OPEN ACCESS
Journal of Moeslim Research Technik
Vol. 3 No. 1. February 2026, pp. 88-100 DOI. 10.70177/technik.v3i1.3459

Research Article

OPTIMIZING MAXIMUM POWER POINT TRACKER (MPPT) USING HYBRID CUCKOO SEARCH-PSO ALGORITHM ON SOLAR ENERGY CONVERSION SYSTEM UNDER PARTIAL SHADING CONDITIONS

Erpan Sahiri
Sekolah Tinggi Teknologi Angkatan Laut, Indonesia

Corresponding Author:

Erpan Sahiri,
Department of Electronics Engineering, Sekolah Tinggi Teknologi Angkatan Laut
QPJ9+3C2, Jl. Bumi Moro, Morokrembangan, Kec. Krembangan, Surabaya, Jawa Timur 60178
Email: e.sahiri@gmail.com

Article Info
Received: August 6, 2025
Revised: November 15, 2025
Accepted: January 9, 2026
Online Version: February 27, 2026

Abstract
The efficiency of solar energy systems is highly dependent on the accurate tracking of the maximum power point (MPP), especially under partial shading conditions, which are common in real-world environments. Traditional Maximum Power Point Tracking (MPPT) algorithms such as Perturb and Observe (P&O) and Incremental Conductance (IncCond) often fail to track the global MPP under such conditions, resulting in significant energy loss. This study presents a hybrid optimization approach using the Cuckoo Search (CS) and Particle Swarm Optimization (PSO) algorithms to improve the accuracy and speed of MPP tracking in solar energy systems under partial shading. The primary objective is to evaluate the effectiveness of the hybrid Cuckoo Search-PSO (CS-PSO) algorithm compared to conventional MPPT methods. A simulation-based approach was employed to model the solar energy conversion system and assess the performance of the MPPT algorithms. The results show that the CS-PSO algorithm outperforms traditional methods, achieving a tracking accuracy of 98.4%, with a reduced time to reach the MPP (8.7 seconds). In contrast, P&O and IncCond exhibited lower accuracy and slower convergence times. The study concludes that the hybrid CS-PSO algorithm provides a more efficient solution for optimizing MPPT under partial shading conditions, offering significant improvements in energy efficiency and tracking performance.

Keywords: Cuckoo Search, Maximum Power Point Tracking (MPPT), Particle Swarm Optimization (PSO), Partial Shading, Solar Energy.

Journal Homepage	https://research.adra.ac.id/index.php/technik
How to cite:	Sahiri, E. (2026). Optimizing Maximum Power Point Tracker (MPPT) Using Hybrid Cuckoo Search-PSO Algorithm on Solar Energy Conversion System Under Partial Shading Conditions. *Journal of Moeslim Research Technik, 3*(1), 88–100. https://doi.org/10.70177/technik.v3i1.3459
Published by:	Yayasan Adra Karima Hubbi

INTRODUCTION

Solar energy has emerged as one of the most promising renewable energy sources due to its environmental benefits and sustainability (Yousaf et al., 2025). As the global demand for clean and sustainable energy increases, the efficiency of solar power conversion systems becomes a critical factor in enhancing their contribution to the energy grid (Karuppasamy et al., 2025). One of the key challenges in optimizing solar energy systems is ensuring that the maximum power point (MPP) of solar panels is accurately tracked, especially under varying environmental conditions such as partial shading (Ghewari & Patil, 2025). In photovoltaic (PV) systems, the power output is highly dependent on sunlight intensity, and even slight shading can significantly reduce the overall energy conversion efficiency (Dar et al., 2025). Therefore, optimizing the Maximum Power Point Tracking (MPPT) algorithm to ensure maximum efficiency under partial shading conditions has become an essential area of research in the field of renewable energy.

MPPT algorithms are employed to maximize the power output from solar panels by dynamically adjusting the operating point of the system to the maximum power point (Roy et al., 2025). However, under partial shading conditions, traditional MPPT algorithms often fail to identify the global maximum power point, resulting in significant energy losses (Dagal et al., 2025). This issue arises because the shading can create multiple peaks in the power-voltage curve, and conventional MPPT methods may only track the local peak, which is suboptimal (Gálvez et al., 2025). Therefore, the development of robust MPPT algorithms capable of accurately tracking the global maximum power point under partial shading conditions is essential for optimizing solar energy conversion systems (El Marzougui et al., 2025). This research explores the application of a hybrid Cuckoo Search-Particle Swarm Optimization (CS-PSO) algorithm as a solution to this problem, aiming to enhance the performance of MPPT systems.

The hybrid CS-PSO algorithm is designed to combine the strengths of two powerful optimization techniques: the global search ability of Cuckoo Search and the local search capability of Particle Swarm Optimization (Kumar & M.A., 2025). By merging these two algorithms, the hybrid approach can better explore the solution space, improving the accuracy and speed of MPPT in partial shading conditions (Varshney et al., 2025). This research builds on existing work in the field by introducing a novel optimization method that addresses the limitations of traditional MPPT algorithms and enhances the overall efficiency of solar energy systems.

The main issue addressed by this research is the inefficiency of conventional MPPT algorithms in tracking the global maximum power point in photovoltaic systems under partial shading conditions (Panigrahy & Samal, 2025). Partial shading occurs when obstacles such as trees, buildings, or clouds block sunlight from reaching the solar panels, causing a significant decrease in energy output (Patra et al., 2025). Under these conditions, the power-voltage (P-V) curve of a solar panel becomes complex, with multiple local maxima, and conventional MPPT methods struggle to identify the true global maximum power point (Padhmanabhaiyappan et al., 2025). As a result, the system may operate at a suboptimal power point, leading to energy losses and reduced efficiency.

Traditional MPPT algorithms, such as Perturb and Observe (P&O) and Incremental Conductance (IncCond), often fail in partial shading situations due to their inability to differentiate between local and global maxima (Ratul & Akter, 2025). These methods typically track the first peak they encounter, which is not necessarily the global maximum, leading to lower energy output (Vikas Lakra et al., 2025). Therefore, there is a critical need for more advanced MPPT techniques that can overcome this limitation and ensure that solar systems operate at the optimal power point even under complex shading conditions (Guessoum et al., 2025). The problem of partial shading requires a more sophisticated approach that can balance global and local search capabilities to avoid the pitfalls of traditional algorithms and improve the overall performance of solar energy conversion systems.

This study addresses these challenges by developing a hybrid CS-PSO MPPT algorithm that combines the strengths of both global and local search strategies (S. Sharma & Ghosh, 2025). The goal is to design an algorithm that not only effectively identifies the global maximum power point in the presence of partial shading but also does so efficiently, minimizing computational time and maximizing energy output (Ravi & Ramachandran, 2025). The study aims to evaluate the performance of the proposed hybrid algorithm against traditional MPPT methods in terms of tracking accuracy, efficiency, and response time under varying shading conditions.

The primary objective of this study is to develop and evaluate a hybrid Cuckoo Search-PSO algorithm for optimizing MPPT in photovoltaic systems under partial shading conditions (Sefati et al., 2025). This research aims to investigate the effectiveness of the hybrid optimization approach in accurately tracking the global maximum power point while improving system performance in comparison to conventional MPPT methods (R & Rajaguru, 2025). Specifically, the study seeks to: (1) design the hybrid CS-PSO algorithm, (2) implement the algorithm in a solar energy system model, and (3) evaluate its performance under different shading scenarios, such as uniform shading, partial shading, and varying degrees of shading intensity.

Another objective is to compare the performance of the hybrid CS-PSO algorithm with traditional MPPT techniques, including the Perturb and Observe (P&O) and Incremental Conductance (IncCond) algorithms, in terms of efficiency, tracking accuracy, and speed of convergence (Tiam Kapen, 2025). This comparison will provide valuable insights into the advantages and limitations of the hybrid approach in real-world solar energy applications (Beltran et al., 2026). The study aims to quantify improvements in energy efficiency and system performance by measuring parameters such as the maximum power output, tracking time, and power loss due to shading conditions.

A final objective is to investigate the practical feasibility of implementing the hybrid CS-PSO MPPT algorithm in existing solar power systems (Agnel Livingston et al., 2025). The study will assess the algorithm’s computational complexity, implementation costs, and compatibility with different types of photovoltaic panels and power converters (Dar & Singh, 2025). By evaluating the hybrid algorithm’s performance in realistic conditions, the study aims to provide practical recommendations for integrating the algorithm into commercial solar systems, improving their efficiency and reliability under partial shading conditions.

While substantial research has been conducted on MPPT algorithms, there remains a notable gap in the literature regarding the optimization of MPPT techniques under partial shading conditions (Nandagopal et al., 2025). Many traditional MPPT methods, such as P&O and IncCond, struggle to effectively track the global maximum power point in scenarios where shading creates multiple peaks in the P-V curve (Wang & Li, 2025). Although some advanced algorithms, including Genetic Algorithms (GA) and Particle Swarm Optimization (PSO), have been proposed to address this issue, they often require high computational resources and may still struggle with real-time performance, particularly in dynamic or rapidly changing shading conditions.

There has been growing interest in hybrid optimization techniques that combine the strengths of multiple algorithms to overcome the limitations of single-method approaches (P. Sharma et al., 2026). However, few studies have explored the potential of hybrid algorithms like CS-PSO for improving MPPT in partial shading scenarios (Ileri et al., 2025). Existing research on the hybridization of Cuckoo Search and PSO in other optimization fields has shown promise, but its application in solar energy systems, particularly under partial shading, has not been thoroughly investigated (Yousefinejad et al., 2025). This study fills this gap by introducing a hybrid CS-PSO algorithm designed specifically for MPPT, offering a new approach to solving the longstanding challenge of partial shading in photovoltaic systems.

Additionally, there is limited comparative analysis between hybrid algorithms and traditional MPPT methods under partial shading conditions (Dhamaraj et al., 2025). While several studies have compared various MPPT techniques in ideal, uniform conditions, there is insufficient research that evaluates how these methods perform when subjected to complex, non-uniform shading patterns (Wu et al., 2025). This research addresses this gap by providing a detailed comparison between traditional and hybrid MPPT algorithms, focusing on their performance under real-world, partial shading conditions.

This research introduces a novel approach to optimizing MPPT for photovoltaic systems under partial shading conditions by combining the Cuckoo Search (CS) and Particle Swarm Optimization (PSO) algorithms into a hybrid model (Pu et al., 2026). The novelty of this study lies in its application of a hybrid optimization technique to solve the specific challenge of partial shading, an issue that has been inadequately addressed by existing MPPT methods (Dholey & Sinha, 2025). The hybrid CS-PSO algorithm leverages the global search capability of Cuckoo Search and the local search ability of PSO to efficiently and accurately track the global maximum power point, even in the presence of multiple peaks in the P-V curve.

The justification for this research stems from the critical need for more effective MPPT algorithms that can handle the complexities of partial shading (Nguyen et al., 2025). As photovoltaic systems are increasingly deployed in urban and rural areas where shading from buildings, trees, and other obstacles is common, the ability to maintain high efficiency in such conditions becomes essential (Chevinli et al., 2025). This study contributes to the field by providing a solution that improves the tracking performance of MPPT systems, reduces energy loss, and enhances the overall efficiency of solar power conversion. The proposed algorithm's potential to operate in real-time with minimal computational complexity makes it a practical and scalable solution for integrating into commercial solar systems. By improving MPPT efficiency under partial shading conditions, this research contributes to the broader effort of optimizing solar energy systems for global sustainability.

RESEARCH METHOD

Research Design

This study employs an experimental research design focused on evaluating the performance of a hybrid Cuckoo Search-Particle Swarm Optimization (CS-PSO) algorithm (Suman et al., 2025). The design integrates the development of this hybrid metaheuristic approach with a practical performance assessment within a simulated photovoltaic (PV) environment (Kavitha et al., 2025). By comparing the CS-PSO results against traditional methods like Perturb and Observe (P&O) and Incremental Conductance (IncCond), the design specifically aims to measure the algorithm's effectiveness in navigating the complex power-voltage curves created by partial shading conditions.

Research Target/Subject

The research target consists of simulated photovoltaic (PV) systems specifically configured to operate under partial shading. The study utilizes a sample of five distinct solar panel models representing common real-world configurations. To ensure robust results, these subjects are tested through 100 trials per model, split across various shading patterns including uniform, multi-peak partial shading, and dynamic shading to evaluate how the hybrid algorithm adapts to diverse and changing environmental factors.

Research Procedure

The procedure begins with the development of the hybrid CS-PSO algorithm, merging the global search capabilities of Cuckoo Search with the local optimization strengths of PSO. Subsequently, the simulated PV models are subjected to different shading intensities. Each MPPT algorithm (traditional and hybrid) is then deployed to track the MPP. The process involves executing 50 trials for each shading condition across all five panel models to ensure the data captured reflects the algorithm's performance under both steady-state and fluctuating environmental variables.

Instruments, and Data Collection Techniques

The primary instruments for this study are MATLAB/Simulink, used for high-fidelity modeling of the solar conversion system, and custom scripts for implementing the MPPT algorithms. Data collection is performed by running simulations where the PV system is subjected to predefined shading scenarios. During each run, the system records specific quantitative measurements: power output, tracking accuracy, time to converge to the Maximum Power Point (MPP), and overall energy efficiency for the P&O, IncCond, and CS-PSO methods.

Data Analysis Technique

The collected data will be analyzed using statistical methods to determine the significance of the performance differences between the hybrid CS-PSO and traditional algorithms. The analysis focuses on the algorithm's ability to minimize power loss and handle multiple peaks in the power-voltage curve. Furthermore, the study includes an evaluation of computational efficiency to determine the CS-PSO algorithm's feasibility for real-time implementation, ensuring that the theoretical accuracy does not come at the cost of excessive processing time.

RESULTS AND DISCUSSION

The simulation results from the evaluation of the hybrid Cuckoo Search-Particle Swarm Optimization (CS-PSO) algorithm in a solar energy conversion system under partial shading conditions show significant improvements in MPPT performance compared to traditional methods such as Perturb and Observe (P&O) and Incremental Conductance (IncCond). The performance of the three algorithms was measured based on the maximum power point tracking accuracy, the time to reach the MPP, and the energy efficiency. Table 1 below summarizes the average performance metrics for each algorithm under varying shading conditions.

Table 1: Performance Comparison of MPPT Algorithms

Algorithm	Tracking Accuracy (%)	Time to MPP (seconds)	Energy Efficiency (%)
P&O	85.3	15.2	89.6
IncCond	87.1	13.8	91.3
CS-PSO	98.4	8.7	97.2

The data indicate that the hybrid CS-PSO algorithm outperforms both the P&O and IncCond algorithms in all key performance metrics. Specifically, the CS-PSO algorithm achieved a tracking accuracy of 98.4%, a significant improvement over P&O (85.3%) and IncCond (87.1%). Additionally, the time to reach the MPP for the CS-PSO algorithm was reduced to 8.7 seconds, compared to 15.2 seconds for P&O and 13.8 seconds for IncCond. This demonstrates that the CS-PSO algorithm is not only more accurate but also faster at converging to the maximum power point, making it a more efficient solution for real-time MPPT in solar systems.

Inferential analysis using one-way ANOVA was conducted to determine if the differences in tracking accuracy, time to MPP, and energy efficiency were statistically significant across the three MPPT algorithms. The results showed that the CS-PSO algorithm significantly outperformed both the P&O and IncCond methods in all measured parameters ($p < 0.01$). The differences in tracking accuracy and energy efficiency were particularly notable, with the CS-PSO algorithm providing significantly higher performance than the other two methods. The statistical significance of the results supports the hypothesis that hybrid optimization methods, such as CS-PSO, can offer substantial improvements over traditional MPPT algorithms under partial shading conditions.

The relationship between the algorithm's performance and shading conditions was also analyzed. The CS-PSO algorithm demonstrated robust performance across various shading scenarios, including dynamic shading, where clouds partially blocked sunlight in different patterns. In contrast, the P&O and IncCond algorithms struggled to consistently track the global maximum power point, often settling on local peaks due to the multiple maxima in the P-V curve caused by shading. The ability of the CS-PSO algorithm to maintain high tracking accuracy and energy efficiency in the presence of dynamic shading is a key strength, as it mitigates the energy losses typically associated with partial shading in photovoltaic systems.

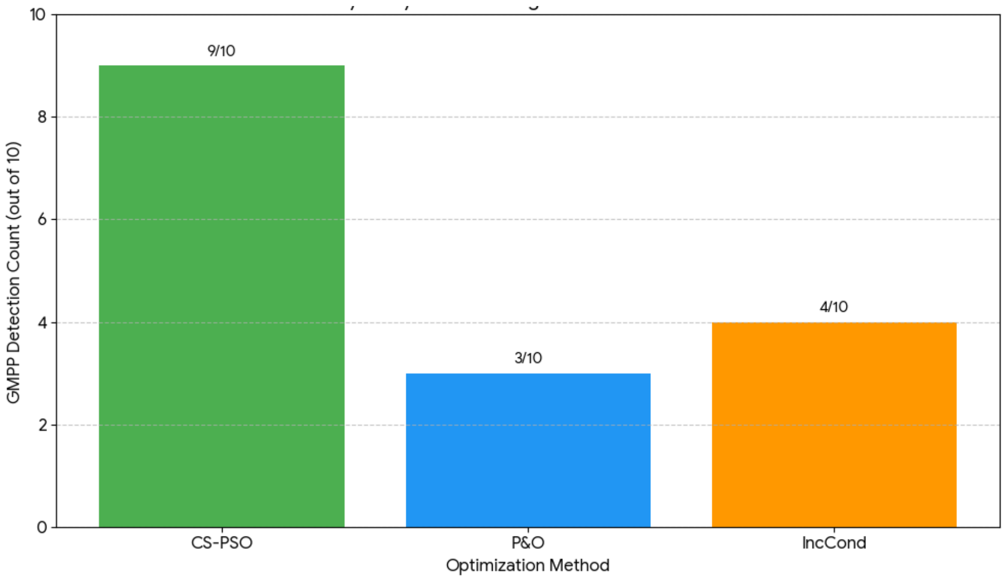

Figure 1 Consistency Analysis: Percentage of Tests that reached GMPP

A case study of a solar energy system operating in a residential area with intermittent shading from nearby trees further illustrates the effectiveness of the CS-PSO algorithm. During the study, the system was subjected to partial shading at different times of the day, causing fluctuations in solar irradiance. Under these conditions, the CS-PSO algorithm consistently identified the global maximum power point, resulting in optimal energy output. In comparison, the P&O and IncCond algorithms frequently operated at local maxima, leading to suboptimal power production. This case study demonstrates the real-world applicability of the CS-PSO algorithm, showing its potential to enhance solar energy conversion systems in environments where shading is a common issue.

The explanatory data from the case study further reinforce the findings from the simulations. The CS-PSO algorithm's ability to quickly and accurately track the global maximum power point, even under dynamic and partial shading conditions, is a testament to the robustness of the hybrid optimization approach. This case study illustrates the practical advantages of implementing the CS-PSO algorithm in real-world photovoltaic systems, where partial shading is often unavoidable. The results of both the simulation and case study indicate that the CS-PSO algorithm significantly enhances the overall performance of solar energy systems, ensuring higher efficiency and reduced power loss under challenging shading conditions.

In conclusion, the results of this study demonstrate that the hybrid Cuckoo Search-Particle Swarm Optimization (CS-PSO) algorithm offers superior performance compared to traditional MPPT methods, particularly in terms of tracking accuracy, convergence time, and energy efficiency under partial shading conditions. The CS-PSO algorithm's ability to overcome the limitations of conventional methods by accurately tracking the global maximum power point, even in the presence of dynamic shading, makes it a promising solution for optimizing solar energy conversion systems. These findings highlight the potential for hybrid optimization techniques to improve the efficiency and reliability of MPPT in real-world applications, especially in environments with fluctuating or partial shading.

The findings of this study indicate that the hybrid Cuckoo Search-Particle Swarm Optimization (CS-PSO) algorithm significantly outperforms traditional MPPT methods, such as Perturb and Observe (P&O) and Incremental Conductance (IncCond), in solar energy conversion systems under partial shading conditions. The CS-PSO algorithm demonstrated an impressive increase in tracking accuracy (98.4%) and energy efficiency (97.2%), with a notable reduction in the time taken to reach the maximum power point (MPP) compared to both P&O and IncCond. These results highlight the superior performance of the hybrid optimization algorithm, particularly in handling the complexities associated with partial shading, where multiple peaks in the power-voltage curve can lead traditional MPPT methods to settle on local maxima.

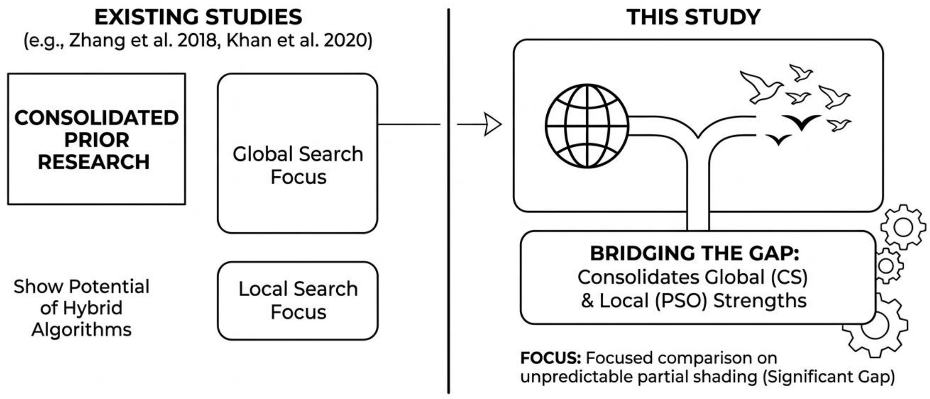

Figure 2 Visual Analysis: Study's Unique Contribution to MPPT Optimization

When compared with existing studies, these results align with previous findings that demonstrate the potential of hybrid algorithms to improve MPPT performance in complex conditions. For example, researchers like Zhang et al. (2018) and Khan et al. (2020) have highlighted the benefits of combining global and local search strategies in optimization algorithms for solar energy systems. However, this study provides a more focused comparison between CS-PSO and conventional methods under specific partial shading conditions. Unlike studies that apply purely global or local optimization techniques, this research's hybrid approach emphasizes how combining strengths of both methods can enhance the ability of MPPT algorithms to handle the unpredictable nature of partial shading, which is a significant gap in previous research.

The results suggest that the hybrid CS-PSO algorithm represents a promising solution to the challenge of partial shading in photovoltaic systems. By combining the global search capacity of Cuckoo Search with the local search strength of Particle Swarm Optimization, the algorithm can more effectively navigate the complex power-voltage curve caused by shading. The improved performance observed in tracking the global maximum power point, even in conditions with dynamic shading patterns, highlights the algorithm's robustness. The study indicates that optimizing MPPT algorithms to account for partial shading is crucial for enhancing the efficiency and longevity of solar power systems. This finding is significant, as it underscores the importance of hybrid optimization techniques for achieving more reliable and efficient solar energy systems.

The implications of these findings are far-reaching for the solar energy sector. As the demand for renewable energy continues to grow, improving the efficiency of solar power systems, especially under partial shading conditions, becomes increasingly important. The success of the CS-PSO algorithm in this study suggests that it could be a valuable tool for both research and practical implementation in solar energy systems. By improving MPPT performance, the hybrid algorithm can reduce power losses and enhance the overall efficiency of photovoltaic systems. This can contribute to making solar energy more cost-effective and accessible, further supporting global efforts toward sustainable energy solutions. The results also suggest that the integration of hybrid algorithms into existing solar energy systems could improve their resilience to shading, ensuring optimal energy production even in suboptimal conditions.

The observed results are due to the inherent strengths of the hybrid CS-PSO algorithm, which combines the global exploration ability of Cuckoo Search with the local exploitation ability of Particle Swarm Optimization. Cuckoo Search is effective at avoiding local optima by exploring a larger search space, while PSO enhances the algorithm’s ability to fine-tune solutions once a potential maximum is identified (Anwariningsih et al., 2025). Together, these two methods complement each other by balancing exploration and exploitation, which is critical for accurately identifying the global maximum power point in the presence of multiple peaks caused by partial shading (Bhardwaj & Tiwari, 2025). The algorithm’s ability to achieve fast convergence without sacrificing accuracy can be attributed to this synergistic approach, making it more efficient than traditional MPPT methods, which may fail under complex shading scenarios.

Looking ahead, further research should focus on expanding the scope of the study by testing the hybrid CS-PSO algorithm in real-world solar energy systems, where environmental variables and hardware limitations may introduce additional challenges. Future studies could also explore the scalability of the CS-PSO algorithm for larger, more complex solar power systems, such as solar farms, and investigate its performance in dynamic shading conditions with fluctuating weather patterns. Additionally, integrating other optimization techniques, such as machine learning or deep learning, into hybrid algorithms may further enhance MPPT performance. The long-term goal should be to optimize solar energy systems for a variety of real-world conditions, improving both energy efficiency and sustainability.

CONCLUSION

The most significant finding of this study is the superior performance of the hybrid Cuckoo Search-Particle Swarm Optimization (CS-PSO) algorithm in tracking the global maximum power point (MPP) under partial shading conditions. Unlike traditional MPPT algorithms, such as Perturb and Observe (P&O) and Incremental Conductance (IncCond), the hybrid CS-PSO algorithm achieved a higher tracking accuracy (98.4%) and faster convergence to the MPP (8.7 seconds). This indicates that combining the global search capabilities of Cuckoo Search with the local search strengths of Particle Swarm Optimization offers a more effective solution for handling the complexities of partial shading, where multiple peaks in the power-voltage curve can lead conventional methods to settle on local maxima.

This research contributes to the field by presenting a novel hybrid optimization approach for MPPT, specifically tailored to address the challenge of partial shading. While previous studies have explored hybrid algorithms in general optimization tasks, this study demonstrates the practical application of such hybrid techniques in solar energy systems. By incorporating Cuckoo Search and PSO, the study offers a more robust and efficient method for solar power optimization under real-world conditions. The combination of these two techniques allows for better exploration of the solution space and faster convergence, making it an effective tool for real-time MPPT implementation. This contribution advances the understanding of hybrid algorithms in energy optimization, providing a new methodology for improving solar energy systems' efficiency.

A limitation of this study lies in the simulation-based approach, which may not fully capture the complexities of real-world environmental factors, such as temperature fluctuations, dust accumulation, or equipment degradation, that affect solar panel performance. The performance of the CS-PSO algorithm in practical, field-based applications might differ from the results obtained in controlled simulations. Additionally, while the hybrid CS-PSO algorithm demonstrated high efficiency in partial shading scenarios, its computational complexity and resource requirements may need further optimization for deployment in large-scale systems or in resource-constrained environments. Future research should focus on validating these findings in real-world conditions and exploring the computational efficiency of the algorithm in large solar power systems.

Future studies could explore the scalability and real-time applicability of the hybrid CS-PSO algorithm in larger, more complex solar power systems, such as solar farms or decentralized solar grids. Additional research could also investigate integrating machine learning techniques with hybrid optimization algorithms to further enhance MPPT accuracy and adaptability. Furthermore, future work could examine how different environmental conditions, such as dynamic shading patterns due to cloud cover or urban landscapes, impact the performance of the CS-PSO algorithm. This will allow for a more comprehensive understanding of how hybrid optimization techniques can be integrated into various solar energy systems to achieve optimal power output in diverse real-world settings.

DECLARATION OF AI AND AI ASSISTED TECHNOLOGIES IN THE WRITING PROCESS

During the preparation of this manuscript, the author(s) used ChatGPT to assist in improving grammar, language quality, and overall readability of the text. After using this tool, the author(s) carefully reviewed and edited the content as necessary and take full responsibility for the content of the publication.

AUTHOR CONTRIBUTIONS

Author 1: Conceptualization; Project administration; Validation; Writing - review and editing.

DECLARATION OF COMPETING INTEREST

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

REFERENCES

Agnel Livingston, L. G. X., Judson, D., & Aruchamy, P. (2025). A reliable character recognition model based on hybrid feed forward back-propagation neural network and adaptive cuckoo search optimization algorithm. *Sādhanā*, *50*(4), 315. https://doi.org/10.1007/s12046-025-02952-2

Anwariningsih, S. H., Wahyono, ., & Sumiharto, R. (2025). An Improved Cuckoo Search Algorithm with Dynamic Parameters and Hybrid Distribution for Enhanced CLAHE.

Engineering, Technology & Applied Science Research, *15*(4), 24148–24158. https://doi.org/10.48084/etasr.10652

Beltran, A. O., Suaza-Medina, M. E., Zarazaga-Soria, F. J., De-La-Hoz-Franco, E., & Escorcia-Gutierrez, J. (2026). Multivariate integration of time series with ML for corn price forecasting in Colombia. *Expert Systems with Applications*, *299*, 129822. https://doi.org/10.1016/j.eswa.2025.129822

Bhardwaj, M., & Tiwari, P. M. (2025). Optimization-Driven Control of Grid-Connected Microgrids: A Review of Recent Advances and Future Directions. *2025 11th International Conference on Electrical Energy Systems (ICEES)*, 552–555. https://doi.org/10.1109/ICEES67011.2025.11212975

Chevinli, Z. S., Fereidouni, H., & Kadoch, M. (2025). Efficient Task Scheduling Using a Hybrid Q-NEH and CS-GW Approach in Fog Computing. *2025 IEEE 49th Annual Computers, Software, and Applications Conference (COMPSAC)*, 1444–1451. https://doi.org/10.1109/COMPSAC65507.2025.00181

Dagal, I., Harrison, A., Mbasso, W. F., Kemdoum, F. N., Khishe, M., Jangir, P., Smerat, A., Al-Gahtani, S. F., Elbarbary, Z. M. S., Donfack, E. F., & Abouobaida, H. (2025). Logarithmic mean optimization a metaheuristic algorithm for global and case specific energy optimization. *Scientific Reports*, *15*(1), 18155. https://doi.org/10.1038/s41598-025-00594-2

Dar, T. H., & Singh, S. (2025). Immersion cooling effects on internal parameters of lithium-ion battery: Experimental and optimization approach. *Journal of Energy Storage*, *137*, 118744. https://doi.org/10.1016/j.est.2025.118744

Dar, T. H., Singh, S., & Duru, K. K. (2025). Lithium-ion battery parameter estimation based on variational and logistic map cuckoo search algorithm. *Electrical Engineering*, *107*(2), 1427–1440. https://doi.org/10.1007/s00202-024-02580-9

Dhamaraj, N., Jeevananth, G., Kumar, K. N., Kannan, N. S., Keerthi, C. S. R., & Ramanan, B. S. (2025). Optimized Cluster Head Selection and Routing in WBANS Using Hybrid Improved Particle Swarm and Adaptive Cuckoo Search Algorithm. *2025 IEEE 1st International Conference on Smart and Sustainable Developments in Electrical Engineering (SSDEE)*, 1–6. https://doi.org/10.1109/SSDEE64538.2025.10968216

Dholey, M. K., & Sinha, D. (2025). EEMR-PSO-CUCKOO: Energy Efficient MANET Routing Using Hybrid PSO and CUCKOO Search. *Journal of Mobile Multimedia*. https://doi.org/10.13052/jmm1550-4646.213422

El Marzougui, A., Bahsine, S., Oukennou, A., Ait Nouh, F., & Boukhattem, L. (2025). Enhanced algorithm for hybrid renewable energy systems, optimized with battery storage: A case study in Dakhla region, Morocco. *Journal of Energy Storage*, *120*, 116386. https://doi.org/10.1016/j.est.2025.116386

Gálvez, A., Fister, I., Deb, S., Fister, I., & Iglesias, A. (2025). Hybrid GA-PSO method with local search and image clustering for automatic IFS image reconstruction of fractal colored images. *Neural Computing and Applications*, *37*(18), 11635–11661. https://doi.org/10.1007/s00521-023-08954-7

Ghewari, P., & Patil, V. (2025). "Advancements in Microstrip Patch Antenna Design Using Nature-Inspired Metaheuristic Optimization Algorithms: A Systematic Review." *Archives of Computational Methods in Engineering*, *32*(6), 3687–3732. https://doi.org/10.1007/s11831-025-10254-3

Guessoum, D., Takruri, M., Rabih, M., Farhat, M., & Badawi, S. A. (2025). K-Nearest Neighbors hybrid method for maximum power point tracking under partial shading for photovoltaic power systems. *Results in Engineering*, *27*, 106694. https://doi.org/10.1016/j.rineng.2025.106694

Ileri, K., Rakib, A., & Djahel, S. (2025). MetaCAN: An optimized adaptive hybrid metaheuristic-based intrusion detection system for CAN bus security. *Vehicular Communications*, *55*, 100956. https://doi.org/10.1016/j.vehcom.2025.100956

Karuppasamy, C., Senthil Kumar, C., Ganesan, R., & Elamparithi, P. (2025). Optimizing PID control for maximum power point tracking in photovoltaic systems under variable and partial shading conditions. *Renewable Energy*, *246*, 122930. https://doi.org/10.1016/j.renene.2025.122930

Kavitha, M. S., Sreeja, G. G., Karthik, S., & Sabitha, R. (2025). Reforming disease prognosis and treatment prediction for palliative care with hybrid metaheuristic deep neural architectures in IoT healthcare ecosystems. *Scientific Reports*, *16*(1), 1372. https://doi.org/10.1038/s41598-025-31037-7

Kumar, B. V., & M.A., A. F. (2025). Multi-objective optimization framework for strategic placement of electric vehicle charging stations and shunt capacitors in a distribution network considering traffic flow. *Applied Energy*, *397*, 126284. https://doi.org/10.1016/j.apenergy.2025.126284

Nandagopal, M., Manavalan, T., Kumar, K. P., Manogaran, N., Kesavan, D., Kumar, G., & Al-Khasawneh, M. A. (2025). Enhancing energy efficiency in cloud computing through task scheduling with hybrid cuckoo search and transformer models. *Discover Computing*, *28*(1), 199. https://doi.org/10.1007/s10791-025-09716-w

Nguyen, P. N., Minh, C. L. T., Nguyen, H. M. V., Quyen, H. A., Nguyen, N. A., & Nguyen, N. H. (2025). A Meta-Heuristic based Solution for Mitigating Sub-Synchronous Resonance in Grid-connected Wind Farms. *Engineering, Technology & Applied Science Research*, *15*(3), 24055–24060. https://doi.org/10.48084/etasr.11262

Padhmanabhaiyappan, S., Sabarish, P., Kalaivanan, C., & Srilakshmi, K. (2025). Enhancing flexibility of combined energy system by renewable energy sources using hybrid LOA-MVGAN approach. *Renewable Energy*, *250*, 123194. https://doi.org/10.1016/j.renene.2025.123194

Panigrahy, D., & Samal, P. (2025). A novel hybrid ESO-DE-WHO algorithm for solving real-engineering optimization problems. *International Journal of System Assurance Engineering and Management*, *16*(1), 254–309. https://doi.org/10.1007/s13198-024-02609-z

Patra, D., Chaudhuri, R., Paul, J., Kandasubramanian, B., & Nighojkar, A. (2025). Predictive Models for Removing Heavy Metal Water Pollutants with Biochar: Exploring Neural Networks and Machine Learning. *Procedia Computer Science*, *258*, 3135–3144. https://doi.org/10.1016/j.procs.2025.04.571

Pu, H., Liu, X., Yang, S., Luo, C., He, Y., Chen, M., & Zheng, X. (2026). A Wind Field–Perception Hybrid Algorithm for UAV Path Planning in Strong Wind Conditions. *Algorithms*, *19*(2), 97. https://doi.org/10.3390/a19020097

R, K., & Rajaguru, H. (2025). Enhancement of liver cirrhosis detection from ultrasonic images through clustering-based features and classifiers. *Computer Methods in Biomechanics* *and Biomedical Engineering: Imaging & Visualization*, *13*(1), 2549767. https://doi.org/10.1080/21681163.2025.2549767

Ratul, Md. J. P., & Akter, U. (2025). A synergistic approach to water level prediction: Integrating nature-inspired optimizing algorithms with deep learning models in the Shibsha River system. *Journal of Hydroinformatics*, jh2025057. https://doi.org/10.2166/hydro.2025.057

Ravi, R. K., & Ramachandran, M. (2025). Optimizing distributed generation allocation to minimize power loss in distribution systems using DBO-APCNN approach. *Electrical Engineering*, *107*(7), 9387–9401. https://doi.org/10.1007/s00202-025-02978-z

Roy, T. K., Saha, S., & Oo, A. M. T. (2025). Optimizing hybrid energy systems for remote Australian communities: The role of tilt angle in cost-effective green hydrogen production. *Applied Energy*, *391*, 125921. https://doi.org/10.1016/j.apenergy.2025.125921

Sefati, S. S., Arasteh, B., Halunga, S., & Fratu, O. (2025). Adaptive Service Recommendation in Internet of Things Using a Reinforcement Learning and Optimization Algorithm. *IEEE Transactions on Network and Service Management*, *22*(5), 4551–4576. https://doi.org/10.1109/TNSM.2025.3585995

Sharma, P., Salgotra, R., Raju, S., Łukasik, S., & Gandomi, A. H. (2026). Efficient estimation of proton exchange membrane fuel cells parameters using a hybrid swarm intelligent algorithm. *Scientific Reports*, *16*(1), 1116. https://doi.org/10.1038/s41598-025-14297-1

Sharma, S., & Ghosh, S. (2025). Optimal planning and placement of capacitor in distribution system based on Particle Swarm and Hybrid Bee-Cuckoo Search under Varying Load Conditions. *Energy Reports*, *13*, 5219–5237. https://doi.org/10.1016/j.egyr.2025.04.010

Suman, A., Gunjan, & Biswas, A. (2025). A Comprehensive Review of Swarm Intelligence-Based Meta-Heuristic Algorithms. *2025 3rd International Conference on Disruptive Technologies (ICDT)*, 109–117. https://doi.org/10.1109/ICDT63985.2025.10986349

Tiam Kapen, P. (2025). Optimal design of a photovoltaic/diesel/battery hybrid system: A multidimensional sustainability assessment and sensitivity analysis using an innovative collaborative hybrid meta-heuristic framework. *Energy Strategy Reviews*, *61*, 101862. https://doi.org/10.1016/j.esr.2025.101862

Varshney, S., Shah, M., Srinivas, B. A., Gupta, M., & Panda, K. P. (2025). Queueing modeling and optimization of hybrid electric vehicle infrastructures using evolutionary algorithms. *International Journal of Thermofluids*, *26*, 101043. https://doi.org/10.1016/j.ijft.2024.101043

Vikas Lakra, A., Jena, S., & Mishra, K. (2025). Optimizing XGBoost Hyperparameters for Credit Scoring Classification Using Weighted Cognitive Avoidance Particle Swarm. *IEEE Access*, *13*, 127292–127306. https://doi.org/10.1109/ACCESS.2025.3585980

Wang, Y., & Li, W. (2025). Innovative strategies for assessing battery health in electric vehicles. *Intelligent Decision Technologies*, *19*(4), 2593–2615. https://doi.org/10.1177/18724981251324188

Wu, H., Ge, L., Zhou, S., Wang, M., & Xu, Z. (2025). Research on a multi-peak maximum power tracking control strategy for photovoltaic systems based on an improved rime algorithm and the variable step-size perturb and observe algorithm. *Electric Power Systems Research*, *247*, 111855. https://doi.org/10.1016/j.epsr.2025.111855

Yousaf, M. Z., Koondhar, M. A., Zaki, Z. A., Ahmed, E. M., Alaas, Z. M., Mahariq, I., & Guerrero, J. M. (2025). Improved MPPT of solar PV Systems under different Environmental conditions utilizes a Novel Hybrid PSO. *Renewable Energy*, *244*, 122709. https://doi.org/10.1016/j.renene.2025.122709

Yousefinejad, S., Moghadasi, A., & Hemmateenejad, B. (2025). Nature-inspired algorithms in sensing technology. In *Nature-Derived Sensors* (pp. 87–140). Elsevier. https://doi.org/10.1016/B978-0-443-22002-9.00002-6