The first stage is in charge of finding the optimal location of the DGs using a siting planning model (SPM), which chooses the candidate node based on the combined loss sensitivity (CLS). The second stage is responsible for determining the optimal size of the DGs by means of a capacity planning model (CPM), which employs sequential quadratic programming to determine the proper size of the DGs. The proposed method was tested in the 33- and 69-node test systems and compared with other solution methodologies. According to the results, and given its ability to analyze several DGs simultaneously, the proposed method required shorter processing and convergence times. However, even though the obtained results are reliable and of high quality, they do not allow the financial and environmental impacts of DG integration to be assessed.

4.4.2. Financial Focus

Several publications in the specialized literature have assessed the financial impact of DG deployment on power generation and distribution projects. Given the relevance of the installation, operating, and maintenance costs of DGs when assessing a project's viability, this topic has aroused great interest. The following are some of the most relevant studies on the matter:

- In [69], the authors presented a heuristic methodology aimed to lower a project's initial investment costs by optimizing some of a system's technical and operational variables and finding the optimal location and size for the DGs. To achieve this, this methodology uses a genetic algorithm, which, based on the radial distribution of the loads, helps reduce the complexity of the mathematical model and shorten processing times. The proposed methodology was tested in the 33-, 43-, and 46-node test systems. When compared to conventional approaches reported in the literature, the authors found that it is effective in minimizing the initial investment costs and considerably reducing the risk of investment loss. Likewise, as it helps to reduce the complexity of the mathematical model, the amount of data to be processed significantly decreases, which has a positive impact on processing times. One of its main drawbacks, however, is that, due to its heuristic nature, it is likely to fall into local optima. In addition, the information provided by the authors does not allow the quality or repeatability of the obtained solutions to be assessed. Furthermore, since the objective function focuses on improving some of the system's technical and operational variables to obtain financial gains, the environmental benefits brought by DG integration cannot be estimated.
- In [70], the authors developed a model similar to the one suggested in [64] to optimally size and locate DGs in electrical systems. Such a model uses the loss sensitivity factor to determine the proper location of the DGs and the bacterial foraging optimization algorithm (BFOA) to determine their right size. By implementing such a model, the network's power losses can be minimized, the voltage profiles improved, and the system's operating costs minimized, with this latter being the differentiating factor with respect to the method proposed in [60]. After testing the proposed model in the 33- and 69-node test systems under various load scenarios, the authors reported quick results in terms of processing time. However, because the model is heuristic in nature, it sacrifices the solution quality and repeatability for processing speed. Furthermore, the authors failed to analyze the environmental benefits brought about by a proper DG location and sizing.
- By means of a stochastic programming scheme, the authors of [71] designed a methodology for the optimal location and sizing of DGs in low-voltage networks. Their main goal was to find a way to meet the rising demand for electricity caused by the increased use of electric vehicles and their charging needs in low-voltage structures. The financial variables they considered in the objective function included the price of the DGs

and their operating costs. The proposed model was formulated based on the capacity of the DGs in terms of apparent power, i.e., the active and reactive power that the DGs inject into the distribution network. Using a linearization and a modified version of the genetic algorithm (GA), the MINLP was solved, and the number of scenarios was reduced, which is key to determining the right size of the DGs. The proposed methodology was tested in the 69-node test system under different load scenarios and periods. According to the results, it took approximately seven hours to solve the location and sizing problem, which suggests the high computational burden required to solve it. The obtained solutions, nonetheless, were of high quality and showed good repeatability, which allows evaluators to make sound decisions. The authors, however, did not assess the environmental impact of the obtained solutions.

- Microgrids operate in a similar way to power distribution systems. In the methodology proposed in [72], the authors address concepts related to distributed generation by analyzing a microgrid. The proposed methodology involves two stages focused on determining the optimal size of the distributed energy resources and examining the system's behavior during power interruptions. The objective function the authors considered was the reduction in the costs associated with the initial investment and the project's operation. In the first stage, a mixed-integer stochastic programming method is used to simultaneously find the optimal sizes of various DGs while also assessing both the financial benefits and resilience performance. In the second stage, the stochastic sizing problem is converted into an equivalent deterministic MINLP problem to obtain far more efficient solutions. The proposed methodology, which was tested in the resource planning analysis for a military base in the United States produced good results in terms of optimal DG sizing, which considerably enhanced the project's net economic benefit. Although the results reported by the authors do not allow the quality and repeatability of the solution and processing times to be assessed, the authors did highlight the method's ability to simultaneously size various DGs while taking into account the project's economic performance and resilience. Moreover, their analysis would have been considerably enhanced if they had assessed the environmental impact of the proposed methodology (in terms of GHG emissions).
- In [31], the authors designed a stochastic, adaptive, and dynamic strategy to address the optimal DG location and sizing problem, with the objective function being the minimization of the operating costs of a medium-voltage distribution network. To that end, the proposed strategy considers the generation curves of the DGs and uses model predictive control (MPC) to deal with the variations in the power injected into the network. In such a study, the authors also included energy storage systems to complement the system's operational characteristics. When compared to simple stochastic models, the results obtained by the proposed strategy in terms of solution quality were more favorable. In addition, they helped to quantify the savings resulting from the reduction in power losses and operating costs. Additionally, by using the MPC, the optimization process became more robust and had less prediction errors. Nevertheless, unlike in other approaches reported in the literature, this lengthened the processing time. Finally, the authors of this study failed to examine the solution's environmental impact.
- The authors of [73] presented a methodology for the optimal location, sizing, and geographic positioning of DGs in smart grids. The objective function they considered focused on determining the project's net present value, as well as the grid's power balance and maximum generation capacity. The authors employed a Geographic Information Systems and multicriteria decision analysis (GIS-MCDA) approach to determine the potential geographic locations for the DGs and a mixed-integer optimization model to find the proper size and location of the DGs. The proposed methodology was tested using three different scenarios in order to quantify its impact on the price of selling electrical energy, the system's contribution to the overall power demand, and the cost of renewable energy implementation. The information provided

by the authors, however, does not allow the methodology's performance in terms of processing time and repeatability of the solution to be assessed, nor to estimate its environmental benefits. Regarding future research opportunities, the authors suggest analyzing the financial incentives provided by the various control organisms, the bonuses paid by network operators when injecting power into the system, and uncertainties in climate data.

- In [74], the authors proposed a method for the simultaneous integration of various types of DGs and energy storage systems to improve the technical and operational characteristics of electrical systems. This method, which offers a solution for the network planning process, has, as the objective function, the reduction in operating costs. It uses an alternating current OPF algorithm to obtain strategic information about the system's investment and operating costs over a specific time horizon. Furthermore, it employs a modified version of the GA to conduct analyses for periods greater than 24 h and up to 8760 h (1 year), which more accurately represent the behavior of a system. By considering this time horizon, the precision of the solutions can be enhanced. The proposed methodology was tested in a modified version of the 33-node test system considering two scenarios: off-grid and grid-connected. According to the results, it produced better results in the grid-connected scenario, with a reduction in power consumption of approximately 37%. Additionally, the initial investment in grid-connected systems is considerably low because they are not required to meet the entire network's energy demand. For time periods of less than 24 h, the solutions came quickly. Since the quality of the solutions depends on the number of iterations, such quality was found to deteriorate after 15 iterations. The proposed methodology, however, does not make it possible to estimate the environmental benefits of the obtained solutions. Concerning future work, the authors recommended analyzing a confidence interval for the installed generation capacity so that the energy contribution in terms of grid autonomy can be quantified.
- In [75], the authors developed a two-stage methodology based on the cooperative game theory for the optimal location and sizing of DGs, with the objective function being the reduction in the total costs of power generation. In the first stage, a set of candidate nodes are selected based on the locational marginal costs per unit of active power. This helps reduce the search space and optimize the time and number of computational resources required to find a solution to the load flow problem. In the second stage, the Shapley value, which is frequently used in the cooperative game theory, is computed to determine the optimal location and size of the DGs. The reason for this is that this value takes into account the marginal contributions of the generation technologies used as alternative methods. The proposed methodology was tested in the IEEE 14- and 30-node test systems, and when compared to other approaches reported in the literature, it was found to reduce the costs of power generation. The authors, however, did not provide information to evaluate processing times and the repeatability and reliability of the obtained solution. Likewise, the proposed methodology lacks tools to estimate the impact of DG integration on other aspects of interest (e.g., environmental or technical aspects).

After reviewing the studies presented above, we may conclude that financial factors are crucial when executing DG integration projects, as a project's financial viability signals the start of a cultural shift, motivates potential investors, and helps achieve shared goals such as reducing GHG emissions.

4.4.3. Environmental Focus

Few studies in the specialized literature have developed methodologies aiming to less the environmental damage caused by the production of electricity. However, as mentioned earlier, improving the technical and financial conditions of the many processes involved in distributed generation could help reduce GHG emissions. The following are some of the publications that focus on optimizing the environmental aspects of a DG system.

- In [76], the authors proposed a methodology to solve the problem of optimally locating and sizing PV DGs in electrical networks. Their main goal was to replace conventional energy sources with solar PV technologies to more efficiently generate power and with less environmental impact in terms of GHG emissions. Based on the system's power demand and generation curves, the authors designed a MINLP model, which was solved using GAMS. In addition, they employed an artificial neural network to reduce the uncertainties associated with the solar PV power generation. The proposed methodology was tested in the 21-node test system, and the results showed a reduction in GHG emissions of roughly 19%. Additionally, although the number of DGs being installed may affect processing times, the authors reported that their proposed methodology could provide solutions in less than 20 s. Likewise, the obtained solutions showed good quality and repeatability, with a maximum error rate of 1%. In order to find a better solution to the problem being addressed, the authors stress the need for further studies on the equipment's useful life, operating costs, and land availability. They also recommend using energy storage devices, which would increase the system's operational capacities, particularly during periods of peak energy demand.
- The authors of [77] developed a methodology which, although it does not address the issue of distributed generation from its design (DG location and sizing), it does address the OPF problem in systems with already installed DGs. Based on an analysis of Battery Energy Storage Systems (BESSs), this methodology adopts a multi-objective optimization approach that mostly focuses on lowering CO_2 emissions. A nonlinear programming model was designed to lower the costs associated with power losses and the amount of GHGs released into the atmosphere. The resulting nonlinear, nonconvex, and multiperiod OPF problem was solved using GAMS and the weighting factor approach. The authors reported that, when injecting the reactive power for operating the BESSs and taking into account the power electronics stage, some technical aspects of the system were improved. The proposed methodology was tested in the 69-node test system, and it yielded maximum reductions in GHG emissions of 40.9%. The authors, however, failed to provide information on processing times and the quality and repeatability of the solutions. As future work, they recommend reformulating the OPF model to evaluate various time periods using a convex conic representation, which, from a mathematical perspective, ensures finding a global optimum.
- In [78], the authors presented a mathematical model that quantifies the cost of distributed generation based on environmental assessment indexes. In other words, they seek to economically quantify some of the negative effects of GHG emissions and the penalties this brings. To do this, the authors used mathematical modeling, which allowed them to estimate the economic contribution by considering the environmental benefits of distributed generation. The proposed methodology was tested in a real-world case in China using various renewable energy sources. When compared to conventional power generation sources, distributed generation was found to provide economic benefits when taking into account environmental factors. The results of such a study, nonetheless, do not make it possible to determine the optimal sizes and locations for the DGs, nor to assess the processing times and the quality and repeatability of the solutions.

Due to the culture of sustainable development that many world powers have been cultivating and that paves the way forward, environmental aspects are expected to gain traction in the upcoming years. Furthermore, the number of studies seeking to optimize the environmental factors associated with DG implementation is expected to rise given the increasing financial benefits attributed to the use of more environmentally friendly power generation sources.

After reviewing the various studies available in the specialized literature, we may conclude that the different approaches to solving the load flow problem will always be closely related. This is because the technical and operational variables of a DG system have a cross-cutting impact on the outcomes. It would, however, be interesting to propose solution methodologies that evaluate outcomes based on the simultaneous improvements in environmental, technical, and financial aspects. Finally, when evaluating several scenarios in short periods of time, such as in public tenders, analyzing processing times and repeatability is quite important, as well as ensuring that high-quality solutions are obtained each time an algorithm is executed. Table 1 provides a summary of the studies we found in the specialized literature. From left to right, it specifies the selected objective function, the optimization method used to solve the problem, the test system employed to validate the proposed methodology, and whether aspects such as processing times and repeatability were assessed.

Table 1. Related studies found in the specialized literature and their characteristics.

Ref.	Objective Function	Solution Technique	Test System (Number of Nodes)	Comparison with Other Methods	Processing Time	Repeatability
[60]	Minimization of power losses	Loss sensitivity factor	IEEE 12-,34-, and 69-node test systems	Yes	Yes	No
[62]	Minimization of power losses	BAB and MI-SOCP	33- and 69-node test systems	Yes	Yes	Yes
[63]	Minimization of power losses	Analytical approach	33- and 69-node test systems	No	No	No
[64]	Minimization of power losses	EAN	33- and 69-node test systems	Yes	Yes	Yes
[65]	Minimization of power losses	GAMS	34-, 70-, and 135-node test systems	Yes	No	Yes
[66]	Minimization of power losses	PDIP	10- and 42-node test systems	No	No	No
[67]	Minimization of power losses	AMPL solver	90-node test system	No	No	No
[68]	Minimization of power losses	CSL, SQP, and BAB	33- and 69-node test systems	Yes	Yes	Yes
[69]	Minimization of CapEx	GA	33-, 43-, and 46-node test systems	No	Yes	No
[70]	Minimization of OpEx	BFOA	33- and 69-node test systems	No	Yes	No
[71]	Minimization of CapEx and OpEx	Modified GA	69-node test system	Yes	Yes	Yes
[72]	Minimization of CapEx and OpEx	MILP	Military base	No	No	No
[31]	Minimization of OpEx	MPC	33-node test system	Yes	Yes	Yes
[73]	Minimization of CapEx	MCDA	IEEE 12-, 34-, and 69-node test systems	No	No	No
[74]	Minimization of OpEx	AC-OPF	33-node test system	Yes	Yes	Yes
[75]	Minimization of OpEx	MLCS and Shapley value	14- and 30-node test systems	Yes	Yes	Yes
[76]	Reduction in CO_2 emissions	GAMS	21-node test system	No	Yes	Yes
[77]	Reduction in CO_2 emissions	GAMS	69-node test system	No	No	No

Analyzing the last table, it is possible to identify that, in technical aspects, the most employed objective function is the minimization of power losses. In economic terms, the minimization of CapEx and OpEx are the more commonly used indices. In relation to the environmental indicators, the reduction in CO_2 emissions is the most used objective function, mainly in relation to the conventional generators that operate with Diesel fuel. As the development of the thematic of improvements in environmental conditions is currently ongoing, it requires studies and exploration. Furthermore, in this table, it is possible to appreciate the high implementation of the test systems of 33 and 69-node test systems for evaluating the effectiveness of the solution methodologies proposed. The evaluation of the performance of the solutions focused on the evaluation of the solution, repeatability and processing time, by analyzing different works reported in the literature using comparison methods in most cases.

In this table, the need to include the analysis of repeatability and processing time for the methods that will be proposed in the future is highlighted. This guarantees that the solution methodologies obtain a solution of good quality in the minor processing time required each time that this is executed.

5. Conclusions

In the upcoming years, energy production using renewable energy technologies may become one of the key pillars for ensuring sustainability and social growth. In fact, for several years now, research and development activities in the field have led to promising advancements and boosted the competitiveness of this type of technology. Distributed generation, for instance, has been proven to considerably improve the technical, financial, and environmental conditions of electrical networks. However, special attention should be given to crucial aspects such as the optimal location and sizing of DGs.

In this paper, we reviewed some of the studies available in the specialized literature that contribute to the optimization of DG systems. These studies employ mathematical models to simulate test scenarios in which different objective functions (focused on improving the technical, financial, and environmental aspects of distribution networks) are sought to be optimized. Although the majority of these studies strive to improve technical and financial aspects, there are great opportunities in the development of methodologies to analyze the impact of DG location and sizing on technical, financial, and environmental objective functions.

Based in the analysis made in this review paper, it was possible to identify the need to develop new solution methodologies based on sequential programming optimization strategies that avoid the implementation of specialized software, and with the aim to reduce the complexity and cost of the solutions. Furthermore, it is necessary to include integration and operational costs inside the economical functions used for the integration of the distributed generators, with the aim to include the acquisition and maintenance cost of the distributed generators installed. In addition, in technical indices, it is necessary to considering in parallel the power losses and the constraints related to the technical limits of all devices integrated within the electrical grid, as well as the operative bounds related to electrical regulations, such as the chargeability of the branches, and the stability of voltage profiles, among others. In environmental terms, it is currently necessary to propose solution methodologies that consider the different gas emissions related to the operation of fossil fuel, not only the CO_2 emission. This is due to the negative related impact of these gases affecting human life. As such, it is necessary to increase the number of studies that evaluate the impact of the photovoltaic generation in electrical network from an environmental point of view. Being important, evaluating all strategies proposed in terms of quality, repeatability and processing times.

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Abbreviations

The following abbreviations are used in this manuscript:

MI-SOCP	Mixed-integer second-order cone programming
EAM	Efficient analytical method
GAMS	General algebraic modeling system
GA	Genetic algorithm
PDIP	Primal-dual interior point
CLS	Combined loss sensitivity
SQP	Sequential quadratic programming
BAB	Branch and bound
BFOA	Bacterial foraging optimization algorithm
CapEx	Capital expenditures
OpEx	Operating expenditures
MILP	Mixed-integer linear programming
MPC	Model predictive control
MCDA	Multicriteria decision analysis
AC-OPF	Alternating current optimal power flow
LMCs	Locational marginal costs

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