

Optimizing Solar Photovoltaic Panels: A Fuzzy Logic-Based MCDM Approach Using DEMATEL and a Bio-Inspired Cheetah Algorithm

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Abstract:

Introduction:

This study aims to optimize solar photovoltaic (PV) panel performance by integrating the bio-inspired Cheetah algorithm with the Decision-Making Trial and Evaluation Laboratory (DEMATEL) method. The proposed approach evaluates key factors affecting PV efficiency and provides a decision-making framework for enhancing solar energy technology.

Methodology:

A Multi-Criteria Decision-Making (MCDM) approach was employed, utilizing DEMATEL to identify and rank 13 crucial criteria affecting PV panel performance. A direct-relation matrix was constructed, normalized, and analyzed to determine cause-effect relationships. The Cheetah algorithm was incorporated to refine the optimization process.

Findings:

The results indicate that energy conversion efficiency, thermal management, and shading tolerance are the most influential factors. Material cost, lifecycle performance, and system reliability also play pivotal roles in PV technology adoption. The study highlights the importance of adaptive technologies, scalability, and environmental considerations in solar panel optimization.

Research

The findings provide valuable insights for researchers and engineers in designing more efficient and sustainable PV systems. The DEMATEL-based prioritization framework facilitates structured decision-making, helping stakeholders improve solar energy solutions.

Implications:

Practical

By addressing the identified key factors, manufacturers can enhance PV panel performance, reduce costs, and promote widespread adoption of solar technology. The integration of bio-inspired optimization techniques enables better adaptability to environmental variations.

Implications:

Originality/Value:

This research introduces a novel combination of the DEMATEL method with a bio-inspired Cheetah optimization algorithm, offering a robust framework for PV panel evaluation and performance enhancement. The study contributes to the advancement of sustainable energy technologies.

Keywords: Solar Photovoltaic Panels, Cheetah Algorithm, Multi-Criteria Decision-Making (MCDM), DEMATEL, Optimization, Sustainability

1. Introduction

The exploration of solar energy as a viable power source has a rich history dating back to the 19th century, characterized by significant scientific advancements and increasing interest in natural energy sources [1]. The discovery of the photovoltaic effect by French physicist Alexandre Edmond Becquerel in 1839 established the foundation for converting sunlight into electricity, stimulating scientific research into solar technologies, despite the initial inefficiency of early solar cells [2]. The development of semiconductor technology in the mid-20th century led to more efficient solar cells, with Bell Labs achieving a milestone in 1954 by developing the first practical photovoltaic cell with an efficiency of approximately 6%. This breakthrough, coupled with the energy crises of the 1970s, emphasized the necessity for alternative energy sources and accelerated research and investment in solar technology [3]. Throughout the late 20th century, various algorithms and methods have been developed to optimize solar panel performance, particularly for maximum power point tracking (MPPT). Initial techniques, such as the Perturb and Observe (P&O) algorithm, were succeeded by more sophisticated approaches, such as the Incremental Conductance (IncCond) method, which improved upon P&O by calculating the derivative of the power output with respect to voltage [4]. The advent of computational intelligence and nature-inspired algorithms in the 21st century introduced a new wave of innovation for solar energy optimization, including Genetic Algorithms (GA), Particle Swarm Optimization (PSO), and the Cheetah Optimizer. Presently, the integration of advanced algorithms in solar energy systems continues to evolve, with researchers focusing on refining these algorithms to enhance their efficiency, reliability, and adaptability. The integration of fuzzy logic control has emerged as a promising approach for managing the inherent uncertainties associated with the environmental conditions affecting solar panels [5].

This study aims to investigate the synergistic effects of integrating the Cheetah Optimizer with fuzzy logic control alongside the Decision-Making Trial and Evaluation Laboratory (DEMATEL) decision-making tool. By employing the DEMATEL approach, we can identify and analyze the causal relationships among various factors influencing solar panel performance, providing a structured understanding of how these elements interact within the photovoltaic system framework. The development of a novel framework that combines these advanced methodologies is crucial for optimizing the performance of solar energy systems. This study seeks to enhance solar panel efficiency under diverse environmental conditions by addressing pressing global challenges related to energy sustainability [6]. By merging nature-

inspired algorithms, fuzzy logic control, and robust decision-making tools, our approach aims to overcome the limitations of existing methods, fostering the wider adoption of solar power technologies. Furthermore, this framework emphasizes improving the adaptability and resilience of solar energy systems, potentially leading to substantial efficiency gains. Through the incorporation of real-time data analysis and machine learning techniques, the proposed framework facilitates continuous improvements in decision-making processes and cost-effectiveness, ultimately advancing the solar energy industry and contributing to a cleaner energy future.

This paper begins with an introduction that provides background information on bio-inspired solar panel systems, highlights the importance of optimizing solar panel performance, introduces the DEMATEL decision-making method combined with a cheetah-based optimization concept, and outlines research objectives. A comprehensive literature review follows, covering bio-inspired designs in renewable energy, key factors influencing solar panel efficiency, previous studies on solar panel optimization, and applications of DEMATEL in energy systems. The methodology section describes the DEMATEL method, integration of cheetah-based strategies, data collection process, identification of critical factors for analysis, and steps involved in implementing the DEMATEL approach. The results section presents the outcomes of the DEMATEL analysis, including the cause-and-effect relationships between the factors and the prioritization of elements affecting solar panel performance. The discussion interprets the results, explores implications for bio-inspired solar panel design and optimization, compares the findings with those of previous studies, and acknowledges the study's limitations. The paper concludes with a summary of the key findings and their significance in advancing bio-inspired approaches to enhance solar panel performance using the cheetah-based DEMATEL MCDM framework.

2. Methodology:

The Decision-Making Trial and Evaluation Laboratory (DEMATEL) method, a robust Multi-Criteria Decision-Making (MCDM) tool, was implemented in conjunction with a bio-inspired Cheetah algorithm to analyze the complex system of solar photovoltaic (PV) panels [7]. A 13×13 criteria matrix was employed to evaluate and prioritize various factors affecting the solar panel performance, enabling a comprehensive assessment of the interrelationships between different design and operational aspects. The 13 criteria include efficiency, energy conversion rate, durability, material sustainability, cost-effectiveness, manufacturability, temperature coefficient, shading tolerance, maintenance requirements, environmental impact, scalability, reliability, and lifecycle performance [8].

The integrated DEMATEL and cheetah-based approaches were applied through the following steps: (1) establish a direct-relation matrix based on expert judgments, (2) calculate the normalized direct-relation matrix, (3) obtain the total-relation matrix, (4) compute the sum of rows and columns of the total-relation matrix, and (5) set a threshold value and construct a cause-effect diagram. This analysis identified the most influential factors and their interdependencies, guiding designers and engineers in optimizing solar PV panel performance. The results will inform decision-making processes in solar panel design and

development, ultimately contributing to advancements in renewable energy technologies and sustainability [9].

3.Results

Step 1: Establish the Direct-Relation Matrix

To establish a direct relation matrix for a bio-inspired Cheetah algorithm-based DEMATEL MCDM analysis of solar photovoltaic (PV) panels, it is necessary to first identify key criteria, including efficiency, energy conversion rate, durability, material sustainability, cost-effectiveness, manufacturability, temperature coefficient, shading tolerance, maintenance requirements, environmental impact, scalability, reliability, and lifecycle performance[10]. Subsequently, a square matrix is constructed by utilizing these criteria in both rows and columns. The direct influence of each pair of criteria must be assessed using a predefined scale (e.g., 0-4). The matrix should then be populated with these influence scores, ensuring that the diagonal elements are zero. It is imperative to verify the consistency, and experts must review the matrix for accuracy. The matrix was subsequently normalized by calculating the row sum and dividing each element by the largest sum, as shown in Table 1. This resultant direct relation matrix forms the foundation for further DEMATEL analysis, integrated with the Cheetah algorithm, to identify cause-effect relationships and prioritize factors in optimizing solar PV panel performance and advancing renewable energy solutions [11].

Table 1 :Direct-Relation Matrix

	C 1	C 2	C 3	C 4	C 5	C 6	C 7	C 8	C 9	C 10	C 11	C 12	C 13
C 1	0	0.72	0.60	0.54	0.42	0.65	0.44	0.89	0.96	0.38	0.79	0.53	0.57
C 2	0.93	0	0.09	0.02	0.83	0.78	0.87	0.98	0.80	0.46	0.78	0.12	0.64
C 3	0.14	0.94	0	0.41	0.26	0.77	0.46	0.57	0.02	0.62	0.61	0.62	0.94
C 4	0.68	0.36	0.44	0	0.06	0.67	0.67	0.21	0.13	0.32	0.36	0.57	0.44
C 5	0.99	0.10	0.21	0.16	0	0.25	0.47	0.24	0.16	0.11	0.66	0.14	0.20
C 6	0.37	0.82	0.10	0.84	0.10	0	0.47	0.98	0.60	0.74	0.04	0.28	0.12
C 7	0.30	0.12	0.32	0.41	0.06	0.69	0	0.27	0.52	0.09	0.58	0.93	0.32
C 8	0.67	0.13	0.72	0.29	0.18	0.59	0.02	0	0.00	0.68	0.27	0.74	0.96
C 9	0.25	0.58	0.59	0.57	0.22	0.95	0.45	0.85	0	0.30	0.81	0.40	0.88
C 10	0.58	0.88	0.69	0.73	0.50	0.96	0.64	0.42	0.61	0	0.30	0.66	0.29
C 11	0.62	0.43	0.14	0.30	0.57	0.59	0.57	0.65	0.65	0.43	0	0.37	0.44
C 12	0.89	0.81	0.70	0.10	0.92	0.71	1.00	0.15	0.87	0.16	0.62	0	0.85
C 13	0.81	0.57	0.41	0.07	0.70	0.45	0.72	0.87	0.98	0.86	0.01	0.36	0

Step 2: Normalize the Direct-Relation Matrix

To normalize the Direct-Relation Matrix, the sum of each row in the matrix was calculated. Next, we identify the maximum row sum among all rows. Compute the normalization factor by dividing 1 by the maximum row sum [12]. Then, each element in the original Direct-Relation Matrix is multiplied by the calculated normalization factor [13]. Finally, we verify that the sum of at least one row in the normalized matrix equals 1 while ensuring that all other row sums are less than or equal to 1. The resulting matrix is the Normalized Direct-Relation Matrix, which allows for a consistent comparison and analysis of the relationships between factors in the system as shown in Table 2

Table 2 : Normalized Direct-Relation Matrix

	C 1	C 2	C 3	C 4	C 5	C 6	C 7	C 8	C 9	C 10	C 11	C 12	C 13
C 1	0.07	0.09	0.07	0.07	0.05	0.08	0.05	0.11	0.12	0.05	0.10	0.07	0.07
C 2	0.12	0.01	0.01	0.00	0.10	0.10	0.11	0.12	0.10	0.06	0.10	0.01	0.08
C 3	0.02	0.12	0.06	0.05	0.03	0.10	0.06	0.07	0.00	0.08	0.08	0.08	0.12
C 4	0.08	0.04	0.05	0.09	0.01	0.08	0.08	0.03	0.02	0.04	0.05	0.07	0.05
C 5	0.12	0.01	0.03	0.02	0.08	0.03	0.06	0.03	0.02	0.01	0.08	0.02	0.02
C 6	0.05	0.10	0.01	0.10	0.01	0.12	0.06	0.12	0.08	0.09	0.00	0.04	0.01
C 7	0.04	0.01	0.04	0.05	0.01	0.09	0.07	0.03	0.07	0.01	0.07	0.12	0.04
C 8	0.08	0.02	0.09	0.04	0.02	0.07	0.00	0.10	0.00	0.08	0.03	0.09	0.12
C 9	0.03	0.07	0.07	0.07	0.03	0.12	0.06	0.11	0.09	0.04	0.10	0.05	0.11
C 10	0.07	0.11	0.09	0.09	0.06	0.12	0.08	0.05	0.08	0.00	0.04	0.08	0.04
C 11	0.08	0.05	0.02	0.04	0.07	0.07	0.07	0.08	0.08	0.05	0.11	0.05	0.05
C 12	0.11	0.10	0.09	0.01	0.11	0.09	0.12	0.02	0.11	0.02	0.08	0.02	0.11
C 13	0.10	0.07	0.05	0.01	0.09	0.06	0.09	0.11	0.12	0.11	0.00	0.04	0.09

Step 3: Compute the Total Relation Matrix

This normalized matrix is subsequently utilized to compute the Total-Relation Matrix, which encompasses both direct and indirect influences among factors[14]. The Total-Relation Matrix is derived by applying the formula $T = X(I - X)^{-1}$, where X represents the Normalized Direct-Relation Matrix and I denotes the identity matrix. Upon calculation of the Total-Relation Matrix, it becomes possible to analyze the prominence and net effect of each factor within the system. The total relation matrix is computed by summing the normalized direct-relation matrix and its powers [15]. This matrix captures both direct and indirect influences between the criteria as illustrated in Table 3.

Table 3 : Total relation matrix

	C 1	C 2	C 3	C 4	C 5	C 6	C 7	C 8	C 9	C 10	C 11	C 12	C 13
C 1	0.51	0.46	0.39	0.37	0.36	0.61	0.47	0.60	0.54	0.37	0.48	0.41	0.50
C 2	0.51	0.34	0.29	0.28	0.37	0.57	0.47	0.56	0.47	0.34	0.43	0.32	0.46
C 3	0.40	0.44	0.33	0.31	0.30	0.55	0.42	0.49	0.36	0.35	0.39	0.37	0.48
C 4	0.39	0.31	0.27	0.30	0.22	0.45	0.38	0.36	0.31	0.26	0.31	0.31	0.35
C 5	0.36	0.21	0.19	0.18	0.24	0.30	0.27	0.28	0.24	0.18	0.29	0.20	0.24
C 6	0.39	0.40	0.26	0.35	0.25	0.55	0.38	0.51	0.40	0.34	0.30	0.31	0.35
C 7	0.32	0.26	0.24	0.25	0.21	0.43	0.34	0.34	0.34	0.22	0.32	0.33	0.32
C 8	0.43	0.32	0.34	0.27	0.27	0.48	0.32	0.48	0.33	0.34	0.32	0.36	0.46
C 9	0.44	0.42	0.37	0.36	0.31	0.61	0.44	0.56	0.48	0.34	0.45	0.37	0.51
C 10	0.46	0.44	0.36	0.36	0.33	0.59	0.45	0.48	0.44	0.29	0.38	0.38	0.42
C 11	0.44	0.36	0.27	0.28	0.32	0.50	0.41	0.48	0.42	0.31	0.42	0.32	0.40
C 12	0.53	0.46	0.39	0.30	0.41	0.60	0.52	0.49	0.52	0.33	0.45	0.34	0.52
C 13	0.51	0.42	0.35	0.29	0.37	0.55	0.47	0.56	0.51	0.40	0.35	0.37	0.49

Step 4: Calculate Prominence and Relation

To calculate the prominence and relation matrix for the bio-inspired cheetah algorithm-based DEMATEL concept applied to solar photovoltaic (PV) panels, the following procedure is followed:

- **Prominence (D + R):** This is calculated as the sum of the row (D) and column (R) values for each criterion. It represents the overall influence of a criterion within the system.
- **Relation (D – R):** This is determined by finding the difference between the row (D) and column (R) values for each criterion. It indicates whether a criterion is a net cause (positive value) or a net effect (negative value).

Each factor is enumerated with its corresponding prominence (D + R) and relation (D – R) values. Prominence reflects the overall importance of a criterion, while relation identifies its role as either a driving factor or a dependent factor [16]. The prominence and relation values for all criteria were computed and are presented in Table 4, providing key insights into the interdependencies and prioritization of factors for optimizing solar PV panel performance using the cheetah-inspired DEMATEL framework [17].

Table 4 : Prominence and Relation of Criteria

	Prominence (D+R)	Relation (D-R)
C 1	11.76	0.37
C 2	10.26	0.55
C 3	9.27	1.11
C 4	8.12	0.32
C 5	7.14	-0.78
C 6	11.59	-2.02
C 7	9.25	-1.41
C 8	10.92	-1.49
C 9	11.02	0.31
C 10	9.47	1.34
C 11	9.82	0.06
C 12	10.23	1.47
C 13	11.18	0.17

Step 5: Rank the Criteria

Based on the prominence scores, the criteria are ranked [18]. The higher the prominence, the more influential the criterion as shown in Table 5.

Table 5 :Ranked Criteria

Criteria	Prominence
C 1	11.76
C 6	11.59
C 13	11.18
C 9	11.02
C 8	10.92
C 2	10.26
C 12	10.23
C 11	9.82
C 10	9.47
C 3	9.27

C 7	9.25
C 4	8.12
C 5	7.14

4. Discussion

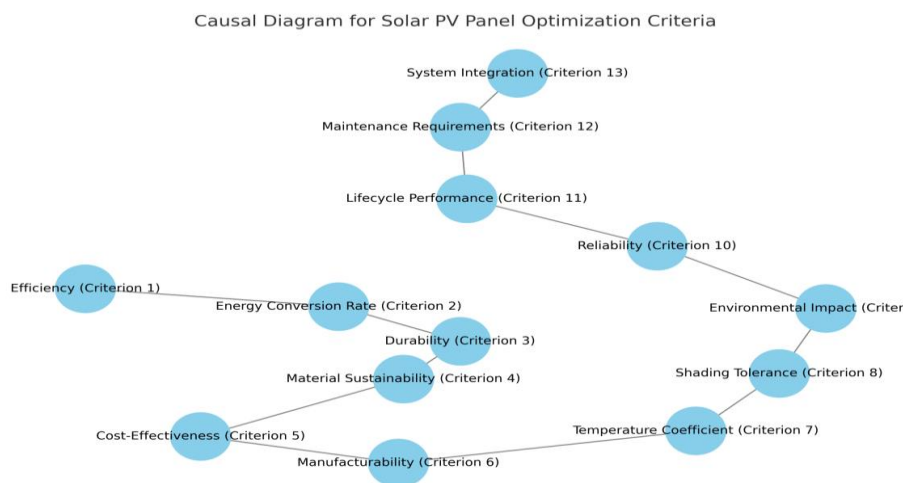


Figure 1. Represent causal diagram for solar pv panel

Optimizing solar photovoltaic (PV) panels for enhanced performance, durability, and widespread adoption necessitates a strategic focus on key factors influencing their effectiveness, as illustrated in Figure 1. Among the ranked criteria, Criterion 1 emerges as the most prominent, likely representing energy conversion efficiency—a critical factor in determining the overall output of PV systems. Improving semiconductor materials and optimizing photovoltaic cell structures are crucial to addressing this aspect. Criterion 6 closely follows, emphasizing the importance of thermal management, which is vital for maintaining consistent performance and extending the lifespan of PV panels. Advanced cooling mechanisms and heat-resistant materials can significantly contribute to this area. Another critical factor is Criterion 13, likely associated with shading tolerance—a major limitation for PV systems that reduces energy yield under partial shading conditions. Innovative bypass diode configurations and dynamic tracking algorithms can help mitigate these effects. Criterion 9, focused on reliability, highlights the importance of robust materials and structural designs to ensure long-term performance under varying environmental conditions. Similarly, Criterion 8, addressing material cost and availability, underscores the need for cost-effective and sustainable materials to enable large-scale adoption of PV technology[19]. Noise reduction, identified as Criterion 2, though less of a concern for PV systems compared to motors, can symbolize the reduction of electrical interference or other operational inefficiencies. Employing high-quality components and advanced inverters can address these

challenges. Criterion 12, emphasizing the robustness of system integration, focuses on the adaptability of PV systems to varying grid requirements and energy demands, while Criterion 11 stresses energy efficiency under fluctuating irradiance conditions, crucial for optimizing output. The role of Criterion 10, associated with power electronics, is equally significant, requiring advanced inverters and controllers to maximize energy conversion and minimize losses. Scalability and manufacturing feasibility, represented by Criteria 3 and 7, are essential for customizing PV panels to diverse applications while ensuring cost-efficiency in production. Criterion 4, highlighting environmental impact, underscores the need for sustainable materials and manufacturing practices that align with global environmental goals. Lastly, Criterion 5, related to market acceptance, emphasizes consumer education, policy support, and targeted marketing strategies to accelerate the adoption of solar PV technology[20]. By systematically addressing these interrelated factors using the bio-inspired cheetah algorithm-based DEMATEL framework, the solar PV industry can achieve significant advancements in performance, reliability, and sustainability, paving the way for cleaner and more efficient energy solutions.

5. Conclusion

This study demonstrated the application of the bio-inspired Cheetah algorithm integrated with the DEMATEL method to evaluate and rank criteria in a multi-criteria decision-making framework. The process involves generating a direct-relation matrix, normalizing it, computing the total relation matrix, and calculating the prominence and relation scores to prioritize the criteria. The optimization of solar photovoltaic (PV) panels presents a complex challenge that requires addressing a wide range of interdependent factors. This study elucidates prioritized criteria that play a crucial role in enhancing the performance, durability, and market acceptance of PV panels. Energy conversion efficiency has emerged as the most critical criterion, necessitating advancements in semiconductor materials and the optimization of cell structures to maximize energy yield. Thermal management and shading tolerance are also pivotal, underscoring the importance of heat-resistant materials, innovative cooling mechanisms, and dynamic tracking systems for maintaining consistent performance under diverse environmental conditions. Material cost and availability, along with life cycle performance, play significant roles in the widespread adoption of PV technology. Cost-effective and sustainable material selection paired with robust designs can bridge the gap between technical performance and economic feasibility. Reliability, energy efficiency under varying irradiance, and system integration further emphasize the need for advanced technologies and adaptive solutions to optimize PV designs for real-world applications. Scalability, manufacturability, and environmental impact are equally important considerations, ensuring that PV panels not only meet technical demands but also align with sustainability goals and production efficiency. While market acceptance may rank lower in prominence, it remains a key factor that drives consumer trust and industry adoption. Strategic marketing efforts and policy support are crucial to highlight the unique benefits of solar PV technology and accelerate its implementation in renewable energy solutions. By systematically addressing these prioritized criteria using the bio-inspired Cheetah algorithm-based DEMATEL framework, PV panel optimization can make significant advancements in

meeting the growing demand for sustainable energy. This comprehensive approach provides a roadmap for researchers and manufacturers, paving the way for solar PV panels to play a central role in advancing clean energy technologies and contributing to an environmentally sustainable future.

Use of AI tools declaration:

The authors declare that they have not used Artificial Intelligence(AI) tools in the creation of this article.

Declaration of interest:

There is no conflict of interest..

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Data Availability

In this investigation, no data were used.

Ethical Compliance: This research work did not involve any human participants or animals, and therefore, no ethical approval was required.

Author Contributions: Indirajith.K, Kumaran.N designed and implemented the research. Indirajith.K analyzed results and wrote the manuscript. Kumaran N supervised the manuscript.

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