Computer Modeling in
Engineering & Sciences

Tech Science Press

Doi:10.32604/cmes.2025.071302

REVIEW

A Comprehensive Review of Sizing and Allocation of Distributed Power Generation: Optimization Techniques, Global Insights, and Smart Grid Implications

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Received: 04 August 2025; Accepted: 14 October 2025; Published: 26 November 2025

ABSTRACT: Optimal sizing and allocation of distributed generators (DGs) have become essential computational challenges in improving the performance, efficiency, and reliability of electrical distribution networks. Despite extensive research, existing approaches often face algorithmic limitations such as slow convergence, premature stagnation in local minima, or suboptimal accuracy in determining optimal DG placement and capacity. This study presents a comprehensive scientometric and systematic review of global research focused on computer-based modelling and algorithmic optimization for renewable DG sizing and placement. It integrates both quantitative and qualitative analyses of the scholarly landscape, mapping influential research domains, co-authorship structures, the articles' citation networks, keyword clusters, and international collaboration patterns. Moreover, the study classifies and evaluates the most prominent objective functions, key computational models and optimization algorithms, DG technologies, and strategic approaches employed in the field. The findings reveal that advanced algorithmic frameworks substantially enhance network stability, minimize real power losses, and improve voltage profiles under various operational constraints. This review serves as a foundational resource for researchers and practitioners, highlighting emerging algorithmic trends, modelling innovations, and data-driven methodologies that can guide future development of intelligent, optimization-based DG integration strategies in smart distribution systems.

KEYWORDS: Systematic and scientometric; global trends; distributed generation; sizing and allocation; multi-objectives; modelling and algorithmic optimization

1 Introduction

Renewable energy sources are increasingly being explored for power generation in Distributed generation (DG) systems. DG sources have long been recognized as a viable remedy for several power system issues, including high power losses, low reliability, power quality, and transmission power network congestion [1–4]. Power distribution networks can benefit from the efficient use of DGs to enhance the voltage stability and reliability while simultaneously reducing voltage deviation and power losses. However, improper implementation of these sources can lead to negative effects such as more power loss, voltage imbalance, inadequate protection coordination, reverse power flow, etc. [5]. Moreover, improper size and location of DGs can impact the fault current values at the common coupling point and power quality [6]. Consequently, it is crucial to consider the best way to use DGs while integrating them into distribution networks. The DG implementation is a nonlinear problem with multiple objectives, which is challenging because each objective is important on multiple units and scales. Because of potential conflicts of interest, multi-objective optimization problems must be carefully formulated. Many multi-distinct objectives can be simplified to single-objective problems by giving them distinct weights [7].

The unnecessary and uncontrolled construction of DGs presented major challenges and obstructions in the power distribution networks two decades ago. Modern distribution networks require both directions of the power flow to address the two primary problems of power loss and voltage changes, as opposed to bidirectional power flow from higher voltages to lower voltages [8,9]. Numerous optimization techniques are applied to attain the optimal DG allocation and sizing. Furthermore, the influence of the DG size and site on energy losses, energy flow, voltage profile and other properties has been studied by researchers over the years and reported in the literature. Scholars worldwide are working to reach the optimal DG sizing and placement to enhance the voltage profile and reduce the power loss in the current distribution network. They have offered a range of strategies and techniques for selecting the appropriate DG allocation and size.

Many research reviews on the best design of DGs have been conducted and published in the literature. For instance, the study in [10] presents the state-of-the-art on optimal DGs allocation in the power system network with multiple objectives and its limitations. Different load models affect DG allocation and size, and most extant literature employs the model of static load. As a result, the research in [10] focused on various models of voltage-dependent loads. Despite the numerous benefits provided by DGs, their random sizing and allocation generate several operational problems in power distribution networks. The power distribution network was created to manage one-way currents; however, the installation of DG results in both directions of the power flow. This results in technical difficulties including variations in power loss, voltage drop (in transmission and reception power), and disturbances in power reliability and consistency, as indicated in [11]. In order to reduce power losses and enhance voltage profiles, the primary goal of the study in [12] is to design an optimization approach for the best size and site of DG units in the network distribution. The Backward-Forward Sweep (BFS) was applied in this study to calculate the power flow, where a very adaptable multiple objective particle swarm optimizer was developed to choose the most suitable sizing and siting for the DG generators. According to the results in [12], adding DG units to specific buses greatly enhanced the voltage profile and reduced both the system's active and reactive power loss. However, the cost of installing DG raises questions, and the technique has not been applied to a genuine electrical power distribution system. Alghamdi et al. in [13] proposed the Gaussian-Bare-Bones Levy Cheetah Optimization (GBBLCO) algorithm to address optimal power flow (OPF) problems for enhanced integration of renewable energy resources in power networks. The study demonstrated that GBBLCO outperformed conventional algorithms in minimizing operating costs, reducing emissions, managing voltage deviations, and improving voltage stability across multiple test systems. Yan et al. in [14] presented a comprehensive review of intelligent detection and classification techniques for power quality disturbances (PQDs) in modern electrical grids, focusing on new methodologies developed over the last five years. The paper evaluates both traditional and advanced PQD detection approaches, highlighting their effectiveness and scenarios for application, and discusses promising future trends to ensure safe and reliable grid operation in the context of renewable energy integration. Megantoro et al. in [15] review the use of metaheuristic algorithms for optimal reactive power dispatch (ORPD), emphasizing the complexities introduced by intermittent renewable distributed generation. Through comparative analysis on IEEE bus test systems, the study shows that algorithms inspired by physical phenomena provide robust solutions for reducing power losses, minimizing voltage deviations, and improving voltage stability in grids with high penetrations of solar and wind sources. Hua et al. in [16] introduced an integrated energy-efficient system that combines demand response, distributed generation, and storage batteries to optimize energy management in smart grids. The approach employs probabilistic modeling and advanced optimization techniques to reduce operational costs, mitigate pollution emissions, and balance load scheduling, demonstrating superior performance compared to conventional models in smart grid environments. The authors in [17] investigated the construction of the DG techniques, the objectives, and the methodologies. A thorough investigation of several objective functions, restrictions, and methods has been introduced in [18] for optimum DG allocation. The authors in [19] reviewed how well DG planning performed regarding both reactive and real power loss, stability, load capability, and fluctuations, transfer of power capability, voltage characteristics, and short circuit capability while being ecologically friendly. Efficient allocation of distributed generation (DG) in distribution networks is crucial for minimizing energy losses, reducing operational costs, and lowering generation expenses, especially as distribution network losses account for over 70% of total system losses [20]. The study [20] introduced an effective DG allocation model that incorporates power demand variation, demonstrating superior performance in reducing losses, system cost, and computational time compared to other models when evaluated with different distribution system scenarios. The allocation and sizing of distributed generation (DG) in the power system, as illustrated in Fig. 1, involve determining the optimal capacity and placement of DG units such as photovoltaic (PV) panels, wind turbines, and reciprocating engines within the distribution network. This process aims to minimize power losses (P_{loss}) and improve voltage profiles ($V_{profile}$) by reducing voltage drops, thereby enhancing system reliability and reducing operational costs. The sizing and allocation problem focuses on technical and economic objectives: ensuring DG units are appropriately sized to meet demand fluctuations while positioned to effectively support the prosumers and existing grid infrastructure.

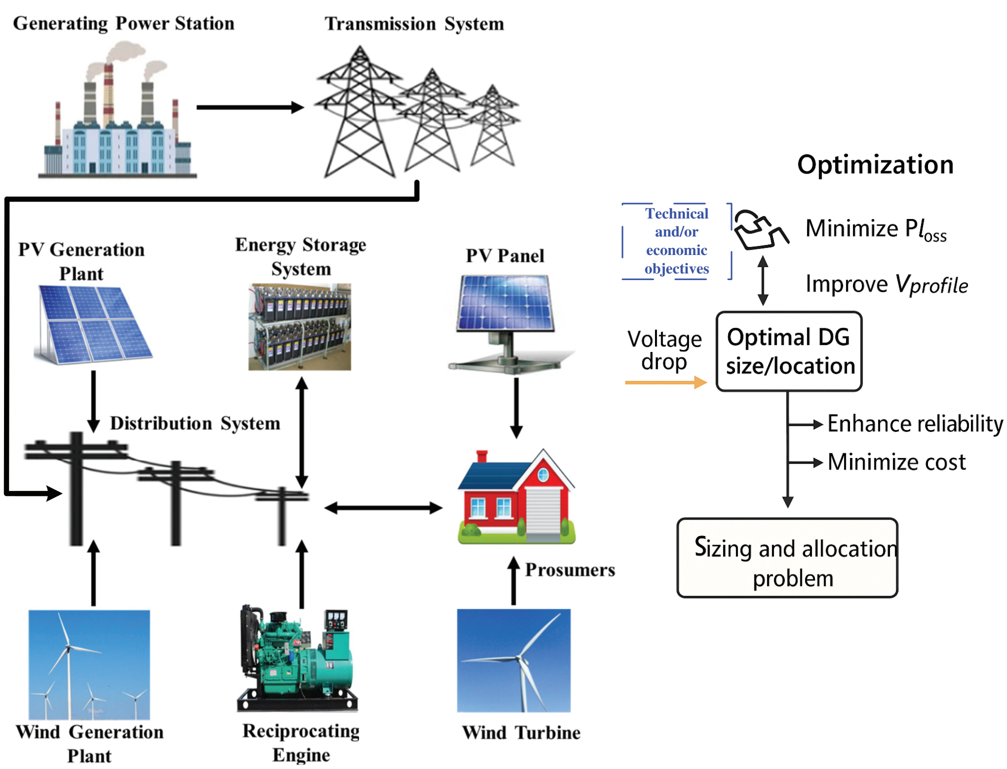

Figure 1: Illustration of the DG sizing and allocation problem in distribution networks

Recent studies emphasize the significant benefits of network reconfiguration combined with the optimal integration of multiple distributed generation (DG) units in radial distribution networks to enhance system reliability and efficiency, as explored in [21]. Optimization techniques like the Arithmetic Optimization Algorithm have been successfully applied for the simultaneous allocation of DG units and capacitor banks to improve voltage profiles and reduce losses in distribution systems, as detailed in [22]. Furthermore, advanced metaheuristic approaches such as the Electric Eel Foraging Optimization Algorithm have been developed for network reconfiguration with DG integration, focusing on power system performance under various load models, as presented in [23]. The combined approach of network reconfiguration, DG deployment, and capacitor bank installation has demonstrated considerable enhancement in distribution system performance, corroborated by findings in [24]. These contributions underscore the critical role of integrated optimization strategies in modern power distribution system management. Additionally, some other recent research [25–27] has advanced methods for the optimal sizing and placement of distributed generation (DG) units within distribution networks, especially under contingency scenarios such as N-1 outages. Innovative hybrid and integrated algorithms, including combinations of crow search, particle swarm, and firefly techniques [25–27], have been developed to improve system resilience, minimize losses, and ensure reliable integration of renewable energy sources even during faulty system conditions. Additionally, new frameworks for planning multi-energy systems consider generator contingencies and are being implemented in active distribution networks to enhance system robustness and sustainable energy integration [27]. The study in [28] integrates renewable energy resources, distributed generators, and energy storage into distribution networks, while also proposing a smart charging strategy for Plug-In Hybrid Electric Vehicles (PHEVs). Using hybrid metaheuristic optimizers Mountain Gazelle Optimizer (MGO), Improved Beluga Whale Optimization (IBWO), and Arithmetic Optimization Algorithm (AOA), the work demonstrates significant reductions in power losses and CO_2 emissions on IEEE 33-bus and 85-bus systems. The findings highlight the potential of multi-objective optimization frameworks to enhance the technical, economic, and environmental performance of modern distribution networks. The review in [29] examines the role of smart grids as enablers of sustainable and resilient smart cities, where electrification and renewable integration address the energy trilemma of sustainability, security, and affordability. It emphasizes the contribution of Internet of Thing (IoT), artificial intelligence, and machine learning to efficient energy management and improved urban living conditions. Moreover, the paper outlines emerging applications, challenges, and strategies to enhance smart city infrastructure against both physical and cyber threats. On the other hand, some recent studies have increasingly emphasized the role of optimization and uncertainty modeling in the design of hybrid renewable energy systems (HRES). For instance, the authors in [30] demonstrated how coupling stochastic simulations with evolutionary algorithms enhances reliability and robustness in system sizing under variable resource conditions. Similarly, the authors in [31] highlighted the potential of decentralized decision-making frameworks to improve resource utilization and promote sustainability in renewable integration. In addition, the authors in [32] addressed the critical influence of fluctuating economic parameters on investment feasibility and operational performance, underscoring the need for risk-aware planning models. Collectively, these works underline that effective HRES planning requires both advanced optimization techniques and comprehensive uncertainty analyses to ensure sustainable, resilient, and economically viable energy solutions [30,32,33]. Table 1 summarizes the most recent research that has been extensively reviewed.

Table 1: The summary of the most recent articles that have been thoroughly reviewed

Ref.	Year	Main purpose	Findings	Research gaps
[34]	2023	Sizing and Allocation	This article reviews current optimal DG sizing and allocation experiments that eliminate the major DG integration issues. The most often used optimal DG allocation techniques have been classified, and the key distinctions have been examined, providing details on optimization technique properties such as converging effectiveness and computational burden.	Studies on optimal DG sizing and allocation might move to the prosumer level, considering peer-to-peer trading of energy to improve prosumer society advantages as well as linked power grid alleviation.
[35]	2023	Sizing and allocation	The hybrid Jaya-Luus-Jaakola (JLJ) technique is applied to attain the sizing and allocation of DGs in a distribution system considering demand-side management into account. The collected results demonstrate that the suggested approach performed well compared to the previously reported approaches.	The findings revealed that adding more DG installations to the system reduces power loss and increases the cost.
[36]	2023	Sizing and allocation	A unique hybrid technique with TVVD loads has been used to propose a framework for the individual and concurrent sizing and allocation of DGs in the power system. The performance of the power distribution network is improved by the increased similarity between demand and generation, according to DG sizing and siting utilizing a hybrid technique for various generating situations.	The best allocation and size of DG generators require a reliable, computationally sophisticated approach.
[37]	2022	Sizing and allocation	A computationally effective model for choosing the optimal size and placement of the power energy storage element in smart grids is presented. Results proved that the proposed technique could result in considerable cost reductions.	To assess the computing load on the main problem, further meta-heuristic methods might be used.
[38]	2022	Sizing and allocation	To enhance voltage profile, reduce power loss, and increase reliability of distribution system, a new technique for simultaneous optimal DG siting and sizing was proposed.	The research concentrated on various voltage-dependent load model categories since the sizing and allocation of DGs vary according to the load models.
[39]	2019	Sizing and allocation	A multi-purpose optimization structure for efficient DGs size and placement in the power distribution system was introduced. Simultaneous voltage stability maximization, power losses, and voltage deviation reduction is investigated.	The studies evaluated for DG location and size primarily address two objectives; anything beyond that complicates the optimization process.
[40]	2020	Sizing and allocation	This paper describes a unique optimization strategy for siting DG effectively in a radial power distribution system, and the findings of the suggested approaches are compared to the existing well-established multi-purpose optimization techniques.	The DG simulation does not account for the effect of increasing load; this may be addressed soon. Furthermore, the suggested technique's performance may be evaluated on a wide range of objective optimization challenges with multiple objectives.

(Continued)

Table 1 (continued)

Ref.	Year	Main purpose	Findings	Research gaps
[41]	2020	Sizing and allocation	A new hybrid optimization technique was suggested to attain the best sizing and siting of DGs with the goal of improving the system's total active and reactive power loss and voltage control. In contrast to the stated values of other pieces of literature, the findings of the offered methodologies have greater performance.	Some major improvements can be provided in the areas of social security and the system's vulnerability index enhancement. Studies taken into consideration for DG location and size are primarily focused on two objectives; anything beyond that makes the optimization process more difficult.
[42]	2019	Sizing and allocation	This study introduces a novel technique for the simultaneous deployment of multiple DGs in the power distribution network with respect to the main objectives: power loss reduction, voltage profile enhancement, and total cost of operation. The findings demonstrated the effects of penetrating the appropriate-sized DGs at the right location using various methodologies.	The outcomes of two distinct optimization strategies were compared. Power loss mitigation using PSO and voltage deviation using MSA are both successful. Therefore, a better algorithm that has the ability to handle more objective data is required.

Despite the substantial body of literature examining technological progress and optimization strategies for the sizing and allocation of distributed generation (DG), a significant gap remains in the form of a comprehensive, systematic analysis that captures global research patterns, influential scholarly networks, and the integration of both qualitative and quantitative mapping of research trends. Most existing reviews [18,43–52] are predominantly 1) focused on individual optimization algorithms, specific methodologies, or case studies limited to particular regions, 2) Previous reviews often generalized DG as a single type, without sufficient differentiation between renewable vs. non-renewable DGs, 3) Prior reviews provided technical surveys but lacked scientometric analysis of the research field. As a result, they frequently lack macro-level bibliometric perspectives and fail to address the complex interrelationships among research clusters, objective functions, optimization techniques, and practical implementation challenges facing real-world power systems.

Furthermore, previous reviews addressing DG planning—encompassing sizing, allocation, multi-objective optimization, and the technical barriers of standalone vs. grid-connected deployment—have not fully resolved persistent challenges related to maximizing power system efficiency and minimizing costs. In particular, there is an evident absence of studies that systematically synthesize the current state of knowledge on DG sizing and allocation within modern distribution systems, especially through the lens of multi-objective optimization. To effectively address the multifaceted issues found in realistic, radial distribution networks—including those emerging from evolving DG technologies and global research trends—there is a pronounced need for an integrated, scientometric, and systematic review that contextualizes the field's evolution and illuminates emerging directions for research and practice.

This review systematically addresses critical aspects of renewable distributed generation (DG) sizing and allocation by providing an exhaustive scientometric and systematic analysis of global research trends from 2000 to 2024. The primary objectives and contributions can be summarized as follows:

- Analyze Global Research Trends: To comprehensively examine the evolution and development of renewable DG sizing and allocation research across reputable, peer-reviewed journals worldwide, highlighting key advances and focus areas over the last two decades.

- Map the Scholarly Landscape: To offer an intricate qualitative and quantitative mapping of the DG research ecosystem, including prominent research channels, co-authorship networks, article citation patterns, keyword co-occurrence, and active countries' collaborations. This mapping aims to foster enhanced international scholarly cooperation and knowledge exchange in the field.
- Categorize and Evaluate Key Themes: To systematically classify, analyze, and assess the predominant global research themes related to DG sizing and allocation. This includes a detailed examination of the most effective objective functions, optimization methods, enabling DG technologies, and strategic approaches applied in modern distribution systems.
- Integrate Technical, Economic, and Policy Perspectives: To provide a holistic understanding by incorporating technical considerations along with commercial and policy-related objectives, thereby encompassing the multifaceted dynamics influencing DG integration decisions.
- Offer a Foundational Reference: To serve as a foundational resource for researchers, practitioners, and policymakers, equipping them with actionable insights and evidence-based guidance to inform future research directions, enhance international collaboration, and support the design and implementation of optimal renewable DG systems within smart grids.

To the best of the authors' knowledge, this work represents the first comprehensive scientometric and systematic review that combines quantitative bibliometric mapping with an in-depth qualitative synthesis of global research trends on renewable DG sizing and allocation.

2 Research Methodology

This part describes the research methodology applied to conduct the systematic and scientometric review of this paper. The study methodology's flowchart, shown in Fig. 2, contains all the logical steps and processes required to carry out this scientometric and systematic review paper. The PRISMA checklists can be found in the Supplementary Materials. To give a thorough overview of the methodology applied, the subsequent sections include descriptions of the key logic processes and procedures.

2.1 Selection of Keywords and Database

Scopus is used to extract research papers about DG allocation and sizing: technologies, strategies, and optimization techniques since bibliometric data is available in a greater variety than other search engine platforms. Also, Scopus integrates well with contemporary scientific mapping programs such as VOSviewer software. Finding the most reliable, pertinent, and recently published papers on the research topic depends heavily on the keywords you use. The main subject of this scientometric systematic review was "distributed generation sizing and allocation via various optimization approaches, main technologies, and strategies". Thus, different search keywords were tested and iterated until the desired results were achieved. The search keywords that produced the desired results were (TITLE-ABS-KEY ("Distributed Generation" OR "Distributed Generator" OR "Distribution Generation" OR "DG" AND TITLE-ABS-KEY "Allocation" OR "Placement" OR "Siting" OR "Sizing" OR "Size" AND TITLE-ABS-KEY "Optimization" OR "Techniques" OR "Algorithms" OR "Approaches" OR "Strategies" OR "Methods").

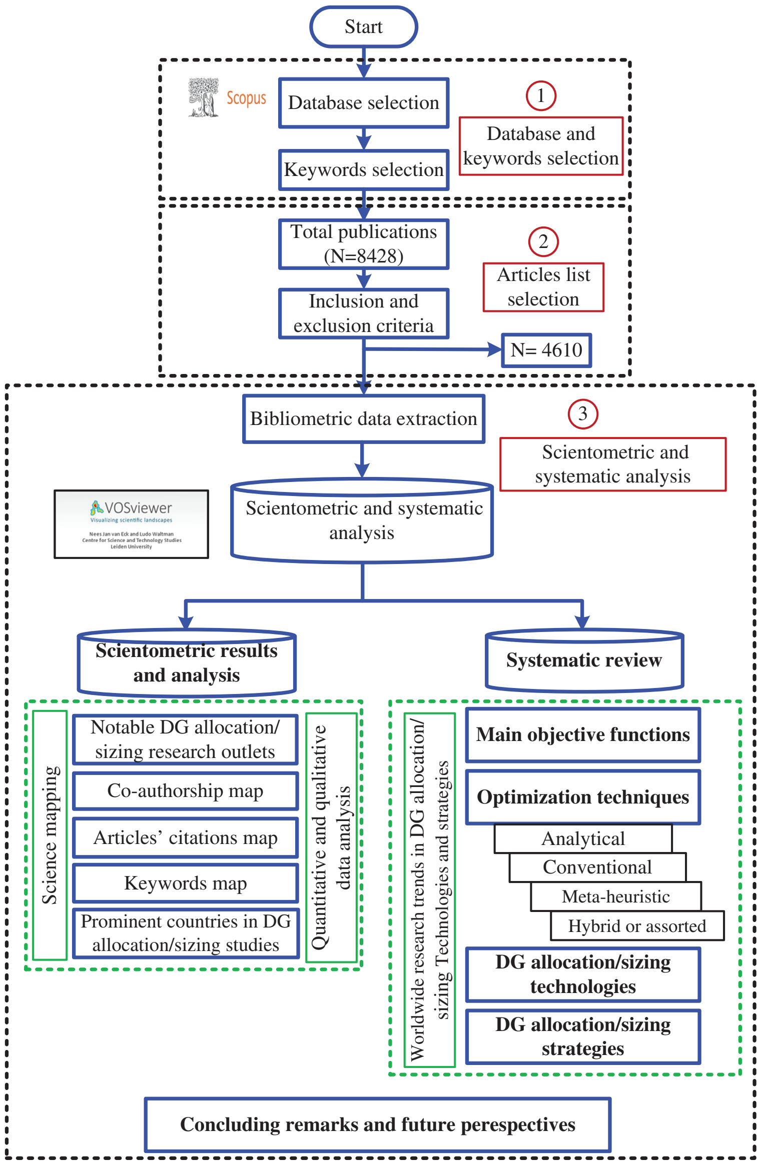

Figure 2: Comprehensive flowchart illustrating the research methodology adopted in this study

2.2 Articles List Selection

Any systematic or scientometric review's inclusion and exclusion criteria must be clearly defined to filter the retrieved papers and preserve only the important ones [53]. The following criteria were used to determine whether a document met the study's inclusion requirements: (1) research papers on DG-sizing/allocation optimization, technologies, and strategies that were published between 2000 and 2024; (2) publications that were only available as "Journal" sources in journals that were peer-reviewed; (3) only "article and review" papers were included; and (4) papers written in English were included. On the other hand, studies published before the year 2000 or after 2024 in which there were few and not recent publications before the year 2000 are excluded, as well as articles published in books, book chapters, conferences, articles in languages besides English, and any other kind of source. The outcomes of the exclusion and inclusion constraints are displayed in Table 2. There are 460 journal publications (Articles and reviews) on the DG-sizing/allocation technologies and strategies using the predetermined keywords and without any constraints. The 3818 document results were disregarded based on the exclusion criteria because of their language, article type, and publication year, which did not fit within the 2000–2024 period. However, as of December 2024, 4610 out of 8428 document findings comply with these limitations, which were in the subsequent scientometric analysis and systematic review.

Table 2: Outcomes of inclusion and exclusion requirements

Inclusion criteria	In		Out		Articles' Number
	Type	**Total**	**Type**	**Publications**	**Sum**
	Articles	4480	Article	377	4857
	Review	130	Review	6	136
Document type			Conference (paper + review)	3095 + 167 = 3262	3262
			Books and book chapters	10 + 137	147
			Others	26	26
Language	English	8040	Others	388	**Sum = 8428**
Year	**2000–2024**	**4610**	**Others**	**3818**	

2.3 *Comprehensive Scientometric and Systematic Review*

The datasets have been extracted using the most often used interchangeable keywords for DG-allocation/sizing optimization, technologies, and strategies to obtain a more comprehensive and trustworthy set of bibliometric information. It was downloaded as "Comma-Separated Values (CSV)" format. VOSviewer has been used to import the CSV file in order to map the DG-Allocation/Sizing optimization, technologies, and strategies research literature in a methodical manner. Using the VOSviewer software, the prominent research channels/sources, co-occurring keyword networks, co-authorship collaborations network, citation network of publications, countries/regions network, science maps, and bibliometric network were created for noteworthy DG-allocation/sizing optimization, technologies, and strategies.

Following the VOSviewer program's import of the bibliometric data, the analysis was done in steps. The following was extracted and established by the authors using the scientometric quantitative analyses:

- The most well-known and fruitful DG-sizing/allocation optimization, technologies, and strategies research channels/sources.
- The most well-known authors and researchers according to the output of both qualitative and quantitative research.
- The most prolific and leading nations/countries in the fields of in DG-sizing/allocation optimization, technologies, and strategies research area.
- The studies are significantly cited in the fields of DG-sizing/allocation optimization, technologies, and strategies.
- The most popular/counted keywords were determined by looking up the authors' keywords.
- Furthermore, the systematic review was conducted to identify research themes from the retrieved literature. This process divides the systematic review into three parts: objective functions and optimization algorithms for DG sizing and allocation, as well as the best technologies and strategies for allocation of DG and sizing.

3 Scientometric Results: Analysis and Discussions

Scientometric analyses are important as they provide quantitative insights into research trends, collaborations, and scholarly impact, thereby guiding future studies and evidence-based decision-making. In this section, the findings of the scientometric analyses that were obtained are presented in this section. These analyses provide valuable insights into the publication trends, publication outlets, topic trends, influential researchers and their work, and most active countries in the domain of DG allocation. By exploring these metrics, researchers can gain a more thorough knowledge of the renewable DG sizing/allocation field and identify key areas for future research.

3.1 Annual Global Research Trends

An analysis of the annual publication patterns within the domain of distributed generation (DG) sizing and allocation reveals a sustained and significant growth trajectory over the past two decades, as depicted in Fig. 3. The dataset comprises 4610 peer-reviewed journal articles retrieved through a rigorous systematic review process. The temporal distribution highlights a modest output in the early 2000s, with only 11 articles published in 2000, followed by a pronounced increase culminating in 499 publications in 2024. The increased publication rate of articles relating to DG sizing/allocation suggests that researchers are becoming more interested in this area of study and are devoting more time and resources to conducting research in this field. This trend indicates that DG sizing/allocation is an important and relevant topic of research and that it is gaining recognition and significance in the broader context of renewable energy research.

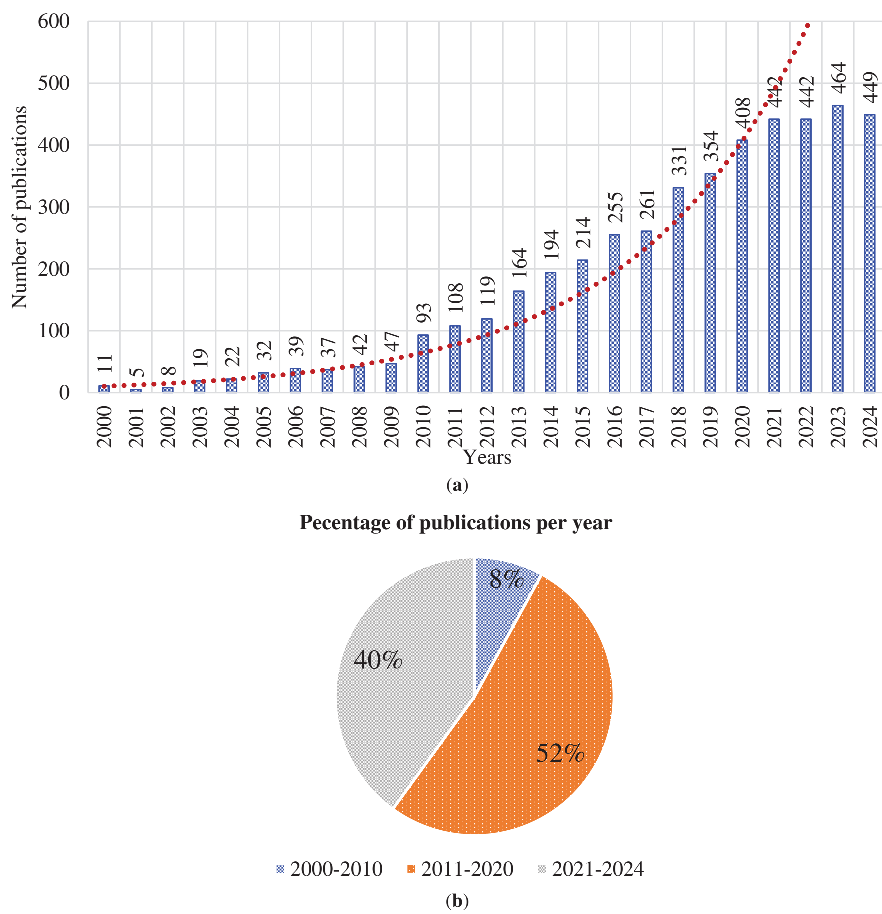

Figure 3: Annual publication trends: (**a**) Number of peer-reviewed articles published each year (Y-axis: number of articles, unitless; X-axis: year, 2000–2024). (**b**) Percentage distribution by decade (Y-axis: percent of total publications, %). Data are sourced from systematic Scopus search (see Section 2.1)

Further scrutiny of the publication distribution across decades, illustrated in Fig. 3b, reveals that merely 8% of the corpus was published during 2000–2010, while the majority (52%) emerged within the decade 2011–2020. Notably, the current decade (2021–2024) already accounts for 40% of the total publications, signifying a sustained momentum in research activities despite its shorter duration. This pattern not only reflects the dynamic evolution and growing relevance of DG sizing and allocation within the renewable energy and smart grid research communities but also suggests that forthcoming years are poised to contribute an even greater volume of scholarly output.

The escalating research intensity can be attributed to the escalating urgency of integrating renewable distributed generation to address environmental concerns, enhance grid reliability, and optimize power system performance. Consequently, the sizeable and growing body of literature indicates that DG sizing and allocation will remain a pivotal and expanding focus area, vital for both academia and industry stakeholders, facilitating innovation and informed decision-making in sustainable energy systems design and operation.

3.2 Mapping Scientific Outlets for Research

The scientific maps for the research outlets publishing articles related to DG sizing/allocation was conducted and explained in this section. The analysis is necessary to identify active research outlets in the area, which may be useful for researchers looking for academic information on DG sizing/allocation. The analysis was performed using the VOSviewer software, which allowed for the visualization of the co-occurrence of research outlets in the DG allocation literature. It should be noted that there is no standard rule for setting thresholds in the VOSviewer software. Twenty documents and one hundred citations were the minimal requirements, respectively. Just 60 of the 998 research outlets fulfilled these requirements. Fig. 4 shows a visualization of the top 60 research outlets on DG sizing/allocation. The map shows that the outlets are clustered into 4 clusters: red, blue, green, and yellow. Items in the same clusters show that they have similar characteristics, such as citation links, and are related to one another compared to items in a different cluster. In this analysis, the node size represents the articles number published in each research outlet. The articles number increases with node size. For the red cluster, "Energies", "IEEE access", and "International transactions on electrical energy systems" have the biggest node size and thus are the most productive research outlets. Similarly, the blue cluster is dominated by "International journal of electrical power and energy systems", "Electric power components and systems", and "International review of electrical engineering" having published 158, 58, and 42 articles, respectively. In the green cluster, the field is dominated by "IEEE transactions on power systems", "Electric power systems research", and "Institution of Engineering and Technology (IET) generation, transmission and distribution". The smallest cluster in terms of numbers of articles is the yellow cluster, which is dominated by "Energy system" and "International journal of emerging electrical power system". Overall, across all the clusters, the most productive publication outlets are "International journal of electrical power and energy systems", "Energies", and "IEEE access".

Table 3 presents the top 30 research outlets for DG allocation research, including the publications number together with information on their average citation, and the overall link strength. Although the number of articles shows how productive a research outlet could be, the average citations give a qualitative reflection of the publication channels [53]. In this connection, "IEEE transactions on power systems", "Renewable and sustainable energy reviews", "IEEE transactions on power delivery", "IEEE transactions on sustainable energy", and "International journal of electrical power and energy systems" are the most productive and impactful publishing channels in the domain of DG sizing/allocation. As can be seen, while looking at the articles number and average citations, the two journals that rank among the top 5 are "International journal of electrical power and energy systems" and "IEEE transactions on power systems".

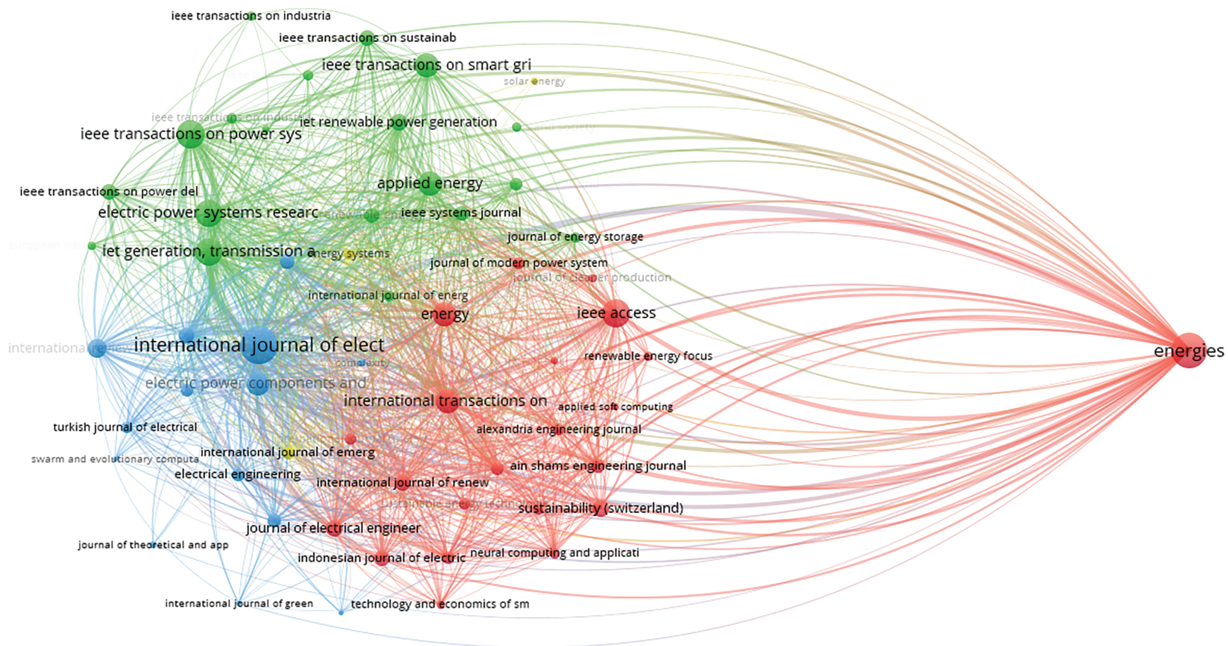

Figure 4: Mapping scientific outlets. Visualization of top 60 research outlets in DG sizing/allocation. Node size: number of articles published by each outlet; clusters represent citation-based thematic groupings (see Section 3.2). Color coding: red, blue, green, yellow clusters as described in text. Data extracted from Scopus dataset, and analyzed in VOSviewer

Table 3: Top 30 research outlets for DG allocation/sizing research

Research outlet	Publications	Citation	Average citation	Overall link strength
International journal of electrical power and energy systems	**158**	**12,486**	**79.03**	**83,224**
Energies	139	2245	16.15	53,218
IEEE access	88	1621	18.42	33,423
IEEE transactions on power systems	**88**	**11,961**	**135.92**	**32,265**
Electric power systems research	85	3280	38.59	24,998
IET generation, transmission, and distribution	84	3681	43.82	37,639
Energy	67	3138	46.84	28,199
International transactions on electrical energy systems	67	855	12.76	39,402
IEEE transactions on smart grid	66	4424	67.03	14,822
Applied energy	63	3816	60.57	22,298
Electric power components and systems	58	1396	24.07	37,160
International review of electrical engineering	42	323	7.69	15,596
IET renewable power generation	34	1107	32.56	13,363
Journal of computational physics	34	684	20.12	387
Journal of electrical engineering and technology	32	128	4.00	16,828
Sustainability (Switzerland)	32	353	11.03	11,605
IEEE transactions on sustainable energy	**30**	**2584**	**86.13**	**7827**

(Continued)

Table 3 (continued)

Research outlet	Publications	Citation	Average citation	Overall link strength
Indonesian journal of electrical engineering and computer science	30	156	5.20	9854
Renewable and sustainable energy reviews	**30**	**3466**	**115.53**	**35,513**
IEEE transactions on power delivery	**28**	**3017**	**107.75**	7931
International journal of renewable energy research	28	275	9.82	16,260
IEEE systems journal	26	964	37.08	7664
Renewable energy	26	1560	60.00	8151
Journal of renewable and sustainable energy	25	300	12.00	14,666
Ain shams engineering journal	23	855	37.17	13,266
Energy reports	22	266	12.09	8331
Journal of scientific computing	22	532	24.18	372
Applied soft computing journal	20	1134	56.70	21,054
Electrical engineering	20	304	15.20	7573
International journal of ambient energy	20	172	8.60	15,028

3.3 Science Mapping of Keyword Occurrence

The selection of appropriate keywords is crucial for any research manuscript, as they highlight the research focus. In doing so, they provide potential readers with an indication of the paper's contents and subject matter. Therefore, keyword co-occurrence analysis was performed to investigate the most used keywords for DG allocation research. Utilizing VOSviewer, the keyword network map is created in Fig. 5 by selecting "fractional counting" as the counting method and "author keyword" as the analysis unit. The minimum keyword occurrences number is not strictly regulated, yet in the VOSviewer program, this parameter was set at thirty. Of the 8718 keywords used in all the articles, only 52 satisfied this threshold. According to Fig. 5, the keywords occur in 5 clusters, indicating different distinct research themes in the domain of DG allocation. The structured interpretation of the visualization of VOSviewer keyword co-occurrence network of Fig. 5 can be provided as follows.

3.3.1 Clustering Colors and Thematic Meaning

- Green cluster (right side): Focuses on optimization, microgrids, power quality, voltage control, renewable integration (e.g., photovoltaic, demand response, energy storage). Thematic meaning: Optimization techniques and system integration of distributed generation.
- Red cluster (left side): Concentrated around voltage stability, power losses, reconfiguration, loss minimization, power loss reduction. Thematic meaning: System reliability, stability, and loss reduction in distribution networks.
- Blue cluster (top-center): Includes genetic algorithm, sensitivity analysis, radial distribution networks. Thematic meaning: Computational intelligence and algorithmic methods for optimization.
- Yellow cluster (top small group): Small and isolated terms like discontinuous Galerkin (DG). Thematic meaning: Specialized or niche mathematical/analytical methods.

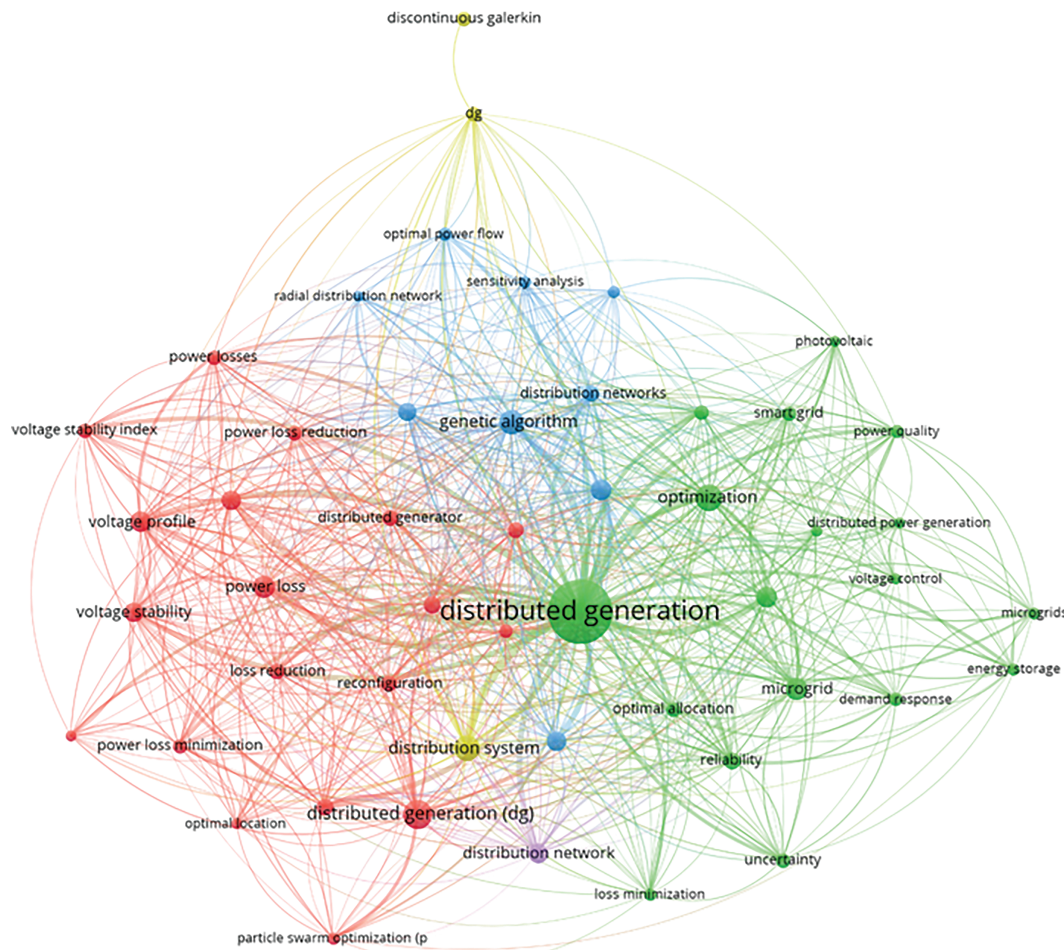

Figure 5: Keyword Co-occurrence Network. Network visualization of top 52 author keywords (minimum 30 occurrences). Node size: keyword frequency (unitless); edge thickness: co-occurrence link strength. Clusters (colors) as described in Section 3.3, representing major thematic groups: optimization, reliability, computational intelligence, etc. Data extracted from Scopus dataset, and analyzed in VOSviewer

3.3.2 Central and Highly Linked Keywords

- "Distributed generation" (green, central, largest node): This is the most frequently occurring and most interconnected keyword. It reflects the core theme of the field: integration of distributed generation into power systems. Its size indicates high occurrence, and its centrality shows it connects multiple subfields (optimization, stability, microgrids).
- "Genetic algorithm" (blue, large node): Prominent as one of the most widely used optimization techniques in distributed generation studies. Its central linkages illustrate the importance of metaheuristic optimization methods in solving placement, allocation, and sizing problems.
- Other significant terms (e.g., "optimization", "microgrid", "voltage stability"): Their strong connections highlight them as recurring themes: ensuring system reliability, improving efficiency, and integrating renewables.

3.3.3 Practical Meaning of Link Strength and Occurrence

- High occurrence (node size): Indicates research hotspots with frequent attention. For example, distributed generation and optimization are core topics that dominate scholarly discussions.
- High link strength (thicker/denser connections): Shows concepts that co-occur frequently in publications, meaning they are often studied together. For example, distributed generation + optimization or genetic algorithm + distribution network. This reflects established methodological pairings in the field.
- Future research implications:
- Strong clustering around optimization algorithms suggests future work will continue to test and hybridize computational methods (e.g., combining genetic algorithms with AI/ML).
- The stability and reliability cluster signals ongoing interest in resilience and smart grid integration.
- Smaller/niche clusters (like discontinuous Galerkin methods) may represent emerging specialized approaches that could gain traction as systems become more complex.

The top 25 keywords are provided in Table 4 and ranked according to overall link strength and keyword occurrences. It could be observed that "distributed generation", "optimization", "distribution system", "genetic algorithm", and "power loss" represent the top keywords in the domain of DG sizing/allocation research. Table 4 aims to provide readers with a clear overview of the most influential research themes and terminology in DG allocation/sizing studies. By highlighting the keywords most frequently used and most interconnected in literature, this table enables researchers to efficiently identify core topics, align their work with prevailing trends, enhance discoverability of their studies, and select appropriate terms for future literature searches or submissions. Thus, Table 4 serves as a valuable resource for understanding key focus areas and fostering effective scholarly communication in the field.

Table 4: The top 25 keywords ranked according to both overall link strength and keyword occurrences

Keyword	Occurrences	Total link strength
Distributed generation	928	669
Optimization	158	122
Distribution system	153	137
Genetic algorithm	133	115
Power loss	113	105
Microgrid	108	69
Renewable energy	103	82
Voltage profile	99	94
Particle swarm optimization	98	88
Radial distribution system	88	81
Distribution network	87	71
Multi-objective optimization	86	69
Voltage stability	84	75
Distributed generators	80	65
Reliability	72	65
Optimal placement	69	62

(Continued)

Table 4 (continued)

Keyword	Occurrences	Total link strength
Network reconfiguration	64	59
Distributed generator	63	49
Loss reduction	62	58
Reconfiguration	61	56
Distribution networks	56	51
Power loss minimization	54	44
Power losses	54	50
Power loss reduction	52	48
Smart grid	52	47

3.4 Authorship, Citation, and Co-Citation Analysis of Scholars

In this context, authorship indicates the number of articles that were authored or co-authored by a researcher. Similarly, one of the key indicators of the impact of a particular research area/field is the citation analysis of scholars. Citation analysis is a astratigy used to evaluate the impact and importance of scholarly publications and authors by examining the number of times other scholars have cited their work. On the other hand, co-citation analysis is a method used to identify the relationships between scholarly publications according to how frequently they are cited in the same body of work. This study's citation and co-citation analyses were performed to investigate the most influential scholars and the key publications that have shaped the research on DG allocation. These analyses provide an insight into the impact and influence of scholars and their work in the field of DG allocation. This analysis can inform researchers and policymakers about future research directions, collaborations, and funding opportunities by identifying the most influential scholars and their key contributions.

The number of articles and citations was fixed to 10 and 100, respectively, for the purpose of conducting the citation analysis. The results show that 76 authors met these criteria, and the resulting network map is shown in Fig. 6. Fig. 6 depicts that the influencing scholars are mapped in 6 clusters. The size of the node indicates the quantity of publications produced by a researcher. This Figure presents a citation network map of influential scholars in the field of distributed generation (DG) allocation, revealing six main clusters that likely correspond to distinct research groups or schools of thought focusing on specialized aspects such as optimization algorithms, DG sizing methodologies, and integration strategies. The top authors identified include Abdelaziz A.Y., Liu Y., Das D., Kamel S., and Li Y., who stand out due to their high publication volumes, strong network centrality indicated by large node sizes, and extensive cross-country collaborations that bridge diverse research communities. The map highlights prominent collaborative networks suggesting leadership roles within these clusters, yet also indicates potential research gaps where certain clusters may be less interconnected, pointing to opportunities for enhanced interdisciplinary coordination and exploration of under-addressed topics in DG allocation. Overall, the visualization underscores both the concentration of expertise among leading authors and the dynamic structure of collaborative efforts shaping the field. As per Table 5, which shows the top 20 scholars in the field of DG allocation in terms of the number of articles, "Abdelaziz A.Y.", "Liu Y.", "Das D.", "Kamel S.", and "Li Y." are the most productive researchers.

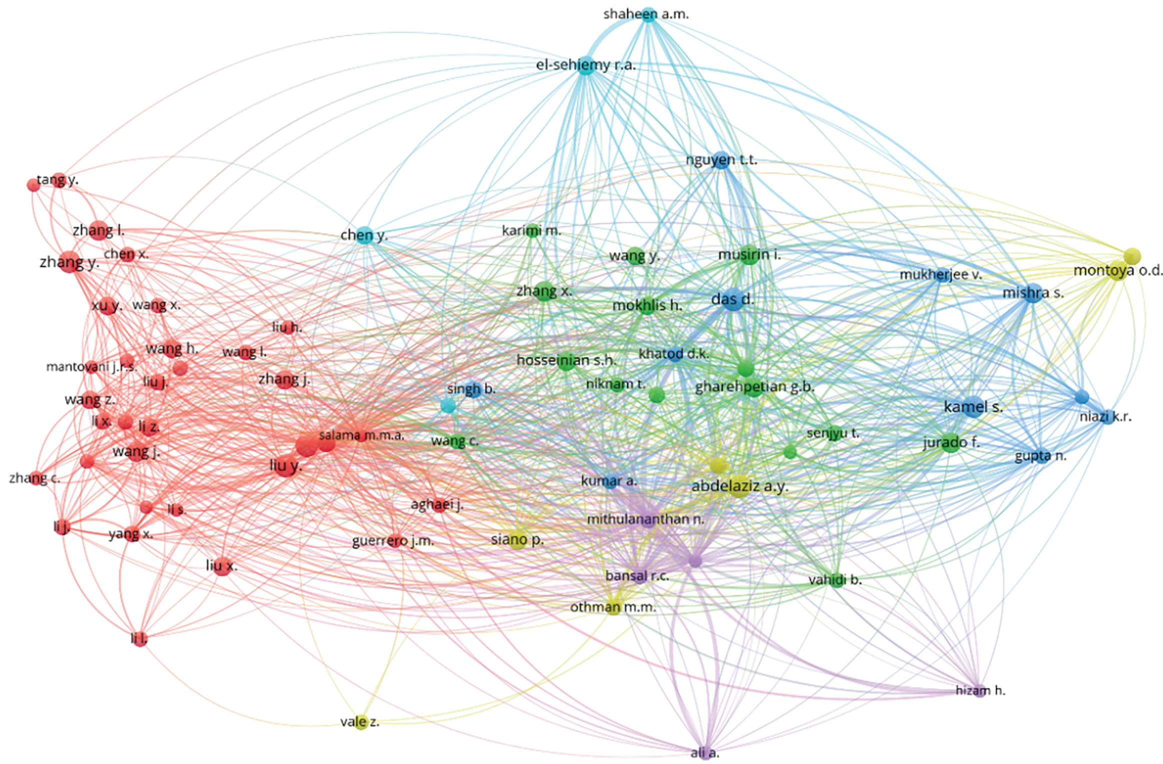

Figure 6: Scholar citation network map. Network map of top 76 contributing scholars in DG sizing/allocation (node size: number of articles; edge thickness: co-citation links; color clusters correspond to collaboration groups). Metrics defined in Table 5. Data extracted from Scopus dataset, and analyzed in VOSviewer

Table 5: Top 20 scholars in descending order based on articles number

Authors	Publications	Citation	Avg. citation	Overall link strength
Abdelaziz A.Y.	**29**	**1169**	**40.31**	**306**
Liu Y.	**29**	**826**	**28.48**	**92**
Das D.	**27**	**855**	**31.67**	**308**
Kamel S.	26	356	13.69	173
Li Y.	25	587	23.48	49
Zhang Y.	**25**	**757**	**30.28**	**63**
Jurado F.	22	513	23.32	112
Montoya O.D.	22	233	10.59	70
Wang J.	**22**	**1733**	**78.77**	**98**
Zhang L.	22	386	17.55	40
Mishra S.	21	208	9.90	182
Musirin I.	21	112	5.33	61
Zhang X.	21	533	25.38	56
El-Sehiemy R.A.	20	599	29.95	144
Liu X.	20	297	14.85	20
Gharehpetian G.B.	19	735	38.68	123
Hosseinian S.H.	**19**	**536**	**28.21**	**78**
Siano P.	19	1372	72.21	91
Zhang J.	19	487	25.63	51
Mokhlis H.	**18**	**1095**	**60.83**	**178**

Although the number of articles indicates how productive a researcher is, the average citation (total citations divided by the number of articles) can give an overall qualitative ranking of a researcher. Hence, the top 20 researchers are shown in Table 5 according to their average amount of citations. According to the table, "Mithulananthan N.", "El-Saadany E.F.", "Salama M.M.A.", "Hung D.Q.", and "Wang J." are the most prominent scholars. Overall, seven scholars: "Abdelaziz A.Y.", "Liu Y.", "Das D.", "Zhang Y.", "Wang J.", "Hosseinian S.H.", and "Mokhlis H." appear in both Tables 5 and 6, indicating their significant contribution to DG allocation/sizing studies.

Table 6: Top 20 scholars in descending order based on average citations

Authors	Articles/Publications	Citation	Avg. citation	Overall link strength
Mithulananthan N.	16	3212	200.75	509
El-Saadany E.F.	17	3135	184.41	322
Salama M.M.A.	10	2333	233.30	237
Hung D.Q.	10	2037	203.70	365
Wang J.	**22**	**1733**	**78.77**	**98**
Khatod D.K.	13	1483	114.08	252
Siano P.	19	1372	72.21	91
Wang C.	12	1331	110.92	150
Haghifam M.-R.	14	1216	86.86	163
Bansal R.C.	12	1216	101.33	221
Abdelaziz A.Y.	**29**	**1169**	**40.31**	**306**
Mokhlis H.	**18**	**1095**	**60.83**	**178**
Das D.	**27**	**855**	**31.67**	**308**
Liu Y.	**29**	**826**	**28.48**	**92**
Yang X.	14	819	58.50	66
Zeineldin H.H.	10	794	79.40	37
Zhang Y.	**25**	**757**	**30.28**	**63**
Gharehpetian G.B.	19	735	38.68	123
Shaaban M.F.	11	722	65.64	108
Liu Z.	13	713	54.85	42
Ehsan M.	15	675	45.00	121
Aghaei J.	12	640	53.33	47
Chen Y.	17	629	37.00	47
Xu Y.	18	620	34.44	36
El-Sehiemy R.A.	20	599	29.95	144
Li Y.	25	587	23.48	49
Li Z.	17	568	33.41	30
Wang H.	17	559	32.88	10
Wang L.	12	539	44.92	35
Hosseinian S.H.	**19**	**536**	**28.21**	**78**

Co-citation analysis identifies authors who are frequently cited together, indicating that their works are foundational or closely related in the field, thus revealing the intellectual structure of research topics. In Fig. 7, three distinct clusters emerge, each representing a major research subfield or scholarly community within distributed generation (DG) allocation: the green cluster centered on Mithulananthan N., the blue cluster dominated by Wang J., and the red cluster focused around Salama M.M.A. These clusters reflect thematic or methodological concentrations that shape DG research. Authors such as Mithulananthan N., Das D., and El-Saadany E.F. exhibit the highest total link strengths, marking them as highly influential and central nodes within the knowledge network whose work underpins key developments in DG allocation. They have the highest total link strength of 1289.64, 865.59, and 704.7, respectively. The clustering suggests strong collaboration or citation patterns within subfields, while also hinting at possible interdisciplinary linkages between clusters. The co-citation analysis of the top 20 scholars based on the total/overall link strength is shown in Table 7. Overall, the robust co-citation links underscore the integration and maturity of these research lines, reflecting a well-connected and coherent scholarly domain.

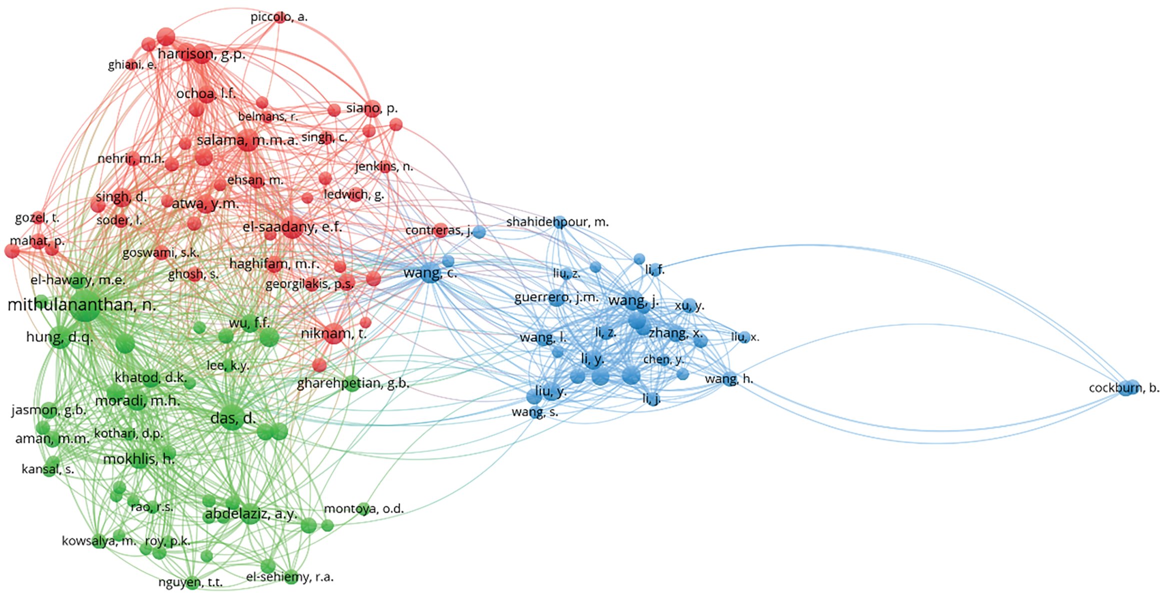

Figure 7: Co-citation mapping of authors. Visualization of co-citation clusters among leading scholars. Node size: total citations; edge thickness: co-citation frequency. Colors correspond to research clusters detailed in Section 3.4 and Table 7. Data extracted from Scopus dataset, and analyzed in VOSviewer

Table 7: Co-citation analysis of the top 20 ranked scholars

Authors	Citations	Total link strength
Mithulananthan, N.	1366	1289.64
Das, D.	933	865.59
El-Saadany, E.F.	731	704.7
Hung, D.Q.	728	704.6
Salama, M.M.A.	720	695.95
Wang, C.	631	606.96
Abdelaziz, A.Y.	617	576.47
Mokhlis, H.	592	566.51
Moradi, M.H.	574	559.85
Wang, J.	588	531.53
Atwa, Y.M.	546	530.61
Niknam, T.	617	526.72
Harrison, G.P.	557	525.02
Bansal, R.C.	512	501.52
Baran, M.E.	506	494.51
Abedini, M.	502	494.41
Khatod, D.K.	500	487.55
Singh, D.	534	485.3
Wu, F.F.	485	476.46
Liu, Y.	495	462.86

3.5 Articles' Citations Network Analysis

Citation network analysis is a mapping technique used to study the relationships between articles based on their citations. In this study, citation network analysis was done to determine the most influential articles in the field of DG allocation. The analysis was attained using the VOSviewer program with a minimum of 100 citations for an article to be included in the network map. 174 articles met this criterion, and the map is demonstrated in Fig. 8. The citation network map in Fig. 8 illustrates how articles influence each other through direct citation connections, enabling the visualization of key studies that have shaped the evolution of research on distributed generation (DG) sizing and allocation. In this context, "links" represent direct citation relationships between articles, while citation counts measure the impact of each publication based on how frequently it has been referenced by others. The top-cited articles, such as Atwa Y.M. (2010b) on optimal energy storage allocation, Wang C. (2004) on analytical placement approaches, and Acharya N. (2006) on DG allocation methodologies, are foundational due to their methodological innovations and comprehensive treatment of optimization problems, making them widely used references in the field. The network also reveals clusters of interconnected articles that focus on similar DG sizing and allocation challenges or share common optimization techniques, reflecting thematic subgroups within the literature. Overall, examining citation patterns in this map helps identify landmark works that have significantly influenced DG research and highlights emerging trends and directions for future study.

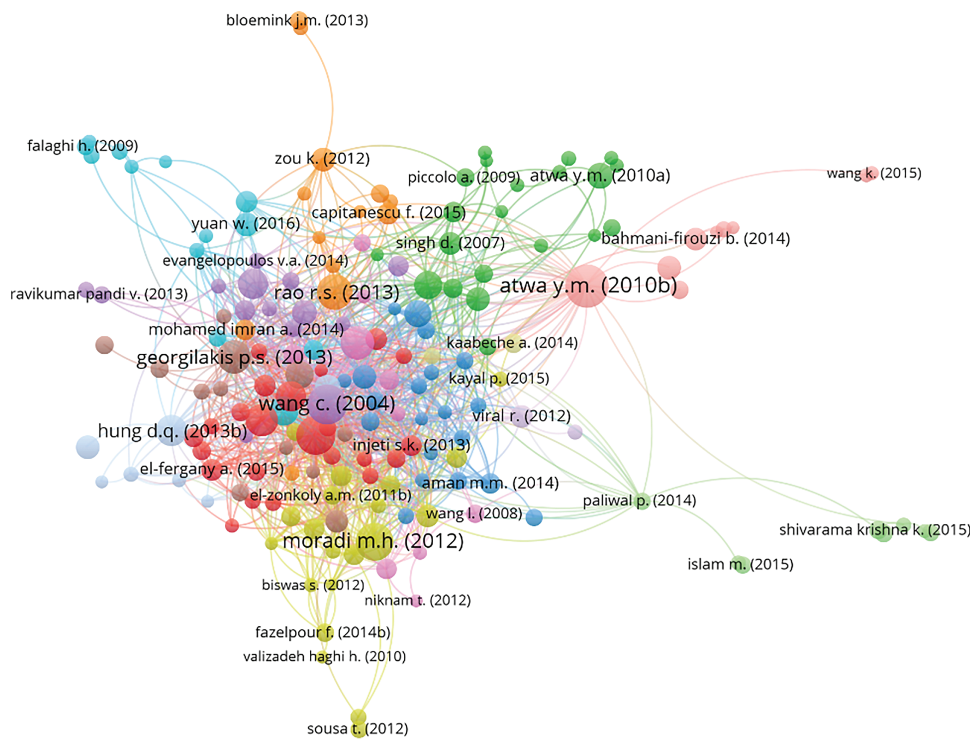

Figure 8: Article citation network. Network map of 174 most-cited articles (minimum 100 citations) in DG allocation research. Node size: citation count (see Table 8); edges: direct citation links. Colors signify thematic groupings among articles as determined by VOSviewer analysis (Section 3.5). Data extracted from Scopus dataset, and analyzed in VOSviewer

Table 8 shows the top 20 articles with their citation counts and links. The articles with the highest citation are "Optimal allocation of Energy Storage System in Distribution Systems with a High Penetration of Wind Energy" by Atwa Y.M. (2010b), with a link to 44; "Analytical Approaches for Optimal Placement of Distributed Generation Sources in Power Systems" with a link of 52, and "An Analytical Approach for DG Allocation in Primary Distribution Network" with a link of 55. This result indicates that this article is highly influential and has been cited frequently in previous literature related to DG allocation. The analysis's findings can aid researchers in comprehending the most influential articles in the field and present research trends and directions.

Table 8: Top 20 articles in DG allocation research area

Author and year	Citations	Links
Atwa Y.M. (2010b)	1086	44
Wang C. (2004)	937	52
Acharya N. (2006)	848	55
Moradi M.H. (2012)	828	30
Rao R.S. (2013)	752	14
Georgilakis P.S. (2013)	669	46
Celli G. (2005)	648	43
Abu-Mouti F.S. (2011)	591	28
Hung D.Q. (2013b)	582	29
Hung D.Q. (2010)	543	33
Gözel T. (2009)	526	5
Subrahmanyam K.S. (2008)	519	0
Borges C.L.T. (2006)	505	25
El-Khattam W. (2005)	451	18
El-Khattam W. (2004)	445	18
Al Abri R.S. (2013)	410	18
Singh D. (2009)	405	31
Atwa Y.M. (2010a)	394	7
Liu Z. (2011)	373	12
Strasser T. (2015)	368	0

3.6 Active Countries in the Domain of DG Allocation

In this section, the active countries that are contributing to the research domain of DG allocation/sizing are analyzed. This analysis is important as it sheds light on the geographical distribution of research activities in this field. The data derived from the authors' affiliations with the papers that comprised this analysis was utilized to identify countries/nations that were actively involved. VOSviewer adjusted a country's minimum articles number and citations at five and one hundred, respectively. Out of 117 countries, 59 of them met the threshold requirements. Fig. 9 shows the network map of the active nations/countries in the DG sizing/allocation field. In Fig. 9, the node size typifies the number of articles published by each study. Fig. 9 identifies India, Iran, China, USA, and Egypt as the countries with the highest productivity in terms of publications. On the other hand, Table 9 presents the top 20 countries/nations in terms of the average citation number. In this context, the top 5 most productive countries are Canada, North Macedonia, Greece, the Czech Republic, and Qatar.

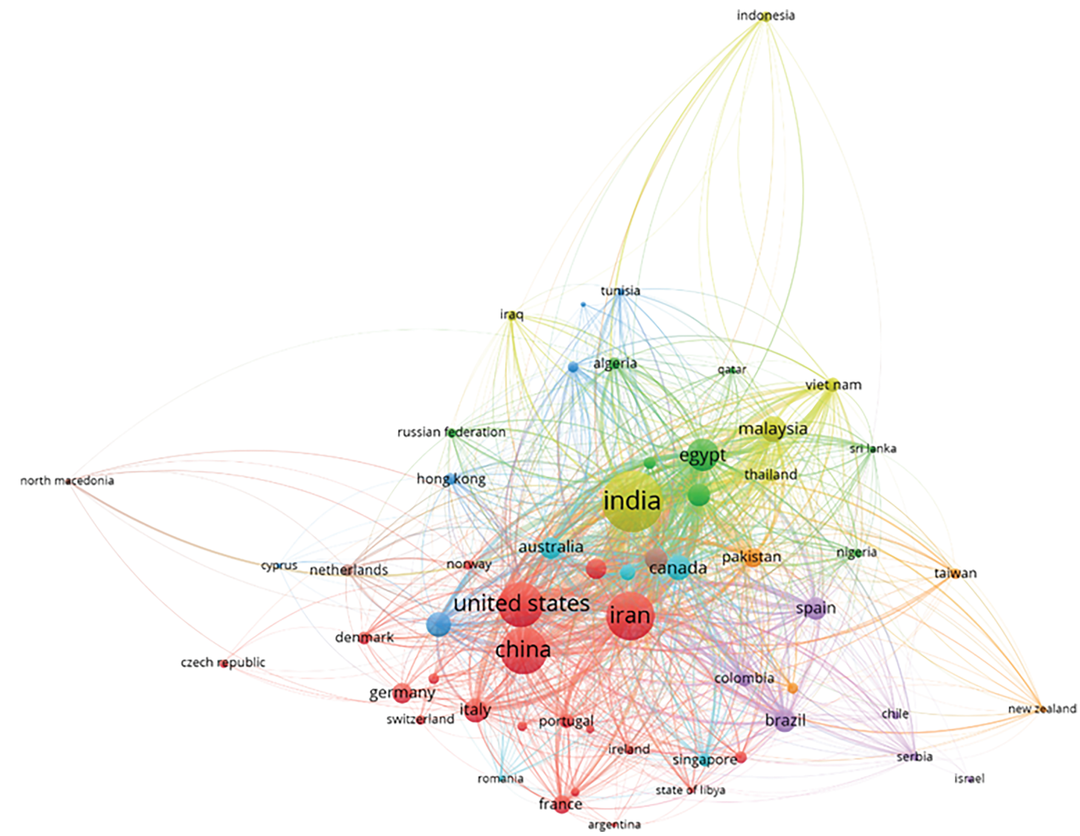

Figure 9: Country activity visualization. Network map of 59 most active countries in DG sizing/allocation (node size: article count; edge thickness: collaborative link strength as defined by co-authorship and citations). Color clusters correspond to regional or collaborative groupings identified in Section 3.6. Data extracted from Scopus dataset, analyzed in VOSviewer

Table 9: Top 20 countries with the highest productivity in terms of average citations

Nation/Country	Documents	Citations	Average citations	Overall link strength
Canada	133	9625	72.37	2131
North Macedonia	5	361	72.20	61
Greece	28	1952	69.71	667
Czech Republic	16	871	54.44	11
Qatar	9	488	54.22	97
Australia	102	5530	54.22	1826
Austria	16	837	52.31	54
Sweden	17	815	47.94	64
Italy	124	5934	47.85	840
Portugal	43	1835	42.67	258
Singapore	41	1735	42.32	242
United Kingdom	137	5558	40.57	973
United States	446	17,779	39.86	2481

(Continued)

Table 9 (continued)

Nation/Country	Documents	Citations	Average citations	Overall link strength
Switzerland	24	943	39.29	26
Belgium	25	981	39.24	92
Thailand	39	1529	39.21	604
Turkey	51	1974	38.71	615
Norway	20	738	36.90	75
United Arab Emirates	32	1176	36.75	261
Viet Nam	47	1692	36.00	1083

This analysis offers insightful information on how research activities are distributed in DG sizing/allocation field. Identifying the most active and impactful countries can help researchers identify potential collaborators and research partners in different regions of the world. Furthermore, it can help policymakers identify countries investing heavily in research and development in this field, and potentially guide funding and resource allocation decisions.

4 Major Global Research Trends of DG Sizing/Allocation Optimization, Technologies, and Strategies

Researchers' interest in DG technologies has increased significantly because of their great benefits, including reduced power loss, friendly to the environment, improved voltage, deferred system upgrades, and higher reliability. However, the practical use of the DGs is challenging because social, political, and economic considerations influence the final best solution. Selecting the best placement, size, and kind of DG and network connection is necessary for integrating DG units into an existing energy system. Total power loss is decreased, as are the system stability and voltage profile, in addition to its dependability, load capacity, security, power quality, and power factor. All the benefits listed above would be undermined by improper DG-unit distribution. Therefore, it is crucial to allocate the DGs units at the best places and at the proper sizes.

Optimization approaches are used to develop solution strategies for DG-unit deployment. The DGs sizing and allocation can be considered as a nonlinear optimization problem. The system voltages are often maximized, while cost and power loss are typically reduced. The requirements for the solutions varied amongst applications. As a result, the methodology needs more data because it considers further objectives and constraints, which tends to make implementation more challenging. Different DG-unit problems have been mitigated using efficient optimization techniques. In this area, interesting and still-evolving technologies include meta-heuristic approaches like genetic algorithms, particle swarm optimizer, and evolutionary programming (EP). Some of those methods have been altered to improve the performance of their solutions or get around certain restrictions. Additionally, most of these tools have a lot of adjustable parameters.

4.1 Objective Functions for DG Sizing and Allocation

Utilizing a DG unit in power distribution networks has the benefit of reducing the power loss across the entire system while still meeting certain operational requirements. Put another way, applying DG units may be seen as an exercise in figuring out how to best put and amplify a given DG unit while staying within the bounds of equality and inequality to meet the required objective function. The power-flow analysis employed affects the DG-unit solution algorithm's accuracy, precision, and adaptability. Hence, the accuracy of the technique is strongly dependent on that analysis. The power-flow analysis might represent the algorithm's brains for the DGs solution. Consider the example of a two-bus power system with a DG unit illustrated in Fig. 10.

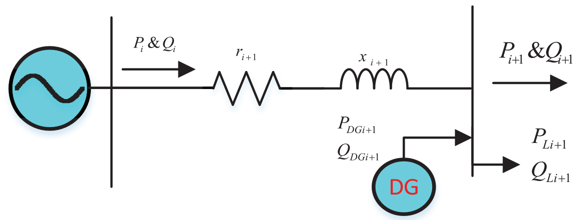

Figure 10: Single line diagram of a two-bus power system. Two-Bus Power System (Technical Diagram). Single-line diagram variables: P_i and Q_i: active/reactive power at bus i (in MW/MVAR); *Vi*: bus voltage (in kV); *ri* + 1: resistance of line segment (in Ω). System objective defined in Eq. (1) (Section 4.1)

The objective is to lower the system's actual power loss as shown below [54].

$$Obj.Fun = minimize \sum_{i=0}^{n} \left(\frac{P_i^2 + Q_i^2}{V_i^2} \right) \times r_{i+1} \tag{1}$$

The system is characterized by three nonlinear power-flow equations [54]. These equations represent the equality constraints which can be described as follows [54]:

$$P_i - \frac{r_{i+1}\left(P_i^2 + Q_i^2\right)}{V_i^2} - P_{Li+1} + \mu_P AP_{i+1} - P_{i+1} = 0 \tag{2}$$

$$Q_i - \frac{x_{i+1}\left(P_i^2 + Q_i^2\right)}{V_i^2} - Q_{Li+1} + \mu_Q RQ_{i+1} - Q_{i+1} = 0 \tag{3}$$

$$V_{i+1}^2 = V_i^2 - 2\left(r_{i+1}P_i + x_{i+1}Q_i\right) + \left(\frac{\left(r_{i+1}^2 + x_{i+1}^2\right)\left(P_i^2 + Q_i^2\right)}{V_i^2} \right) \tag{4}$$

where $i = 1, 2, 3, \ldots, n$.

The power system's voltage limitations which are ±5% of the nominal voltage are the inequality restrictions/constraints [54]:

$$\left|V_{\min}^{spec}\right| \le \left|V_i^{sys}\right| \le \left|V_{\max}^{spec}\right| \tag{5}$$

Furthermore, the thermal capacity of the system's lines are considered as inequality restrictions and constraints.

$$S_{i,i+1}^{sys} \le S_{i,i+1}^{rated} \ge S_{i+1,i}^{sys} \tag{6}$$

The DG's kVA size and power factor serve as the border (discrete) inequality restrictions.

$$\begin{aligned} S_{\max}^{DG} \ge S_i^{DG} \ge S_{\min}^{DG} \\ p.f_{\max}^{DG} \ge p.f_i^{DG} \ge p.f_{\min}^{DG} \end{aligned} \tag{7}$$

In the proposed method in [54], practical considerations like DG sizes and power factors have been taken into consideration. The correctness of the findings is ensured by the proposed method's initial treatment of rounded-off concerns related to the DG's size or power factor. The predetermined DG sizes cover between 10% and 80% of the total system requirements (i.e., $\sum |S_{L,i+1}|$) and are roughly expressed as integer values with sizes separated by 100 steps.

The DGs power factor(PF) is programmed to work at realistic values [55], i.e., unity, 0.95, 0.90, and 0.85 in the direction of the best outcome. Additionally, the load PF of the bus where the DGs is placed and the PF of the operating DG-unit must differ [56]. As a result, the bus where the DGs is located will have less net total power, including reactive and active.

In brief, the optimal DGs sizing, and allocation depends on the objective functions that are prespecified by the planners and designers and sought to be attained. The objectives may be single or multi-objectives and they can consist of economic and/or technical objectives. Fig. 11 summarizes the main objectives for DG allocation and sizing whether the objectives are single or multi-objectives and technical or economical or techno-economic.

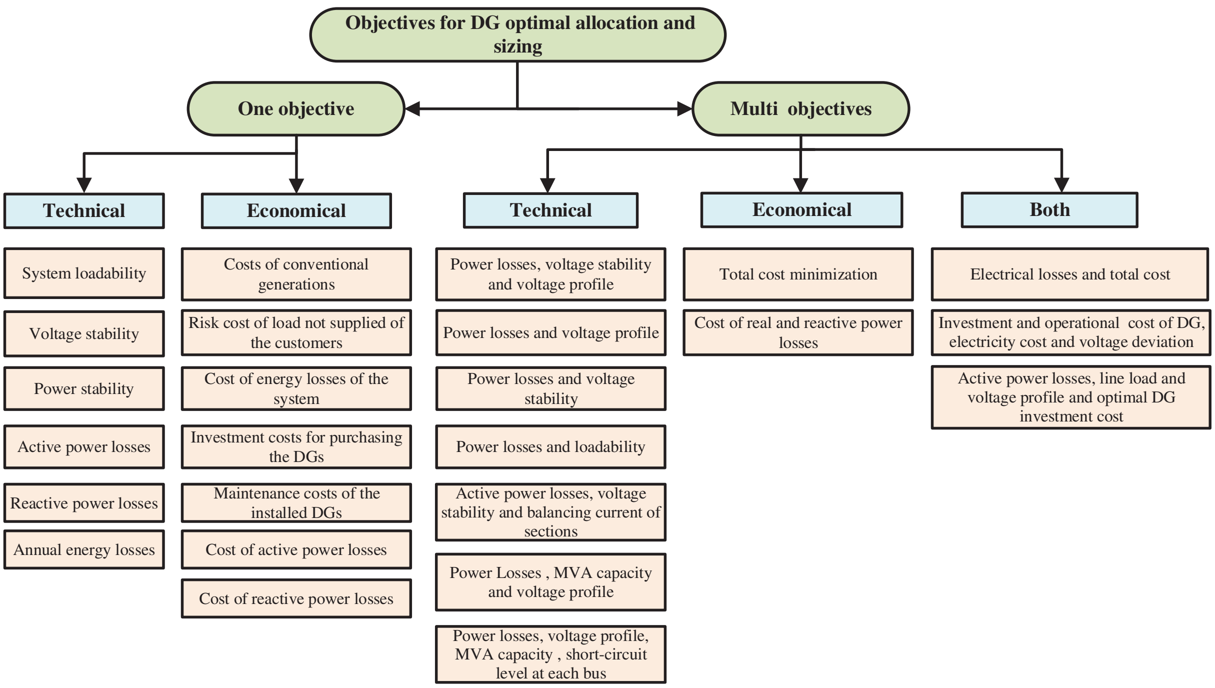

Figure 11: Planning objectives for optimal DGs allocation and sizing. Schematic summarizing technical and economic objectives for DG sizing/allocation (see Section 4.1)

4.2 The Optimization Techniques for DG Sizing and Allocation

To optimize the techno-economic benefits, DG units must be allocated at the ideal or optimal location and with the appropriate size. Benefits include operating and maintenance costs minimization and voltage profile enhancement, power system stability, quality, and reliability. The following categories represent the main technological techniques for appropriate DG sizing and allocation:

1. Analytical approaches
2. Conventional (non-heuristic) approaches
3. Meta-heuristic optimization approaches
4. Hybrid approaches
5. Assorted approaches

The optimal DG size and allocation in a distribution system will be significantly influenced by all the technical optimization techniques listed above. Various optimization approaches applied for perfect DG allocation and sizing are shown in Fig. 12. A system with enormous and complicated networks is not ideal for analytical and conventional (non-heuristic) techniques, which perform well for small and simple systems. However, the effectiveness of several meta-heuristic methods is improved. Their great precision and quick convergence are appropriate for extremely big and complicated systems. Combining two or more optimization techniques results in a hybrid optimization. It provides difficult multi-objective problems with more dependable and efficient global optimal solutions. According to methodology, algorithm, objective function, test system, benefits, and downsides, several DG deployment strategies are provided in Table 10.

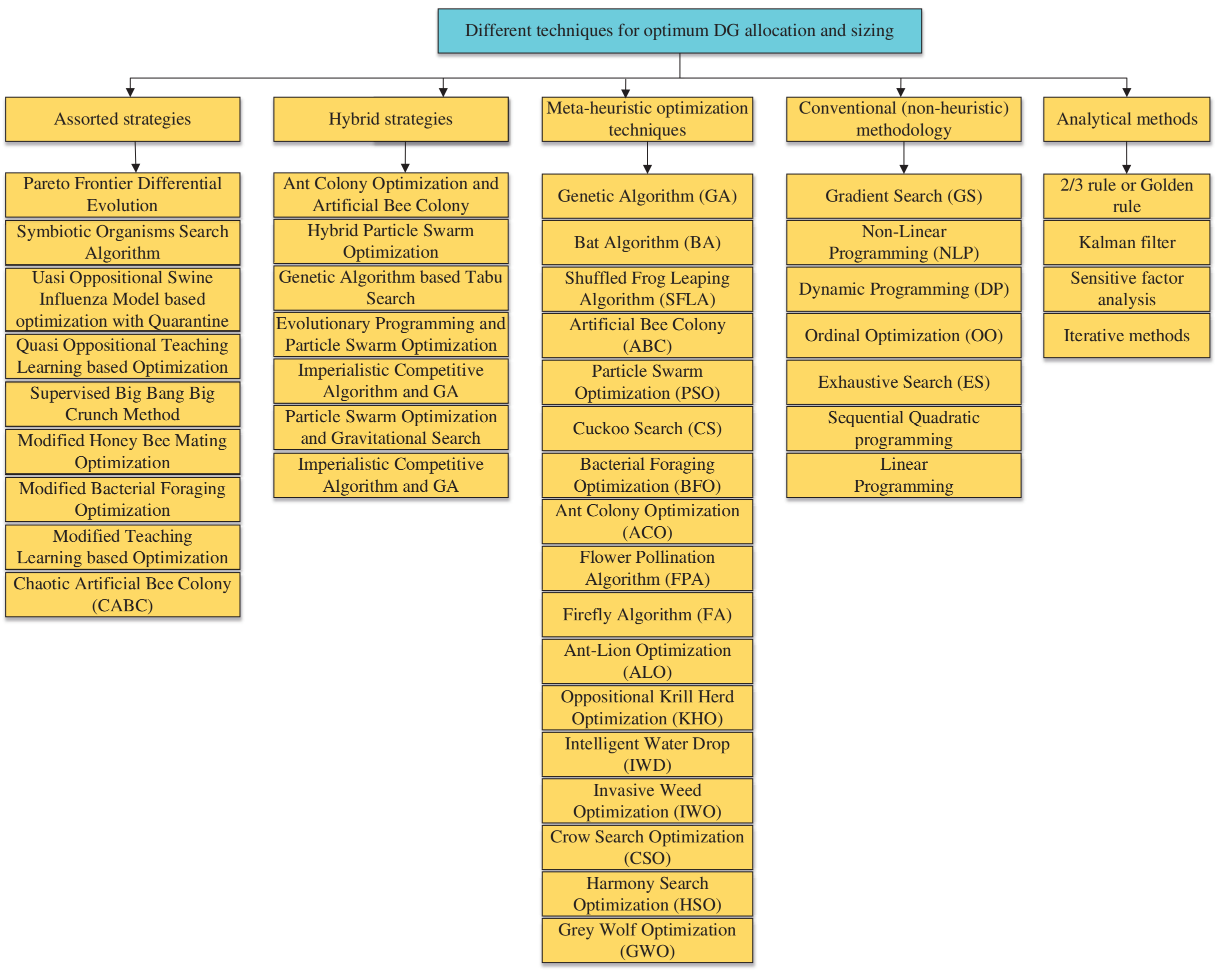

Figure 12: Different optimization approaches for optimal DG allocation and sizing. Diagram illustrates five main classes of optimization techniques (analytical, conventional, meta-heuristic, hybrid, assorted) as detailed in Section 4.2. Each block lists an approach applied to DG sizing/allocation

Table 10: Numerous DG deployment methodologies

Ref.	Category	Technique	Objectives	Test/Standard system	Merits	Limitations
[57]	Analytical	Linear differential	Minimizing power loss	IEEE 6 and 30 bus systems	This approach works well, is instructional, and aids in choosing an appropriate placement for the installation of the DGs.	DG size is not optimal; economic and geographic aspects were left out.
[58]	Analytical	Iterative method	Reduce yearly energy losses	69-bus distribution system	Combining dispatchable and non-dispatchable sustainable DGs	DGs maintain a constant power factor, which is essentially impossible.
[59]	Analytical	Exhaustive search with a sensitivity factor	Reduce loss while considering various DG units	IEEE 69-, 33-, 16-bus systems	Reduced computation time	Size and location are only considered during peak loads.
[60]	Analytical	Iterative method	Reduce both reactive and active power losses.	IEEE 33- and 15-bus RDS	A DG unit's size is solely dependent on base case load flow.	Unbalanced meshed networks cannot be used with the proposed approach.
[61]	Analytical	Power Stability Index (PSI)	Enhance voltage stability and profile with loss minimization	69-, 12-, and modified 12- bus RDS	Decreases losses and increases overall system effectiveness	Line's thermal limit is not considered
[62]	Analytical	Loss sensitivity index	Total power loss minimization	IEEE 69-, 34-, and 12-bus power system network	Without utilizing the inverse admittance matrix (Zbus), the Jacobean matrix, or the admittance (Ybus) matrix	Methods for injecting phasor current consider irrational assumptions, such as evenly and concentrically increasing load
[63]	Analytical	Voltage Sensitive Index (VSI)	Reduce both power losses including active and reactive	A practical 69-bus power distribution network	Properly maintaining voltage limits	Applicable to loads with constant impedance and constant current
[64]	Analytical	Existing sensitivity methods	Reduce power and installation costs	69- and 33-bus power distribution system	Lessens the load on the input side of the distribution system caused by reactive power.	Lagging power factors were only taken into consideration for unity and 0.9.
[65]	Conventional (non-heuristic)	Non-Linear Program-ming	Reduce DG units, energy losses, and voltage stability margin	34-bus power distribution network	It is not necessary to convert nonlinear programming to mixed integer nonlinear programming.	Chances of an impractical solution because of the convergence issue
[66]	Conventional (non-heuristic)	Mixed integral non-linear program-ming with a probabilistic approach	Reduce energy losses by integrating generation-specific load variables and loss compensation parameters.	A practical 40-node test system	Maintaining voltage limitation, feeder capacity maximum penetration limits, and DGs discrete size	The need for calculation
[67]	Conventional (non-heuristic)	Probabilistic approach	Minimize annual system energy losses	A practical 40-node test system	Investment maximization and DG unit penetration restrictions	Only appropriate for RDS
[68]	Conventional (non-heuristic)	Continuation power flow	Increase the voltage limit loadability	85-node distribution system	Reliability improvement	Unevaluated system losses

(Continued)

Table 10 (continued)

Ref.	Category	Technique	Objectives	Test/Standard system	Merits	Limitations
[69]	Conventional (non-heuristic)	Dynamic programming	Enhance dependability and voltage profile to reduce power loss	A practical 132/33 kV power distribution network	Monetary and technological advantages	Reactive power's impact is ignored
[70]	Conventional (non-heuristic)	Ordinal optimization	Reduce waste and increase DG size	69-bus power distribution network	Guaranteed solution	Heavy computational load
[71]	Meta-heuristic	Genetic algorithm	Reduce the expenses associated with network upgrades, power outages, energy that isn't delivered, and energy needed by the clients serviced.	142 MV/LV nodes and substations make up just a small percentage of the distribution system.	High loadability with minimal power losses	Accuracy is poor for solutions of high grade.
[72]	Meta-heuristic	Genetic algorithm	Reduce losses in the electrical network.	43-node Brazilian actual system	Analytical assessment of losses, voltage profiles based on reliability indices, and power flow	Premature convergence
[73]	Meta-heuristic	Enhanced genetic algorithm	Reduce overall electricity losses	16-bus distribution system	Solution that is easy to comprehend	Constraint violation values are not considered
[74]	Metaheuristic	GA	Boost voltage profile, and cut down on power loss	UK-based 114-bus mixture urban and rural 11kV	System security and dependability will enhance with security-constrained optimization.	Only considered generator power factor
[75]	Meta-heuristic	Genetic algorithm	Maximize DG capacity	A 11kV RDS with 69-nodes	Effectively distribute the necessary amount of DG	Solely considered deterministic sources
[76]	Meta-heuristic	Genetic algorithm	Reduce actual electricity losses	IEEE 16- and 37-bus distribution network	Appropriate for load models in residential, commercial, and industrial	Numerous runs are necessary
[77]	Meta-heuristic	Adaptive genetic algorithm	Maximize node voltage deviation while minimizing power losses	IEEE 33- and 52-bus Indian practical power network	Better convergence	Self-compared algorithm
[78]	Meta-heuristic	NSGA-II	Reduce levels of power loss and short circuits.	IEEE 34-node test system	Suitable for simulations of generation and load fluctuation	Reactive power's effectiveness is not considered
[79]	Meta-heuristic	NSGA-II	Reduce costs and increase dependability	300-, 100-, and 21-bus power networks	Reduced computational expense	Problem with comparison
[80]	Metaheuristic	NSGA-II	Lower power loss and raise the net present values of the wind turbine investment	A 11.4 kV 84- bus radial distribution system	Appropriate for stochastic load demand	Breaking voltage restrictions
[81]	Meta-heuristic	NSGA-II	Maximize cost savings each year and boost power quality	69- and 89-node test systems	Reduced voltage distortion and THD	High computational burden

(Continued)

Table 10 (continued)

Ref.	Category	Technique	Objectives	Test/Standard system	Merits	Limitations
[82]	Meta-heuristic	Tabu search optimizer	Reduce power costs, energy waste, and the reactive power required.	IEEE 69-, and 33-bus power systems	Appropriate for DGs distribution of real and reactive power	Thermal limitations are ignored
[83]	Meta-heuristic	Tabu search optimizer	Reduce investment and operating (I&O) expenses while increasing dependability	54-bus system	Appropriate for a multistage distribution system	Challenging in terms of trade-offs from the solution set
[84]	Meta-heuristic	Particle swarm optimizer	Improve voltage stability margin	41-bus distribution system	Efficient voltage profile and stability analysis	Optimization Difficult process
[85]	Meta-heuristic	Adaptive particle swarm optimizer	Reduce overall energy losses, generating costs, emissions, and bus voltage variation.	86-bus Taiwan power company system	Adaptable to wind generation's stochastic nature and load requirements	Unconsidered is the correlation between DG units.
[86]	Meta-heuristic	Particle swarm optimizer	Minimize energy costs and losses	A 11.4 kV 84- bus radial distribution system	Appropriate for stochastic load demand	Violating voltage limits
[87]	Meta-heuristic	Modified particle swarm optimizer	Reduce total spending, cut power waste, and boost voltage stability	IEEE 33-bus power system	Appropriate for concerns with short-term DGs planning	Reactive power's effectiveness is not considered
[88]	Metaheuristic	PSO	Minimize power loss, improve voltage stability, and maintain system component current balance.	IEEE 33-bus and a real-world Portuguese RDS with 94 buses	Appropriate for DG distribution of power including active and reactive	Violating voltage limits
[89]	Metaheuristic	PSO	Reduce real power losses	IEEE standard 69 bus and 33 bus radial networks	Management and coordination of many DGs	Magnitude of low voltage
[90]	Metaheuristic	PSO	Minimize power losses and enhance voltage distribution	IEEE standard 30- and 16-bus modified systems	Suited for the placement of capacitors	Almost perfect solution
[91]	Metaheuristic	PSO	Actual power loss, branch current capacity, and voltage variation should all be kept to a minimum.	51-bus RDS	Considered technological, economic, and environmental factors	Reactive power's effectiveness is not taken into account
[92]	Metaheuristic	Ant Colony Optimizer (ACO)	Reduce loss, enhance voltage profile, and balance feeder loads	A Tai-power 11.4 kV distribution network and an IEEE standard 33-bus system	Suitable for DGs distribution of real and reactive power	Limited number of restrictions considered
[93]	Metaheuristic	ACO	Reduce interruption cost	A 47-node test system	Dependable switch relocation technique	Parameter tuning

(Continued)

Table 10 (continued)

Ref.	Category	Technique	Objectives	Test/Standard system	Merits	Limitations
[94]	Metaheuristic	ACO	I&O cost reduction	A test system with a 10 kV 201-node and a 34.5 kV 23-node	Less computational time	Difficult parameter tuning
[95]	Metaheuristic	ACO	Minimize real power losses	IEEE 136-bus and IEEE 14-bus power network	Less computational time	Reactive power's effectiveness is not considered
[96]	Metaheuristic	ACO	Decrease the expenses associated with switching, power procurement, customer fines, and transformer maintenance.	IEEE 118-bus distribution test system	Study using intervals for stochastic load modelling	Load balancing and voltage stability
[97]	Metaheuristic	Cuckoo search	improve the voltage profile, and minimize actual power losses	Two power distribution networks: 38 and 69 buses	Not requiring any parameter adjusting	Increase voltage profile and minimize real power losses as much as feasible
[98]	Metaheuristic	Cuckoo search	Minimizing actual power losses and enhancing voltage stability	IEEE power networks with 33, 69, and 119 buses	Considered several approaches to achieve the same goal	Reactive power's effectiveness is not considered
[99]	Metaheuristic	BFO	Cost reduction	Power system with 25 and 23 nodes	Reduced adjustment of the parameters	Standard systems are not considered
[100]	Metaheuristic	BFO	Minimize power losses	IEEE 85- and 34-bus networks	Optimization of simple and rapid loss reduction	Low voltage magnitude
[101]	Metaheuristic	Flower Pollination Algorithm (FPA)	Reduce power losses and enhance the voltage profile	IEEE 69- 34-, and 15-bus networks	Enhanced the voltage profile	Thermal limitations are ignored
[102]	Metaheuristic	Firefly optimizer	Power losses reduction	IEEE 33-bus power system	An enhanced voltage profile	Appropriate just for a single goal
[103]	Metaheuristic	Ant lion optimizer	Power losses reduction	IEEE 85-bus 69-bus, IEEE 33-, and 15-bus	Improved performance in lagging power factors	Reactive power's effectiveness is not considered
[104]	Metaheuristic	Cat swarm optimizer	Reduce actual power loss to a minimum and increase reliability.	IEEE 69-, 34-, and 16-bus networks	Increased computational effectiveness	Effectiveness of reactive power is ignored
[105]	Metaheuristic	Oppositional krill herd optimizer	Reduce yearly energy losses	IEEE 118-, 69-, and 33-bus networks	Renewable DGs are applied	algorithm that compares itself
[106]	Hybrid	ACO-ABC	Reduce electricity costs, overall emissions, and power loss	IEEE standard systems: 69, and 33-bus	Educated on the random character of wind power	Arduous methodology
[107]	Hybrid	Hybrid evolutionary algorithm	Minimizing total energy losses, total energy cost and total emissions	IEEE 69-bus	Improvement of the voltage profile	Simplified modeling, Limited DG technologies, Uncertainty exclusion, Operational constraints

(Continued)

Table 10 (continued)

Ref.	Category	Technique	Objectives	Test/Standard system	Merits	Limitations
[108]	Hybrid	Hybrid PSO and Shuffled Frog-Leaping	Power losses reduction	33-bus test system	Low processing time and fewer repetitions	Not appropriate for mesh networks
[109]	Hybrid	Imperialistic Competitive Algorithm and GA	Lower power loss, improve load balance, voltage profile of the system, and costs	IEEE standard systems: 69, and 33-bus	Capability for transmission and distribution relief for utilities and clients	Only applicable to systems with uniform and steady power
[110]	Hybrid	Particle swarm and gravitational search optimizer	Reduce grid megavolt ampere consumption, voltage profile, DG amount, and overall actual power loss to a minimum.	IEEE 69-bus network	High computing effectiveness	Self-compared algorithm
[111]	Assorted	Pareto frontier differential evolution	Improve voltage stability and reduce the power losses and fluctuations in the voltage profile.	IEEE 69, 33-bus test systems	Methodology for ranking without dominance to discover the best answer	Reactive power's impact is disregarded
[112]	Assorted	Symbiotic organisms search algorithm	Minimize loss	IEEE standard systems: 69, and 33-bus	Less time for convergence	Large amount of computing time needed
[113]	Assorted	Quasi oppositional swine influenza model with quarantine	Reduce power loss and enhance stability and voltage control	IEEE 69, 33-bus test systems	Computerized effectiveness	Premature convergence
[114]	Assorted	Quasi oppositional teaching learning optimizer	Diminish power loss, the voltage instability index, and voltage deviation	IEEE 118-, 69- , 33-bus test systems	Solves the TLBO's sluggish convergence issue	Self-compared algorithm
[115]	Assorted	Big bang big crunch	Reduce the loss of power and energy.	IEEE 37-bus system	Affected systems include both balanced and unbalanced ones.	Algorithm that compares itself
[116]	Assorted	Modified honeybee mating optimizer	Reduce expenses, emissions, and losses.	Typical 70-bus test system	Performs better when dealing with problems that have one or more objectives.	Problem with comparison
[117]	Assorted	Modified bacterial foraging optimizer	Reduce overall power loss and enhance the voltage profile.	IEEE standard systems: 69, 34-bus and 12-bus	Avoids the BFO-caused delay	Algorithm that compares itself

Table 10 presents a broad range of optimization methods categorized as Analytical, Conventional (non-heuristic), Meta-heuristic, Hybrid, and Assorted approaches, along with their main objectives, test systems, strengths (merits), and limitations.

- Analytical methods are instructional and computationally light but are non-optimal and lack applicability to large, complex networks. For example, linear differential and sensitivity-based methods work on small IEEE test systems but ignore economic/geographic factors and often only consider peak load conditions.
- Conventional (non-heuristic) approaches such as Non-Linear Programming, Mixed-Integer Non-Linear Programming, and Dynamic Programming include real operational constraints but frequently encounter issues like impractical solutions, high computational needs, and limitations when applied to real-world, large-scale systems.
- Meta-heuristic techniques (Genetic Algorithm, PSO, Tabu Search, etc.) are widely adopted for DG sizing/allocation due to their ability to handle nonlinear, multi-objective, and large-scale problems. For instance, the GA and PSO families are frequently used for loss reduction and voltage improvement. Table 10's evidence indicates that metaheuristics generally offer better convergence, flexibility, and practical suitability for real/large systems. However, weaknesses include risk of premature convergence (GA), violation of constraints (PSO), or high computational burden (multi-objective cases).
- Hybrid approaches (e.g., hybrid PSO, ACO-ABC, PSO-EP) combine two algorithms, addressing the drawbacks of single methods and directly achieving better loss reduction, reliability, and computational efficacy for multi-dimensional, real-world cases. The table shows they achieve improved performance on benchmark networks but may have increased methodological complexity.
- Assorted methods such as Symbiotic Organisms Search, Pareto Frontier Differential Evolution, and Big Bang Big Crunch excel at global search and handling complex/realistic system objectives but tend to be computationally heavy or may require multiple runs for adequate convergence.

As detailed in Table 10, Analytical and Conventional methods are limited to small/simple systems, while Meta-heuristic and Hybrid techniques demonstrate superior performance for modern, large-scale, and multi-objective DG allocation tasks. For example, GA and PSO approaches achieve high solution quality but can face premature convergence or constraint violations, whereas Hybrid methods, such as PSO-EP, address these drawbacks at the cost of greater algorithmic complexity. Drawing directly from Table 10, for practical deployments in smart grids, Hybrid and Meta-heuristic approaches should be prioritized due to their proven balance of scalability, solution quality, and flexibility.

4.3 The Best DG Sizing and Allocation Technologies

The most widely utilized traditional DG technology from previous decades uses reciprocating internal combustion engines (diesel, micro-turbines). However, diesel generator units are only used for emergency standby due to rising fuel prices and environmental concerns. Fig. 13 depicts current centralized power generation as well as projected dispersed generation. Fig. 14 illustrates several DG systems for non-renewable and renewable sources together with their technological, environmental, and economical advantages.

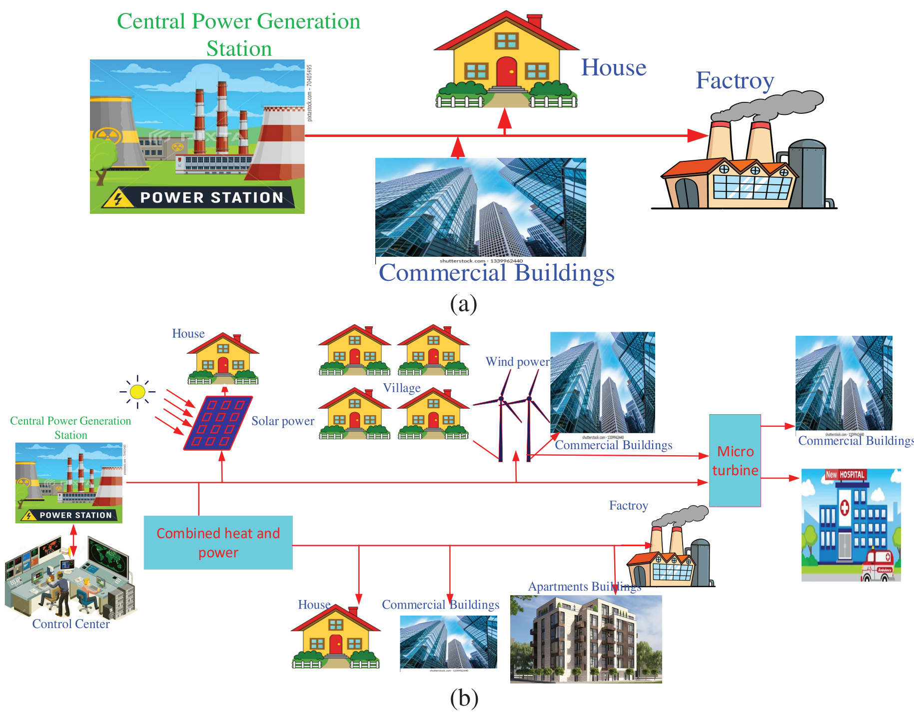

Figure 13: Centralized vs. distributed generation. (**a**) Current centralized generation configuration. (**b**) Projected future distributed generation arrangement (DG: distributed generation). Diagrams are conceptual; energy flows indicated by arrows. See Section 4.3 for context

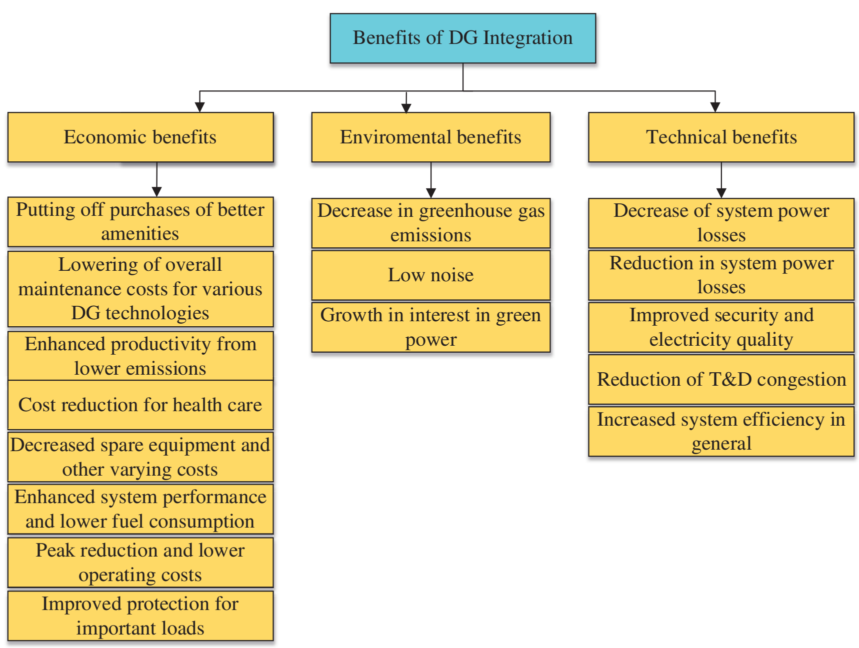

Figure 14: Techno- economic and environmental benefits. Diagrammatic summary of benefits from DG incorporation, listing technical, economic, and environmental impacts

4.3.1 Non-Renewable DG Allocation and Sizing Technologies

The reciprocating engine (RE), a non-renewable DGs technology, is a widely used and widely recognized technology. Based on the Environmental Protection Agency report, reciprocating engines produce more than 200 million units annually around the world, according to the US. The reciprocating engine power generators range is 10 to 18 MW. Frequently, over 95% of them can be used in applications that produce static power. Both diesel and spark ignition configurations have been used in REs. The Combined heat and power (CHP) systems based on REs often provide both thermal and electrical needs. Another form of REs is the microturbine, which has a high-speed, solitary shaft and simple mechanical assemblies. Since natural gas is utilized in micro-turbines for the ignition, this technology has lower NO_x emissions than diesel generators. Micro-turbines are not environmentally favourable, despite having minimal NO_x emissions [118–120]. Diesel generators stand out among non-renewable DGs because of their low cost and great dependability, which is the most widely used DG technique. Diesel generators will become dispatchable sources when they have instantaneous start and stop operation. It most likely works well when used alone.

4.3.2 Renewable DG Allocation and Sizing Technologies

The word "renewable" refers to primary, clean, domestic, or limitless energy sources. Reducing CO_2, NOx, and other greenhouse emissions motivates the integration of Renewable Energy Resources (RER)-based DGs in the power distribution systems. The most popular DGs technologies that use renewable energy resources are fuel cells, biomass, solar PV, wind turbine generators, small/mini/micro hydropower, and biomass [121,122]. Reputable RER-based DG technologies are given in [123]. Due to its steady availability and enormous capacity, hydropower accounts for a significant portion of renewable energy worldwide. Since solar energy is so widely available and is non-polluting, it has drawn more attention. By 2030, Spain will need less energy, thanks to the production of power from renewable sources, with solar PV technology receiving particular attention. Another significant renewable energy source that creates clean energy is wind turbines. However, stochastic analyses are needed since solar and wind energy are intermittent. Another RER employed is biomass. It is made from organic resources (wood, agricultural waste, or trash), and once gasified, it can be utilized as gas turbine fuel [124–129]. A biogas-fuelled gas engine is assigned as DG in an imbalanced radial distribution network [130]. Unlike solar PV and wind energy sources, fuel cell green DG technologies would not be geographically constrained and could be installed anywhere in a distribution network. Fuel cells employ oxygen and hydrogen to produce heat, water, and electricity. The fuel cells have a substantially higher theoretical efficiency than traditional power plants.

4.4 The DG Allocation and Sizing Strategies

4.4.1 Prespecified/Predefined Allocation Strategy

The prespecified allocation strategy is based on the pre-specification of prospective candidate buses for allocating DGs into the current traditional distribution system (TDS) based on sensitivity indicators. Several studies have employed this strategy [131–135] to identify the prospective candidate buses and then allocate single or multiple DGs within the current TDS according to various sensitivity metrics. Prespecified busses with the lowest voltage profile are used in [131–135] to allocate one or two DGs. When allocating numerous DGs in a system, the voltage stability metric is applied to identify the weak busses [131,132,135]. In contrast, the authors of [136,137] use the voltage stability metric as well as the lowest voltage profile to determine which buses are candidates for the allocation of three DGs. In addition, using various mathematical formulas, the researchers in [67,138,139] found the ideal place to assign one DG in accordance with the reduction of power loss and or voltage profile.

4.4.2 Ranking Buses Strategy for DG Sizing/Allocation

The ranking buses strategy relies on non-sequential ordering or selecting/ranking the worst buses to allocate DG according to a certain objective or a sensitivity measure. For instance, the authors in [140] used a novel sensitivity measure to rank the top 10 buses for DG allocation. The optimum loss saving and related DG size are established for the buses other than the reference bus in [60]. The first optimum DG allocation corresponds to the highest saving loss given a specific DG size. Repetition of the previous procedure with the size and first DG fixed will place the subsequent DG. Repeating the same steps till there is no change in loss saving is another option. Moreover, the authors of [70,141] evaluated the power stability metric for each branch and determined that the first DG should be located at the point on the line where the power stability measure value is highest. According to how the first DG affected power stability metric in a multiple DGs placement, the subsequent DG placement was decided to be at the point where the power stability measure value is highest.

4.4.3 The Allocation Strategy Is Inherent in Sizing

The above-discussed strategies have various drawbacks. First, both strategies attempt to handle the DGs allocation and scaling issues individually despite their interdependencies. Therefore, to accomplish optimization, they should be dealt with concurrently. Second, depending on certain sensitivity indices, certain DGs at predetermined or ranked buses are applied. The energy system could profit technically and economically from this, but it wouldn't be the optimal solution. The allocation inherited by the sizing strategy is proposed in [142] to overcome these drawbacks of the previous two strategies. This technique does not provide renewable distributed energy to specific buses like the previously stated solutions do. In the meantime, it assigns DG units first to each load bus. The optimizer then chooses which load bus among all the others, is the best fit for the DGs unit allocation. The optimizer can cancel the unfeasible solutions automatically. Therefore, the optimal size inherits the optimal placement of DGs.

5 Conclusion, Limitations and Future Perspectives

Integrating DG resources from renewable sources into the power system networks is crucial to improving power distribution network performance. The technological, economic, and environmental merits of appropriate DG incorporation have been identified, such as lowering power losses and enhancing the voltage profile, fuel saving, cost of energy reduction, lower investment with low operating and maintenance costs, and decreased greenhouse gas and CO_2 emissions. Furthermore, they have also been recognized as an effective solution to several power system challenges.

The following are a few notable significant conclusions and recommendations that can be drawn from this thorough systematic and scientometric review:

- There are certain downsides to both prespecified and ranking systems. First, notwithstanding their interdependencies, both solutions try to investigate the sizing and allocation of the DGs separately. Therefore, they should be addressed together to achieve the optimum. Second, certain DGs are applied to specified or ranked buses according to specific sensitivity indices. Technically and economically, the energy system may benefit from this, but it wouldn't be the best solution for action. The allocation inherited by the size technique is introduced and preferred to address and overcome these critical issues with the prior two sizing and allocation strategies.
- Several analytical heuristics, metaheuristics, and hybrid optimizers are also modified and proposed for the best DG sizing and allocation. For small and simple network systems, analytical and conventional approaches may suffice, but in practical, large-scale, and complex real-world distribution systems,

metaheuristic and hybrid algorithms should be prioritized for robust and scalable solutions. The system will get more complicated as DG output, load demand, electricity price, and emission uncertainty are considered. For extremely massive systems, metaheuristic and hybrid approaches are ideally suited. They possess excellent convergence characteristics and great precision. These approaches offered basic single-objective solutions as well as complicated multi-objective issues with global optimal solutions. It has been discovered that numerous meta-heuristic optimization approaches are doing incredibly well in terms of achieving the best DG allocation and scaling. Many methods, including Salp Swarm Algorithm (SSA), Artificial Bee Colony (ABC), Shuffled Frog Leaping Algorithm (SFLA), Invasive Weed Optimization (IWO), Whale Optimization Algorithm (WOA), Intelligent Water Drops (IWD), and Cat Swarm Optimization (CSO), could appear to have promise in the future. Consequently, advising practitioners that, based on recent comparative research, hybrid metaheuristic approaches (e.g., PSO-GA, ACO-ABC) are most effective for addressing multi-objective DG sizing/allocation, especially under uncertainty.
- The publication's number in DG sizing and allocation has increased significantly, particularly in the previous decade, demonstrating the topic's significance. As a result, it represents the global trend of improving traditional power distribution networks' technological, economic, and environmental issues. The authors noticed that the yearly worldwide research trend began with single DG sizing and allocation with a single objective function, and the researchers used classical/analytical techniques to solve this simple optimal power flow problem. After that, multiple DG sizing and allocation with single or multiple objectives, whether technical or economic or both, have been solved using metaheuristic/artificial intelligence and hybrid optimization algorithms to avoid the shortcomings of conventional/analytical techniques. Different strategies have been applied as discussed above, but not all strategies attained the optimal solutions; however, they may provide technological and/or economic advantages to the power distribution networks. These significant concerns are active development research areas that have piqued global scholars' interest, particularly in the past decade.
- For researchers—focus on developing computationally efficient, scalable algorithms validated on large, realistic networks; further integrate stochastic and real-time constraints.
- For practitioners—adopt hybrid/multi-algorithm frameworks for optimal DG planning; select methods based on specific operational needs, network size, and uncertainty level.
- For both communities—the need to report comprehensive effect sizes and robustness analyses, not only solution values, to guide method selection for practical deployment.
- Hybrid DG allocation and scaling solutions are advised since they may produce more efficient and superior results.
- Future algorithm updates for the best DG size and allocation problem might lead to better performance and faster convergence and computational times.
- By taking static, seasonal, and realistic load models for further work, a distribution network expansion and protection plan using DG installation is proposed.
- The scope of future research may be expanded using DG for both on- and off-grid systems, as well as the investigation of the system performance under different scenarios of contingencies.

All output solutions for resolving a certain kind of problem are statistically identical. Selecting the best optimization method for a given issue will rely on the preferences of the individual and the designers.

Key Limitations and areas needing further research and practical validation are summarized as follows:

- Most reviewed studies assume static or simplified load models and focus primarily on radial distribution systems, limiting applicability to complex, dynamic, or meshed real-world networks.

- The optimization techniques discussed are predominantly tested on standard, small-scale benchmark systems (e.g., IEEE 33/69-bus), lacking validation with actual, large-scale distribution networks.
- Many optimization approaches in the literature do not comprehensively integrate practical constraints such as protection coordination, voltage regulation, reliability analysis, economic and regulatory factors, or stochastic behavior (loads and generation).
- The development of distribution systems for DGs with intermittent nature, such as wind turbine generators and solar photovoltaics, can further the research effort. Such planning entails stochastic research.
- Renewable DG integration is generally considered without fully addressing the combined role and modeling of energy storage systems (e.g., batteries), load uncertainties, or seasonal variations, which are critical for modern grids. The present analysis does not consider RERs-based DGs with battery energy storage systems or their importance.
- Many meta-heuristic and hybrid approaches face issues such as extensive parameter tuning, computational complexity for large-scale problems, or premature convergence; their generalizability and reproducibility are not always ensured.
- Some emerging directions (e.g., prosumer-level planning, peer-to-peer energy trading, resilience under contingencies, detailed economic-environmental trade-offs) are either briefly mentioned or remain as open areas for future work.

These points capture the significant limitations of the paper and highlight areas needing further research and practical validation.

Acknowledgement: The authors extend their appreciation to the Deanship of Scientific Research at Imam Mohammad Ibn Saud Islamic University (IMSIU) (grant number: IMSIU-DDRSP2503).

Funding Stetament: This work was supported and funded by the Deanship of Scientific Research at Imam Mohammad Ibn Saud Islamic University (IMSIU) (grant number: IMSIU-DDRSP2503).

Author Contributions: The authors confirm contribution to the paper as follows: study conception and design: Abdullrahman A. Al-Shamma'a, Hassan M. Hussein Farh, Ridwan Taiwo, AL-Wesabi Ibrahim, Abdulrhman Alshaabani, Saad Mekhilef, Mohamed A. Mohamed; data collection: Abdullrahman A. Al-Shamma'a, Hassan M. Hussein Farh, Ridwan Taiwo, AL-Wesabi Ibrahim, Abdulrhman Alshaabani, Saad Mekhilef, Mohamed A. Mohamed; analysis and interpretation of results: Abdullrahman A. Al-Shamma'a, Hassan M. Hussein Farh, Ridwan Taiwo, AL-Wesabi Ibrahim, Abdulrhman Alshaabani, Saad Mekhilef, Mohamed A. Mohamed, Abdullrahman A. Al-Shamma'a, Hassan M. Hussein Farh, Ridwan Taiwo, AL-Wesabi Ibrahim, Abdulrhman Alshaabani, Saad Mekhilef, Mohamed A. Mohamed; draft manuscript preparation: Abdullrahman A. Al-Shamma'a, Hassan M. Hussein Farh, Ridwan Taiwo, AL-Wesabi Ibrahim, Abdulrhman Alshaabani, Saad Mekhilef, Mohamed A. Mohamed. All authors reviewed the results and approved the final version of the manuscript.

Availability of Data and Materials: All the data is available in the paper.

Ethics Approval: Not applicable.

Conflicts of Interest: The authors declare no conflicts of interest to report regarding the present study.

Supplementary Materials: The PRISMA checklists can be found in the supplementary materials. The supplementary material is available online at https://www.techscience.com/doi/10.32604/cmes.2025.071302/s1.

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