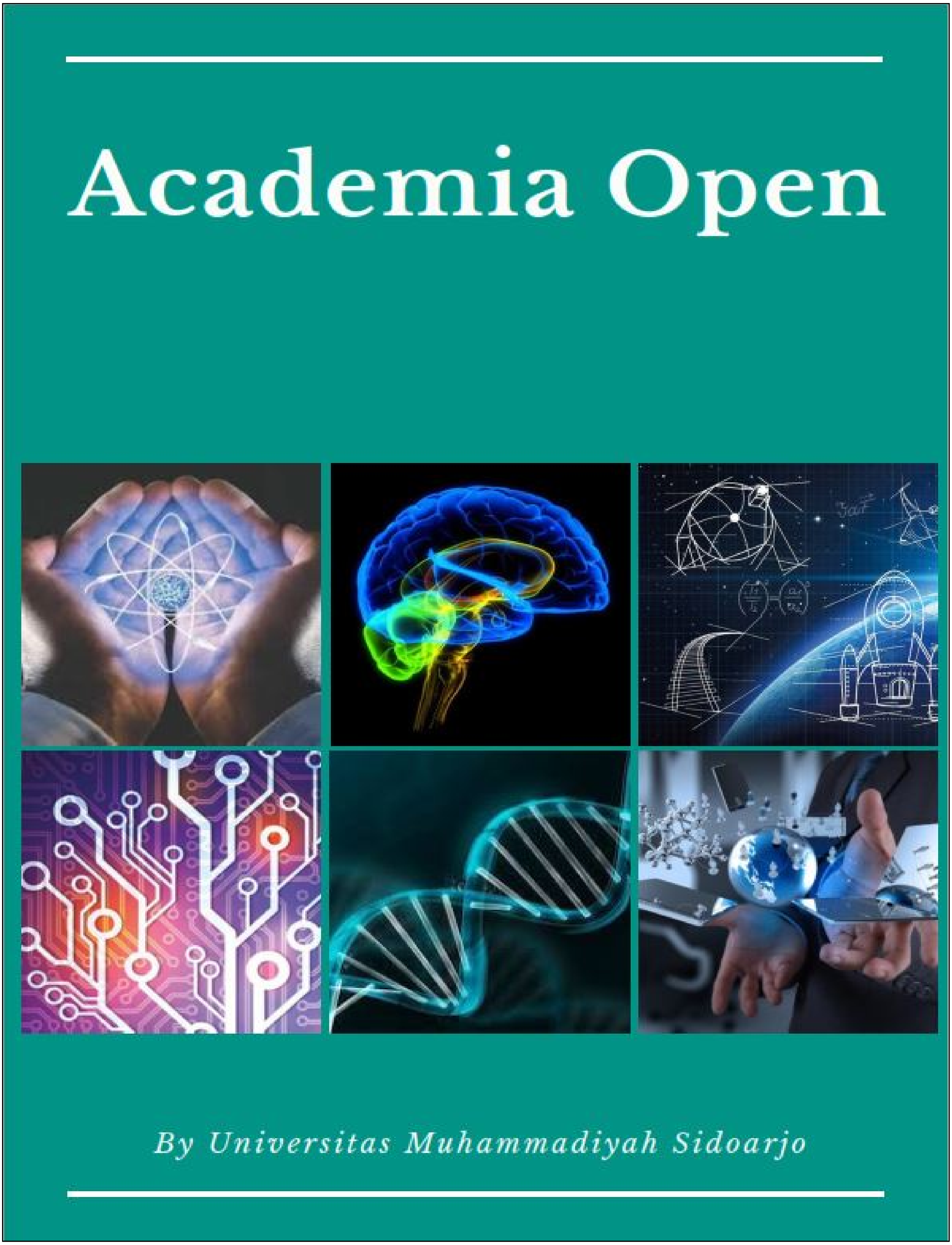
Academia Open
Vol 10 No 1 (2025): June (In Progress)
DOI: 10.21070/acopen.10.2025.10638 . Article type: (Engineering)

Table Of Content

ISSN 2714-7444 (online), https://acopen.umsida.ac.id, published by Universitas Muhammadiyah Sidoarjo

Academia Open
Vol 10 No 1 (2025): June (In Progress)
DOI: 10.21070/acopen.10.2025.10638 . Article type: (Engineering)



ISSN 2714-7444 (online), https://acopen.umsida.ac.id, published by Universitas Muhammadiyah Sidoarjo

Originality Statement

The author[s] declare that this article is their own work and to the best of their knowledge it contains no materials previously published or written by another person, or substantial proportions of material which have been accepted for the published of any other published materials, except where due acknowledgement is made in the article. Any contribution made to the research by others, with whom author[s] have work, is explicitly acknowledged in the article.

Conflict of Interest Statement

The author[s] declare that this article was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Copyright Statement

Academia Open
Vol 10 No 1 (2025): June (In Progress)
DOI: 10.21070/acopen.10.2025.10638 . Article type: (Engineering)

Academia Open
Vol 10 No 1 (2025): June (In Progress)
DOI: 10.21070/acopen.10.2025.10638 . Article type: (Engineering)

Article information

Check this article update (crossmark)

Check this article impact (*)

Save this article to Mendeley

(*) Time for indexing process is various, depends on indexing database platform

Academia Open
Vol 10 No 1 (2025): June (In Progress)
DOI: 10.21070/acopen.10.2025.10638 . Article type: (Engineering)

Optimization Strategies for Energy Management Systems of Solar-Powered Unmanned Aerial Vehicles

Strategi Optimasi Sistem Manajemen Energi pada Kendaraan Udara Nirawak Bertenaga Surya

Javokhir Narimanov, javokhir.nv@gmail.com, (1)
Tashkent State Transport University, Uzbekistan

Nuriddin Abdujabarov, nuriddin@gmail.com, (0)
Tashkent State Transport University, Uzbekistan

(1) Corresponding author

Abstract

General Background: The rapid advancements in solar-powered unmanned aerial vehicles (UAVs) have increased interest in optimizing their energy management systems (EMS) to enhance performance and flight endurance. **Specific Background:** Effective EMS in solar UAVs requires advanced strategies for solar energy harvesting, energy storage, and power distribution to maximize operational efficiency under varying environmental conditions. **Knowledge Gap:** Despite recent progress, challenges remain in energy conversion efficiency, battery storage capacity, and the integration of intelligent predictive control mechanisms, limiting the UAVs' ability to operate autonomously for extended periods. **Aims:** This review investigates current EMS optimization strategies for solar-powered UAVs, emphasizing multi-objective optimization techniques, energy management algorithms, and the impact of environmental conditions on UAV performance. It also explores the role of artificial intelligence (AI) and machine learning in improving EMS efficiency. **Results:** Studies highlight that multi-objective genetic algorithms (MOGAs) effectively balance energy allocation between propulsion, battery storage, and payload, leading to significant endurance improvements. Fuzzy logic-based power management systems enhance energy efficiency by dynamically adjusting power distribution based on real-time UAV energy demands. Adaptive energy management strategies that integrate environmental and operational data improve flight times by up to 30% under extreme conditions. **Novelty:** This review synthesizes state-of-the-art EMS strategies, identifying key optimization techniques and emerging AI-driven solutions for adaptive and predictive energy management. By consolidating findings from diverse methodologies, it provides a comprehensive assessment of how intelligent control systems enhance UAV autonomy. **Implications:** The findings underscore the necessity of developing more efficient power conversion technologies, advanced battery storage solutions, and AI-based EMS frameworks to enable long-duration UAV operations. Future research should focus on refining these technologies to improve UAV performance in energy-intensive applications such as surveillance, environmental monitoring, and disaster response.

Highlights:

1. Optimization: MOGAs and fuzzy logic improve energy efficiency and endurance.
2. Adaptation: Real-time power adjustments enhance UAV performance in harsh conditions.
3. AI Integration: Machine learning enables predictive, autonomous energy management.

Keywords: Solar-powered UAVs, Energy Management Systems, Optimization Algorithms,

ISSN 2714-7444 (online), https://acopen.umsida.ac.id, published by Universitas Muhammadiyah Sidoarjo

Adaptive Control, Artificial Intelligence

Published date: 2025-02-13 00:00:00

Academia Open
Vol 10 No 1 (2025): June (In Progress)
DOI: 10.21070/acopen.10.2025.10638 . Article type: (Engineering)

Introduction

Solar-powered Unmanned Aerial Vehicles (UAVs) represent a significant advancement in the field of UAV technology, enabling extended flight durations and reduced reliance on traditional fuel sources [1, 2]. Unlike traditional UAVs that rely on fuel or rechargeable batteries, solar-powered UAVs are designed for long-duration flights, as they can harness the energy from the sun to continuously recharge their power systems while in the air [3, 4]. However, achieving efficient energy management in solar-powered UAVs is crucial for their operational viability, particularly for applications requiring long endurance, such as environmental monitoring, surveillance, and communication networks [5, 6].

Energy management systems (EMS) for solar UAVs must balance the generation, storage, and consumption of energy, while adapting to fluctuating environmental conditions such as varying solar intensity and temperature. As these systems are integral to the UAV's performance, optimizing EMS is essential for maximizing flight times and ensuring reliable operations. To achieve long flight duration and maximize energy efficiency, wing design [7] and selection of the right type of solar cells [8] play a crucial role. This paper reviews the state-of-the-art energy management strategies for solar UAVs, examining both theoretical and practical advancements. It also identifies gaps in current research and propose future directions for improving the efficiency and autonomy of solar-powered UAVs. Solar-powered UAV components and energy management systems are shown in Figure 1 [9].

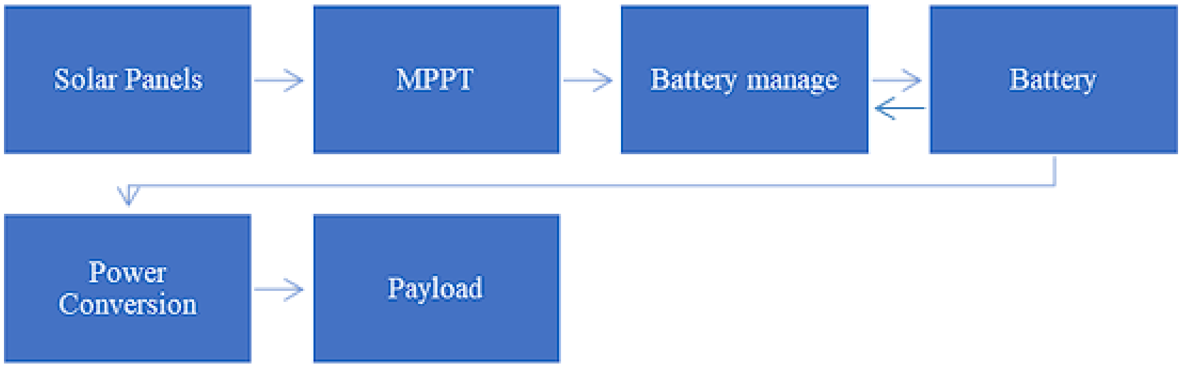


Figure 1. *Diagram of solar-powered UAV components and EMS [9]*

Literature Review

2.1. Energy Management Techniques and Strategies. Recent studies have introduced various strategies for optimizing energy management in solar-powered UAVs. Wang et al. [10] proposed a multi-objective genetic algorithm (MOGA) to optimize the allocation of solar energy between the battery, propulsion system, and payload. This approach ensures that multiple objectives – such as maximizing flight duration and minimizing energy consumption – are efficiently balanced. Their findings suggest that multi-objective genetic algorithm-based solutions offer significant improvements in flight endurance, even under variable solar conditions.

MOGAs assist in determining optimal design parameters for solar-powered UAVs, including wing area, cruise speed, drag, lift coefficient, and aspect ratio. By considering multiple objectives, such as payload capacity and energy efficiency, MOGAs help in achieving a balanced design that meets various performance criteria [11].

A fuzzy logic-based Power Management System (PMS) has been proposed to optimize power allocation in hybrid UAV power systems, improving energy efficiency. The system uses inputs like battery state of charge (SOC), power demand (PD), and photovoltaic (PV) power to generate control commands, with PV power prioritized and fuel cell power as the lowest priority. The SOC is classified into low, medium, and high states, while PD has fuzzy states such as medium, high, and very high. Fuel cell power (PFC) also follows five fuzzy states, including medium and high. An example of fuzzification for a battery/fuel cell control system is presented in Table 12 [12, 13].

PFC				PD		
		VH	H	M	L	VL
	L	VH	VH	H	M	L
SOC	M	VH	H	M	L	L
	H	H	M	L	VL	VL

Table 1. *An example of fuzzification for a battery/fuel cell control system [12, 13]*

ISSN 2714-7444 (online), https://acopen.umsida.ac.id, published by Universitas Muhammadiyah Sidoarjo

Academia Open
Vol 10 No 1 (2025): June (In Progress)
DOI: 10.21070/acopen.10.2025.10638 . Article type: (Engineering)

2.2. Challenges in Extreme Environmental Conditions. Solar UAVs often face performance degradation in extreme conditions, such as low-light or high-altitude flights, where solar energy availability is limited. Zhang et al. [14] addressed this challenge by developing an adaptive energy management strategy. This system adjusts the power distribution between the solar panel and battery based on real-time environmental data, ensuring that the UAV can maintain optimal performance even in adverse weather conditions. Their approach demonstrated a 30% improvement in flight time under such conditions, highlighting the importance of adaptive control in energy management.

2.3. Design of Adaptive Energy Management Systems. Gao et al. [15] focused on the real-time adaptive control of solar UAVs, integrating sensor data to dynamically adjust the UAV's power distribution. By incorporating real-time monitoring of battery charge levels, solar intensity, and energy consumption, their system optimizes energy usage and prevents battery depletion during critical flight phases. The use of adaptive control algorithms in their study resulted in up to 15% longer flight times compared to traditional EMS designs, underscoring the effectiveness of adaptive energy management in enhancing UAV autonomy.

2.4. Future Challenges and Research Directions. Despite significant progress, several challenges remain in optimizing EMS for solar-powered UAVs. These include reducing energy losses during conversion and transmission, enhancing battery storage capacity, and integrating artificial intelligence (AI) to predict energy demands more accurately. Future research should focus on developing more efficient power conversion technologies, improving battery management systems, and leveraging AI for predictive and adaptive energy management to enhance solar-powered UAV performance under varying conditions.

Result and Discussion

The reviewed strategies show considerable improvements in solar-powered UAV performance, particularly in energy efficiency and flight endurance. Key findings include:

•*Multi-Objective Optimization.* Wang et al. [10] demonstrated that their multi-objective genetic algorithm approach significantly improved flight duration by optimizing energy allocation between the solar panels, battery, and propulsion system. In scenarios with variable sunlight, multi-objective genetic algorithm achieved up to a 25% improvement in flight time compared to traditional methods.

•*Adaptive Energy Management.* Zhang et al. [14] showed that adaptive energy management strategies could maintain optimal energy use even under extreme environmental conditions. By adjusting the power distribution in real time, their system increased flight time by 30% in low-light and high-altitude conditions.

•*Real-Time Monitoring and Control.* Gao et al. [15] demonstrated the importance of real-time energy monitoring and adaptive control in improving flight time. Their EMS system extended UAV flight time by 15%, thanks to dynamic energy distribution based on solar intensity and battery levels.

The energy management strategies reviewed in this paper underscore the importance of balancing multiple objectives, such as maximizing energy efficiency, extending flight times, and ensuring system reliability. The use of multi-objective genetic algorithms, as demonstrated by Wang et al. [10], provides an effective solution for optimizing energy allocation in solar-powered UAVs. Furthermore, adaptive energy management systems, like the one proposed by Zhang et al. [14], offer significant improvements by responding dynamically to environmental conditions, ensuring that solar-powered UAVs can perform well even in challenging environments.

However, while these strategies have proven effective, several challenges remain. For example, further work is needed to reduce energy losses during power conversion and improve battery storage systems to support longer flight durations. Additionally, the integration of AI and machine learning for predictive energy management could revolutionize solar-powered UAV performance by allowing the system to anticipate and adjust to changes in environmental conditions before they occur.

Conclusion

The optimization of energy management systems for solar-powered UAVs is critical to enhancing their performance and extending the duration of their operations. By incorporating multi-objective optimization algorithms alongside adaptive control strategies, notable advancements have been made in improving energy consumption and overall flight endurance. However, several challenges remain, particularly concerning the efficiency of energy conversion, the capacity of battery storage, and the integration of artificial intelligence (AI) for dynamic energy management. Moving forward, research should aim at refining power conversion technologies, improving battery efficiency, and developing advanced AI-based systems capable of both adaptive and predictive energy management. These advancements will be key to enabling UAVs to operate over longer durations and improve their performance in energy-intensive tasks.

ISSN 2714-7444 (online), https://acopen.umsida.ac.id, published by Universitas Muhammadiyah Sidoarjo

References

1. B. S. K. Reddy, P. Aneesh, K. Bhanu, and M. Natarajan, “Design Analysis of Solar-Powered Unmanned Aerial Vehicle,” J. Aerosp. Technol. Manag., vol. 8, no. 4, pp. 397–407, 2016.
2. P. Rajendran and H. Smith, “Development of Design Methodology for a Small Solar-Powered Unmanned Aerial Vehicle,” Int. J. Aerosp. Eng., vol. 2018, p. 2820717, 2018, doi: 10.1155/2018/2820717.
3. J. Meyer, W. A. Clarke, and F. du Plessis, “Design Considerations for Long Endurance Unmanned Aerial Vehicles,” in Aerial Vehicles, ch. 22, pp. 443–496, 2009.
4. A. Noth, Design of Solar Powered Airplanes for Continuous Flight, Diss. ETH No. 18010, ETH Zurich, 2008.
5. K. Li, Y. Wu, A. Bakar, S. Wang, Y. Li, and D. Wen, “Energy System Optimization and Simulation for Low-Altitude Solar-Powered Unmanned Aerial Vehicles,” Aerospace, vol. 9, no. 5, p. 331, 2022.
6. T. K. Hong, C. Y. Lin, H. J. Lin, and N. Ruseno, “Taiwan Solar-Powered UAV Flight Endurance Record,” Drone Syst. Appl., vol. 12, pp. 1–14, 2024.
7. J. S. H. Narimanov, “Wing Design Considerations for Low-Altitude, Long-Endurance Solar-Powered UAVs,” 2024. [Online]. Available: https://doi.org/10.5281/zenodo.13624400.
8. J. S. H. Narimanov, “Analysis of Solar Cells Used in the Design of Solar-Powered UAV,” Tashkent State Transport Univ. J. Transp., vol. 2181, p. 2438, 2024.
9. A. Hamza, A. Mohammed, and A. Isah, “Towards Solar-Powered Unmanned Aerial Vehicles for Improved Flight Performance,” in 2019 2nd Int. Conf. IEEE Nigeria Comput. Chapter (NigeriaComputConf), Zaria, Nigeria, 2019, pp. 1–5.
10. H. Wang, P. Li, H. Xiao, X. Zhou, and R. Lei, “Intelligent Energy Management for Solar-Powered Unmanned Aerial Vehicles Using Multi-Objective Genetic Algorithm,” Energy Convers. Manag., vol. 280, p. 116805, 2023.
11. H. Suryoatmojo, M. F. Afif, V. Lystianingrum, E. Setijadi, and R. Mardiyanto, “Optimal Sizing of Solar-Powered Unmanned Aerial Vehicle System for Continuous Flight Based on Multi-Objective Genetic Algorithm,” ICIC Express Lett., vol. 14, no. 8, pp. 741–749, 2020.
12. M. N. Boukoberine, Z. Zhou, and M. Benbouzid, “A Critical Review on Unmanned Aerial Vehicles Power Supply and Energy Management: Solutions, Strategies, and Prospects,” Appl. Energy, vol. 255, p. 113831, 2019.
13. X. Zhang, L. Liu, Y. Dai, and T. Lu, “Experimental Investigation on the Online Fuzzy Energy Management of Hybrid Fuel Cell/Battery Power System for UAVs,” Int. J. Hydrogen Energy, vol. 43, no. 21, pp. 10094–10103, 2018.
14. Z. J. Zhang, R. T. Ji, Y. Wang, M. Chang, X. P. Ma, J. Sha, and D. L. Mao, “An Improved Energy Management Strategy for the Solar-Powered Unmanned Aerial Vehicle at the Extreme Condition,” J. Energy Storage, vol. 43, p. 103114, 2021.
15. Y. Gao, Z. Qiao, X. Pei, G. Wu, and Y. Bai, “Design of Energy-Management Strategy for Solar-Powered UAV,” Sustainability, vol. 15, no. 15, p. 14972, 2023.

ISSN 2714-7444 (online), https://acopen.umsida.ac.id, published by Universitas Muhammadiyah Sidoarjo