

Hybrid Fuzzy Logic–Controlled Solar Tracking and Cooling System for Enhancing Photovoltaic Performance

Samwel Ng'ang'a Kariuki ¹, Peter K. Kihato ², Fred Mulei¹

¹Department of Renewable Energy and Environmental Engineering, School of Energy and Built Environment
Mount Kenya University, Kenya

² Department of Electrical and Electronic Engineering, Jomo Kenyatta University of Agriculture and Technology,
Kenya

* Corresponding author: kariukisammuel@mylife.mku.ac.ke

Article Info

Article history:

Received , 23/01/2026

Revised , 19/04/2026

Accepted , 08/05/2026

Keywords:

Dual-Axis Tracking;
Fuzzy Logic Control;
Photovoltaic Cooling;
Renewable Energy;
Optimization;
Solar Photovoltaics

ABSTRACT

Photovoltaic (PV) systems experience performance degradation due to fixed module orientation and elevated operating temperatures under real outdoor conditions. This study proposes and experimentally validates a hybrid photovoltaic system that integrates dual-axis solar tracking with an adaptive cooling subsystem controlled by a multi-fuzzy logic architecture. The system was modelled and simulated in MATLAB/Simulink and subsequently validated through a prototype tested under field conditions. The fuzzy logic tracker achieved a faster response time (approximately 0.3 s) and minimal overshoot compared to a conventional PID controller. The cooling subsystem maintained the module temperature near 35 °C, reducing thermally induced voltage losses. Experimental results demonstrated that the hybrid system delivered a net daily energy gain of approximately 38 Wh per 40 Wp module, representing an improvement of about 56% over a fixed, uncooled module. Auxiliary energy consumption from motors and cooling pump remained minimal relative to the additional harvested energy. The findings demonstrate that integrating adaptive tracking and temperature regulation significantly enhances PV performance in high-irradiance regions

I. Introduction

Energy remains a fundamental driver of social, economic, and industrial development, yet its demand continues to rise in tandem with global population growth, rapid urbanization, and technological advancement [1, 2]. Conventional energy systems dominated by fossil fuels have contributed significantly to greenhouse gas emissions, climate change, and environmental degradation, underscoring the urgent need to transition toward sustainable, clean energy alternatives [3]. Among renewable sources, solar energy is the most abundant, delivering an estimated 178 billion MW annually—enough to exceed global energy demand by over 2,000 times [4], [5]. Its scalability, abundance, and declining costs make photovoltaic (PV) technology a cornerstone of the renewable energy transition [6].

Despite its vast potential, PV system performance often falls short of theoretical expectations due to two major factors: suboptimal solar incidence caused by fixed panel orientations, and elevated module temperatures leading to thermal losses [7]. Under standard test conditions (STC: 25 °C, 1000 W/m²), modules deliver peak performance [8]. However, in real outdoor conditions, PV panels are rarely aligned perpendicularly to incoming solar radiation throughout the day, and prolonged exposure to high irradiance causes temperatures to rise above

35 °C, which reduces open-circuit voltage and overall output [9]. Temperature elevation increases the reverse saturation current of the cell, narrowing the bandgap and thereby decreasing efficiency [7], [10] .

Solar tracking has emerged as a powerful method for addressing orientation-related losses [4]. Single-axis trackers compensate for daily east–west solar movement, while dual-axis systems also capture seasonal elevation changes, maintaining optimal incidence throughout the year [11] . Empirical studies report that dual-axis tracking can improve daily energy yield by 20–35% compared to fixed systems [12]. However, the same improved irradiance capture accelerates heating, creating a secondary bottleneck in performance [12].

Cooling techniques have therefore been extensively explored to mitigate thermal degradation. Passive methods such as natural convection and heat sinks are cost-effective but often insufficient under strong irradiance .[13] Active methods, including air circulation, liquid cooling, and phase-change materials, demonstrate improved effectiveness but at higher cost and complexity . Studies show that continuous water cooling, for example, can reduce module temperatures by 10–15 °C and increase output efficiency by 12–15% [14]. Nonetheless, these approaches generally operate independently of solar orientation and are seldom integrated into a unified control scheme.

Hybrid tracking–cooling systems present a promising solution. By combining optimal solar incidence with intelligent thermal regulation, these systems maximize irradiance capture while maintaining performance stability. Yet, most existing prototypes have been limited by simplistic control strategies, such as proportional-integral-derivative (PID) controllers, which can suffer from overshoot, sluggish response, or unnecessary actuator movement under intermittent condition.

Fuzzy logic controllers (FLC’s) have gained attention as an adaptive AI-based solution capable of managing nonlinear dynamics and uncertain environmental inputs [15], [16]. Unlike conventional methods, fuzzy logic enables decision-making based on linguistic rules (e.g., “if hot, then cool faster”), making it well-suited for systems exposed to rapidly changing irradiance and temperature. Prior research shows that FLC-based trackers achieve higher accuracy, faster settling times, and reduced oscillation compared to PID controllers [9] [17]. Similarly, fuzzy logic–driven cooling systems activate only when needed, optimizing energy use and improving stability [15], [18].

This study develops and evaluates a hybrid photovoltaic system that integrates a dual-axis solar tracker and an adaptive cooling unit under a unified fuzzy logic control architecture. By leveraging multi-fuzzy rules for both orientation and temperature regulation, the system aims to optimize net power output, reduce thermal-induced voltage drops, and ensure reliable operation under variable weather conditions. The proposed system was designed and simulated in MATLAB/Simulink and subsequently validated via a prototype in Nyandarua County, Kenya. Results indicate that the hybrid design improves efficiency to about 17% compared to fixed, uncooled systems, underscoring its potential as a scalable solution for high-irradiance regions.

By leveraging fuzzy inference rules, the hybrid controller can intelligently balance orientation and cooling decisions based on real-time solar and temperature conditions, thereby optimizing overall PV performance.

This paper makes the following contributions:

1. Proposes a unified multi-layer fuzzy logic control architecture integrating dual-axis solar tracking with temperature-regulated cooling.
2. Develops a duty-cycled actuation strategy to minimize auxiliary energy consumption in tracking motors and cooling subsystems.
3. Implements a MATLAB/Simulink-based simulation model for evaluating the performance of the hybrid PV tracking–cooling system.
4. Demonstrates experimental validation using a 40 W photovoltaic prototype system under real-world operating conditions in Nyandarua County, Kenya.
5. Quantifies the net energy gain by accounting for both photovoltaic energy generation and auxiliary subsystem energy consumption.

II. Research Method

II.1 Solar Tracking Control Strategy

The desired panel orientation angles are defined as:

- θ_s : solar azimuth angle

- α_s : solar elevation angle

The tracking objective is to minimize the angular misalignment between the photovoltaic panel and the sun, expressed as:

$$\begin{aligned} e_{az}(t) &= \theta_s(t) - \theta_p(t) \\ e_{el}(t) &= \alpha_s(t) - \alpha_p(t) \end{aligned} \quad (1)$$

Where $\theta_p(t)$ and $\alpha_p(t)$ are the panel azimuth and elevation angles, respectively [19].

These angular errors are supplied to a fuzzy logic controller, which determines whether corrective movement is required and selects the appropriate direction and duration of motor actuation. Instead of attempting continuous angular correction, the controller operates under a threshold-based fuzzy rule set, allowing small misalignments to persist without correction when their impact on irradiance capture is negligible.

The rotational dynamics of the tracking platform are modelled using the equation [20]:

$$J\ddot{\theta} + B\dot{\theta} + \tau_f = \tau_m \quad (2)$$

where J is the equivalent moment of inertia of the PV panel and mechanical structure, B is the viscous damping coefficient representing mechanical friction, τ_f denotes Coulomb friction torque, and τ_m is the electromagnetic torque generated by the DC motor. The terms $\ddot{\theta}$ and $\dot{\theta}$ represent angular velocity and angular acceleration, respectively.

Motor torque is expressed as

$$\tau_m = K_t I_m \quad (3)$$

where K_t is the motor torque constant and I_m is the armature current [21].

The electrical behaviour of the motor is described by:

$$I_m = \frac{V_m - K_e \dot{\theta}}{R_m} \quad (4)$$

in which V_m is the applied motor voltage, K_e is the back electromotive force constant, and R_m is the armature resistance [21].

A fuzzy logic controller processes angular error and rate of change to generate motor actuation signals. Tracking occurs at 4-minute intervals to minimize unnecessary motion. A MATLAB model of the solar tracking system is shown in figure 1 below.

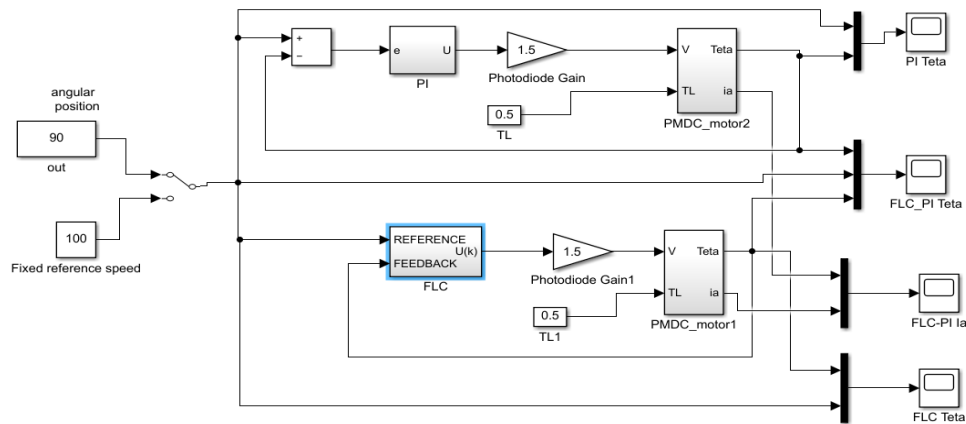


Figure 1. Simulink model of fuzzy logic solar tracker

II.2 Cooling Control Strategy

The PV module was modelled using the diode equivalent circuits as:

$$I = I_{ph} - I_0 \left(e^{\frac{q(V+IR_s)}{nKT}} - 1 \right) - \frac{V+IR_s}{R_{sh}} \quad (5)$$

where I and V are the output current and voltage, I_{ph} is the photo-generated current proportional to irradiance, I_0 is the diode reverse saturation current, R_s and R_{sh} are the series and shunt resistances, q is the electron charge, k is Boltzmann's constant, n is the diode ideality factor, and T is the absolute cell temperature [22].

The temperature dependence of the saturation current is given by

$$I_0(T) = I_{0n} \left(\frac{T}{T_n} \right)^3 \exp \left[\frac{qE_g}{nk} \left(\frac{1}{T_n} - \frac{1}{T} \right) \right] \quad (6)$$

where I_{0n} is the saturation current at nominal temperature T_n , and E_g is the semiconductor band-gap energy.

This relationship explains the reduction in output voltage at elevated temperatures. As a result, a cooling system was necessary to keep the temperatures lower for minimum power loss [22].

The cooling subsystem was developed to maintain PV module temperatures close to an identified optimal threshold of 35 °C. The absorbed heat was modelled using the equation:

$$Q_{in} = G_T A (\alpha - \eta) \quad (7)$$

where G_T is the global solar irradiance incident on the module surface, A is the module area, α is the absorptivity of the PV surface, and η is the electrical conversion efficiency [22].

Convective heat loss is expressed as

$$Q_{out} = hA(T_s - T_a) \quad (8)$$

where h is the convective heat-transfer coefficient, T_s is the PV surface temperature, and T_a is the ambient temperature. For forced-air cooling,

$$h = h_0 + kv_{air} \quad (9)$$

with h_0 representing natural convection, k an airflow enhancement constant, and v_{air} the air velocity produced by the cooling fan [18].

A secondary fuzzy controller activates a variable-speed pump when module temperature exceeds 35 °C. The MATLAB Simulink model of the cooling system is as shown in figure 2 below.

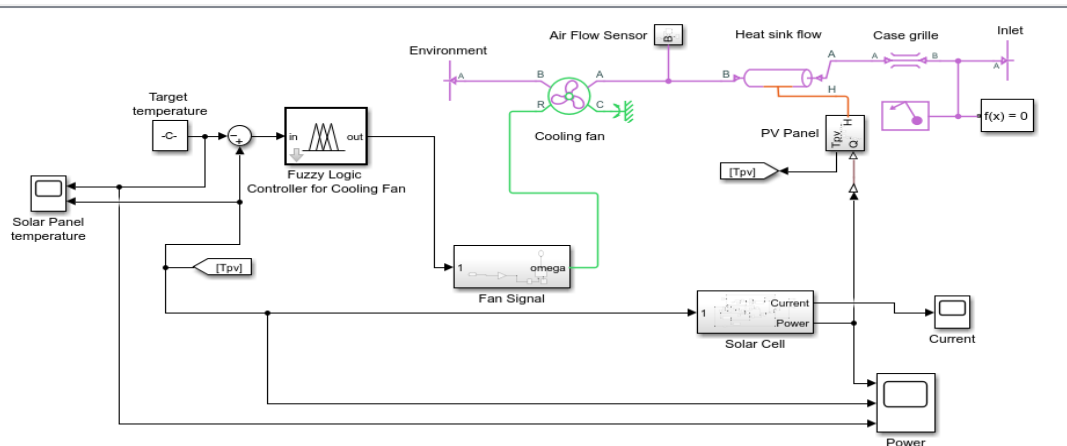


Figure 2. Simulink model of fuzzy logic cooling system

II.3 Experimental Setup

A prototype was developed using two 40 W monocrystalline PV modules. One module was equipped with hybrid tracking and cooling, while the second served as a fixed, uncooled reference. The figure 3 below shows the setup of the two panels side-by-side



Figure 3. Fixed and hybrid tracking and cooling solar PV systems

Data acquisition was performed using an Arduino Mega microcontroller. Voltage and current were measured using INA219 sensors, temperature via DS18B20 sensors, and irradiance via a pyranometer. Data were logged at one-minute intervals. The data acquisition system is shown in Figure 4 below.

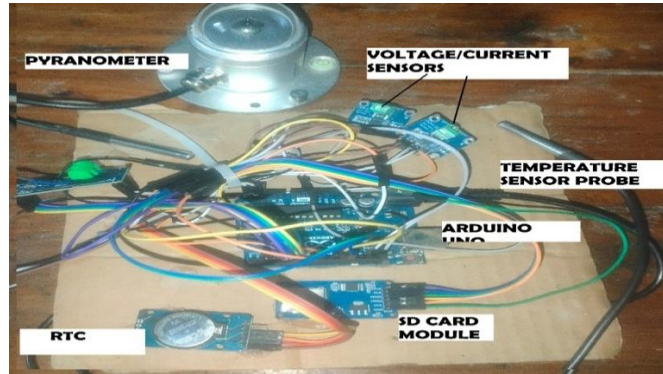


Figure 4. Data acquisition system schematic

II.4 Auxiliary Energy Consumption

The tracking mechanism employs 12 V DC geared motors rated 12 V 1 A. Although the motors are rated for higher currents, field measurements during operation indicated an average current draw of approximately 0.4 A due to the torque amplification provided by the gearbox. The instantaneous tracking motor power is therefore expressed as:

$$P_{motor} = V \times I \quad (10)$$

The tracking controller operates under a duty-cycled scheme, activating the motors for three seconds every four minutes only when angular deviation exceeds the fuzzy threshold. This duty cycle is used to compute the average tracking power.

The cooling subsystem utilizes a 12 V DC pump rated at 1 A; however, measurements under atmospheric pressure conditions showed a reduced operating current in the range of 0.4–0.6 A. To ensure conservative estimation, the upper measured value was adopted. Cooling duty cycles vary depending on irradiance level and temperature deviation, as defined by the fuzzy control rules.

The total auxiliary energy consumption is computed by integrating the average auxiliary power over the effective operating period [23]:

$$E_{aux} = \int P_{aux\ avg}(t).dt \quad (11)$$

This formulation enables direct comparison between auxiliary energy consumption and the incremental energy harvested by the hybrid system, which is presented and analysed in the Results and Discussion chapter.

III. Data and results

III.1 Tracking Performance Analysis

Figure 5 presents the angular response of the fuzzy solar tracking system compared with the PID controlled panel configuration. The fuzzy tracking mechanism maintained optimal alignment throughout daylight hours, resulting in improved irradiance capture. It also showed minimum overshoot and thus settled quickly reducing the auxiliary power consumption for the tracking system

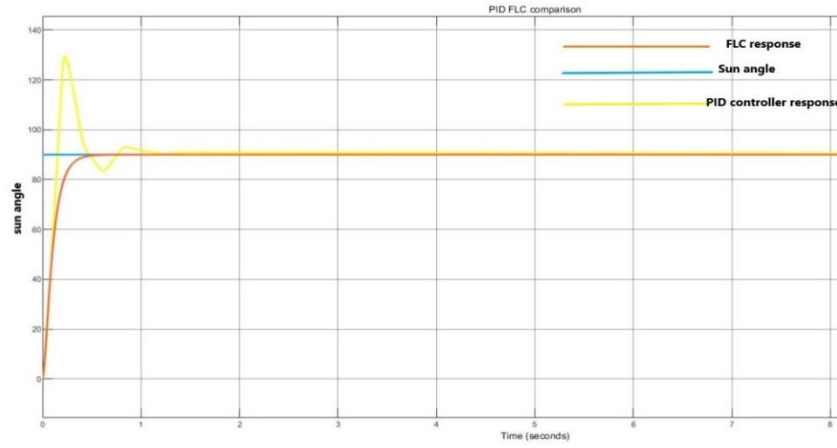
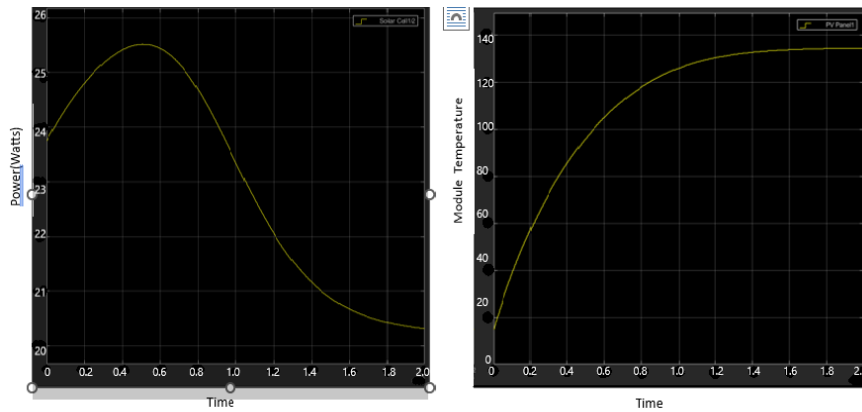


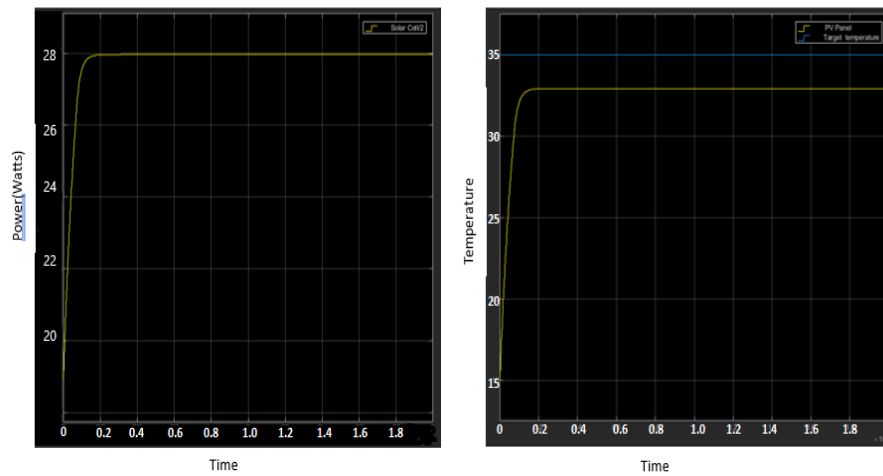
Figure 5. Angular positioning performance of the solar tracking fuzzy logic system.

II.2 Temperature Regulation Performance

The effectiveness of the cooling subsystem is illustrated in Figure 6, where reduced operating temperature of the PV module during the peak solar irradiance period resulted in increased power output compared to the non-cooled PV module.



(a) Output power under uncontrolled module temperature



(b) Output power with fuzzy-controlled cooling.

Figure. 6 (a) and (b). Comparison of PV output power with and without temperature regulation

III.3. Power Output Enhancement

The combined tracking and cooling system produced higher power output compared to the fixed module configuration without the tracking as shown in Figure 7.

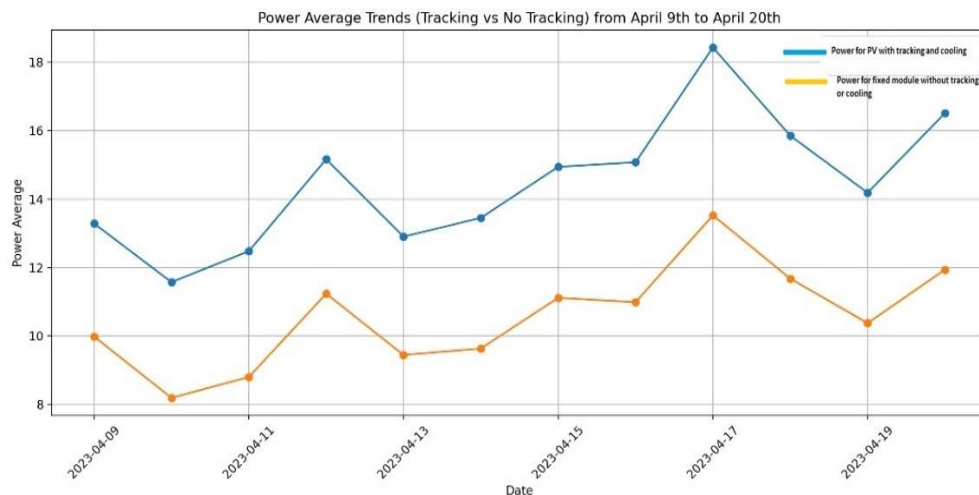


Figure 7. Output power comparison between fixed and hybrid PV systems.

The results show that the hybrid PV system (with both tracking and cooling) consistently generates higher electrical power than the fixed module system. This improvement occurs because solar tracking keeps the panels more directly aligned with the sun, increasing irradiation capture, while cooling reduces temperature-related efficiency losses in the PV cells. As a result, the combined system achieves better overall energy output compared to the fixed configuration.

III 4. Energy yield gains

The table 1 below shows a summary of the power output and the energy yield gain.

Component / Mode	Average Power (W)	Operating Duration (h)	Energy (Wh/day)
PV panel (fixed, uncooled)	9.0	10	90
PV panel with tracking only	14.0	10	140
Additional PV energy due to tracking	+5.0	10	+50
Tracking motors	0.06	10	-0.6
Cooling pump (high irradiance)	1.8	6	-10.8
Cooling pump (low irradiance)	0.16	4	-0.64
Total auxiliary energy consumption	1.20	10	-12.04
Net daily energy gain (tracking + cooling)	+3.8	10	+37.96

Table 1. Energy production and auxiliary consumption comparison between fixed and hybrid PV systems.

The fixed system produced an average power of 9.0 W, yielding 90 Wh/day over a 10-hour period. With the addition of solar tracking, the average power increased to 14.0 W, resulting in 140 Wh/day. This represents an energy gain of 50 Wh/day, equivalent to approximately 55.6% improvement, primarily due to improved alignment with solar irradiance throughout the day.

The energy consumption of the tracking system was minimal due to its duty-cycled operation, consuming only 0.6 Wh/day, which is negligible compared to the energy gained. In contrast, the cooling subsystem contributed a higher energy overhead, consuming 10.8 Wh under high irradiance and 0.64 Wh under low irradiance conditions. This variation reflects the adaptive nature of the fuzzy control system, which adjusts cooling based on environmental conditions to maintain panel efficiency.

Overall, the total auxiliary energy consumption amounted to 12.04 Wh/day. Despite this, the hybrid system achieved a net energy gain of 37.96 Wh/day, corresponding to an overall improvement of approximately 42.2% compared to the fixed system. These results confirm that the hybrid approach is energetically beneficial, as the additional energy harvested significantly outweighs the auxiliary energy consumed.

The study demonstrates that a fuzzy logic-controlled hybrid PV system, integrating dual-axis tracking and active cooling, significantly enhances energy yield. Both simulations and field tests confirmed that fuzzy logic tracking outperforms conventional PID control by achieving faster, more stable panel alignment with minimal overshoot. Thermal management proved crucial, as uncontrolled PV temperatures led to voltage drops and power loss, while active cooling maintained the module temperatures near 35 °C, mitigating thermal losses.

IV. Conclusion

The findings of this study demonstrate that integrating fuzzy logic-controlled dual-axis tracking with an active cooling system significantly enhances the performance of photovoltaic modules. The hybrid system effectively maximizes solar irradiance capture while mitigating thermal-induced losses, resulting in a net daily energy gain of approximately 38 Wh per 40 Wp module—a 56% improvement over fixed, uncooled panels. Both simulation and experimental results confirmed that fuzzy logic tracking offers faster response, minimal overshoot, and more stable panel orientation compared to conventional PID controllers. Temperature regulation proved equally important, as uncontrolled PV temperatures caused voltage drops and reduced power output, while active cooling maintained the module temperatures near 35 °C, ensuring consistent performance throughout the day.

The hybrid system maintained superior performance under varying environmental conditions, including clear and partly cloudy skies, demonstrating robustness and adaptability for real-world operation. Auxiliary energy

consumption from the tracking motors and cooling pump was minimal relative to the energy gains, confirming the overall efficiency of the approach. These results highlight the potential of fuzzy logic-controlled hybrid systems as scalable and practical solutions for high-solar-resource regions, where elevated module temperatures and suboptimal panel orientation significantly limit photovoltaic performance.

Based on these findings, it is recommended that future PV installations in high-irradiance regions incorporate both tracking and temperature regulation systems, preferably using adaptive fuzzy logic control for optimal performance. Further improvements could include scaling the system for larger PV arrays, implementing low-power and energy-efficient cooling solutions, and integrating real-time monitoring to dynamically adjust tracking and cooling duty cycles according to instantaneous solar irradiance and module temperature. Long-term field studies are also suggested to evaluate the durability, maintenance requirements, and economic feasibility of such hybrid systems at a commercial scale, ensuring their practical applicability and sustainability.

Acknowledgements

The authors acknowledge the support provided by Mount Kenya University and Jomo Kenyatta University of Agriculture and Technology during the development and testing of the prototype system. Appreciation is also extended to supervisors and collaborators who contributed to this work, with honourable mention going to Jane Njeri Kariuki, Dr Kihato and Engineer Mulei.

References

- [1] J. Fang, G. Gozgor, M. K. Mahalik, H. Mallick, and H. Padhan, "Does urbanisation induce renewable energy consumption in emerging economies? The role of education in energy switching policies," *Energy Economics*, vol. 111, p. 106081, 2022/07/01/ 2022.
- [2] Y. Elaouzy and A. El Fadar, "Energy, economic and environmental benefits of integrating passive design strategies into buildings: A review," *Renewable and Sustainable Energy Reviews*, vol. 167, p. 112828, 2022/10/01/ 2022.
- [3] S. R. Paramati, U. Shahzad, and B. Doğan, "The role of environmental technology for energy demand and energy efficiency: Evidence from OECD countries," *Renewable and Sustainable Energy Reviews*, vol. 153, p. 111735, 2022/01/01/ 2022.
- [4] R. Sadeghi, M. Parenti, S. Memme, M. Fossa, and S. Morchio, "A Review and Comparative Analysis of Solar Tracking Systems," vol. 18, no. 10, p. 2553, 2025.
- [5] S. S. Hosseini Dehshiri and B. Firoozabadi, "Comparison, Evaluation and Prioritization of Solar Photovoltaic Tracking Systems Using Multi Criteria Decision Making Methods," *Sustainable Energy Technologies and Assessments*, vol. 55, p. 102989, 2023.
- [6] M. Moldovan, B. G. Burduhos, and I. Visa, "Efficiency Assessment of Five Types of Photovoltaic Modules Installed on a Fixed and on a Dual-Axis Solar-Tracked Platform," *Energies*, vol. 16, no. 3, p. 1229, 2023.
- [7] P. Dwivedi and et al., "Advanced Cooling Techniques of PV Modules: A State of Art," *Case Studies in Thermal Engineering*, vol. 21, p. 100674, 2020.
- [8] Y. Cao and et al., "Ultrathin Microcrystalline Hydrogenated Si/Ge Alloyed Tandem Solar Cells Towards Full Solar Spectrum Conversion," *Frontiers of Chemical Science and Engineering*, vol. 14, no. 6, pp. 997-1005, 2020.
- [9] M. Ali and et al., "Optimization on PID and ANFIS Controller on Dual Axis Tracking for Photovoltaic Based on Firefly Algorithm," in *2019 International Conference on Electrical, Electronics and Information Engineering (ICEEIE)*, 2019: IEEE.
- [10] M. Sharaf, M. S. Yousef, and A. S. Huzayyin, "Review of cooling techniques used to enhance the efficiency of photovoltaic power systems," *Environmental Science and Pollution Research*, vol. 29, no. 18, pp. 26131-26159, 2022/04/01 2022.
- [11] G. Singh and A. Kaur, "Comparative study of PID and fuzzy controllers for solar tracking systems," *International Journal of Emerging Electric Power Systems*, vol. 20, no. 4, p. 20190023, 2019.

- [12] N. Al-Rousan and et al., "Efficient Single and Dual Axis Solar Tracking System Controllers Based on Adaptive Neural Fuzzy Inference System," *Journal of King Saud University – Engineering Sciences*, vol. 32, no. 7, pp. 459-469, 2020.
- [13] A. Johnson, Smith, B., & Williams, C. , "Advances in Air Cooling Systems for Electronic Components.," *Journal of Thermal Management*, pp. 15(2), 45-58., 2021.
- [14] F. L. Rashid, M. A. Eleiwi, H. I. Mohammed, A. Ameen, and S. Ahmad, "A Review of Using Solar Energy for Cooling Systems: Applications, Challenges, and Effects," *Energies*, vol. 16, no. 24, p. 8075. doi: 10.3390/en16248075
- [15] P. Whig, B. Bhatia, A. B. Bhatia, and P. Sharma, "Renewable Energy Optimization System Using Fuzzy Logic," in *Machine Learning and Metaheuristics: Methods and Analysis*, U. N. Dulhare and E. H. Houssein, Eds. Singapore: Springer Nature Singapore, 2023, pp. 177-198.
- [16] S. Mansour *et al.*, "Fuzzy Logic Controller Equilibrium Base to Enhance AGC System Performance with Renewable Energy Disturbances," vol. 15, no. 18, p. 6709, 2022.
- [17] H. A. Issa, L. M. Abdali, H. Alhusseini, and V. I. Velkin, "Design, modeling, and control of a dual-axis solar tracker using fractional order PID controllers for enhanced energy efficiency," *Results in Engineering*, vol. 27, p. 106073, 2025/09/01/ 2025.
- [18] M. D. Susanti, M. K. Asy'Ari, N. L. Hamidah, and A. Musyafa', "Enhancing Solar Panel Efficiency Through Fuzzy Logic Control: A Case Study on Water Spraying and Air Cooling Techniques," in *2024 IEEE 12th Conference on Systems, Process & Control (ICSPC)*, 2024, pp. 407-412.
- [19] N. Al-Rousan, N. A. Mat Isa, and M. K. Mat Desa, "Efficient single and dual axis solar tracking system controllers based on adaptive neural fuzzy inference system," *Journal of King Saud University - Engineering Sciences*, vol. 32, no. 7, pp. 459-469, 2020/11/01/ 2020.
- [20] Y. Yang, J. Shao, W. Zhou, Z. Li, and J. Li, "Interzone duty cycle control of switched reluctance motor with comprehensive current error," *IEICE Electronics Express*, vol. 22, no. 15, pp. 20250165-20250165, 2025.
- [21] K. S, P. K. P, J. Rodríguez-García, and C. Álvarez-Bel, "A Comprehensive Review of Torque and Speed Control Strategies for Switched Reluctance Motor Drives," *CES Transactions on Electrical Machines and Systems*, vol. 9, no. 1, pp. 46-75, 2025.
- [22] M. Sharaf and et al., "Review of Cooling Techniques Used to Enhance the Efficiency of Photovoltaic Power Systems," *Environmental Science and Pollution Research*, vol. 29, no. 18, pp. 26131-26159, 2022.
- [23] J. G. Kassakian, D. J. Perreault, G. C. Verghese, and M. F. Schlecht, *Principles of Power Electronics*, 2nd ed. ed. Cambridge: Cambridge University Press, 2023.