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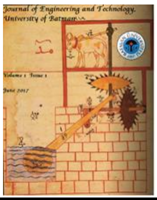

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Modeling and Performance Analysis of a Rooftop Photovoltaic System for Batman: Impact of Seasonal Shading on Energy Efficiency

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ABSTRACT

The increasing depletion of conventional energy resources and the escalating environmental impacts necessitate a transition to renewable energy sources. Among these, solar energy emerges as a sustainable and viable alternative, with photovoltaic (PV) systems offering efficient energy conversion. This study focuses on the modeling and performance simulation of a rooftop PV system designed for the Batman Dicle Elektrik Dağıtım A.Ş. (DEDAŞ) building. The primary objectives are to mitigate energy costs and enhance environmental sustainability by harnessing solar energy. The PV system was designed and analyzed using PVsyst software, incorporating various shading scenarios to assess performance impacts. Simulation results indicate that shading significantly affects energy production, particularly during winter months, with losses reaching up to 28% in December. Conversely, in summer, shading effects are minimized, resulting in a 4% energy loss in June. The findings highlight the importance of accounting for local climatic and geographical factors in PV system design, demonstrating the potential for optimizing renewable energy utilization in similar projects.

1. Introduction

The rapid increase in energy demand and the depletion of fossil fuels have led to the search for new energy production solutions. The environmental impacts of fossil fuels contribute to global warming and climate change, leading to problems such as air and water pollution and habitat destruction. Renewable energy sources offer sustainable solutions as an alternative to these damages; solar energy in particular stands out with its low carbon emissions and continuous energy production capacity. Grid-connected photovoltaic (PV) systems are systems that convert sunlight into electricity and transfer this energy to the electricity grid. These systems have the advantages of being environmentally friendly, increasing energy security, offering low operation and maintenance costs, reducing energy costs and scalability. Turkey is a country with high solar energy potential, with an average annual solar radiation of 1527 kWh/m², making solar electricity generation sustainable. Batman province has this potential with an annual solar radiation of 1700-1800 kWh/m² and offers favorable conditions for solar energy projects. Grid-connected PV systems to be installed in Batman can increase local energy production and ensure energy security, while creating new job opportunities and reducing energy costs. This study aims to optimize this potential by addressing the modeling and simulation of a rooftop grid-connected PV system for Dicle Elektrik Dağıtım A.Ş. building. The data to be obtained will be evaluated in terms of energy generation capacity, economic evaluation and environmental impacts and will serve as a reference for similar projects. Solar energy technologies, especially photovoltaic (PV) systems, have received significant attention in the field of sustainable and environmentally friendly energy generation. This chapter provides a comprehensive review of the existing literature on the design, performance analysis and economic evaluation of rooftop grid-connected photovoltaic systems. The review will cover a wide range of topics from PV system component selection, system design, energy efficiency and performance analysis to economic evaluation methods. The studies in the literature include technical and economic aspects of PV systems, simulation techniques and application examples, and focus on current developments worldwide. For instance, Mohammed M.A et al. (2024) investigates the LVRT capabilities and control algorithms of three-phase grid-connected PV systems, while Mishra P.R et al. (2024) describes the role of PVSyst software in system performance evaluation. In other studies, topics such as energy flow and losses analysis, shade losses and seasonal optimization of rooftop systems are addressed with PVsyst. PVsyst software is widely used in the design of solar energy systems with its large database and user-friendly interface. Many studies in Turkey have used PVsyst to examine solar photovoltaic system designs and provide data to optimize system performance according to local conditions. Among the examples, studies carried out in Bursa compared the performance of systems installed with different PV technologies and analyzed their energy generation capacity and efficiency.

Mohammed M.A et al. (2024) focus on the modeling of three-phase grid-connected photovoltaic systems. The authors investigate the low-voltage operation (LVRT) capability and the control algorithms used in these systems. This suggests solutions aimed at improving the stability and efficiency of grid-connected systems. The paper by Mishra P.R et al. (2024) and Ciftci, S et. al. (2020) describes how PVSyst software is used for performance evaluation of grid-connected photovoltaic systems. The authors emphasize that PVSyst is a powerful tool for analyzing power generation losses and simulating system efficiency. Rawat R. et al. (2019) analyze the energy flow and losses of a grid-connected 30.5 kWp PV system using PVsyst simulation software. The authors focus on component selection and performance evaluation. Vidur P.R et al. (2022) discusses shading losses, layout and system design of rooftop solar systems. This study provides important information on system scaling and simulation methods. Dong H. et al. (2023) investigate how rooftop PV systems can be optimized by taking seasonal effects into account. The authors analyze the effects of energy storage strategies and seasonal generation fluctuations on system performance.

In the literature, there are many studies on the applications of PVsyst. Kumar et al. (2021) studied the office energy load requirements of the mechanical engineering department of an engineering college in Bikaner, India, and designed a standalone PV system to meet these requirements. In their study, they determined the average annual energy requirement of the system as 1086.24 kWh using PVsyst software and found that the amount of energy obtained through solar panels was 1143.6 kWh. The amount of energy provided to the user was recorded as 1068.12 kWh, and it was emphasized that the decreasing power capacity of the system occurred due to various losses. In a similar study, Baqir et al. (2022) conducted the design and performance analysis of a 700 kWp grid-connected PV system in Daykundi province of Afghanistan. Mohammadi and Gezegin (2022) investigated the design and simulation of a 5 MW solar power plant in Ghor province of Afghanistan. The main objective of the study is to evaluate the capacity of generating electrical energy from local resources to provide reliable and sustainable energy to an area in the center of Ghor province that is not connected to the national electricity grid. Sharma et al. (2018) investigated the solar photovoltaic system design of an academic institution using PVsyst software. The basis of the study is how the performance of photovoltaic systems is affected by factors such as geographical location, solar radiation, module type and orientation. Siregar et al. (2020) (2020) presented the design and simulation of a 600 m² solar PV system at the University of Sumatera Utara, Indonesia. This study revealed that the optimal design using Si-Mono 310 Wp panels produced 144.21 MWh of energy per year. The effects of partial shading on energy and exergy efficiency for photovoltaic panels were studied by Bayrak et al. Badea et al Maximizing solar photovoltaic energy efficiency: Extensive work has been done on investigating MPPT techniques based on shading effects.

Extensive studies have been conducted by Albatayneh on enhancing the energy efficiency of buildings by shading with PV panels in semi-arid climate zone.

In Cakmak (2022), PVsyst simulation program has enabled many studies on solar photovoltaic system design in Turkey. İzgi and Özcan (2020) presented the monthly and annual performance analysis of a 1 MW grid-connected photovoltaic power plant installed in Osmangazi district of Bursa using mono-crystal, poly-crystal and thin film technologies. In the first phase of the research, a detailed shading analysis was carried out to determine the suitability of the area for PV installation. This analysis was performed using Google Sketchup and PVsyst software. In the next stage, PVsyst and PV*SOL software were used to simulate the performance of three different photovoltaic technologies. For performance evaluation, parameters such as string efficiency, final efficiency, PV efficiency and performance ratio were considered. In another study by Demiryürek et al. (2020), the data of Lebit Enerji's solar power plant with an installed capacity of 200 kWp were transferred to the PVsyst V6.67-TRIAL program and simulation was performed. This simulation data was compared with the actual generation data. The simulation report analyzes the losses in the system; various factors such as thermal losses, cabling losses, shading losses and panel losses were evaluated. As a result of the analysis, a difference of approximately 0.56% was found between simulation data and actual generation values. This finding provides important contributions to feasibility studies for PV systems in the design phase, and can also guide revision studies to increase the efficiency of existing systems. In the study by Kılıç and Kurtaran (2023), a rooftop photovoltaic system with an installed capacity of 11.06 kWp was designed to meet the energy needs of an environmental consultancy firm with an area of 864.55 m² in Osmangazi district of Bursa. According to the performance analysis performed with PVsyst 7.3.4 simulation program, it was determined that the system can generate 14,602.63 kWh of electricity per year. The electrical energy transferred to the grid is observed as 13,714 kWh when system losses are taken into account. The performance rate was calculated as 81.69% and the loss rate as 18.31%. Factors such as high module temperature, insufficient sunshine duration and inefficiency of system components caused system losses. In July and August, a decrease in the efficiency of the panels was observed due to high temperatures. In the study by Etci and Bilhan (2021), the model of two different systems producing electricity from solar energy in Konya province was created and production data were compared. In Marhraoui (2019), while the annual energy production of the fixed-axis system was determined as 193.7 MWh/year, this value was calculated as 232.4 MWh/year in the dual-axis system. It was determined that the biaxial system produced 16.7% more energy than the fixed axis system. In Sancar and Altinkaynak (2021) and Eklas (2018), rooftop photovoltaic systems are considered for Isparta province and six different simulations are performed with different roof types and orientation angles. These studies provide important data for the design of solar photovoltaic systems in Turkey and provide guidance for optimizing system performance according to local conditions.

This literature review will strengthen the scientific background of the study on the modeling and simulation of rooftop PV system for DEDAŞ building by highlighting the critical factors in the design of solar energy systems and the necessary strategies to optimize the system performance.

The motivation for this study stems from problems such as global warming and climate change caused by increasing energy demand, depletion of fossil fuel reserves and environmental impacts of traditional energy sources. In the search for sustainable energy solutions, solar energy, which has low carbon emissions and is widely available, stands out. In this context, modeling and simulation of a rooftop PV system was performed for the DEDAŞ building in a region with high solar radiation potential such as Batman. The study aims to reduce energy production costs and increase environmental sustainability. The proposed method aims to address the performance losses encountered by PV systems due to shading effects. It has been determined that losses of up to 28% in energy production occur especially in winter months due to low sun angle and long shadows. In summer months, the shading effect decreases and losses drop to 4%. This problem shows the lack of system designs that take into account local climatic and geographical conditions and that shading analyses are not sufficiently integrated into the design processes. Existing diagnostic methods generally address PV system designs in general terms and do not consider local conditions in detail. Shading effects, seasonal differences or the effects of local sun angles on energy production are not sufficiently examined. As a result, design processes and simulation results cannot provide optimum performance in real life. The proposed method of this study offers several advantages over existing approaches. These are; the system design was carried out considering the specific solar radiation profile and shading conditions of Batman. In addition, shading effects were analyzed in detail under different seasons and scenarios using PVsyst software. The study provides a directly applicable reference for similar projects by taking a real application such as the DEDAŞ building as a basis.

2. Photovoltaic Systems

Photovoltaic systems consist of interconnected components designed to fulfill specific purposes. These purposes can range from meeting the power needs of a small device to supplying electricity to the main distribution grid. Photovoltaic systems are classified according to the diagram shown in Figure 1. The two main categories in this classification are stand-alone and grid-connected systems (Messenger, 2018). In stand-alone systems, solar power generation is directly matched to load demand (Akcan E.,et. al, 2020).

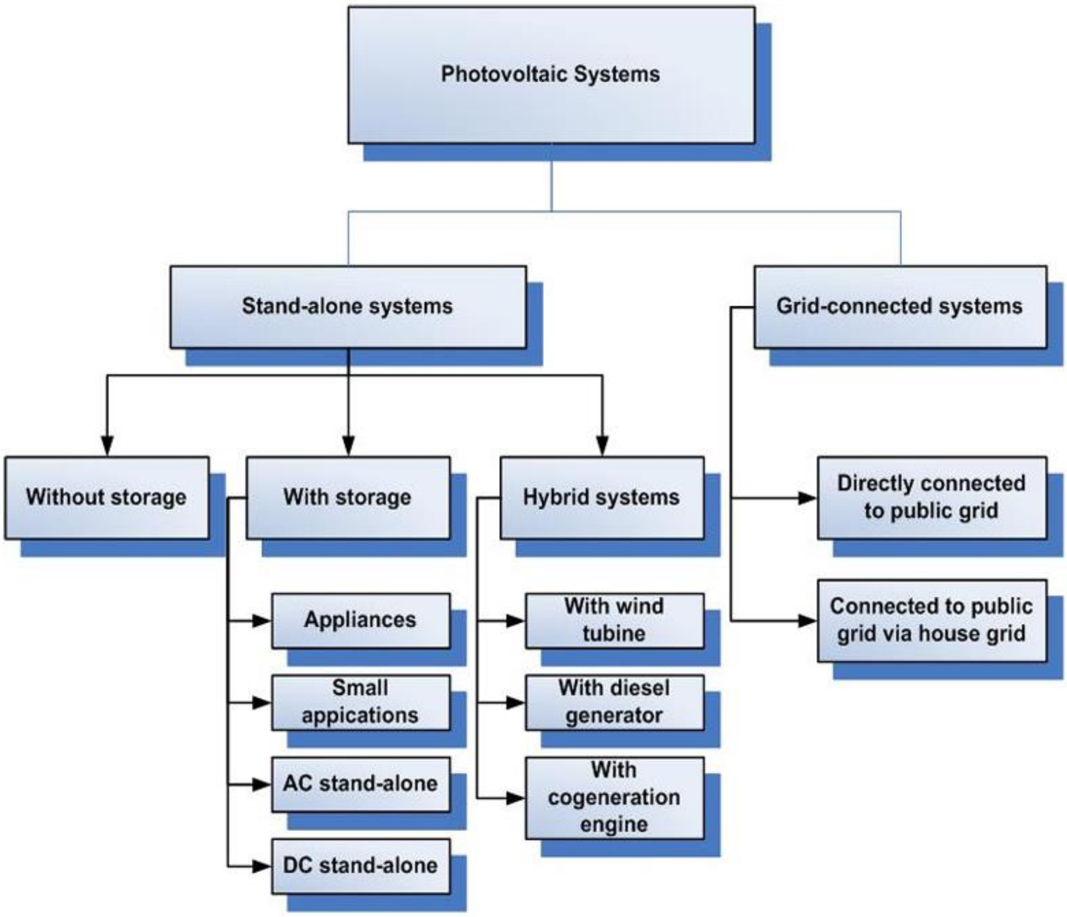
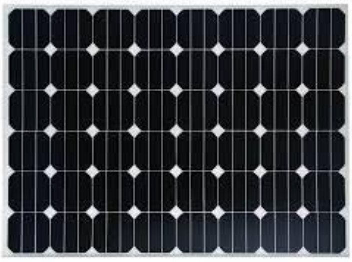
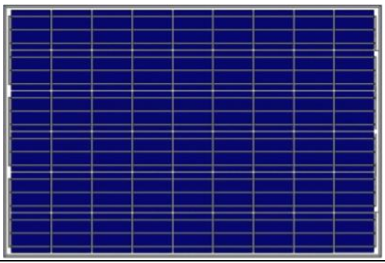
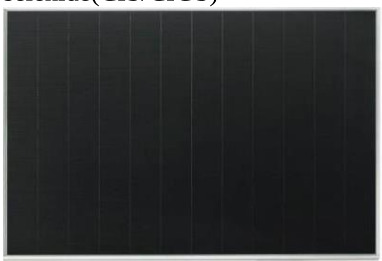


Figure 1. Classification of PV systems (Dzimano, 2008)

2.1 Advancements in Photovoltaic Cell Materials: Crystalline, Thin-Film, and Emerging Alternatives

PV cells are composed of semiconductor materials made of two basic types of materials: crystalline and thin film. Most PV cells are silicon-based, but in the near future other thin-film materials are likely to overtake silicon PV cells in terms of cost and performance (Archer, 2014). PV materials generally belong to one or more of the following classes: crystalline, thin-film, amorphous, multijunction, organic or photo-chemical.

Table 1. Strengths and shortcomings of different photovoltaic technologies (Makarova, 2017)

PV Technology	Strengths	Weaknesses
Monocrystalline Silicon (mono-Si): 36 % of market share 	efficiency: 15-20 % (21.5 % as current maximum) - durability up to 25 years - space-efficient	- the highest price - sensitivity to ambient temperature (performance decrease significantly with an increase of ambient temperature) - sensitivity to shading issues, snow and dirt - wasteful manufacturing process
Polycrystalline Silicon (p-Si veya m-Si): 55 % of market share 	-simple, cost-efficient and not wasteful manufacturing process -insignificant intolerance to high ambient temperature	- impurities and efficiency of 13-16 % - not space efficient - energy extensive manufacturing process
Thin-film (TFSC): - Amorphous silicon (a-Si) - Cadmium telluride (CdTe) - Copper indium gallium selenide(CIS/CIGS) 	- cost-efficient and simple manufacturing process - flexible configurations applicable different installations - high tolerance to shading issues and variation of ambient temperature	- low efficiency: 9-12 % - low space efficiency - high degradation rate

Mono-crystalline silicon cells used to occupy a dominant position in the photovoltaic market in the past, but have nowadays been overtaken by polycrystalline silicon. Mono-crystalline silicon was popular due to its high stability and desirable physical, chemical and electronic properties; moreover, its success in microelectronics has had a positive impact on the PV industry. However, polycrystalline silicon has become the most widely used material due to its lower cost. Since the cost of silicon accounts for a large part of the total cost of the solar cell, the production processes of polycrystalline silicon reduce the cost and enable the formation of large crystalline structures. As a result, this leads to the production of cheaper cells with lower efficiency, while the ease of assembly offsets the disadvantage of low efficiency.

2.2 Features, Limitations, and Applications in PV System Design and Simulation

PVsyst is a software package designed for the study, sizing and data analysis of solar photovoltaic systems. It covers grid-connected, stand-alone, pump systems and DC grid PV systems and includes a large database of meteorological data and PV system components. PVsyst is recognized worldwide as a standard software for PV systems design and simulation. The software simulates with inputs such as PV arrays, inverter models and battery packs and produces results with various parameters, which can be reported monthly, daily or hourly. Actual component prices and additional costs can be used for economic evaluation (Cakmak F. 2024).

However, PVsyst has some limitations: the screen cannot be made full size, it cannot perform detailed shadow analysis and it does not provide a single line diagram. PVsyst version 6.8 (Figure 2) is preferred for system design and analysis and provides simulation result reports for off-grid or grid-connected energy systems. Thanks to the 3D application of the software, shading effects on the system can also be modeled. PVsyst offers a large database of brands and manufacturers and users can manually enter technical data for missing elements. Furthermore, meteorological data can be synthetically generated with the Meteonorm 7.2 tool (PVsyst, 2024).

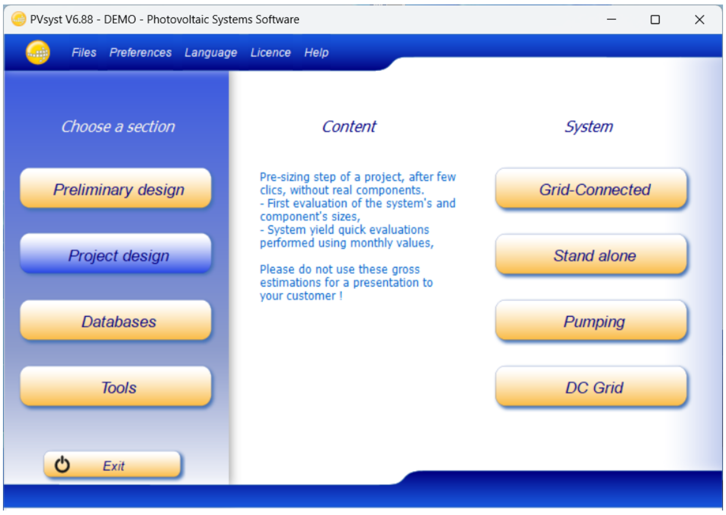


Figure 2. PVsyst screen capture

3. Project Design of Photovoltaic System with PVsyst

Before starting the PVsyst simulation, some preliminary definitions should be made to the software. In the start screen of the PVsyst software shown in Figure 2, the "Grid-connected" option should be selected since a grid-connected system will be built for the DEDAŞ building SPP plant in Batman province. After this selection, the main screen shown in Figure 3 opens. On this screen, there are sections where general information about the project is defined (PVsyst, 2024). The first step is to define the project name. Then, the meteorological data of the region is provided by entering the coordinates from the "Weather database" tab on the interface. The technical and economic information required for the energy system such as the brand, model, number, orientation, user needs, losses that may occur in the system, 3D shading analysis and economic analysis of the panel and battery are defined in the "Main parameters" tab on the interface. When all options turn green, the simulation is started by clicking on the "Run simulation" option. In the next step, the meteorological data of the region where the photovoltaic energy systems will be installed must be generated through the resources available in the system database. PVsyst simulation software can generate meteorological data through various databases. These databases include Meteonorm 7.2, NASA-SSE, PVGIS TMY and NREL/NSRBD TMY (PVsyst, 2024). In this study, the area where DEDAŞ SPP will be installed was selected on the map and Meteonorm 7.2 data of the region in question were taken. These data are shown in Table 1. The total annual global irradiation in the region where the SPP plant will be built is 1548.2 kWh/m2 and the highest temperature is 31.9 °C on average in July. In the table containing meteorological data created by the software, extra data can be added and removed as needed. These data also include horizontal diffuse irradiation, wind speed, turbidity and humidity.

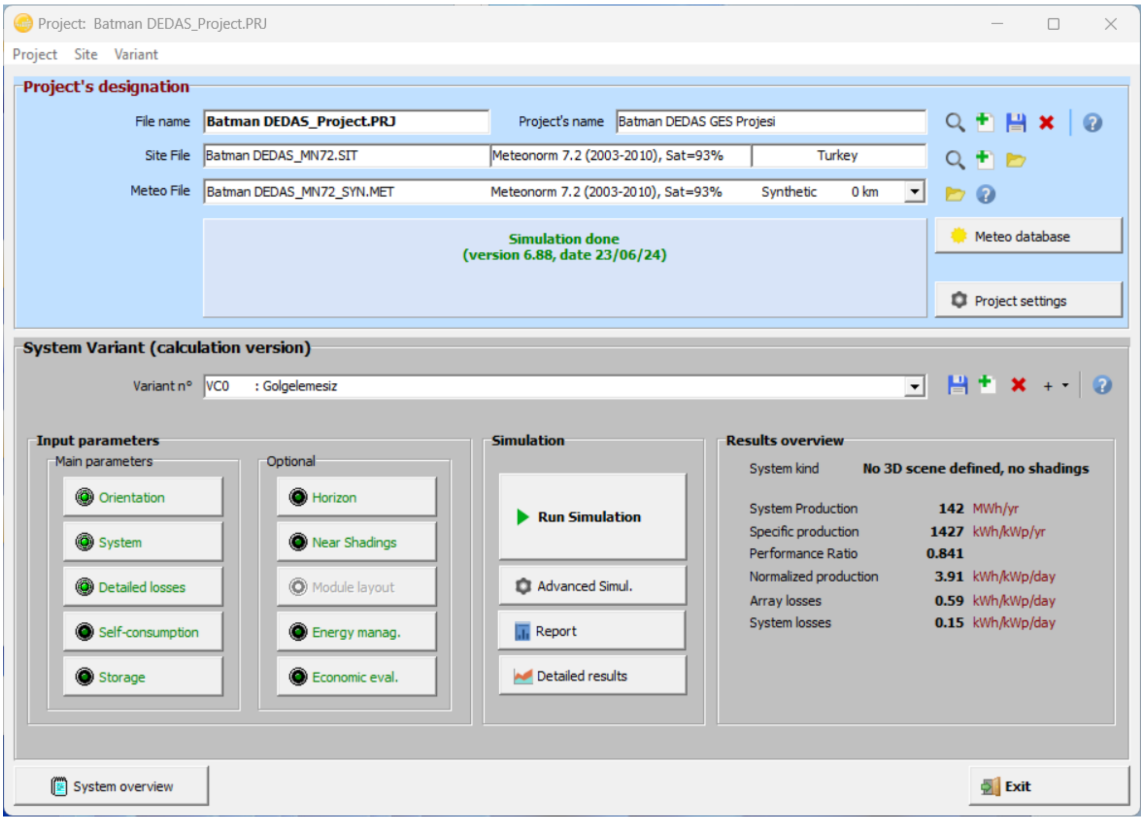


Figure 3. Creating the Project with PVsyst

Table 1. Meteonorm 7.2 Data for Batman DEDAŞ region

	Global Horizontal Irradiation	Horizontal Diffuse Irradiation	Temperature
	kWh/m^2.month	kWh/m^2.month	°C
January	55,5	32,2	2,4
February	70,5	38,0	4,8
March	112,8	58,0	10,1
April	141,0	66,2	14,2
May	181,7	79,1	20,1
June	204,7	69,3	27,2
July	208,0	76,5	31,9
August	193,6	75,4	31,1
September	153,6	53,4	25,1
October	103,5	47,2	19,0
November	70,0	32,0	10,0
December	53,3	30,0	4,7
YEAR	**1548,2**	**657,3**	**16,7**

Diagrams showing the output power distribution of the plant without shading and under shading conditions are presented in Figure 4. In these diagrams, it is possible to examine the power provided by the system to the grid in the range of 0 kW to 100 kW. The obtained results reflect the determining effect of the inverter performance in this power range. Since the same inverter is used in both scenarios, the differences between the shaded and unshaded cases are minimal and do not have a significant impact on the output power of the system. This similarity demonstrates how effective the inverter's power transfer capacity is in compensating for the possible variations of the shadowing effect and points to the stability of the power distribution. Graphs showing the annual loss diagrams of the plant without and with shading are presented in Figure 4 and Figure 5. In both scenarios, it is assumed that an equal amount of global radiation, i.e. 1548 kWh/m², is reflected to the collector and the percentage loss of radiation is shown in detail.

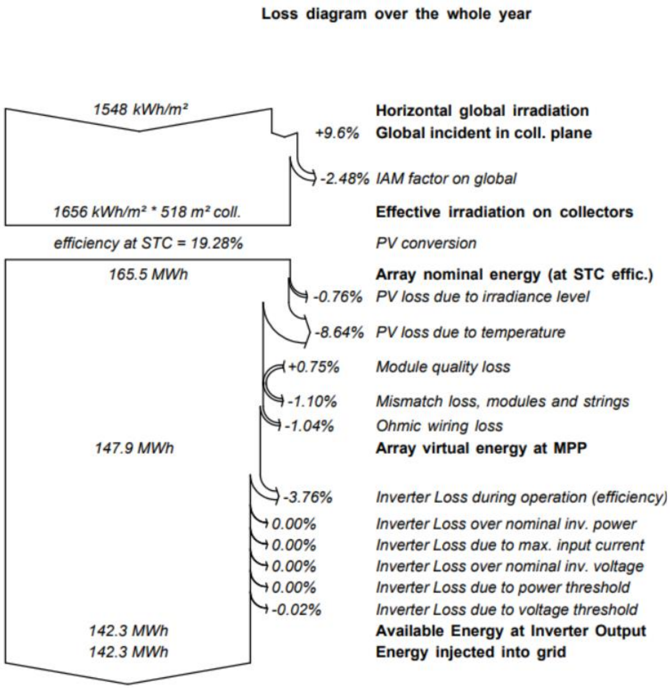


Figure 4. Simulation Loss Diagram without Shading

While the losses due to temperature were calculated as 8.64% in the unshaded condition, these losses reached a similar value of 8.45% in the shaded condition. Similarly, losses due to the inverter were 3.76% in the unshaded condition and 3.88% in the shaded condition. Losses due to module quality and ohmic wiring remained constant in both scenarios.

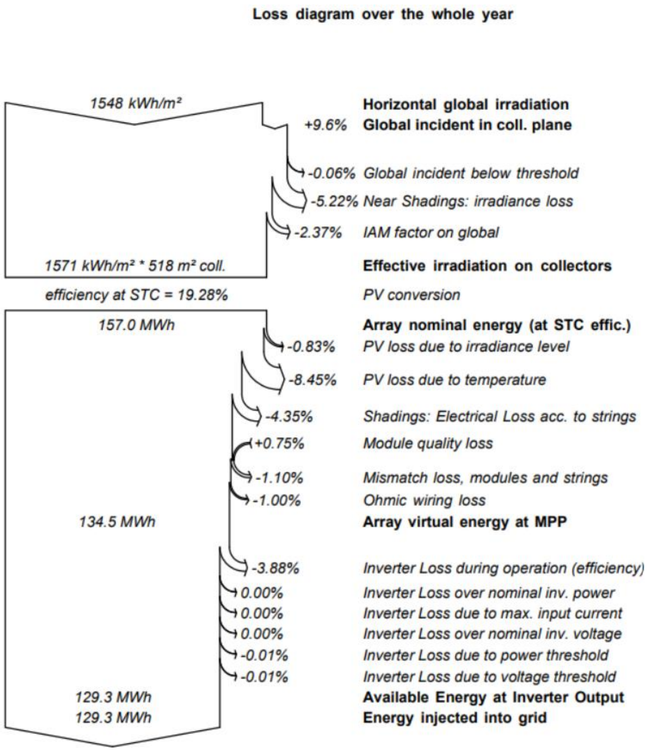


Figure 5. Simulation Loss Diagram with Shading

The main variation is observed in the losses due to shading. In the simulation without shading, shading losses were 0%, while in the simulation with shading, losses due to near shading effects were 5.22% and losses due to shading of other panels in the same array were 4.36%. These findings highlight the significant impact of shading on system efficiency and the importance of optimizing shading management.

Diagrams showing the daily energy production of the facility under both unshaded and shaded conditions are presented in Figure 6. In this graph, instances where energy production values display a linear distribution can be interpreted as high system performance. In the second diagram, which examines the shading effect, the irregular and scattered placement of data points indicates losses in energy production and demonstrates the negative impact of shading on PV system performance. This irregularity causes disruptions in the continuity and stability of the energy production process under shaded conditions, leading to notable decreases in system efficiency.

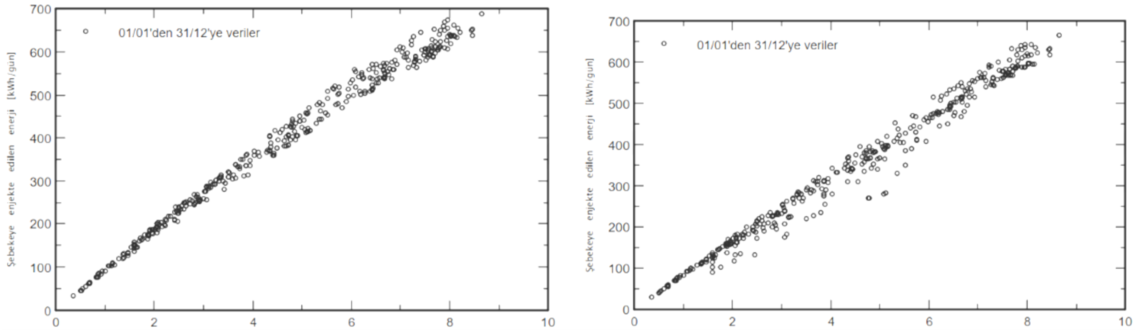


Figure 6. Daily Energy Production Diagrams for Simulations Under Unshaded and Shaded Conditions kWh/m^2

In the facility simulation report, an analysis of the monthly production graphs for unshaded and shaded conditions, as shown in Figure 7, reveals significant differences, especially during October, November, December, January, February, and March, when solar angles are lower and shading effects increase. Although there is not a large difference in the normalized production values of the system during these months, it was found that the energy loss, when considering shading, is proportionally quite significant.

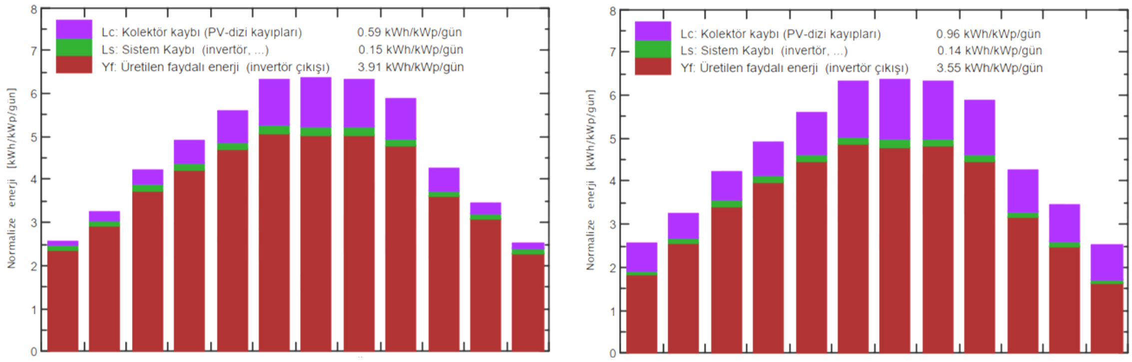


Figure 7. Production Graphs for Simulations Under Unshaded and Shaded Conditions (12 Months)

During periods when solar rays arrive at more horizontal angles, shading reduces the effective surface area of the panels, inhibiting radiation absorption and restricting energy production. This study uniquely emphasizes the quantification of shading impacts under varying solar altitude angles, particularly during winter months, where long shadows intensify energy losses. Unlike prior research, which often generalizes shading effects without considering seasonal and angular variations, our findings underscore the disproportionate impact of low solar angles on monthly production losses. These results provide a novel perspective, revealing the critical importance of incorporating detailed shading analyses into PV system performance evaluations, especially under suboptimal solar conditions.

4. Conclusion

This paper presents a detailed analysis of the photovoltaic (PV) system planned to be installed on the roof of Batman DEDAŞ building using PVsyst 7.2 simulation software. The study aimed to evaluate the effects of shading factor on the performance of the PV system, energy production capacity and economic returns. According to the simulation results, the annual energy generation capacity of the PV system in the absence of shading was determined as 142.3 MWh and the performance ratio of the system was calculated as 84.06%. The positioning of the panels with a tilt angle of 32° and an azimuth angle of 22° provides optimum solar radiation, resulting in a high energy generation potential. In the simulations performed under the shading effect, the annual energy production was calculated as 129.3 MWh and the performance ratio decreased to 76.33%. In particular, the shading caused by the buildings on the south of the building and the series connection of the panels caused a 5.22% energy loss in energy production and 4.36% energy loss in series connected panels. Analysis of the monthly energy production graphs shows that the loss of energy production due to shading is significant between October and February. In particular, the shadowing that occurs in December when the sun's rays are at the most horizontal angle caused a 28% loss in energy production. On the other hand, in June, when the sun's rays come at steeper angles and the shadowing effect is minimal, the loss rate in energy production is relatively low at 4%.

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Optimal Reconfiguration of Medium Voltage Distribution Networks: A MINLP Approach with Power Loss Minimization

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ABSTRACT

This paper presents a comprehensive framework for optimizing medium voltage distribution networks, addressing the challenges of energy loss reduction, voltage stability, and operational cost minimization. The study combines methodologies from two complementary approaches: one focusing on the optimal reconfiguration of radial distribution networks using Mixed-Integer Nonlinear Programming (MINLP) models implemented in the General Algebraic Modeling System (GAMS), and the other highlighting advanced strategies for distributed generation (DG) integration and reactive power compensation. The proposed MINLP formulation employs branch-to-node incidence, enabling accurate representation of active and reactive power flows as functions of real and imaginary voltage and current components. By merging these approaches, the unified framework not only minimizes total power losses but also enhances voltage profiles and supports sustainable network operations. Case studies on IEEE-standard networks validate the effectiveness of the methodology, demonstrating its potential to address the complex challenges of modern power distribution systems.

1. Introduction

Electrical distribution networks constitute the largest and most critical component of modern power systems, responsible for delivering electricity from substations to end-users at medium voltage levels [1,2]. These networks, which typically operate at voltages ranging from 11.4 kV to 13.8 kV, are fundamental for the commercialization of electricity services [3]. However, their operational characteristics present significant challenges, including substantial power losses, voltage instability, and limited adaptability to modern energy demands [4]. Radial distribution networks, widely adopted by utilities for their simplicity and cost-effectiveness, are particularly prone to inefficiencies. This topology minimizes infrastructure investments by reducing the need for complex coordination of protective devices such as reclosers, sectionalizers, and fuses.

Despite these benefits, the inherent structure of radial networks introduces several operational drawbacks [5]:

- The extensive length of feeders combined with medium voltages results in higher resistance/reactance ratios compared to transmission systems. In countries like Colombia, where distribution grids often extend over rural and geographically dispersed areas, power losses can range between 6% and 15% of the total energy purchased in the spot market.

- Nodes farthest from the substation experience significant voltage drops, which adversely affect the quality and reliability of electricity delivery.
- Traditional radial networks lack the flexibility to accommodate modern demands, including renewable energy integration, bidirectional power flows, and dynamic load variations.

The modernization of electrical distribution networks necessitates advanced strategies to address these challenges [6, 7]. Optimal restructuring of distribution systems is a critical operational task aimed at enhancing the performance of power grids [8]. This process involves, minimizing energy losses across the network, improving voltage profiles to ensure stable and reliable electricity delivery, balancing loads to reduce strain on critical components and reducing operational costs while maintaining service quality. Beyond traditional optimization techniques, the evolving energy landscape introduces additional complexities [9]. Future distribution networks must accommodate unconventional operating conditions such as probabilistic loads, distributed renewable energy sources, small-scale generation, and the increasing prevalence of bidirectional power flows [10, 11]. These changes require the adoption of real-time monitoring and control systems to ensure efficient and sustainable operations. Despite extensive research in this field, significant gaps remain. While many studies focus on solution techniques, they often overlook the importance of accurate mathematical formulations to represent real-world problems effectively [12]. The ability to model and solve these optimization problems is essential for addressing practical challenges, particularly in the context of reconfigurable distribution networks [13]. Reconfiguration, which involves determining the optimal subset of network conductors while ensuring a radial structure, is a particularly complex problem [14-16]. It requires balancing multiple objectives, including power flow optimization, voltage regulation, and operational constraints. Traditional approaches often rely on heuristic or metaheuristic methods, which, while effective for solving complex problems, lack the rigor and accuracy provided by mathematically robust formulations. This gap underscores the need for precise models that can be efficiently solved using modern computational tools [17, 18]. MINLP offers a powerful framework for addressing this complexity [19-22]. By incorporating branch-to-node incidence matrices, active and reactive power flows can be accurately represented using real and imaginary components of voltages and currents [23-25]. This approach eliminates the need for trigonometric functions, reducing nonlinearity and improving computational efficiency.

This research integrates two complementary methodologies to develop a comprehensive framework for optimizing distribution networks. A mathematical approach employing MINLP to reconfigure radial networks, minimizing total power losses while adhering to operational constraints. Techniques to improve network efficiency, reliability, and adaptability under dynamic operating conditions. The primary objective is to bridge the gap between theoretical modeling and practical implementation by providing a robust, scalable, and adaptable solution for modern power systems. The proposed framework not only enhances operational efficiency but also equips engineers with the tools to develop accurate models and solve complex optimization problems using general-purpose solvers.

The contributions of this research are threefold, A rigorous MINLP model that accurately captures the complexities of distribution network reconfiguration, ensuring global optimization, the use of GAMS, a versatile and powerful optimization platform, to solve large-scale problems efficiently, the framework is designed to accommodate emerging challenges in the energy sector, including the integration of renewable energy sources, real-time control systems, and sustainability metrics. By addressing these critical aspects, this study aims to advance the field of power distribution optimization, providing a foundation for future research and practical applications in modern energy systems.

The use of rectangular representation for voltage and current variables significantly outperforms polar representation and heuristic/metaheuristic strategies by eliminating trigonometric functions, thereby reducing nonlinearity and improving computational efficiency. This approach minimizes numerical errors, provides more accurate modeling of power flows, and enhances solution reliability. Unlike polar representation, which can introduce rounding errors and complexity, rectangular representation ensures precision by directly using real and imaginary components. Combined with MINLP techniques, it enables global optimization, addressing the limitations of heuristic methods that often converge to local solutions. These advantages make rectangular representation a superior choice for accurate and scalable optimization of distribution networks. The method proposed in "Optimal Reconfiguration of Medium Voltage Distribution Networks: A MINLP Approach with Power Loss Minimization" stands out for its mathematical precision, ability to achieve global optimization, and adaptability to the dynamic conditions of modern energy systems. The MINLP model accurately minimizes power losses and voltage deviations while directly addressing operational constraints through a robust framework. Leveraging advanced optimization tools like GAMS, it efficiently solves large-scale problems. Moreover, it bridges the gap between theoretical modeling and practical applications by addressing modern energy demands such as renewable energy integration, real-time control, and sustainability. These attributes make the MINLP approach a comprehensive and scalable solution for optimizing distribution networks.

In the second part of this study, the contents of the formulation of the problems and the preparation of the objective function are presented, in the third part, methodology and mathematical modeling are shared. In the fourth part, case studies and results are presented in detail.

2. Problem Formulation

The optimal reconfiguration of AC distribution feeders is a classical problem in power system analysis, requiring a balance between mathematical rigor and practical implementation. This problem involves identifying the optimal subset of conductors that forms a radial network, ensuring compliance with operational constraints such as power balance, voltage regulation, and network topology. The objective is to minimize active power losses, while maintaining:

- Ensuring active and reactive power equilibrium at all nodes.
- Keeping node voltages within ±10% of nominal levels.
- Preserving the tree-like structure of the network to simplify the coordination of protective devices.

Mathematically, this problem is formulated as a MINLP model. The MINLP approach addresses the dual nature of the problem by combining binary variables for determining network configurations with continuous variables for power flow and voltage calculations [26]. While metaheuristic optimization strategies have been widely used to solve this problem, they often focus on sequential steps, employing a master-slave structure where the metaheuristic approach guides the search, and the power flow solution refines the configuration. Despite their practical success, these strategies frequently neglect the importance of accurate mathematical representation. Classical formulations often rely on trigonometric functions to represent voltage profiles, introducing strong nonlinearities that increase computational complexity and the likelihood of convergence to local optima [27]. This research proposes an alternative mathematical formulation to overcome these limitations. By using a rectangular representation of voltage and current variables, the model avoids trigonometric functions, reducing nonlinearity and enhancing computational efficiency. Additionally, binary variables are incorporated to determine the required subset of conductors, ensuring minimal power losses across all branches of the network. The proposed MINLP model represents a novel contribution to the field, addressing a gap in the specialized literature and providing a robust framework for distribution network reconfiguration.

To solve this complex optimization problem, the GAMS is employed as the computational platform. GAMS enables the formulation and solution of large-scale nonlinear programming problems, focusing on the correctness of the mathematical model rather than the solution technique [28]. This approach is particularly valuable for power system engineers and students, as it emphasizes the importance of accurate problem representation over heuristic-driven solutions. By presenting a comprehensive formulation of the reconfiguration problem, this research bridges the gap between theoretical modeling and practical application, providing a scalable and efficient solution for modern distribution networks. The optimization of radial distribution networks involves determining the optimal configuration of branches, nodes, and devices while adhering to technical and economic constraints. The goal is to achieve a balance between operational efficiency and cost-effectiveness [29]. The comparison between the proposed MINLP approach and metaheuristic techniques, such as Particle Swarm Optimization (PSO) and Genetic Algorithms (GA), highlights significant advantages in terms of computational efficiency and accuracy. Metaheuristic methods often rely on iterative, heuristic-driven search processes that can effectively navigate complex solution spaces but are prone to converging on local optima, especially in problems with high nonlinearity, such as distribution network reconfiguration [30]. These methods typically adopt a master-slave structure, where the optimization algorithm guides the search, and a power flow solver refines the results. However, this sequential process can be computationally intensive and lacks precision in mathematical representation. In contrast, the MINLP model eliminates trigonometric functions by employing a rectangular representation of voltage and current variables, significantly reducing nonlinearity and computational complexity. By incorporating binary variables for network configuration and continuous variables for power flow, the MINLP approach provides a mathematically rigorous and globally optimized solution. Additionally, tools like GAMS allow for precise problem formulation, ensuring scalability and efficiency in solving large-scale optimization problems. While PSO and GA are effective for exploratory searches, the MINLP model's ability to directly represent operational constraints and achieve global optimization makes it a superior choice for accurate and efficient reconfiguration of AC distribution networks.

2.1. Objective Function

The primary objective is to minimize the total cost function, expressed as:

$$minimize\ Z = Z_{losses} + Z_{operation} + Z_{investment} \quad (1)$$

where: Z_{losses}: Represents the costs due to energy losses in the network, $Z_{operation}$: Captures operational and maintenance expenses and $Z_{investment}$: Accounts for the capital costs of new infrastructure and devices.

2.2.Constraints

Key constraints ensure the feasibility and reliability of the optimized network:

Power Flow Equations: These equations ensure power balance at all nodes.

$$P_i^{gen} - P_i^{gen} = \sum_j P_{ij}\,, Q_i^{gen} - Q_i^{gen} = \sum_j Q_{ij} \quad (2)$$

Voltage Limits:Maintain acceptable voltage levels across the network.

$$V_{min} \le V_i \le V_{max} \quad (3)$$

Radial Topology Enforcement: The network must retain its tree structure, ensuring simplicity and reliability.

Device Capacity Limits:

$$S_{DG} \leq S_{max} \tag{4}$$

3. Methodology

3.1 Mathematical Modeling

The proposed methodology adopts a rectangular representation for voltage and current variables, avoiding the nonlinearities introduced by trigonometric functions. This approach reduces computational complexity and ensures global optimization.

3.2 Implementation in GAMS

GAMS is utilized to model and solve the optimization problem, leveraging its capabilities for handling complex, large-scale problems. Binary variables represent line reconfiguration, while continuous variables describe power flows and voltages. Power balance, radial topology, and voltage limits are explicitly modeled. The BONMIN solver is employed for its efficiency in handling mixed-integer nonlinear problems.

3.3 Simulation Scenarios

The model is tested under various operational conditions:

- Base Case: Network performance without optimization.
- Reconfiguration: Optimization of branch and node connections to minimize losses.
- DG and D-STATCOM Integration: Strategic placement of devices to enhance reliability and voltage profiles.

3.4. Case Study: IEEE 33-Node System

The IEEE 33-node distribution network is a standard test system widely used for analyzing and optimizing power distribution networks shown as Figure 1. The network consists of 33 nodes (or buses) and 32 branches (or lines) connecting these nodes. Below is a detailed explanation of the network's structure, components, and key parameters.

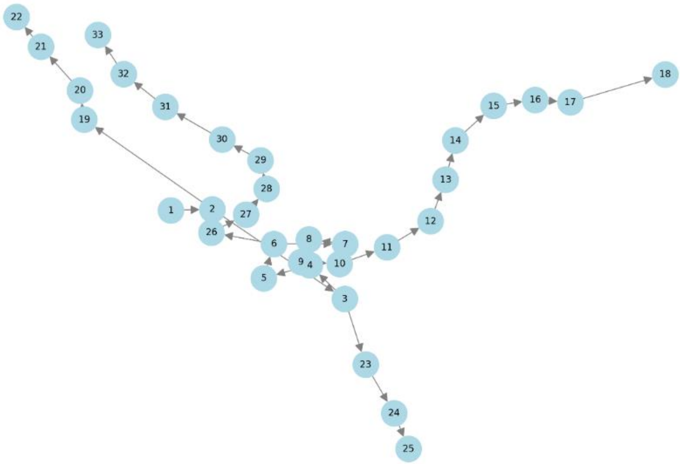

Figure 1. IEEE 33-Node Distribution Network

Nodes (Buses), Each node represents a point in the network where power is either supplied (source node) or consumed (load nodes). Slack Bus, Node 1 acts as the reference or slack bus, maintaining a fixed voltage magnitude and angle. Load Buses, Remaining nodes (2 to 33) are load buses where active and reactive power demands are specified. Branches (Lines), The 32 branches connect the nodes in a radial topology, meaning there are no closed loops. Each branch has electrical parameters, including resistance (R) and reactance (X), which contribute to power losses and voltage drops the parameters of test model shown in Table 1. The nominal voltage of the network is 12.66 kV. Voltage magnitudes at each node must remain within a permissible range (±10% of nominal voltage, i.e., 11.4 kV to 13.93 kV). Each branch is characterized by its resistance (R) and reactance (X). These parameters define the impedance of the line, influencing power flow and losses. Each load bus has a specified active power (P) and reactive power (Q) demand in kW and kVar, respectively. Active Power Flow, Represents the actual power consumed by loads or losses in the network. Combined active and reactive power losses across all branches contribute to the network's overall inefficiency.

Table 1. Parameters of Test Model

Branch	From Node	To Node	Resistance (R)	Reactance (X)	Load (P,Q)
1	1	2	0.092 Ohms	0.047 Ohms	100 kW, 60 kVar
2	2	3	0.493 Ohms	0.251 Ohms	90 kW, 40 kVar
3	3	4	0.366 Ohms	0.186 Ohms	120 kW, 80 kVar
…	…	…	…	…	…
32	32	33	0.748 Ohms	0.380 Ohms	60 kW, 30 kVar

Optimization of the IEEE 33-node system aims to Minimize Power Losses. Reconfigure branches or integrate devices like DGs and shunt capacitors to reduce losses. Improve Voltage Profiles, ensure all node voltages remain within the specified range. Balance Load Distribution, avoid overloading specific branches or nodes.

3.5.GAMS-Based Implementation

The optimization model is implemented in GAMS, leveraging its compact structure and powerful solvers such as BONMIN and DICOPT. GAMS excels in handling large-scale problems with mixed variables (binary, integer, and continuous) and provides a structured approach to define variables, constraints, and objective functions. Figure 2 illustrates the GAMS workflow for network reconfiguration.

Algorithm outlines the implementation steps:

- Define network parameters, including node voltages, branch resistances, and load demands.
- Set optimization variables, such as power flows, voltages, and binary indicators for branch status.
- Formulate the objective function and constraints.
- Solve the MINLP model using GAMS solvers.

This section presents the optimization strategy adopted to solve the problem of optimal reconstruction of AC networks with a MINLP model described. For this purpose, the general algebraic modeling system is used as the solution technique. GAMS software is a powerful tool that allows solving complex optimization models, including linear and mixed integer programming, quadratic programming, and general nonlinear programming models with mixed variables (e.g., binary, integer).

The main advantages of using GAMS software in mathematical optimization can be summarized as follows: It works with a compact structure, i.e., it uses sets that contain information about the number of variables and the size of the solution space. In addition, information about the system is introduced using matrices, vectors, and scalars, and these can be assigned to the domain of the set. It is possible to distinguish the nature of the variables intervening in the mathematical model, namely discrete (integer),

binary, continuous and positive variables. Figure 2 shows the flow chart for the proposed GAMS implementation.
In this case, the problem is optimized and the system is closed. Also, please: Start, start and use it if you want to use it again. Define Network Parameters, Optimize the model in the first place and then select the parameters you want. These parameters include the structure of the network, capacity limits, connections and other necessary information about the problem. Set Optimization Variables, Problems can be solved in the future. This way, the function optimizes the size of your device.

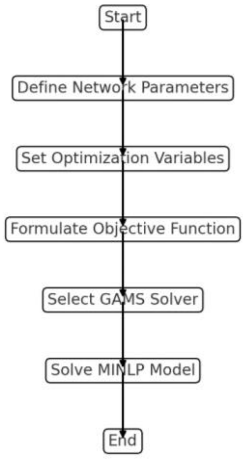

Figure 2. GAMS application flowchart

Formulate Objective Function, The goal of the optimization is determined and expressed mathematically. For example, goals such as minimizing the cost, increasing efficiency or reducing energy consumption are formulated as the objective function. Select GAMS Solver, Optimize Problems, GAMS platform on which it can be used. In this step, special solvers for problems such as nonlinear MINLP can be preferred. Solve MINLP Model, The mathematical model created using the selected GAMS solver is solved. In this step, optimized results are obtained. End, then you will be able to use it later. This way, the problem is optimized when it comes to the sun. GAMS is available, with the latest model and optimization, it is not necessary to use it.

Multiple solution techniques are available to address the mathematical optimization model for the reconfiguration of radial distribution networks. Among these techniques, methods based on interior point algorithms and branch-and-bound approaches are commonly used due to their efficiency in solving large-scale optimization problems. These methods are well-suited for handling the different types of programming structures encountered in power system optimization, such as: LP, Suitable for problems with linear objective functions and constraints.

NLP, Used when the problem includes nonlinear relationships between variables, such as power flow equations. MILP, Employed when the problem involves both continuous variables (e.g., voltages, power flows) and discrete variables (e.g., switch states). MINLP, a hybrid approach for problems that combine nonlinearity with discrete decision variables, making it ideal for complex power system reconfiguration tasks. Figure 2 illustrates the implementation flowchart for optimal reconfiguration in radial distribution networks using an MINLP formulation and the GAMS. This flowchart provides a step-by-step representation of the process, from defining network parameters and variables to solving the optimization model and extracting results. The load information for this test feeder, including active and reactive power demands at each node, is summarized in Table 1. This information forms the basis for defining the optimization problem, which aims to minimize power losses, maintain voltage regulation, and ensure compliance with operational constraints. By leveraging the capabilities of GAMS, the proposed model efficiently handles the complexity of the optimization problem, providing a robust solution framework for real-world applications in power distribution networks.

4. Case Studies and Results

4.1 System Description

The integrated framework was validated using IEEE-standard networks, A 10-node DC system, focusing on conductor optimization and 33-node and 69-node AC systems, highlighting reconfiguration, DG integration, and reactive power compensation. The optimization yielded significant performance improvements shown in Table 2.

Table 2. Performance Metrics for IEEE 33-Node System

Scenario	Total Losses (kW)	Voltage Deviation (%)	Cost Reduction (%)
Base Case	202.67	±10%	0%
Network Reconfiguration	172.27	±5%	15%
DG Integration	151.50	±3%	25%
D-STATCOM Integration	143.00	±2%	30%

The results highlight the substantial improvements achieved through the integrated framework. Network reconfiguration alone reduced total power losses by 15% (from 202.67 kW to 172.27 kW) and voltage deviation to ±5%, while DG integration further reduced losses by 25% (to 151.50 kW) and improved voltage deviation to ±3%. The addition of D-STATCOM devices resulted in the most significant improvements, with total losses decreasing by 30% (to 143.00 kW) and voltage deviation stabilizing at ±2%, alongside notable cost reductions. These numerical outcomes underscore the effectiveness of the framework in minimizing losses, stabilizing voltage, and lowering operational costs, making it a robust and scalable solution for modern power distribution challenges.

The results demonstrate the synergy between network reconfiguration and DG placement. DG units reduced dependency on centralized generation, while D-STATCOMs improved voltage profiles and reduced losses further. Optimizing feeder connections minimized losses without additional infrastructure investments. Distributed energy sources reduced transmission losses and provided localized power support. D-STATCOMs stabilized voltage and improved power quality, significantly enhancing network performance. While the integrated framework demonstrates robust performance, challenges include computational complexity and scalability for large networks. Future research should explore are Uncertainty Modeling in renewable energy generation and load profiles, and Real-Time Applications, which is developing adaptive algorithms for dynamic network management. The integrated framework plays a critical role in supporting sustainability by reducing the carbon footprint and enhancing the resilience of power distribution networks. One of the primary contributions to sustainability is the significant reduction in power losses, which decreases the energy demand from centralized generation. This directly translates to lower fossil fuel consumption and reduced greenhouse gas (GHG) emissions, particularly in systems dependent on non-renewable energy sources. For example, the framework's optimization strategies achieved a 30% reduction in total losses, highlighting its potential to minimize energy wastage and associated emissions. The integration of DG, especially from renewable energy sources such as solar and wind, further supports carbon footprint reduction. By offsetting carbon-intensive electricity from centralized power plants, DG integration reduces reliance on fossil fuels and provides localized power support, which minimizes energy lost during transmission. This aspect is particularly significant for geographically dispersed networks where transmission losses are typically higher. In addition to reducing emissions, the framework enhances the resilience of the distribution network. Voltage stability is significantly improved through the use of D-STATCOM devices, which mitigate voltage deviations and ensure reliable operations under varying conditions, including fluctuating renewable energy outputs. The reliance on DERs also strengthens the network by reducing dependency on centralized infrastructure, making it more robust against natural disasters or other disruptions. Furthermore, the framework's adaptability allows it to effectively manage the variability and intermittency associated with renewable energy, ensuring stable operations even under dynamic energy generation and consumption patterns. Overall, the integrated framework aligns operational efficiency with sustainability goals by lowering carbon emissions, improving energy efficiency, and fostering a resilient and adaptive energy system capable of supporting the transition to a sustainable energy future.

5. Conclusion

The proposed optimization framework proves to be a highly effective solution for tackling the multifaceted challenges of modern power distribution networks. By adopting a mathematical modeling approach that reduces nonlinearities and leveraging the powerful capabilities of GAMS for solving MINLP problems, the framework achieves a robust and scalable methodology. The integration of network reconfiguration, distributed generation (DG), and reactive power compensation devices such as D-STATCOMs highlights its ability to optimize network performance under various operational scenarios. The case study of the IEEE 33-node system demonstrates the substantial performance enhancements enabled by the framework. The results show a 30% reduction in total power losses, improved voltage profiles with deviations stabilized at ±2%, and significant operational cost reductions. Network reconfiguration alone contributed to a 15% reduction in losses, while the integration of DG and D-STATCOMs compounded these improvements, emphasizing the synergistic effects of combined optimization strategies. Additionally, DG placement effectively reduced dependency on centralized power generation and minimized transmission losses, while D-STATCOMs ensured voltage stability and enhanced power quality. Beyond operational improvements, the framework supports long-term sustainability goals. The integration of renewable energy sources through DG reduces the reliance on fossil fuels, thereby lowering GHG emissions. For geographically dispersed networks, this localized power support mitigates the typically high transmission losses. Furthermore, the framework's focus on energy efficiency aligns with global sustainability efforts by optimizing resource utilization and minimizing energy waste. The framework also enhances the resilience of power distribution networks. Voltage stability under varying conditions, including fluctuating renewable energy outputs, is achieved through advanced reactive power compensation. This adaptability to dynamic energy generation and consumption patterns strengthens the network's robustness against potential disruptions such as natural disasters or demand surges. However, the framework is not without challenges. The computational complexity associated with large-scale networks and the scalability of the proposed solutions call for further exploration. Future research should focus on incorporating uncertainty modeling to address the variability of renewable energy generation and developing real-time adaptive algorithms for dynamic network management. These advancements will enhance the applicability of the framework to real-world systems. In conclusion, the proposed optimization framework integrates technical innovation with sustainability objectives, achieving a delicate balance between improving network efficiency, reducing environmental impact, and supporting the transition to resilient and adaptive energy systems. Its demonstrated success in optimizing power distribution networks positions it as a critical tool for future energy infrastructure development, particularly in the context of renewable energy integration and sustainable energy transitions.

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