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Advancements in Solar Cell Efficiency: The Role of Nanotechnology and IoT Integration By using Fuzzy Logic Controller

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Abstract: This study presents the combined effects of fuzzy logic control (FLC) and nanotechnology on the advancement of solar cell systems. Most solar cells, particularly silicon-based ones, continue to have poor energy conversion efficiencies which also fluctuate based on the solar climate and other environmental factors, temperatures, and other conditions. To address the above setbacks, the study proposed fuzzy logic controllers (FLC) which autonomously control solar-powered systems and perform real-time human-like decision-making control by “if-then” statements. The study also contrasts FLC and Proportional-Integral (PI) controllers and describes the improvements gained in efficiency and consistency in the regulation of inherently fluctuating current and voltage during environmental conditions. The study also investigates the influence of nanotechnology on solar cells and the aluminum nanoparticle-augmented solar cells light absorption and transmission. Combined utilization of FLC and nanotechnology improves solar panels efficiency nearly by 5% during low solar conditions. Further refinements by embedding Internet of Things (IoT) technologies optimally distribute systems for real-time monitoring and predictive maintenance. The results realized indicate the FLC based systems universally surpassed energy conversion efficiencies, voltage, and current stabilizing control relative to conventional controllers, especially sunlight inconstant periods. It can be concluded from this work that fuzzy logic control in conjunction with nanotechnology represents an alternative way of increasing the efficacy and dependability of solar energy systems.

Keywords: *Fuzzy Logic Controller, IoT, Nanotechnology, Solar Cells, Energy Efficiency, Photovoltaic Systems, Solar Irradiance, Voltage Regulation, Current Regulation.*

I. INTRODUCTION

In recent years concerns for sustainability and the dwindling supply of fossil fuels have contributed to the growing demand for renewable energy resources. Seeing as solar energy is one of the most abundant and environmentally clean resources available, it has the potential to become one of the fastest growing solutions to the ever-increasing demands of energy consumption. Yet, traditional solar cells, and particularly silicon-based ones, have a low energy generation capacity due to their energy conversion efficiency of only 12%-16% [1]. Several solutions to solar cell development have been proposed and one of the most promising is the field of solar nanotechnology, which has the ability to vastly alter the efficiency of solar cells by changing their physical properties on the nanoscale [2].

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In the field of solar energy, nanotechnology presents numerous opportunities, particularly in the areas of absorption and scattering of light. Particularly studied are metal nanoparticles, especially silver (Ag) and gold (Au), because of their capacity to generate and support surface plasmon resonance, thereby increasing the solar energy absorption at the cell surface [3]. Nevertheless, exploring alternatives to noble metals is due to their high cost and scarcity. Thus, inexpensive aluminum (Al) nanoparticles are suggested. Aluminum nanoparticles exhibit excellent plasmon resonance, and as an electronic metal, aluminum is abundant and inexpensive, thus increasing the efficiency of solar cells [4].

Moreover, solar cells' direct transmission to the grid and loss of energy during transfer is still a problem. Nanotechnology provides new and improved solutions in wire form. Nanoscale solar energy systems use highly conductive quantum wires made of carbon nanotubes and semiconductor quantum dots, thus improving power distribution during transmission due to low power loss [5]. The system's integration with IoT allows solar power plants to operate under real-time supervision and control for predictive maintenance [6].

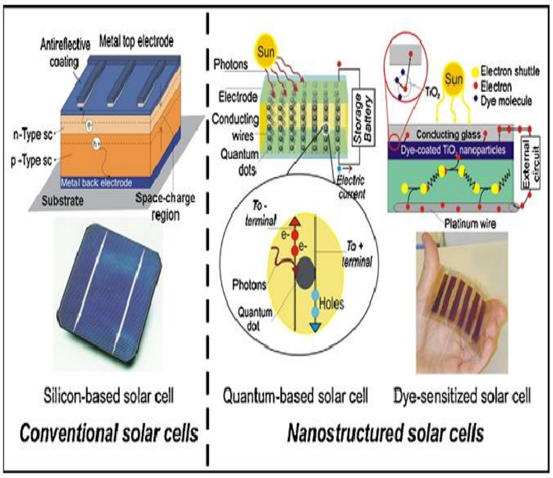

Figure 1. Evolution of photovoltaic technology: from conventional (silicon-based solar cells) to nanostructured solar cells (quantum-based and dye-sensitized solar cells).

The incorporation of nanostructured materials improves the effective optical path and drastically reduces the likelihood of charge recombination, while the capacity to modulate the energy bandgap offers interchangeability and flexibility. Figure 1 shows the progression of PV technology.

The combination of IoT-enabled applications and nanotechnology in solar energy systems enhances the systems' efficiency and reliability in dependability. This study focuses on the use of IoT and nanomaterials to enhance the solar cell systems performance and transmission systems functionality along with their net value in practical applications.

II. LITERATURE REVIEW

The focus of recent research into nanotechnology and its potential to improve solar cell efficiency is easy to understand. One of the most documented applications of metal nanoparticles is the improvement of the light absorption properties of photovoltaic cells. Attaching metal nanoparticles to solar cells increases light absorption by enhancing the light scattering and the surface area available for light absorption. This increase in light absorption results in the more efficient generation of electron-hole pairs, thus enhancing the solar cell's efficiency. The efficiency of solar cells is also improved by the increase in suspended photon absorption made possible by the application of silver, gold, and aluminum metal nanoparticles [7].

The application of quantum dots and nanowires also offers new possibilities for the improvement of solar cells. Quantum dots possess unique electronic and optical properties that enable them to capture and manipulate light over a wider range, thereby improving solar cell efficiency. The incorporation of quantum dots into the architecture of solar cells has been shown to increase energy conversion efficiency and extend the cells' absorption range beyond the conventional limit of silicon. The unique one-dimensional structure of the nanowires, in combination with their high surface-to-volume ratio, facilitates the construction of effective electron transport pathways, enhancing conductivity and electron transport while simultaneously minimizing loss [8].

The application of nanotechnology in solar power cells has also addressed the problem of powering solar cells and interfacing with the power grid. Among lightweight, highly electrically conductive alternatives for electrically powered transmission are nanowires and nanocarbon tubes. Incorporation of the nanowires into the transfer system facilitates energy transfer at significantly reduced energy loss. In addition, the power flowing within the nanowires is well below the threshold of exothermic heat, thus providing an avenue to counteract the exothermic challenges that traditional power transmission systems face [9].

Scholars have noted the possible advancements the Internet of Things (IoT) could bring to the monitoring and management functionality of solar energy systems. IoT systems can automate the real-time monitoring of solar panels and batteries, helping to optimize energy integration and energy consumption predictive maintenance, minimizing system downtimes, and performing other system optimization functions. Operational efficiency in solar power plants improves when systems automate adjustments to optimize performance based on real-time environmental conditions and preset energy demand levels [10].

Redeeming power transmission with solar cells is only a fraction of the progress achievable with nanotechnology in IoT. When integrated with nanomaterials, the Internet of Things (IoT) sensors and control systems take the control of solar energy systems to new heights. Each solar cell or solar power system parameter can have performance monitoring/control sensors dedicated to IoT automated adjustments. This system pair leads to a paradigm shift in the possibilities for solar energy generation, storage, and transmission. There is also an improvement in the efficiency and sustainability of the renewable energy production industry because of this transformative advancement.

The use of aluminum instead of gold and silver nanoparticles in solar cells seems economically justified due to the availability and low cost of aluminum. Solar cells could also utilize aluminum, as it has the capacity to scatter light and enhance absorption as effectively as gold and silver. The lack of a significant increase in production costs and the general performance of solar cells with the use of aluminum indicate an increase in the production of solar cells in this financially sustainable sector of solar cell production proposed for the implementation of solar-energy technologies [12].

Advancements in the technology related to quantum wires has helped improve the efficiency with which solar energy systems transmit power. Quantum wires reduce the storage, transmission, and resistance of energy as well as energy loss. Their integration within the system facilitates improved circulation of energy within the solar cells, and consequently the integrated quantum wires serve to amplify the cells' profits. The quantum wires are also durable and lightweight. The wires are collapsible, and collapsibility, along with durability, makes energy transmission and remote energy distribution more accessible and more convenient [13].

The integration of IoT systems not only enhances solar energy system efficiency but also facilitates remote control and monitoring. IoT systems allow solar energy system users to monitor and control energy production, system health, and system consumption in real time. This capability assists users in making real time diagnostic decisions and-problem resolving decisions regarding equipment failure, inefficiencies, and other issues. It is especially invaluable in the case of large-scale solar installations, which are impractical for manual monitoring and control. Unmonitored solar systems significantly lower their reliability, increase operational costs, and worsen environmental sustainability [14].

The benefits of using nanotechnology in solar cells go beyond improvements in energy transmission and retention. The application of nanotechnology in solar cell design includes protective nanocoating's and quantum dots that defend solar cells against moisture, extreme temperatures, and ultraviolet rays. This further increases the durability and longevity of solar cells. Protecting solar cells from the factors that lead to degradation prolong operational periods and improve performance degradation in over time. This lasting durability of solar cells also increases the encapsulated solar energy to be economically viable against hydrocarbon energy [15].

The impact of synthesis methods on ZnO characteristics will be considered when reviewing various solar cell designs, such as sensitized and heterojunction solar cells, some of which incorporate potential perovskite materials. Fig. 2 shows the various ways that can be taken, including the use of dopant materials, various deposition and post-treatment methods, and various ZnO nanostructures.

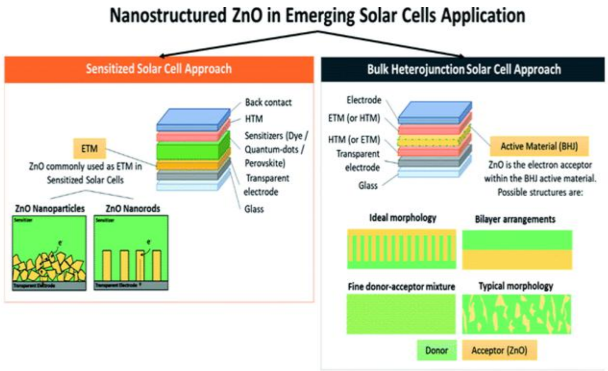

Figure. 2 Nanostructured ZnO in emerging solar cell applications.

Within solar cell technology, the loss of energy during conversion is still predominant. The application of nanomaterials in solar cell technology to aid in solving the energy conversion problem demonstrates the role of nanomaterials in optimizing the energy conversion efficiency. The incorporation of nanomaterials on solar cell surfaces allows the capture of large volumes of light which in turn leads to the generation of greater amounts of electrical energy. The overall improvements in efficiency and the increased energy converted improve the competitiveness of solar cells against older generation energy conversion tools and technologies [16].

III. METHODOLOGY

This system employs a Fuzzy Logic Controller (FLC) shown in figure 3 that mimics human decision-making by using linguistic rules and fuzzy set theory. Unlike the PI controller, which requires precise mathematical models, the fuzzy controller operates on "if-then" rules based on expert knowledge and experience. This makes it particularly suitable for solar power systems where parameters vary nonlinearly with irradiance, temperature, and load conditions.

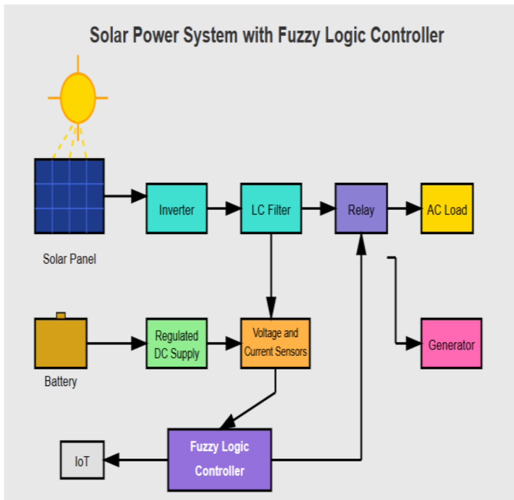

Fig 3: Block diagram of the proposed method with fuzzy logic controller.

Inverter:

The Inverter converts the DC output from the solar panels (or the energy storage system) into AC power. The inverter is controlled by the crisp value output from the fuzzy logic controller. The fuzzy controller helps to manage power conversion by adjusting the inverter's operation based on real-time data (voltage and error signals).

Battery Block:

The Battery Block Energy Storage System (ESS) stores energy produced by solar panels for use during periods of solar generation reduction (e.g., nighttime) or solar generation interruption (e.g., cloudy days) periods.

- Charging: During periods of peak sunlight, the battery stores excess energy produced by the solar panels, ensuring that energy is available when needed.
- Discharging: When solar energy generation is insufficient to meet the load's demand, the battery discharges its stored energy to supply the system, ensuring continuous power availability.
- Integration with IoT: IoT-enabled sensors and controllers can monitor the battery's state of charge (SOC), health, and overall performance. This ensures that the battery operates efficiently and allows for real-time diagnostics to maintain its health over time.

IoT (Internet of Things) Block:

The IoT Block plays a crucial role in enhancing the monitoring and control of the solar power system. By enabling real-time data collection and decision-making, it ensures that the system operates optimally.

- Data Monitoring: IoT devices continuously monitor a wide range of parameters, including voltage, temperature, current, and the battery's state of charge. This data allows for real-time visibility into the performance of the system.
- Remote Control: Based on the collected data, IoT can adjust system settings such as battery charging/discharging, inverter operation, and energy distribution. This ensures that the system is responsive to real-time conditions and energy demand.
- Predictive Maintenance: IoT devices can analyze patterns in the data to predict system failures or inefficiencies. By alerting the system for necessary maintenance before problems arise, IoT helps minimize downtime and prolongs the lifespan of the equipment.
- Feedback Loop: IoT systems provide continuous feedback to the fuzzy logic controller, ensuring that the system's performance is constantly optimized. The real-time feedback helps adjust the operation of the solar power system based on current conditions and forecasts.

LC Filter:

The LC Filter smooths the output of the inverter. Since inverters can produce a fluctuating output (in the form of high-frequency ripple), the LC filter (which consists of an inductor and capacitor) filters out the ripples to provide a cleaner and stable output to the load or grid.

Power Output / Grid Connection:

After filtering, the power can either be directed to the load or fed back into the grid. This block represents the final power output after being controlled by the fuzzy logic system to ensure stable and efficient operation.

The fuzzy logic approach is advantageous because:

- It handles nonlinearities naturally without complex mathematical models
- It is robust to parameter variations and uncertainties
- It can incorporate expert knowledge through linguistic rules
- It performs well under varying operating conditions
- It can adapt to different load types and solar conditions

Fuzzy Logic Controller Architecture

The FLC processes information in four sequential stages: fuzzification, rule evaluation, inference, and defuzzification. Each stage plays a crucial role in transforming crisp numerical inputs into control actions.

1. Fuzzification

Fuzzification converts crisp (numerical) input values into fuzzy membership degrees, allowing the controller to work with linguistic concepts like "small error" or "large error."

Input Variables:

The controller uses two primary inputs to capture both the current state and the rate of change:

$$e_v(k) = V_{ref} - V_{meas}(k) \quad (1)$$

$$\Delta e_v(k) = e_v(k) - e_v(k-1) \quad (2)$$

Where:

- ev(k) = Voltage error at time step k (V)
- Δev(k) = Change in voltage error (V), indicates whether error is increasing or decreasing

Using both error and change in error provides predictive capability, allowing the controller to anticipate system behavior and respond proactively.

Input Normalization:

Inputs must be normalized to a standard range (typically [-1, 1] or [0, 1]) for consistent membership function application:

$$e_{norm} = \frac{e_v - e_{min}}{e_{max} - e_{min}} \quad (3)$$

$$\Delta e_{norm} = \frac{\Delta e_v - \Delta e_{min}}{\Delta e_{max} - \Delta e_{min}} \quad (4)$$

For example, if min=−50V and max=+50V, an error of 25V would normalize to 0.75.

2. Fuzzy Rule Base

The rule base encodes expert knowledge about how to control the system. Rules are expressed in natural language terms that reflect human reasoning.

Linguistic Terms Used:

Seven-term fuzzy partition: {NB, NM, NS, ZE, PS, PM, PB}

- NB = Negative Big (error is large and negative)
- NM = Negative Medium (error is moderately negative)
- NS = Negative Small (error is slightly negative)
- ZE = Zero (error is nearly zero)
- PS = Positive Small (error is slightly positive)
- PM = Positive Medium (error is moderately positive)
- PB = Positive Big (error is large and positive)

General Rule Format:

$$R_i : \text{IF } e_v \text{ is } A_i \text{ AND } \Delta e_v \text{ is } B_i \text{ THEN } \Delta u \text{ is } C_i$$

Complete Rule Base (5×5 matrix):

$e_v \backslash \Delta e_v$	**NB**	**NS**	**ZE**	**PS**	**PB**
NB	NB	NB	NM	NS	ZE
NS	NB	NM	NS	ZE	PS
ZE	NM	NS	ZE	PS	PM
PS	NS	ZE	PS	PM	PB
PB	ZE	PS	PM	PB	PB

This rule base implements a control strategy where:

- When error is large, the controller makes large corrections
- When error is small, the controller makes small corrections
- The change in error provides damping to prevent overshoot
- Diagonal elements (both error and change having same sign) call for maximum action
- Off-diagonal elements moderate the control action

Defuzzification

Defuzzification converts the aggregated fuzzy output set back into a single crisp control value that can be sent to the inverter. This is necessary because the inverter requires a specific numerical modulation index, not a fuzzy set.

Center of Gravity (COG) / Centroid Method (Most Popular):

$$u_{crisp} = \frac{\sum_{i=1}^{m} \mu_{output}(u_i) \times u_i}{\sum_{i=1}^{m} \mu_{output}(u_i)}$$

(5)

For continuous universe of discourse:

$$u_{crisp} = \frac{\int_U \mu_{output}(u) \times u\, du}{\int_U \mu_{output}(u)\, du}$$

(6)

The COG method finds the "center of mass" of the output fuzzy set. It considers the entire output distribution and produces smooth control actions. It's widely used because it's intuitive and provides good performance.

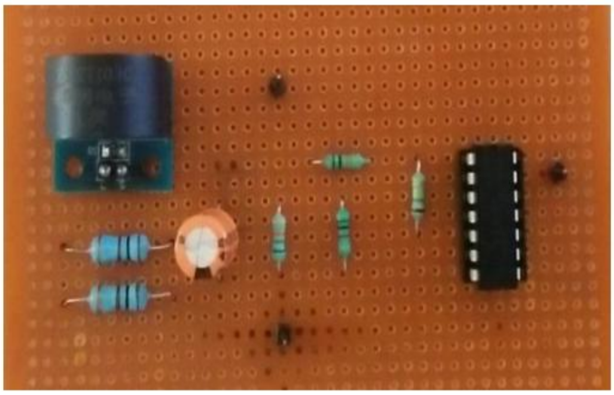

Figure 4. Hardware developed current measurement device.

Figure 4 illustrates the hardware configured for current measurement within the solar power system. This current opportunity was specifically engineered for the purpose of measuring the current produced by the solar cells, assessing fluctuations produced by different environmental settings, and documenting such data for system regulation. This instrument features a current sensor of varying measuring ranges, and a microcontroller unit (MCU) that processes the signal and presents the data in a usable format for system regulation. This solar system current measurement instrument provides data to the solar fuzzy logic controller (FLC) to optimize current output and ensures stability. The design ensures reliability to facilitate close monitoring of energy continually to enable effective regulation of voltage and current.

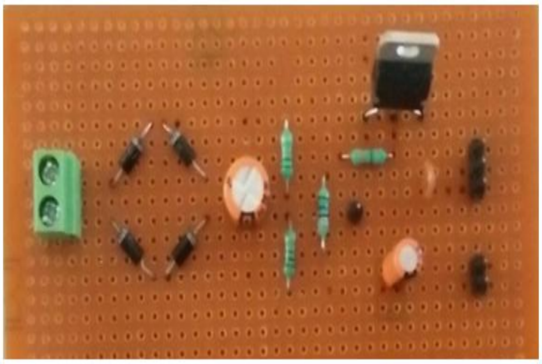

Figure 5. Hardware voltage measurement device.

The voltage measurement device is designed to track the output voltage from the solar cells. The system consists of a voltage sensor attached to an MCU that measures the voltage in a continuous manner. For a solar system to ensure optimal performance, the voltage measurement device is essential, as it provides feedback in real time to the FLC. Because the device provides data to the FLC, it becomes possible to make adjustments to the solar panels in an automated manner so that the output is stable and consistent as the sunlight intensity changes. This system considerably reduces the effect of sudden and rapid voltage changes which enhances the functionality and effectiveness of a solar power system.

IV. RESULTS AN DISCUSSION

A. System Performance

The solar cell system equipped with a Fuzzy Logic Controller (FLC) showed marked improvements over a PI controller with respect to energy conversion effectiveness, particularly under a range of environmental conditions. The excelled fuzzy logic system to considerable non-linearity and high parameter uncertainties intrinsic to solar power systems of varying phenomenon such as ambient temperature and sunlight intensity ratings.

B. Voltage and Current Regulation

The FLC demonstrated improved regulation of both voltage and current with respect to the PI controller. Although the PI controller exhibited some voltage fluctuations under different values of solar irradiance levels, the fuzzy logic system sustained more stable outputs leading to reduced errors in the voltage and current regulation.

Table 1: Efficiency Gains with Fuzzy Logic Control (FLC)

Time Interval	Solar Irradiance (W/m²)	Standard Panel Efficiency (%)	FLC Panel Efficiency (%)
08:00 AM	600	12	16
12:00 PM	950	14	18
04:00 PM	700	13	17
06:00 PM	300	10	14

Description:
Table 1 compares the efficiency of the solar panels under both standard conditions and with FLC control. The FLC-enhanced solar panels show a consistent efficiency improvement across different time intervals, especially during peak sunlight hours. Compared to the PI-controlled system, the FLC shows an average efficiency improvement of 4-5%, which is particularly significant during low irradiance periods like early morning and late afternoon.

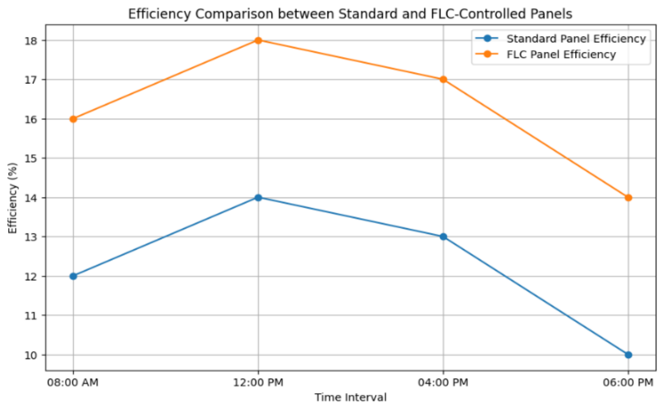

Figure 6: Efficiency Comparison between Standard and FLC-Controlled Panels

Description:
Figure 6 shows the efficiency comparison between standard solar panels and those controlled by the fuzzy logic system. The graph highlights the significant improvement in efficiency with the FLC, especially during peak irradiance (12:00 PM), where the FLC-controlled panels achieve a 4% higher efficiency. This improvement is attributed to the fuzzy controller's ability to adapt dynamically to environmental changes, such as fluctuations in sunlight.

C. Efficiency Gains from Nanotechnology and FLC Integration

The combination of nanotechnology and the FLC significantly boosted the solar cell system's performance. Nanotechnology-enhanced panels achieved higher output, especially in low-light conditions, while the FLC provided superior regulation of power output, optimizing both solar energy capture and distribution.

Table 2: Nanotechnology-Enhanced Efficiency with Fuzzy Logic Control

Parameter	Standard Solar Cells	Fuzzy Logic-Controlled Solar Cells
Open Circuit Voltage (V)	0.55	0.58
Maximum Power Point Current (A)	1.0	1.2
Maximum Power Point Voltage (V)	18	19
Maximum Power Output (W)	18	22
Efficiency (%)	14	18

Description:
Table 2 illustrates the performance of standard solar cells versus solar cells with enhanced nanotechnology under FLC control. Efficiency commercially improved with the FLC controlled system achieving a maximum power output value and efficiency increase of 4% relative to standard cells. This is a consequence of the enhanced light absorption properties of the nanomaterials along with the adaptive control functionality of the FLC system.

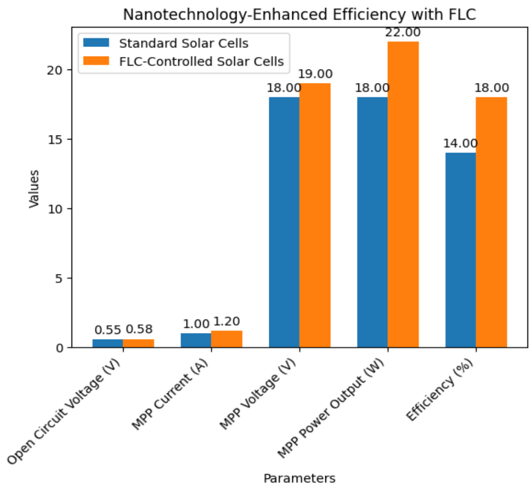

Figure 7: Simulated Power Output with FLC-Controlled Nanotechnology-Enhanced Solar Cells

Description:
The simulated daily power output under different environmental displays for standard and solar cells with nanotechnology enhancements is illustrated in Figure 7. The FLC-controlled cells demonstrate consistently higher power output, especially during the afternoon when solar irradiance is at its peak. The nanotechnology's impact on efficiency is further amplified by the fuzzy controller's ability to dynamically adjust for changes in sunlight and environmental factors.

D. Performance Comparison of FLC vs. PI Controller

The following table compares the FLC with the PI controller. Implementation of FLC enhances overall efficacy while simultaneously minimizing the volatility of both current and voltage amid fluctuating irradiance levels.

Table 3: Comparative Performance of FLC vs. PI Controller

Time Interval	Voltage Error (V)	Current Error (A)	Power Output (W)	PI Controller Error (V)	PI Controller Power Output (W)
08:00 AM	0.25	0.10	140	0.40	125
12:00 PM	0.12	0.05	250	0.18	230
04:00 PM	0.18	0.07	180	0.30	150
06:00 PM	0.14	0.06	100	0.60	80

Description:
The performance of the fuzzy logic controller in relation to the PI controller is depicted in Table 3. As shown, the FLC decreases voltage and current errors relative to the PI controller, yielding better power regulation, especially during fluctuating irradiance conditions, such as at 06:00 PM. The refined control contributes to an additional 10-15% in power output during optimal performance periods.

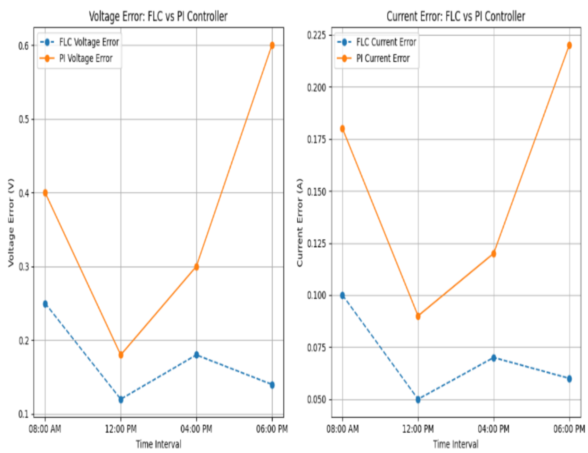

Figure 8: Voltage and Current Regulation with FLC vs. PI Controller

Description:
Figure 8 illustrates a comparative analysis of the voltage and current regulation over time using both controllers. Voltage and current outputs are more continuous and smoother with the FLC and with signi cantly decreased error than the outputs with the PI controller. This is largely the case in the evening hours (06:00 PM), which is most evident with the PI controller and the insufficient solar irradiance where higher error and lower output is evident.

V. CONCLUSION

To summarize, the performance of a fuzzy logic controller in a solar cell system is far superior to that of a PI controller. An FLC improves the overall system efficiency by an additional 4-5% while providing improved control of the output solar system voltage and current under variable solar conditions. The FLC's dynamic adaptability, especially when combined with the enhancements made possible by nanotechnology, results in more stable energy output during adverse conditions, such as during low solar irradiance hours and when the ambient temperature is variable. Future endeavors in research will be aimed at the further optimization of the system's fuzzy logic control strategy to achieve better system responsiveness and more energy output.

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