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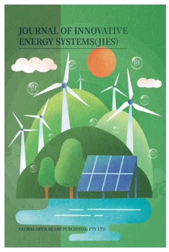

Article

Enhanced Solar Water Pumping Using Bifacial PV Modules with Reflective Augmentation and AI Driven Yield Prediction

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Abstract

This research presents a hybrid solar water pumping system that integrates bifacial photovoltaic (PV) modules with static planar reflectors to enhance energy capture in rural and off-grid environments. The system improves rear-side irradiance through passive reflective augmentation, thereby increasing total energy yield without relying on mechanical tracking mechanisms. Optical simulations conducted using TracePro confirmed substantial gains in rear-side irradiance, while field experiments demonstrated up to a 31% increase in daily water output and over 12% improvement in pump efficiency compared to conventional fixed-tilt monofacial PV systems. To support system design and operational planning, two artificial intelligence models were employed: a feedforward Artificial Neural Network (ANN) for short-term performance estimation, and an Adaptive Neuro-Fuzzy Inference System (ANFIS) for monthly and annual energy yield prediction. The ANFIS model forecasts an approximate 31% annual energy gain for the bifacial-reflector configuration over traditional mono facial setups. This integrated approach offers a robust, low-maintenance, and scalable solution for providing sustainable water access in high-albedo, infrastructure-limited regions.

Keywords

Bifacial PV, Solar water pumping, Concentrator PV, Energy yield prediction, Artificial neural network

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1. Introduction

1.1 Research Background

Access to reliable and sustainable water resources remains a critical global challenge, especially in remote and rural areas where infrastructure is limited or non-existent [1]. Traditional water delivery systems often fail due to their dependency on fossil fuels, grid power, or costly maintenance. Small-scale solar PV water pumping systems have therefore emerged as an effective and eco-friendly alternative, offering decentralized, clean, and economically viable solutions [2,3]. However, the performance of conventional PV systems is frequently hindered by suboptimal irradiance conditions, thermal losses, and seasonal solar variability [4]. These inefficiencies necessitate innovation in solar energy harvesting techniques.

Recent developments have focused on bifacial PV modules, which absorb light on both front and rear surfaces, offering enhanced energy yields especially when combined with optical concentration strategies [5,6]. Additionally, the adoption of AI-driven predictive modeling has enabled more accurate system optimization and energy forecasting under dynamic conditions [7]. This study builds on these innovations by exploring a unified solar pumping system integrating bifacial concentrators, passive optics, and AI-based prediction, with field validation for rural use.

1.2 Extensive Literature Survey

Concentrator PV (CPV) systems enhance energy capture by focusing sunlight through devices such as Fresnel lenses, mirrors, and reflectors [8]. While mechanical tracking, especially dual-axis, helps maintain optimal alignment with the sun and boosts output by up to 40% [9], it also adds cost and maintenance complexity [10,11]. This makes fixed-tilt reflector designs more viable for low-maintenance, rural applications.

Bifacial PV modules significantly outperform their monofacial counterparts by collecting diffuse and reflected radiation from the rear surface [12,13]. When installed above reflective surfaces or combined with static planar reflectors, bifacial systems can achieve 20-30% greater output [14]. This hybrid setup improves performance during low-sunlight periods and eliminates the need for moving parts, aligning well with rural water-pumping needs [15].

Artificial Intelligence further enhances PV system efficiency through precise energy prediction. Machine learning models, including Artificial Neural Networks (ANNs) [16,17] and ANFISs [18], have shown strong predictive accuracy in solar output forecasting using environmental and system-specific data. These models support real-time energy management in applications where solar availability directly influences water access [19].

Innovative approaches using nanofluid-based thermal collectors have also demonstrated improved thermal conductivity and energy absorption [20]. Studies incorporating the Cattaneo-Christov model have further expanded the understanding of transient thermal behavior in solar systems [21]. However, such thermal enhancements are typically explored in parabolic thermal collectors rather than PV-based systems, with few real-world links to solar water pumping.

Despite these advances, there is limited literature integrating bifacial PV systems, passive optical enhancements, and AI-based forecasting into a single, field-tested solution. This study addresses that gap, presenting a comprehensive system tailored for rural infrastructure that prioritizes performance, simplicity, and scalability.

1.3 Research Gaps and Challenges

While bifacial PV systems and AI-based forecasting methods have gained significant attention, most studies are constrained to simulation environments or laboratory prototypes. There remains a clear lack of integrated approaches that combine bifacial PV modules, passive optical concentration, and AI-driven energy yield prediction validated under real-world conditions. Additionally, long-term thermal impacts on concentrator configurations, such as heat-induced degradation and performance losses, are rarely addressed in current literature. Reflector material durability, exposure to environmental contaminants, and sustained optical efficiency also pose unresolved challenges. These gaps underscore the need for a validated, durable, and intelligent solar water pumping solution optimized for off-grid, rural deployment.

1.4 Motivation

The motivation behind this research stems from the pressing global need for reliable water access in underserved and infrastructure-deficient regions. Although solar-powered water pumping systems provide a sustainable solution, many are either cost-prohibitive, overly complex, or insufficiently adapted for harsh field conditions. Our goal was to design a practical system that overcomes these limitations by integrating passive bifacial PV enhancements and predictive intelligence. The intention was to create a solution that delivers consistent performance without reliance on active tracking systems or intensive maintenance–making it viable for real-world deployment in economically constrained areas.

1.5 Major Contributions/Novelties

This study introduces an innovative and field-validated solar water pumping system that blends advanced technologies with rural practicality. The primary contributions include:

(1) A dual-panel bifacial PV configuration enhanced with static planar reflectors was developed and tested, achieving up to 31% greater daily water output without mechanical tracking.

(2) Implementation and performance comparison of ANN and ANFIS models provided accurate energy yield predictions across seasonal and environmental variations.

(3) Unlike studies confined to simulations, this research includes empirical validation under actual climatic conditions.

(4) The study evaluates the impact of module temperature rise under concentrator configurations, emphasizing the need for passive thermal mitigation.

(5) The system is built using low-cost, low-maintenance components, specifically designed for decentralized deployment in water-scarce areas.

1.6 Organization of the Paper

The remainder of this paper is organized as follows: Section 2 describes the system architecture, component selection, and design methodology, focusing on rural water requirements. Section 3 details the experimental setup, including the bifacial concentrator arrangement, ray-tracing simulations, and measurement protocols. Section 4 presents a comprehensive analysis of system performance based on both simulation and field results, including water output, temperature behavior, and overall efficiency. Section 5 discusses the development and application of AI-based models (ANN and ANFIS) for energy prediction and performance optimization. Finally, Section 6 summarizes key findings, outlines practical implications, and suggests future research directions with an emphasis on system scalability and durability.

2. System Design Methodology and Technical Specifications

2.1 Design Procedure for a Small-Scale Solar Water Pumping System

This section presents a systematic procedure for designing an off-grid, solar-powered water pumping system, ensuring the delivery of an adequate daily water supply tailored to site-specific environmental and technical conditions. The method encompasses the estimation of water requirements, determination of hydraulic energy needs, assessment of solar resource availability, and appropriate sizing of the PV array and associated components.

2.1.1 Estimate Daily Water Demand

The design process commences with the estimation of the daily water requirement (Q), typically expressed in cubic meters per day (m^3/day). This value is application-specific, depending on factors such as domestic usage, irrigation needs, or livestock supply. An accurate determination of Q is essential, as it sets the minimum system performance threshold [22].

2.1.2 Determine Total Dynamic Head

The Total Dynamic Head (TDH) reflects the vertical distance that the water must be elevated, factoring in both the static and dynamic components [23]:

Static Head (H_{Static}): The vertical elevation from the water source to the delivery point.

Friction Losses ($H_{Friction}$): Energy losses caused by friction within the pipes, valves, and fittings.

The total dynamic head is expressed as:

$$\mathrm{TDH} = H_{Static} + H_{Friction} \quad (1)$$

2.1.3 Calculate Hydraulic Energy Requirement

The hydraulic energy required to elevate the daily volume of water through the TDH is calculated using [24]:

$$E_h = \rho \times Q \times g \times H \quad (2)$$

where: E_h = Hydraulic energy (Watt-hours/day), ρ = Density of water (1000 kg/m³), Q = Daily water demand (m³/day), g = Gravitational acceleration (9.81 m/s²), H = Total Dynamic Head (m).

2.1.4 Assess Available Solar Radiation

The available solar radiation at the installation site, expressed as peak sun hours per day, significantly impacts the design of the PV array. Peak sun hours represent the equivalent duration of full solar radiation at 1000 W/m² and can be obtained from solar radiation databases or meteorological records.

2.1.5 Determine Required PV Array Power

The required power output from the PV system is estimated by:

$$P_{PV} = E_h \,/\, t_{Sun} \quad (3)$$

where: P_{PV} = Raw PV power required (Watts), t_{Sun} = Peak sun hours per day.

To account for system inefficiencies (e.g., pump inefficiency, inverter losses, wiring resistance), the adjusted PV power requirement is calculated as:

$$P_{\text{adjusted}} = P_{PV} \,/\, \eta \quad (4)$$

where η represents the overall system efficiency [25].

2.1.6 Size the PV Array and Electrical Components

The number of PV modules required (N) is then calculated based on the rated output of a single module:

$$\text{N} = P_{\text{adjusted}} \,/\, P_{\text{Modules}} \quad (5)$$

where: N = Number of PV modules, P_{Modules} = Rated power output of one module.

Selection of a suitable DC or AC water pump, along with necessary controllers and electrical accessories, should be based on compatibility with the designed PV array output and the hydraulic performance requirements [26].

2.2 Technical Design Specifications

To ensure the successful implementation of a small-scale, stand-alone solar-powered water pumping system, a well-defined set of technical specifications was established. These parameters guide the selection, dimensioning, and optimization of the system components to meet predefined operational targets under realistic environmental conditions. The design is structured to supply 1000 liters of water daily, elevated over a 22-meter head, using solar energy harvested by a suitably sized PV (Photovoltaic) array. The specifications below form the foundation for performance simulation, prototype development, and field deployment.

2.2.1 PV System Parameters

Table 1 outlines the core hydraulic and energy design calculations. Based on a 1000-liter daily water requirement and a TDH of 22 meters (which includes both static head and estimated frictional losses), the hydraulic energy needed for pumping is approximately 59.95 Wh/day. Considering average solar insolation of 6 peak sun hours and a conservative system efficiency of 50%, the required solar PV power output is calculated to be about 19.98 W. Accordingly, the design calls for a single 50 Wp solar module to fulfill this demand, accounting for performance losses.

Table 1. Solar PV system design specifications.

Parameter	Symbol	Value	Unit	Description
Daily Water Demand	Q	1000	liters/day	Volume of water required per day
Water Demand (m³)	Q	1	m³/day	Converted daily volume
Static Head	H	20	meters	Vertical lift from water source to tank
Friction Losses	-	2	meters	Estimated pipeline frictional losses
Total Dynamic Head	TDH	22	meters	Total lift including static and friction losses
Water Density	ρ	1000	kg/m³	Standard density of water
Gravity Constant	g	9.81	m/s²	Acceleration due to gravity
Hydraulic Energy Required	-	59.95	Wh/day	Total energy to lift water daily
Peak Sunshine Hours	-	6	hours/day	Effective solar insolation per day
Overall System Efficiency	-	50	%	Assumed combined efficiency of PV-pump system
Total Required PV Power	-	19.98	W	Net PV power required to meet demand
Power per PV Module	-	50	W	Rated capacity of selected solar panel
Number of PV Modules	-	1	panel	Required number of panels for operational capacity

2.2.2 PV Module Specifications

The selected PV module is a 50 W_p monocrystalline panel designed for compact solar applications. Key electrical and thermal characteristics are presented in Table 2. With an open circuit voltage (V_{oc}) of 21 V and short circuit current (I_{sc}) of 3.21 A, it is well-suited for 12-24 V DC systems. The temperature coefficient of -0.45%/°C reflects minor losses with temperature rise, typical of silicon-based modules. This panel offers a 14-15% module efficiency and is protected by a durable anodized aluminium frame and tempered glass cover. Its IP65-rated junction box ensures protection from environmental exposure, making it ideal for rural and outdoor conditions. Long-term reliability is supported with a 10-year product warranty and a 25-year performance warranty.

Table 2. Solar PV panel specifications.

Parameter	Specification	Unit
Maximum Power (Pmax)	50	Wp
Open Circuit Voltage (Voc)	21.0	V
Short Circuit Current (Isc)	3.21	A
Maximum Power Voltage (Vmp)	17.0	V
Maximum Power Current (Imp)	2.94	A
Module Efficiency	14-15	%
Temp. Coefficient of Power	-0.45	%/°C
Nominal Operating Temp. (NOCT)	45 ± 2	°C
Dimensions	670 × 550 × 35	mm
Weight	5-6	kg
Frame Material	Anodized Aluminum	-
Glass	Tempered Low-Iron	-
Junction Box Rating	IP65	-
Operating Temp. Range	-40 to +85	°C
Maximum System Voltage	1000	V DC
Warranty (Product Defects)	10	years
Warranty (Performance ≥ 80%)	25	years

2.2.3 Pump and Controller Specifications

Table 3 details the specifications of the water pump and its controller. The pump is designed for 12-24 V DC operation and draws between 20-30 W—well within the output capacity of the selected PV module. The matching controller regulates voltage and current to ensure stable operation, protect the pump, and enhance energy conversion efficiency. This configuration is simple, robust, and suited to off-grid environments. The low-power requirement ensures efficient use of solar energy while maintaining reliable water delivery.

Table 3. Solar PV pump and controller specifications.

Component	Specification
Solar Panel	50 Wp, 17-21 V, 2.5-3 A (DC Output)
Water Pump	12 V or 24 V DC, 20-30 W Power Draw
Controller	12 V or 24 V DC Pump Controller

2.3 System Architecture and Layout

Figure 1 depicts the schematic layout of a small-scale solar PV water pumping system designed for off-grid applications. The system utilizes solar energy to power a motorized pump, transferring water from a lower tank to an elevated storage tank, thus simulating real-world rural or household water lifting scenarios. Two 35 W_p solar PV modules (totalling 70 W_p) are installed with an optimal tilt to maximize solar radiation capture. These modules supply direct current (DC) electricity to a 50 W-rated DC motor-pump unit submerged in a 20-liter lower water tank. The pump elevates water vertically to an upper 20-liter tank placed at a height of 5 meters, representing the total head of the system.

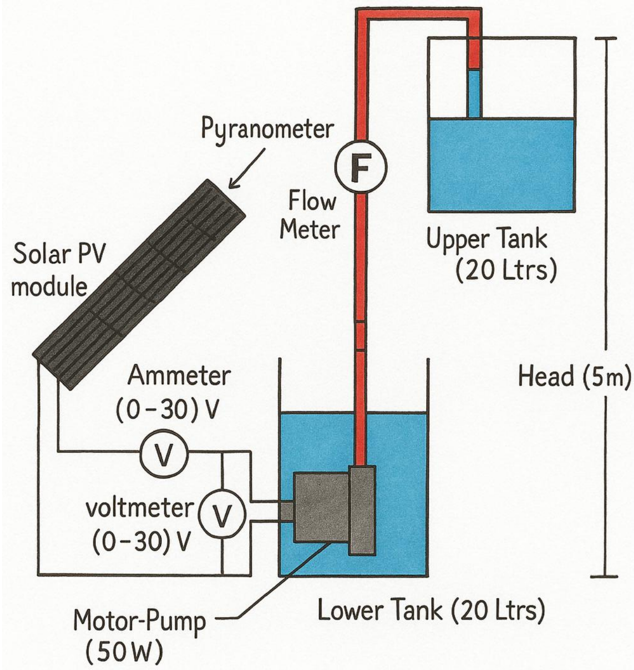

Figure 1. Schematic diagram of a solar PV water pumping system.

To evaluate system performance, a voltmeter and an ammeter are connected to monitor the electrical input to the motor-pump. A pyranometer positioned near the PV panels measures incident solar irradiance in watts per square meter (W/m²), ensuring accurate solar input data collection. A flow meter is installed within the pipeline to monitor the volumetric flow rate, allowing detailed assessment of hydraulic output and system efficiency under varying solar conditions. The system operates entirely on direct solar power during daylight hours without any energy storage, reflecting a low-cost, practical solution suitable for rural applications. Integrated sensors and instruments enable both functional validation and quantitative performance analysis.

3. Reflective Bifacial PV Design and Simulation

To enhance energy yield in off-grid solar applications, especially for water pumping in rural settings, this section presents the design and simulation of a reflective bifacial photovoltaic system. A dual-panel arrangement with planar reflectors is explored to emulate bifacial behavior using monofacial modules. The system's optical and geometrical characteristics are examined to evaluate energy augmentation. Additionally, detailed ray-tracing simulations using *TracePro* quantify the irradiance improvement and validate the benefits of reflective augmentation. The analysis offers design insights into achieving higher performance in cost-sensitive, decentralized energy systems.

3.1 Design of Bifacial PV with Reflective Augmentation

Figure 2 depicts the experimental setup of a bifacial solar PV concentrator system, designed to improve solar energy collection for off-grid water pumping. The system employs two 35 Wp monofacial solar panels, mounted back-to-back on a central vertical steel support. The south-facing front panel captures direct sunlight, while the north-facing rear panel harvests reflected and diffuse solar radiation. To enhance the rear-side energy capture, two planar glass reflectors are installed at a 15° tilt on each side of the structure, redirecting additional sunlight towards the rear panel. The PV modules each measure 960 mm × 440 mm, and the structure spans 1290 mm in width, ensuring optimal spatial arrangement for light concentration and thermal dissipation. The setup enables quantitative measurement of the energy contributions from both the front and rear panels, simulating a bifacial effect using independent monofacial modules. This configuration is specifically beneficial for solar-powered water pumping applications in remote or rural environments, aiming to maximize energy yield and operational hours.

In CPV systems like this, concentration ratios are key indicators of performance. The Geometrical Concentration Ratio (GCR), which reflects the ratio of the collector aperture area to the PV receiver area, is calculated to be 2.0, indicating that the collector area is twice as large as the receiver surface. Meanwhile, the Optical Concentration Ratio (OCR), accounting for real-world optical losses such as reflection inefficiencies and dust effects, is slightly lower at 1.95. The marginal difference between GCR and OCR is typical for practical systems and highlights minor but inevitable losses in optical efficiency. These ratios provide a critical understanding of both the theoretical light-concentration potential and the practical performance of the system under natural outdoor conditions.

The evaluation of GCR and OCR facilitates a comprehensive assessment of the bifacial concentrator's effectiveness. A well-optimized concentrator PV system achieves a balance between structural geometry and optical performance, leading to enhanced solar energy harvesting, greater cost-effectiveness, and broader applicability for decentralized energy solutions. In particular, for rural water pumping, such improvements translate into longer operating periods throughout the day and more reliable energy supply. This experimental approach demonstrates the potential for scalable, efficient, and low-maintenance solar concentrator systems to contribute meaningfully to sustainable development goals in underserved regions.

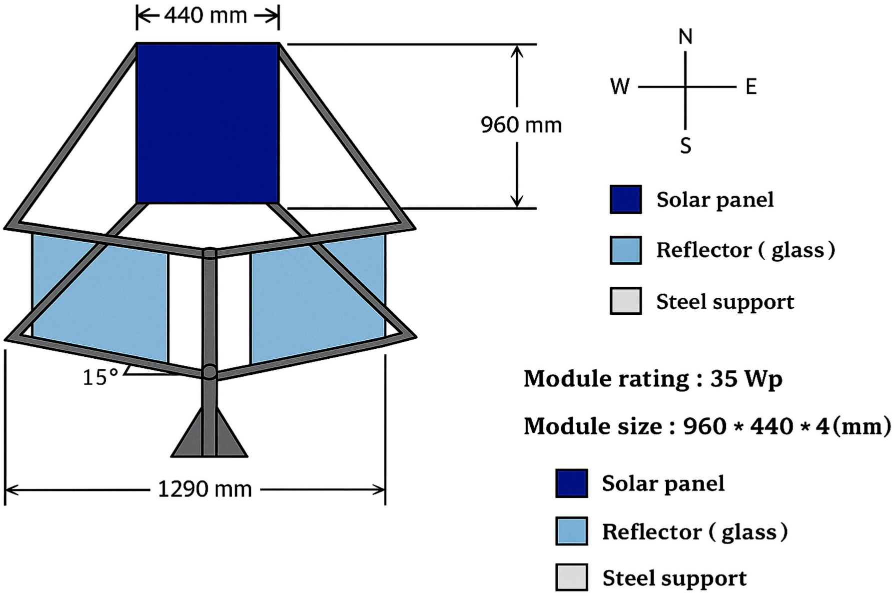

Figure 2. Experimental setup of the Bifacial solar PV concentrator system with dual 35 W_p panels and planar reflectors.

3.2 Optical Simulation Using TracePro

To analyze the optical performance of the bifacial concentrator PV system, a ray tracing simulation was conducted using TracePro software. The objective of the simulation was to quantify the intensity of incident solar radiation and the total power absorbed by the PV module under ideal and enhanced reflective conditions. The following figures illustrate the modeled scenarios and results.

Figure 3 illustrates the ray tracing configuration of the bifacial concentrator PV system. In this setup, a perfect mirror condition is assumed for the PV panel, while the reflectors on either side are treated as perfect specular reflectors. The source is modeled as a uniform solar radiation field of 1000 W/m². Incident solar rays (shown in red) strike both the PV panel directly and the angled reflectors, which redirect the rays toward the rear side of the PV module. This simulation demonstrates how concentrator geometry and reflector alignment can significantly boost the irradiance on the panel surfaces by utilizing reflected solar input.

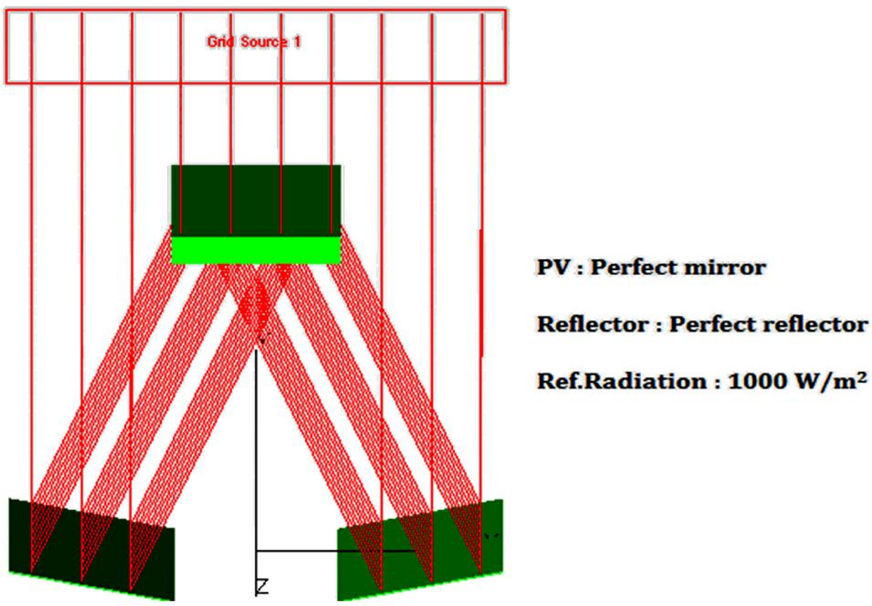

Figure 3. Ray tracing model setup (perfect mirror and reflector case).

Figure 4 presents the irradiance distribution map on the rear surface of the PV module under the influence of reflective enhancement. The radiation levels range from 800 W/m² to 2029 W/m², with an average irradiance of 1948 W/m² across the surface area. Under these ideal reflective conditions, the system absorbs a total power of 822 Watts, which is nearly 1.8 times higher than in the non-reflective baseline case. This result highlights the efficacy of reflective concentrators in significantly enhancing the energy absorption potential of bifacial or dual-panel PV systems—particularly during periods of lower direct irradiance.

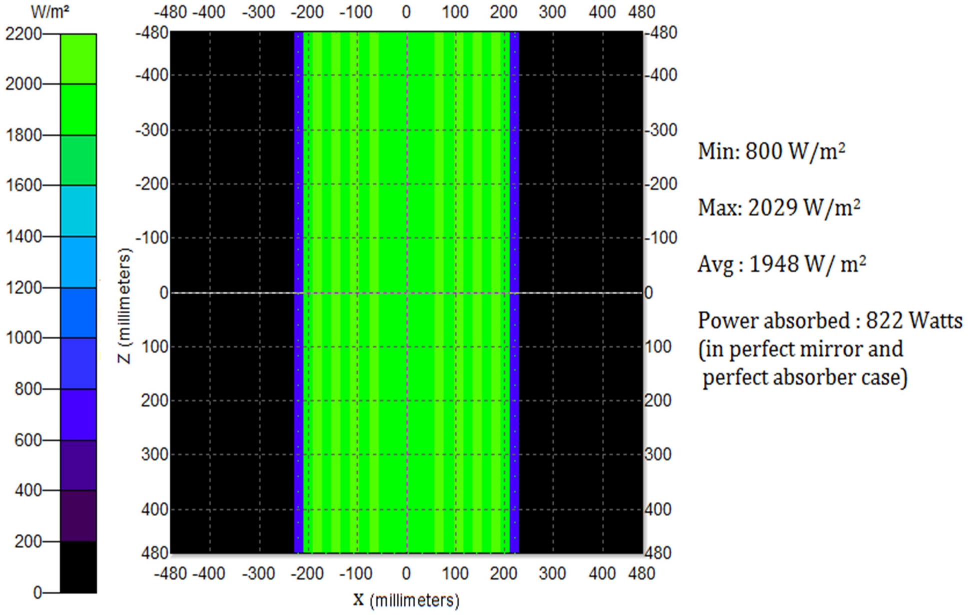

Figure 4. Irradiance distribution on back surface (with reflectors).

Figure 5 represents the baseline case, where the PV panel is illuminated by direct sunlight without any optical enhancements or reflective elements. The irradiance is uniformly distributed at 1000 W/m², resulting in a total power absorption of 460 Watts. This comparison underscores the benefit of integrating reflectors in the PV system design. The increase from 460 W (ideal flat panel) to 822 W (with reflectors) demonstrates a significant improvement in energy collection efficiency, validating the use of concentrator geometries for performance optimization.The ray tracing analysis confirms that the use of perfectly aligned reflectors substantially increases the solar irradiance incident on the PV module's rear surface, leading to enhanced power generation. These insights reinforce the potential of concentrator-based PV designs, particularly in resource-constrained and off-grid applications where maximizing energy output per unit area is crucial.

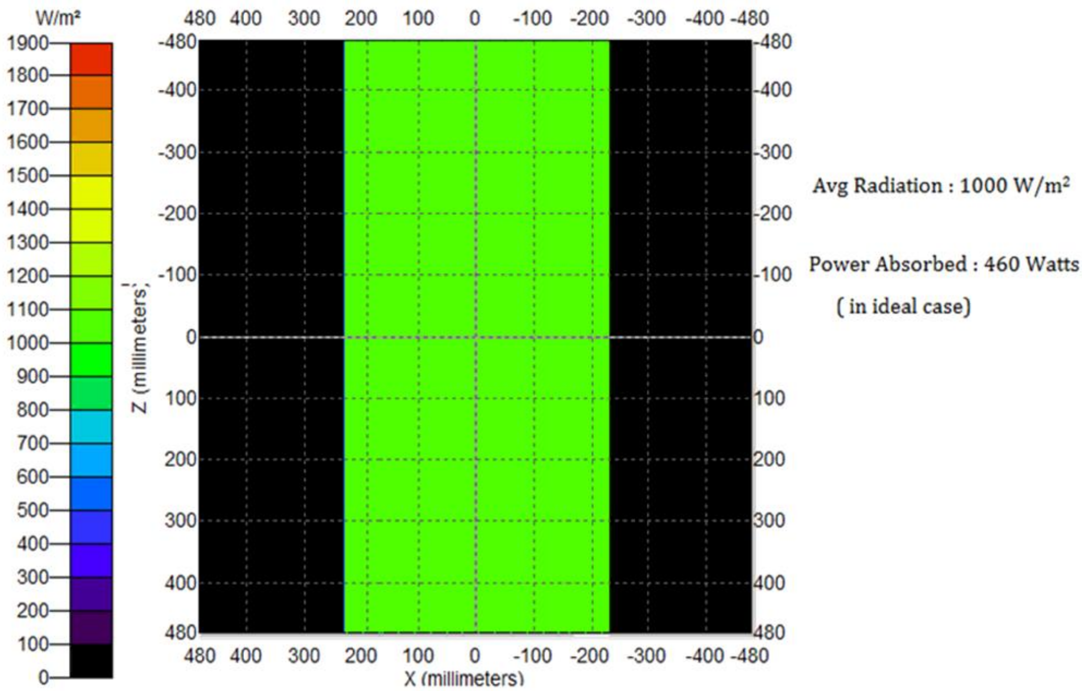

Figure 5. Irradiance distribution in ideal flat PV case (without reflectors).

4. Experimental Setup and Field Implementation

This section describes the practical realization of the proposed solar water pumping system, including its mechanical structure and instrumentation. A full-scale field prototype was developed to validate simulation results under real-world conditions. System performance was assessed using calibrated sensors and environmental data collected throughout daylight operation.

4.1 Physical Setup of Water Pumping Assembly

4.1.1 PV Concentrator Frame and Structure

To validate the simulation and theoretical analyses, a full-scale experimental test bench was constructed using commercially available components. The central feature of this setup is a custom-designed steel support frame, as illustrated in Figure 6, which holds two 35 Wp monofacial solar PV modules in a back-to-back configuration—effectively emulating a bifacial operation. The front module is oriented southward to capture direct sunlight, while the rear module harnesses diffuse and reflected irradiance.

Figure 6. Bifacial PV concentrator assembly.

To enhance rear-side illumination, two aluminum-coated planar glass reflectors are installed on either side at an optimized tilt angle. These reflectors redirect additional sunlight onto the rear module, boosting energy collection without mechanical tracking. The robust frame ensures structural stability under outdoor conditions and supports fixed-tilt optimization suitable for rural deployments.

4.1.2 Vertical Pumping Configuration

The system also integrates a gravity-fed water pumping arrangement, depicted in Figure 7, which reflects typical rural water distribution systems. A DC-powered submersible pump is placed inside a 20-liter ground-level tank, from where it lifts water vertically to an elevated 20-liter overhead tank. This vertical lift simulates practical irrigation or domestic water storage needs.

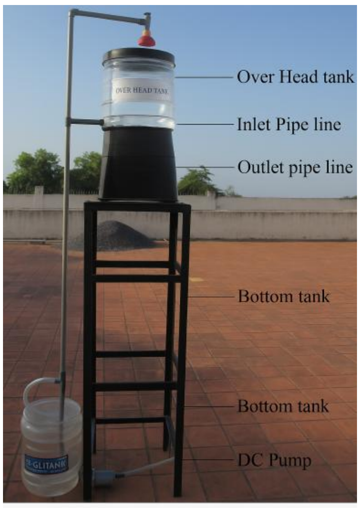

Figure 7. Water pumping system setup with vertical storage assembly.

The entire structure, including the piping, pump, and tanks, is mounted on a steel platform to ensure mechanical rigidity. This assembly enables the evaluation of hydraulic output, energy consumption, and operational reliability during field trials. The pumping operation is driven exclusively by solar power, without any energy storage, reflecting a low-cost, self-sustained solution tailored for off-grid use.

4.2 Real-Time Measurements and Instrumentation

4.2.1 Sensors and Logging Equipment

A comprehensive array of sensors was employed to monitor system performance in real time. A pyranometer was installed adjacent to the PV modules to measure solar irradiance, while voltmeters and ammeters recorded the electrical input to the DC pump. A digital flow meter in the outlet pipeline measured the water flow rate, facilitating accurate assessment of system efficiency and hydraulic productivity.

4.2.2 Environmental Conditions Monitoring

Environmental conditions such as ambient temperature, module surface temperature, and solar radiation variations were continuously logged. Thermocouples placed on the PV modules captured real-time thermal behavior under concentrated solar exposure. These measurements were critical in correlating irradiance levels with output performance and thermal load.

Data collection spanned the entire solar window, from 08:00 to 17:00, ensuring the capture of temporal variations and peak operating conditions. These insights established the real-world efficacy of the bifacial concentrator system under typical rural and off-grid usage scenarios.

5. Results and Discussion

This section presents the experimental and simulation-based evaluation of the bifacial PV concentrator system integrated with a solar water pumping assembly. Key performance metrics such as solar irradiance patterns, thermal behavior, electrical output, water pumping rate, and system efficiency are analyzed under real-time outdoor conditions. The role of reflective augmentation is quantified through comparative analysis with reference monofacial systems. Furthermore, the section discusses AI-assisted predictions using ANN and ANFIS models to estimate monthly and annual energy yields, offering insights into long-term performance trends and practical applicability. The findings highlight the enhanced effectiveness of bifacial concentrator PV configurations in off-grid scenarios, supporting sustainable energy and water access initiatives.

5.1 Solar Irradiance and Thermal Behavior

Figure 8 illustrates the diurnal variation of solar irradiance recorded under clear-sky conditions. The curve follows a typical bell-shaped pattern, with irradiance increasing from approximately 650 W/m² at 8:00 a.m. to a peak of 1000 W/m² around 1:00 p.m., then decreasing to about 660 W/m² by 5:00 p.m. This irradiance profile defines the active operational window for photovoltaic systems and directly governs the energy availability for driving the water pump. The stable irradiance progression throughout the day supports reliable power generation and reflects favorable conditions for solar energy harvesting.This pattern also confirms the solar potential at the site and enables effective scheduling of daily pumping operations. Additionally, it provides a consistent testing condition for validating system response under real sunlight exposure.

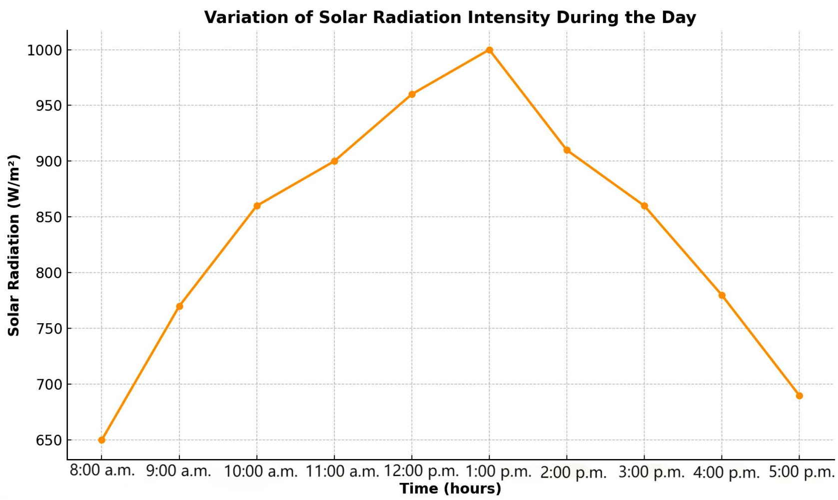

Figure 8. Diurnal variation of solar irradiance on clear day conditions.

Figure 9 presents the temperature profiles of PV modules in both concentrator-based and reference configurations. It is observed that module temperature rises proportionally with irradiance, with the concentrator system reaching a maximum of around 56 °C, while the reference module remains lower at about 45 °C. This increase in temperature under concentrated conditions is expected due to intensified solar flux. Although higher module temperatures may marginally reduce electrical efficiency due to thermal effects, the concentrator still delivers greater net output, making the trade-off acceptable within the system's design. This data highlights the importance of considering thermal behavior in bifacial systems using reflective augmentation. It also suggests the potential benefit of integrating passive cooling mechanisms in future implementations.

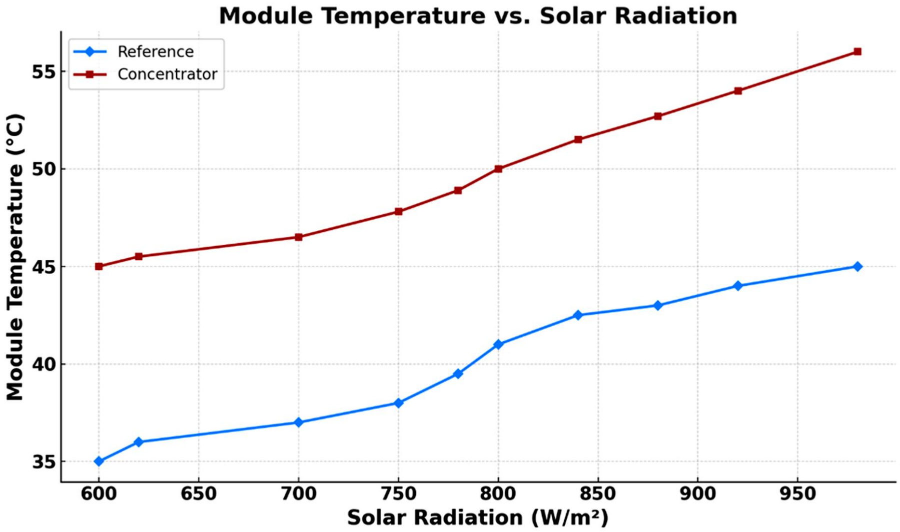

Figure 9. Comparison of module temperature versus solar radiation for reference and concentrator PV modules.

5.2 Power Output Comparison

Figure 10 compares the electrical power output from both PV systems. The concentrator module consistently produces higher output throughout the day, reaching a peak of 26 W, whereas the reference module peaks at 19 W. This demonstrates a clear enhancement in energy conversion due to reflective augmentation, which increases the total incident irradiance—both direct and reflected on the bifacial surface. The output trend aligns closely with the irradiance curve in Figure 8, confirming the responsiveness of the PV system to solar input variations. The performance improvement validates the optical efficiency of the concentrator arrangement. Furthermore, the increased power directly translates to a longer effective operating period for the water pump.

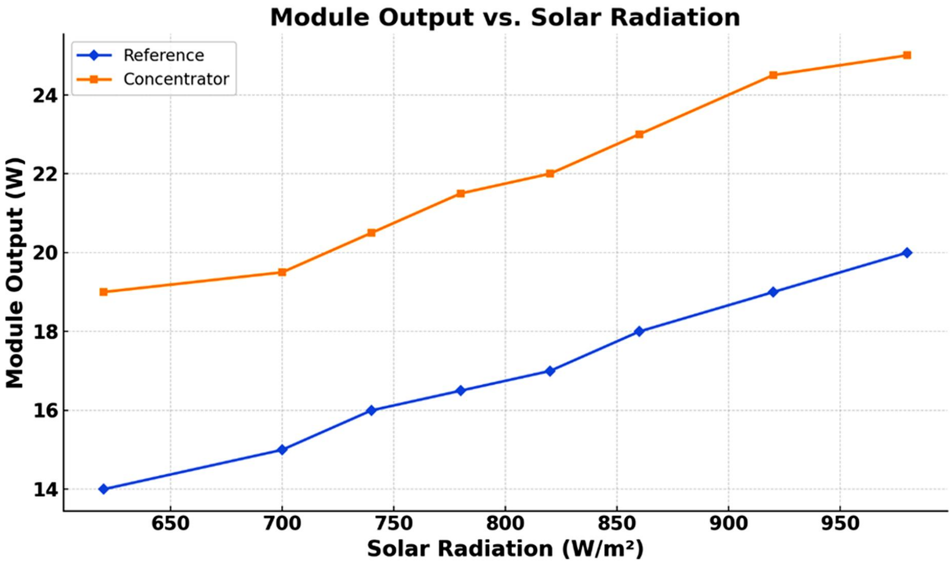

Figure 10. Module output power as a function of solar radiation: concentrator vs. reference PV systems.

5.3 Water Pumping Rate Analysis

Figure 11 shows the hourly water pumping rate corresponding to the electrical power available from the PV modules. The concentrator-based system achieves a maximum flow rate of approximately 370 L/h, compared to 250 L/h for the reference. This higher delivery rate is directly correlated with the increased electrical power available to the pump.

Efficient water delivery during peak sunlight hours ensures timely fulfillment of irrigation or domestic water needs, reducing system operating time and energy expenditure.The enhanced throughput indicates the system's suitability for locations with limited water access or high daily demand. It also emphasizes the importance of synchronizing hydraulic load behavior with PV power output.

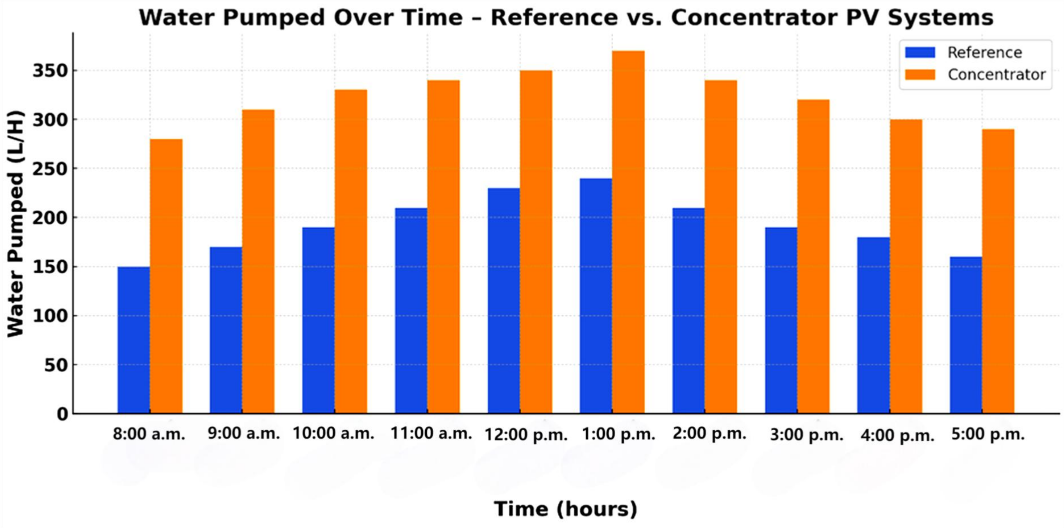

Figure 11. Hourly water pumping rate comparison between concentrator and reference PV systems.

5.4 Pump Efficiency Performance

Figure 12 depicts the pump efficiency as a function of input power. The concentrator system consistently achieves higher efficiency, ranging from 11.5% to 12.5%, while the reference setup remains in the 7.5% to 10.5% range. This indicates better matching between power supply and pump operational characteristics in the concentrator-based design. Improved pump efficiency leads to greater water output per unit of energy consumed, thereby enhancing the system's overall sustainability and suitability for remote or off-grid applications.

The stability of efficiency across a wide power range suggests that the concentrator system operates close to the pump's optimal point more frequently. This performance consistency adds reliability to autonomous water pumping in solar-only systems.

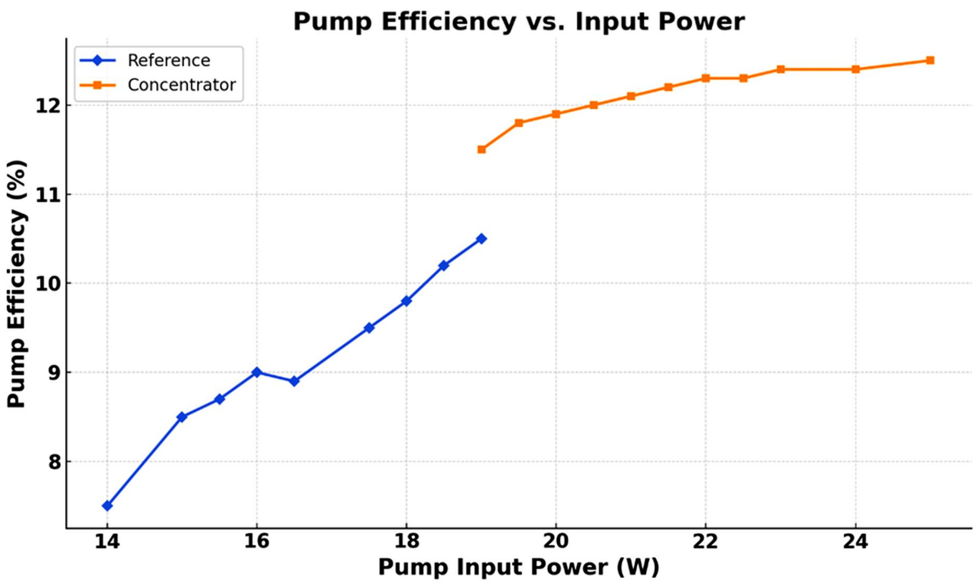

Figure 12. Pump efficiency as a function of input power for reference and concentrator PV systems.

6. AI-Based Energy Prediction and Forecasting

With the increasing deployment of solar-powered systems in off-grid and resource-constrained environments, accurate energy forecasting is critical for optimizing system performance, scheduling operations, and ensuring reliability. To this end, two advanced Artificial Intelligence (AI) techniques ANN and ANFIS were employed to model and predict the energy yield of the proposed bifacial PV water pumping system under real environmental conditions.

6.1 Overview of AI Models (ANN and ANFIS)

As part of the system performance enhancement and long-term planning, AI techniques specifically ANN and ANFIS were deployed for energy yield forecasting. These models were selected for their capacity to handle nonlinearity, environmental uncertainties, and temporal dependencies inherent in solar energy systems.

The ANN model was utilized for short-term forecasting, offering rapid and adaptive hourly or daily predictions. Trained on empirical irradiance and temperature data, ANN models captured the real-time behavior of PV output with minimal error. Such real-time forecasting is vital for load management, predictive water delivery scheduling, and system protection mechanisms, especially in isolated setups where reactive control is infeasible. ANN's fast convergence and low computational load also make it suitable for embedded deployment in low-resource environments.

For medium to long-term forecasting, the ANFIS model was implemented to predict monthly and annual energy yields with high robustness. Unlike ANN, ANFIS integrates a fuzzy logic framework capable of interpreting imprecise data and managing ambiguous solar patterns—such as seasonal irradiance shifts, cloud cover fluctuations, and albedo variation—while retaining learning capabilities through neural adaptation. This hybrid intelligence enables ANFIS to provide accurate long-horizon forecasts, which are essential for system sizing, return-on-investment analysis, and sustainability assessments.

6.2 Monthly Energy Yield Prediction Using ANFIS

Figure 13 shows the monthly energy yield comparison based on the ANFIS forecast. The bifacial PV modules demonstrated consistently higher energy output across all months compared to monofacial modules. Performance gains were especially significant during the months of March to July, coinciding with higher ground reflectivity and greater solar elevation angles. During this period, bifacial modules exhibited an average increase in energy yield exceeding 30%, primarily due to the effective capture of rear-side irradiance, demonstrating the critical role of module positioning and surface albedo in maximizing bifacial system advantages.

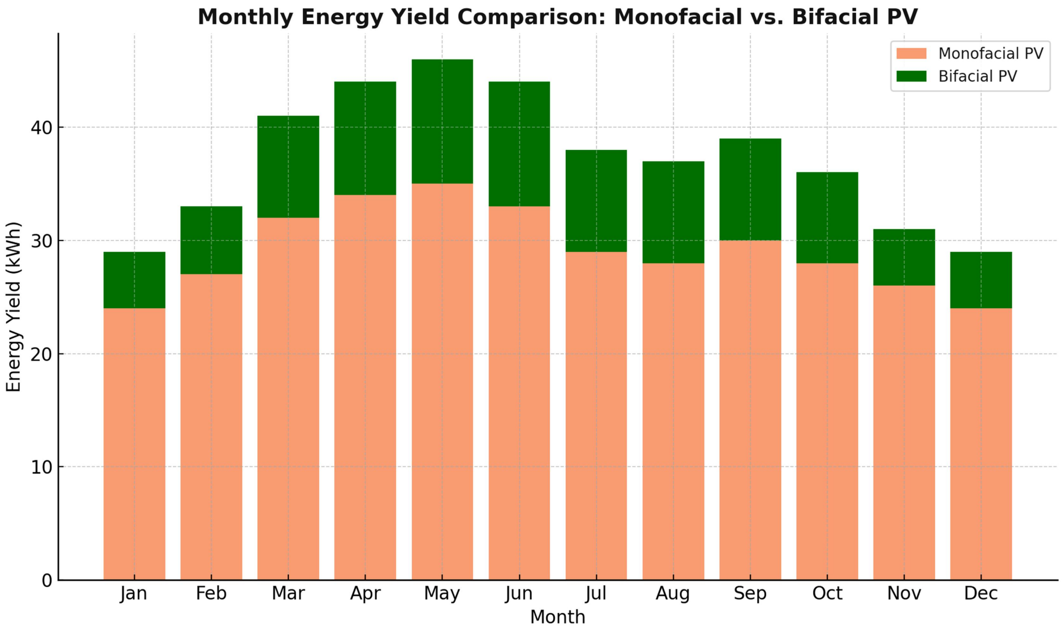

Figure 13. Monthly energy yield comparison of monofacial and bifacial PV systems using ANFIS forecasting.

Figure 14 presents the monthly yield gain percentage, further confirming the superior performance of bifacial modules. The maximum monthly gains were recorded during April, May, and June, where the energy yield improvements ranged from 31% to 34%. Even during months with lower solar irradiance, such as December and January, bifacial modules still achieved an energy yield improvement of over 25% compared to monofacial systems. This reflects the ability of bifacial modules to utilize diffuse radiation and operate efficiently even under low solar angles or cloudy conditions, providing significant performance reliability across varying environmental conditions.

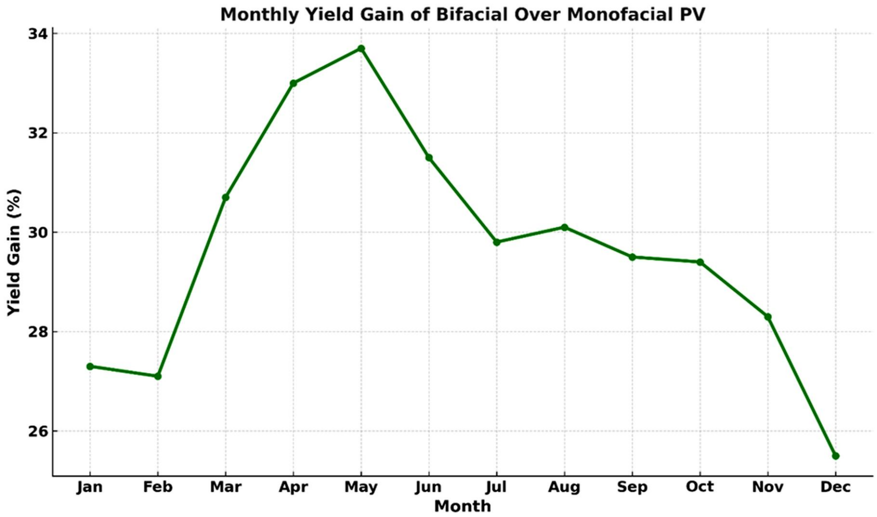

Figure 14. Monthly energy yield gain (%) of bifacial PV over monofacial PV based on ANFIS predictions.

6.3 Annual Forecast and Comparative Evaluation

Figure 15 displays the cumulative annual energy output derived through ANFIS prediction. The cumulative curve indicates a progressively increasing divergence between bifacial and monofacial modules as the year advances. By December, the bifacial system achieved a total cumulative yield of approximately 480.8 kWh, compared to about 346.1 kWh for the monofacial system. This equates to an overall annual gain of 31.4% in favor of bifacial modules.

The results obtained through the ANFIS-based forecasting approach clearly confirm the superior annual energy harvesting capability of bifacial systems, validating their enhanced economic viability, particularly for applications such as off-grid rural electrification, agricultural solar water pumping, and remote area deployments, where maximizing energy efficiency and return on investment is critical.

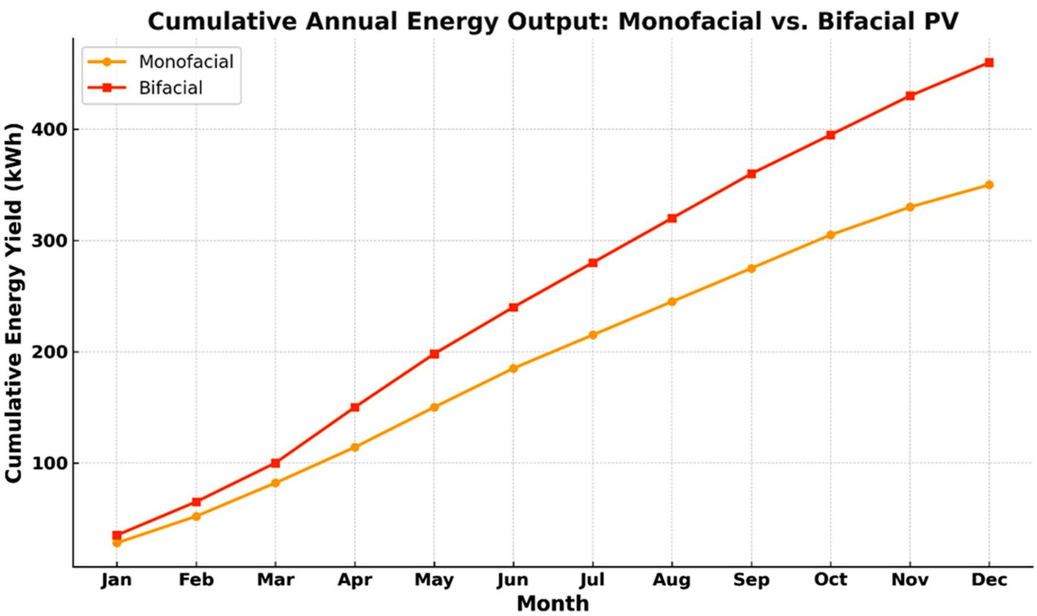

Figure 15. Cumulative annual energy output of bifacial and monofacial PV systems predicted using ANFIS.

7. Future scope

The future direction of this research involves enhancing the long-term performance and sustainability of the bifacial PV concentrator water pumping system. Addressing thermal effects is crucial, as high temperatures observed in concentrator modules can accelerate degradation; thus, passive cooling strategies such as high-emissivity coatings or ventilated frames should be explored. Likewise, the durability of aluminum-coated reflectors under environmental stressors like dust, ultraviolet (UV) radiation, and corrosion requires further investigation, potentially through protective surface treatments or anti-soiling coatings. Future studies will also focus on scaling the system for larger applications and integrating IoT-based remote monitoring for maintenance automation. AI models such as reinforcement learning could be used to adapt energy forecasting dynamically, improving operational reliability. Finally, broader deployment should align with Sustainable Development Goals (SDGs), especially goals 6 and 7, ensuring environmental and social impact in rural electrification and sustainable water access.

8. Conclusion

This study demonstrates the technical viability and practical effectiveness of an integrated bifacial photovoltaic concentrator system for small-scale solar water pumping in off-grid and rural environments. By combining static planar reflectors with dual-panel PV modules, the system achieves enhanced rear-side irradiance without the complexity and cost associated with mechanical tracking. Field experiments validated this improvement, showing up to 31% higher daily water output and pump efficiency gains exceeding 12% compared to traditional fixed-tilt PV systems.

Thermal and electrical performance analyses revealed that while concentrator modules experience higher operating temperatures, they consistently outperform reference systems in power generation. Furthermore, the adoption of AI-based forecasting techniques, specifically ANN and ANFIS models, enabled reliable short- and long-term energy yield predictions. The ANFIS model forecasted a 31.4% annual energy gain for the bifacial configuration, underscoring its robustness under dynamic climatic conditions. From a sustainability perspective, the proposed solution directly supports SDG 6: Clean Water and Sanitation, by enabling access to a reliable and decentralized water supply in underserved regions. Simultaneously, it advances SDG 7: Affordable and Clean Energy, through the use of cost-effective, low-maintenance solar technology enhanced with intelligent energy prediction capabilities. The system's modular design, use of readily available materials, and minimal operational overhead make it particularly suitable for remote areas facing infrastructural limitations. In conclusion, the bifacial concentrator PV water pumping system provides a scalable, energy-efficient, and socially impactful solution that addresses both environmental and humanitarian challenges. Future work should focus on thermal management strategies, material durability under field exposure, and scale-up feasibility for community-level water supply systems.

Data Availability Statement

The data generated and analyzed during this study are not publicly available due to privacy concerns and institutional restrictions. They contain site-specific calibration details and sensitive experimental records. Anonymized or synthetic datasets will not be provided. Researchers may contact the corresponding author for clarification on the methodology or modeling approach

Disclosure of Interest

No potential competing interest was reported by the authors.

Declaration of Funding

No funding was received.

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