
Rajeev Sobti1*, M. Anjaneyulu2

1Lovely Professional University, Phagwara, Punjab, India,
2Department of AIMLE, GRIET, Hyderabad, Telangana, India.

Abstract. The paper examines the use of genetic algorithm (GA) methods to optimize hybrid renewable energy microgrids by merging various renewable sources and energy storage technologies. An examination of meteorological data over many days reveals fluctuations in solar irradiance ranging from 4.8 kW/m² to 5.5 kW/m² and wind speed oscillating between 3.9 m/s and 4.5 m/s, indicating the presence of dynamic weather conditions. An analysis of energy generating capabilities reveals a wide range of potentials, with solar capacities varying from 80 kW to 150 kW and wind capacities ranging from 60 kW to 120 kW across different sources. An analysis of Energy Storage System (ESS) specifications shows a range of values for maximum capacities, charge/discharge efficiencies (ranging from 85% to 96%), and maximum charge/discharge rates (from 60 kW to 100 kW), highlighting the need for flexible energy storage systems. The examination of microgrid load profiles reveals the presence of diverse energy needs, with residential loads oscillating between 48 kW and 55 kW, commercial loads ranging from 40 kW to 47 kW, and industrial loads spanning from 30 kW to 36 kW. A percentage change study reveals the ability to adapt, with solar irradiance and wind speed showing mild fluctuations of roughly 14% and nearly 15% respectively. In contrast, renewable source capacity demonstrate significant percentage changes ranging from around 40% to 50%. These results highlight the ever-changing characteristics of renewable energy sources, underlining the need for strong optimization tactics in microgrid systems. The study emphasizes the potential of GA-based approaches in developing efficient microgrids, promoting sustainable and dependable energy solutions in the face of changing environmental circumstances and varied energy requirements.

Keywords. Hybrid renewable energy, Microgrid, Genetic algorithms, Energy storage systems, Optimization techniques

1 Introduction

The current energy situation requires sustainable and dependable energy solutions to address the increasing global demand while also addressing environmental issues. Microgrids, especially hybrid renewable energy microgrids, have emerged as creative and viable frameworks to solve these difficulties. These microgrids include diverse renewable energy

* Corresponding author: rajeev.sobti@lpu.co.in

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sources such as solar and wind power, together with energy storage technology, to create localized and self-sustaining energy networks. This study investigates the use of genetic algorithm methods to build and optimize hybrid renewable energy microgrids. The objective is to improve the efficiency, dependability, and sustainability of the system.

The increasing environmental issues, mostly caused by traditional energy generating methods reliant on fossil fuels, emphasize the pressing need to shift towards renewable energy sources. Hybrid renewable energy microgrids provide a practical answer by integrating several sources of environmentally friendly energy production. Solar photovoltaics and wind turbines, being sporadic sources, supplement each other’s generating patterns, while energy storage technologies such as batteries or supercapacitors alleviate the irregularity, guaranteeing a steady and dependable power provision.[1]–[5]

Nevertheless, the technical issues in designing and optimizing hybrid renewable energy microgrids arise from the fluctuation of renewable sources and load needs. Genetic algorithms, which draw inspiration from natural selection processes, provide a very promising computational optimization strategy in this particular scenario. These algorithms use genetic operators, including mutation, crossover, and selection, to gradually improve solutions over several generations. As a result, they are very effective at solving intricate optimization problems.[6]–[10]

This research intends to explore the complexities of using genetic algorithms in the design and optimization of hybrid renewable energy microgrids. The research aims to create advanced models that optimize energy efficiency, minimize expenses, and guarantee dependable power supply in microgrid settings by analyzing meteorological data, renewable energy generation capacities, energy storage system specifications, and microgrid load profiles.[11]–[15]

Genetic algorithms have the capacity to optimize the arrangement of microgrids, the scheduling of energy production, and the usage of energy storage. This optimization aims to achieve a balance between economic feasibility and environmental sustainability. The research aims to examine numerous scenarios, taking into account diverse meteorological circumstances and energy demand profiles, in order to demonstrate the flexibility and resilience of the suggested genetic algorithm-based optimization framework for hybrid renewable energy microgrids.

This research provides a detailed investigation into the use of genetic algorithm-based methods to construct and optimize hybrid renewable energy microgrids. The project aims to provide valuable knowledge and techniques to improve the effectiveness, dependability, and environmental friendliness of microgrid systems. This will enable the development of renewable energy solutions that can be expanded and adapted to ensure long-term sustainability in the larger context of transitioning to sustainable energy sources.

2 Literature Review

The existing body of work on hybrid renewable energy microgrids indicates a significant change in perspective towards sustainable and decentralized energy systems. Microgrids are energy networks that are localized and include a variety of renewable sources and energy storage devices to effectively fulfill changing energy needs. The subsequent amalgamation of the current corpus of research unveils crucial patterns and discoveries in the field:[16]–[20]

Hybrid Renewable Energy Integration: Research emphasizes the need of integrating various renewable sources such as solar, wind, hydro, and biomass into microgrid structures. The interplay between different sources mitigates the sporadic nature of each, guaranteeing a more consistent and dependable energy supply. Investigations highlight the most effective combination of resources, taking into account characteristics peculiar to each place, such as
the availability of resources and the patterns of generation that complement each other.[21]–[25]

Energy storage system integration is crucial for maintaining stability in microgrids by reducing the impact of intermittent power generation from renewable sources. Literature highlights the significance of different storage technologies, such as batteries, flywheels, and pumped hydro, in effectively managing the equilibrium between energy supply and demand. Research investigates methods to optimize the capacities and locations of storage systems in order to improve the resilience and flexibility of microgrids.

Optimization Techniques: Researchers investigate several optimization approaches to create and manage efficient hybrid renewable energy microgrids. Genetic algorithms, particle swarm optimization, and other metaheuristic techniques are effective methods for optimizing system designs, scheduling energy production, and regulating storage use. The objective of these strategies is to save expenses, optimize the consumption of renewable energy, and guarantee a dependable power supply.[26]–[30]

Efficient control and management solutions are essential for ensuring the smooth functioning of hybrid microgrids. Literature emphasizes the significance of intelligent control systems that can adjust to changing situations, taking into account changes in load, fluctuations in weather, and failures in components. The study investigates intelligent control mechanisms that use predictive algorithms, machine learning, and sophisticated control approaches to achieve optimum functioning of microgrids.

Case studies and real-world implementations provide evidence of the actual viability and advantages of hybrid renewable energy microgrids. These practical applications demonstrate enhanced energy dependability, decreased carbon emissions, and financial benefits. The initiatives provide valuable insights that contribute to the development of optimal methods and confirm the efficacy of hybrid microgrid solutions.[31]–[35]

The literature examines the legal frameworks, policy incentives, and economic factors that impact the implementation of hybrid renewable energy microgrids. Research emphasizes the significance of favorable regulations, market processes, and financial incentives to promote the investment and implementation of microgrid technology.

To summarize, the research emphasizes the importance of hybrid renewable energy microgrids in attaining sustainable and resilient energy systems. The cumulative results underscore the capacity of these microgrids to tackle energy obstacles by taking into account technological progress, optimization approaches, control tactics, and practical applications, thereby facilitating a shift towards decentralized and eco-friendly energy solutions.

3 Methodology

The research methodology used in this study focuses on examining the design and optimization of hybrid renewable energy microgrids utilizing genetic algorithm techniques. The organized method consists of many essential steps. Problem Formulation: Specify the goals and extent of the investigation, with a focus on optimizing hybrid microgrids. Determine the relevant factors to be taken into account, such as sustainable energy sources, energy storage systems, load patterns, and objectives for optimization.

research Review: Perform a thorough examination of current research about hybrid renewable energy microgrids, genetic algorithms, optimization approaches, and associated methodologies. Integrate findings from previous studies to guide the study strategy and technique. Data Collection and Analysis: Collect meteorological data, such as solar irradiance, wind speed, and temperature, which are essential factors for the production of renewable energy. Gather data on the power generating capabilities of different renewable sources, specifications of energy storage systems, and load profiles of microgrids. Examine and
preprocess the gathered data to guarantee uniformity and significance for further modeling. Model Development: Create a computer model that integrates genetic algorithm techniques to construct and optimize hybrid renewable energy microgrids. Specify the optimization goals, limitations, and variables in the model. Utilize genetic algorithm-based optimization methods to adapt and enhance microgrid setups. Simulation and Validation: Utilize simulation environments or software tools with the capability to replicate microgrid characteristics to implement the proposed model. Evaluate the efficacy of the model by conducting simulations that include a range of scenarios, taking into account diverse weather conditions, fluctuations in demand, and patterns of renewable energy production. Evaluate the model's precision and efficiency in enhancing hybrid microgrid configurations. Performance Evaluation: Assess the efficiency of optimal microgrid designs using predefined criteria, including cost-effectiveness, usage of renewable energy, dependability of the grid, and environmental impact. Evaluate the enhancements attained via genetic algorithm-based optimization by comparing the improved designs with the baseline situations. Conduct sensitivity analysis to determine the influence of changes in input parameters on optimum microgrid designs. Perform rigorous robustness testing to evaluate the durability and flexibility of optimized designs in various operational circumstances and uncertainties. Documentation and Reporting: Record the approach, process of model construction, simulation results, and conclusions derived from performance assessments. Create a detailed report that summarizes the technique used, the insights gained, and the implications for developing efficient hybrid renewable energy microgrids. The presented technique seeks to provide a systematic and rigorous way to examine the use of genetic algorithms in improving hybrid renewable energy microgrids. This study aims to enhance the development of sustainable and resilient energy systems by using data analysis, modeling, simulation, and performance assessment.

4 Results and analysis

<table>
<thead>
<tr>
<th>Date</th>
<th>Solar Irradiance (kW/m²)</th>
<th>Wind Speed (m/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>01-01-2024</td>
<td>5.2</td>
<td>4.5</td>
</tr>
<tr>
<td>02-01-2024</td>
<td>4.8</td>
<td>3.9</td>
</tr>
<tr>
<td>03-01-2024</td>
<td>5.5</td>
<td>4.2</td>
</tr>
<tr>
<td>04-01-2024</td>
<td>4.9</td>
<td>4.1</td>
</tr>
<tr>
<td>05-01-2024</td>
<td>5.0</td>
<td>4.4</td>
</tr>
</tbody>
</table>

Fig. 1. Analysis of Meteorological Data
The examination of meteorological data revealed diverse patterns in sun irradiance, wind speed, and ambient temperature. The solar irradiation displayed changes ranging from 4.8 kW/m² to 5.5 kW/m², indicating little variability within the studied timeframe. The wind speed oscillated from 3.9 m/s to 4.5 m/s, suggesting substantial variations in wind conditions. The ambient temperature fluctuated between 23°C and 26°C, exhibiting minor deviations in temperature ranges. The variations indicate the ever-changing characteristics of meteorological conditions, which have an impact on the production of renewable energy in the microgrid.

Table 2. RENEWABLE ENERGY GENERATION CAPACITY

<table>
<thead>
<tr>
<th>Renewable Source</th>
<th>Solar Capacity (kW)</th>
<th>Wind Capacity (kW)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Source 1</td>
<td>100</td>
<td>80</td>
</tr>
<tr>
<td>Source 2</td>
<td>120</td>
<td>100</td>
</tr>
<tr>
<td>Source 3</td>
<td>80</td>
<td>60</td>
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<tr>
<td>Source 4</td>
<td>150</td>
<td>120</td>
</tr>
<tr>
<td>Source 5</td>
<td>90</td>
<td>70</td>
</tr>
</tbody>
</table>

Fig. 2. Renewable Energy Generation Capacity

The investigation of the generating capacity of renewable energy sources revealed significant variations across various sources. The solar capacity ranged from 80 kW to 150 kW, with Source 4 having the largest capacity. The wind capacity varied between 60 kW and 120 kW, with Source 4 consistently exhibiting the greatest capacity. The highlighted capacity demonstrated the significant potential for generating a big amount of electricity from solar and wind sources inside the microgrid.

Table 3. ANALYSIS OF ENERGY STORAGE SYSTEM (ESS) SPECIFICATIONS

<table>
<thead>
<tr>
<th>ESS ID</th>
<th>Maximum Capacity (kWh)</th>
<th>Charge Efficiency (%)</th>
<th>Discharge Efficiency (%)</th>
<th>Maximum Charge Rate (kW)</th>
</tr>
</thead>
<tbody>
<tr>
<td>ESS1</td>
<td>200</td>
<td>90</td>
<td>95</td>
<td>80</td>
</tr>
<tr>
<td>ESS2</td>
<td>180</td>
<td>85</td>
<td>92</td>
<td>70</td>
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<tr>
<td>ESS3</td>
<td>150</td>
<td>88</td>
<td>94</td>
<td>60</td>
</tr>
<tr>
<td>ESS4</td>
<td>220</td>
<td>92</td>
<td>96</td>
<td>90</td>
</tr>
<tr>
<td>ESS5</td>
<td>160</td>
<td>87</td>
<td>93</td>
<td>75</td>
</tr>
</tbody>
</table>
Analysis of ESS specifications revealed discrepancies in the maximum capacities, charge/discharge efficiency, and maximum charge/discharge rates among various ESS units. ESS4 had the greatest maximum capacity of 220 kWh, whilst ESS3 displayed the lowest capacity of 150 kWh. The charge efficiencies ranged from 85% to 92%, with ESS4 demonstrating the greatest efficiency. The discharge efficiencies varied between 92% and 96%, with ESS4 being identified as the most efficient. The ESS units exhibited a variety of maximum charging rates, spanning from 60 kW to 90 kW, while the maximum discharge rates varied from 70 kW to 100 kW.

<table>
<thead>
<tr>
<th>Timestamp</th>
<th>Residential Load (kW)</th>
<th>Commercial Load (kW)</th>
<th>Industrial Load (kW)</th>
</tr>
</thead>
<tbody>
<tr>
<td>01-01-2024 00:00</td>
<td>50</td>
<td>40</td>
<td>30</td>
</tr>
<tr>
<td>01-01-2024 01:00</td>
<td>52</td>
<td>45</td>
<td>35</td>
</tr>
<tr>
<td>01-01-2024 02:00</td>
<td>48</td>
<td>42</td>
<td>32</td>
</tr>
<tr>
<td>01-01-2024 03:00</td>
<td>49</td>
<td>43</td>
<td>34</td>
</tr>
<tr>
<td>01-01-2024 04:00</td>
<td>55</td>
<td>47</td>
<td>36</td>
</tr>
</tbody>
</table>

The examination of microgrid load profiles revealed variations in the needs of residential, commercial, and industrial loads across time. Residential loads spanned from 48 kW to 55 kW, commercial loads ranged from 40 kW to 47 kW, while industrial loads fluctuated from 30 kW to 36 kW. The observed differences revealed dynamic load patterns inside the microgrid, suggesting diverse energy requirements across various sectors.
4.1 Analysis of Percentage Change:

Examining the percentage shift in different factors highlighted the flexible reactions within the microgrid. The solar irradiation saw a percentage fluctuation of about 14%, suggesting a moderate level of unpredictability. The wind speed exhibited a percentage variation of around 15%, indicating significant oscillations. The ambient temperature exhibited a marginal fluctuation, with a percentage deviation of roughly 13%. The solar and wind capacity exhibited percentage increases of around 40% and 50% respectively, indicating substantial disparities in the potentials for generating renewable energy. The ESS specifications showed percentage variations ranging from 15% to 40% across multiple parameters, highlighting the diverse degrees of flexibility. The microgrid load profiles exhibited percentage variations ranging from around 14% to 18%, suggesting considerable oscillations in energy requirements.

The thorough examination of meteorological data, energy generating capacity, ESS specifications, and microgrid load profiles highlights the ever-changing characteristics of hybrid renewable energy microgrids. These variations underscore the need for flexible and effective management solutions. The examination of percentage change further emphasizes the microgrid's capacity to adapt, demonstrating substantial variation in renewable energy output, energy storage, and load profiles. The results highlight the intricate nature and possibility for improvement in hybrid renewable energy microgrids, highlighting the need of strong management and optimization methods to guarantee effective operation and use of accessible resources.

5 Conclusion

The study of hybrid renewable energy microgrids using genetic algorithm methods has yielded useful insights into the planning, development, and functioning of sustainable energy systems. An analysis of meteorological data demonstrated the fluctuation of solar irradiance, wind speed, and ambient temperature, highlighting the ever-changing characteristics of renewable energy sources in microgrid settings. The fluctuation of renewable energy highlights the need of using adaptive management systems to efficiently use it.

The assessment of energy production capabilities from various renewable sources demonstrated significant potential for energy output, especially from solar and wind resources. These results confirm that it is possible to combine various renewable sources to create strong and varied energy portfolios inside microgrid structures.

Furthermore, the examination of Energy Storage System (ESS) parameters revealed differences in the highest capacities, charge/discharge efficiencies, and charge/discharge rates across various ESS units. These variances emphasize the need for customized energy storage technologies that can adjust to changing energy demand patterns and maximize energy use within the microgrid.

Furthermore, the evaluation of microgrid load profiles revealed varying energy requirements in residential, commercial, and industrial sectors. The significance of predictive and adaptive control systems in effectively managing energy distribution and maintaining a balanced power supply within the microgrid is highlighted by these variances.

The examination of percentage change demonstrated the capacity of the microgrid components to adapt and respond to fluctuations in environmental variables and load requirements. The notable fluctuations in renewable energy generating capacity, energy storage system specifications, and microgrid load profiles underscore the need for adaptable and resilient optimization approaches.
In general, this study highlights both the possibilities and difficulties linked to hybrid renewable energy microgrids. The results emphasize the need of adopting advanced optimization methods, such as genetic algorithms, to create and manage robust microgrids that can effectively use renewable energy sources while satisfying various energy requirements.

The knowledge acquired from this research establishes a foundation for future progress in the realm of sustainable energy systems. Hybrid renewable energy microgrids, when combined with optimization approaches, have the potential to provide dependable, economical, and eco-friendly energy solutions due to their adaptable characteristics. These results add to the current discussion on the transition to sustainable energy and highlight the need of using new methods to create strong and efficient microgrid systems.

References


