# ENHANCED SOLAR POWER GENERATION WITH IOT BASED LUMENS DETECTION, MONITORING, AND CONTROL

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## ABSTRACT

This study demonstrated the enhancement of solar power generation through a microcontroller-based Internet of Things (IoT) system. Equipped with a dual-axis solar tracking system, the model enables real-time monitoring and control to optimize solar panel performance. The new system enhances prior home-based solar systems by incorporating IoT for optimized performance tracking and manual operation, with lumens detection, real-time monitoring, and prototype testing. The prototype used the Design-Build-Test methodology, which employed light-dependent resistors (LDRs) and servo motors for accurate sunlight tracking, with remote management via the Blynk App. The tests revealed a reduction in voltage error to 0.24% in the calibrated system and a 0.45% current error, compared with 9.21% and 84.05%, respectively, in the uncalibrated system, despite varying weather conditions. Voltage ranged from 20.89V to 22.05V, dropping to 8.27V in rain, with power peaking at 37.58W in sunny conditions. For further development, implementing a dust-cleaning system, a battery percentage display, weather-resistant housing, and higher-capacity servo motors would enhance the model's reliability and efficiency. Nonetheless, the IoT-based model has been proven effective in enhancing energy output and addressing environmental variability, thereby supporting further sustainability in the Philippines. The system is designed to offer a scalable model for a wide range of applications, including residential and commercial solar systems.

*Keywords:* Internet of Things (IoT), microcontroller, dual-axis, servo motors, Blynk, lumens detection, solar power generation

## INTRODUCTION

In line with solar power systems, the Internet of Things (IoT) enhances the efficiency of its features through technology. Real-time optimization is achieved when smart sensors and connected devices constantly track environmental factors. Its features include IoT-based light-intensity sensors that enable precise tracking of lumens and facilitate adjustments to solar panel angles and positioning. Integrated monitoring systems facilitate rapid data analysis and operator-controlled adjustments, such as servo mechanisms, enabling swift responses to conditions like weather or light variations. Through IoT, solar installations maintain performance and efficiency.

Furthermore, maximized energy output is ensured by supporting automated or operator-driven interventions, including servo motors designed to adapt to weather or sunlight variations. Renewable energy research recognizes these advancements as ways to optimize system performance.

This research can be applied beyond the area of individual solar power systems. Different nations have been seeking to diversify their energy sources through renewable energy; hence, the development of power generation via IoT solutions is expected to contribute to greater energy resilience and the United Nations' sustainability goals. Consequently, this proponent contributes to reducing greenhouse gas emissions, which combats the growing threat of climate change.

Globally, countries like China and Germany lead in solar power capacity, with China accounting for over 36% of the world's total solar installations as of 2023. However, these systems often face challenges due to environmental variability (Altieri & Rangelova, 2024).

Research suggests that numerous solar farms operate below their potential due to inadequate real-time data on light conditions. Through IoT, operators can monitor light intesity and control the panel orientation to enhance energy output.

The government wants to achieve 20,000 Megawatts of solar capacity in the Philippines by 2040 (Morales, 2023). Despite the country's abundant solar resources, numerous installations face efficiency challenges, primarily due to seasonal and local conditions. Implementing IoT-based lumens detection systems can provide real-time insights, enabling operators to dynamically adjust their systems, thereby enhancing energy output and supporting national energy security.

The provincial government of Nueva Vizcaya, under the leadership of Governor Atty. Jose V. Gambito, is prioritizing renewable energy to combat climate change and reduce electricity costs (Vizcaya Reporter, 2024). The province has launched several initiatives to harness solar power, yet many local systems struggle to optimize performance. By integrating IoT technologies for lumens detection, local solar farms and residential installations can acquire valuable insights into sunlight exposure and operational efficiency. This localized approach empowers individual users to optimize energy generation and promote community-wide participation in the renewable energy endeavor's aspiration for a sustainable future.

## METHODOLOGY

### Research Design

The study employed the Design-Build-Test (DBT) methodology, an iterative approach involving system design, prototype construction, and performance testing. The design phase conceptualized a Wi-Fi-based IoT system with circuit and 2D prototype designs. The build phase assembled the prototype, integrating hardware and software components. The test phase evaluated performance parameters, including voltage, current, and power, through the Blynk application.

### Hardware Design

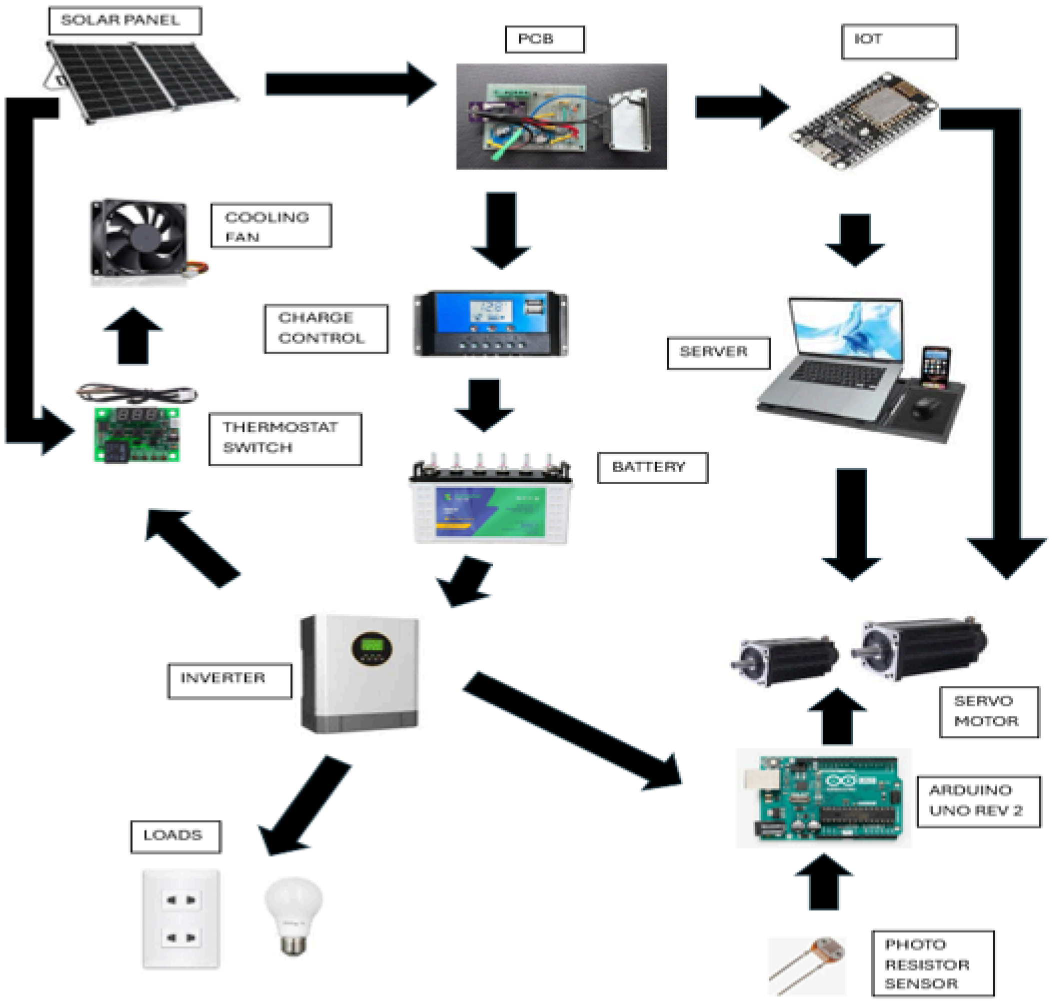
*Conceptual Framework*

The figure below shows the conceptual framework of the solar panel system. The input is underpinned by objectives that guide its development. After going through these processes, the output is a functioning solar panel system that tracks light intensity and can be monitored and controlled via Blynk.

The configuration of the solar panel system used to track, monitor, and control is described below. At its core, the framework uses a renewable energy source as its primary input, which is processed by a control unit that monitors and regulates system performance. An energy storage mechanism captures excess energy, while a conversion unit converts it into a usable form for household or industrial applications. Environmental sensing and control mechanisms, such as sensors and automated actuators, enable the system to adapt dynamically to external conditions, such as light and temperature.

**Figure 1**

*Interconnection of Project*



*Design of the Prototype*

The prototype was assembled by connecting electronic components to a PCB interfaced with the ESP32. The solar panel was connected to the charge controller through a fuse, followed by the battery and inverter. Servo motors were wired to ESP32 pins (5V, ground, pins 2 and 4) for precise control. The Blynk application enabled remote monitoring of voltage, current, power, and servo positions, with data displayed on a web dashboard.

**Software Design**

The researchers used the following software components: Arduino IDE for programming the ESP32 to control the system, Blynk Application for remote monitoring and Wi-Fi-based control, and AutoCAD for designing circuit diagrams and prototypes, collectively supporting the system's development and operation.

Figure 2 below illustrates the project's block diagram, depicting the interconnection of components. The solar panel feeds into the PCB, which interfaces with the ESP32, LDRs, and servo motors. The charge controller manages battery storage, and the inverter powers household loads. The ESP32 connects to the Blynk server for remote monitoring.

**Figure 2**

*Block Diagram of the Project*

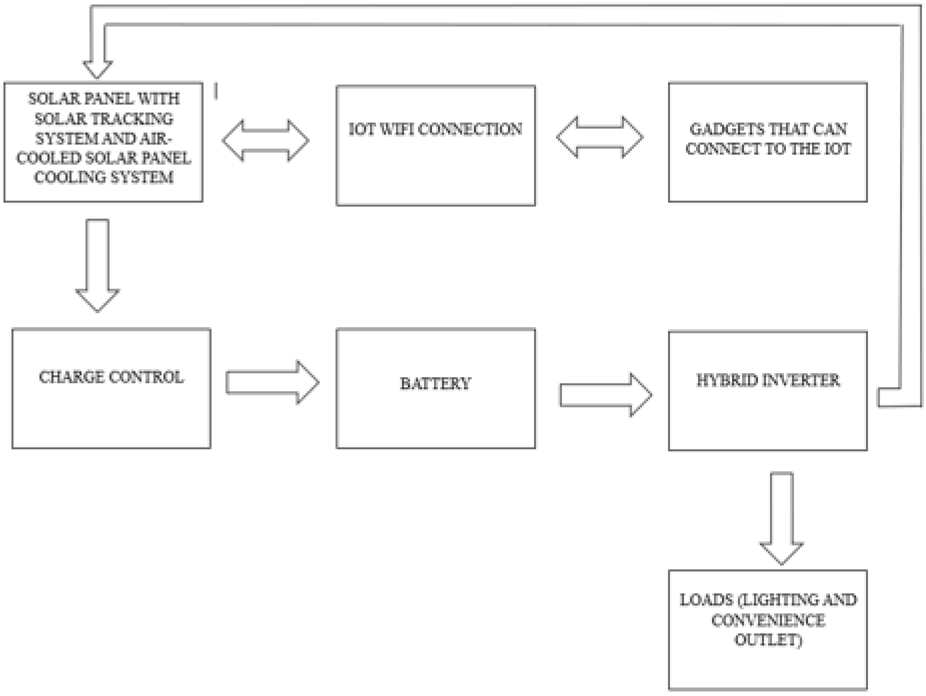
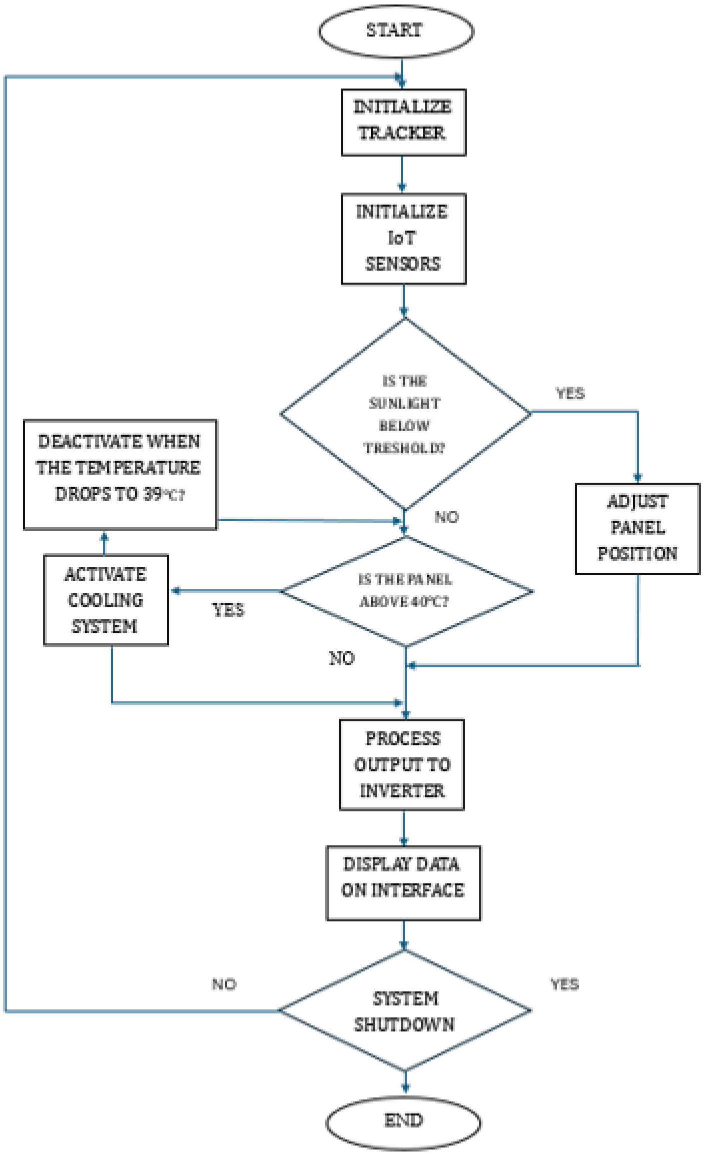


Figure 3 presents the power generation flowchart, outlining the operational sequence. Sunlight is converted to electricity, monitored by sensors, processed by the ESP32, which adjusts panel orientation through servo motors, and transmitted to the Blynk app.

**Figure 1.3**

*Power Generation Flow Chart*



*Design of Current, Voltage, and Power Monitoring*

The system depicts a solar panel monitoring system that uses an ESP32 microcontroller to process and analyze sensor data. It includes an ACS758 current sensor (connected to 5V, GND, and analog input A0) and a voltage divider (50kΩ resistors, linked to analog input A1) to measure current and voltage, respectively, enabling real-time performance monitoring.

## TESTING PROCEDURE

The prototype was tested under various weather conditions (sunny, partly sunny, cloudy, rainy) to assess performance. Data were collected wirelessly through Blynk, comparing uncalibrated and calibrated systems.

The percentage error between the measured and Blynk-reported voltage is:

$$Percentage\ Error\ \% = \left(\frac{|Measured\ Voltage - Voltage\ (Blynk)|}{Voltage\ (Blynk)}\right) \times 100\%$$

The percentage error between the measured and Blynk-reported current is:

$$Percentage\ Error\ \% = \left(\frac{Measured\ Current - Current\ (Blynk)}{Current (Blynk)}\right) \times 100\%$$

Testing involved:

- Uploading code to the ESP32 via Arduino IDE.
- Configuring Blynk datastreams for voltage, current, power, and servo control.
- Monitoring real-time data and adjusting servo positions remotely.

## RESULTS

*Uncalibrated System Performance*

Table 1 presents data from the uncalibrated system, showing a voltage range of 20.52V to 22.05V and a current range of 0.98A to 1.8A. Power output via Blynk ranged from 167W to 209W, with servo positions adjusting from 35° to 165° (Servo 1) and 14° to 38° (Servo 2). Panel temperatures varied from 33.6°C to 42.5°C. The average voltage error was 9.21%, and the current error was 84.05%, indicating significant discrepancies, particularly in current measurements, likely due to sensor inaccuracies or environmental factors.

**Table 1**

*Uncalibrated System Data*

| Time | Voltage (without IoT) | Current (without IoT) | Voltage (with IoT) | Current (with IoT) | Power (with IoT) | Servo 1 rot. | Servo 2 rot. | Panel ℃ | Weather Condition |
|---|---|---|---|---|---|---|---|---|---|
| **8:20 AM** | 21.0V | 1.67 A | 19.01V | 10 A | 190 W | 35° | 14° | 40.6 ℃ | Partly Sunny |
| **9:00 AM** | 22.03V | 1.79 A | 20.04V | 10.2 A | 204 W | 45° | 16° | 42.3 ℃ | Sunny |
| **12:00 PM** | 22.05V | 1.79 A | 20.06V | 10.4 A | 208 W | 90° | 25° | 42.5 ℃ | Sunny |
| **5:00 PM** | 20.52V | 0.98 A | 18.53V | 9.04 A | 167 W | 165° | 38° | 33.6 ℃ | Cloudy |

The percentage error between the measured and Blynk-reported voltage is:

$$Average\ Error\ \% = \left(\frac{10.52 + 9.93 + 9.93 + 9.99 + 9.92 + 10.79 + 9.92 + 9.99 + 10.39 + 10.74}{10}\right)$$

**= 9.21 %**

The percentage error between the measured and Blynk-reported current is:

$$Average\ Error\ \% = \left(\frac{83.3+82.45+82.59+82.63+82.78+89.37+82.78+82.54+82.86+89.16}{10}\right)$$

**= 84.05 %**

**Table 2**

*Calibrated System Performance*

Table 2 shows the calibrated system's performance, with voltage ranging from 8.27V (rainy) to 22.05V (sunny) and current from 0.021A to 1.702A. Power peaked at 37.58W in sunny conditions and dropped to 0.125W during rain. Servo positions ranged from 46° to 175° (Servo 1) and 16° to 38° (Servo 2), with temperatures between 26.6°C and 42.5°C. The average voltage error reduced to 0.24% and the current error to 0.45%, demonstrating significant improvement post-calibration.

| Time | Voltage (Without IoT) | Current (Without IoT) | Voltage (With IoT) | Current (With IoT) | Power (With IoT) | Servo 1 | Servo 2 | Panel ℃ | Weather Condition |
|---|---|---|---|---|---|---|---|---|---|
| **9:02 AM** | 22.03V | 1.7 A | 22.07V | 1.702 A | 37.56 W | 46° | 16° | 42.3 ℃ | Sunny |
| **12:10 PM** | 22.05V | 1.702 A | 22.09V | 1.704 A | 37.64 W | 93° | 27° | 42.5 ℃ | Sunny |
| **4:10 PM** | 8.27V | 0.071A | 8.31V | 0.07 A | 0.125 W | 153° | 35° | 26.7 ℃ | Rainy |
| **6:00 PM** | 12.76V | 0.38A | 12.8V | 0.385 A | 4.93 W | 175° | 38° | 30.3 ℃ | Gloomy |

The percentage error between the measured and Blynk-reported voltage is:

$$Average\ Error\ \% = \left(\frac{0.18 + 0.18 + 0.18 + 0.18 + 0.18 + 0.18 + 0.18 + 0.18 + 0.19+0.48+0.48+0.25+0.31}{13}\right)$$

**= 0.24%**

The percentage error between the measured and Blynk-reported current is:

$$Average\ Error\ \% = \left(\frac{0.12+0.12+0.12+0.64+0.12+0.12+0.12+0.12+1.43+0.94+0.71+1.3}{13}\right)$$

**= 0.45 %**

*System Sensitivity to Weather*

The system showed sensitivity to weather conditions, with performance dropping significantly during rainy periods (e.g., 0.125W at 4:10 PM) and peaking in sunny conditions (37.58W at 11:34 AM). The dual-axis tracking system, controlled by servo motors, effectively adjusted panel orientation to maximize sunlight capture, as evidenced by servo angle changes correlating with sunlight intensity.

## DISCUSSION

The primary objective of this study was to evaluate the efficacy of an IoT-based solar power generation system with lumens detection, real-time monitoring, and control in enhancing energy efficiency. The results demonstrated that the system, incorporating a dual-axis solar tracking mechanism and integration with the Blynk application, significantly improved performance, particularly after calibration. The calibrated system achieved mean voltage and current errors of 0.24% and 0.45%, respectively. These findings contrasted sharply with the uncalibrated system's errors of 9.21% for voltage and 84.05% for current, indicating that calibration achieves high accuracy.

The low error rates in the calibrated system aligned with prior research on IoT-based solar monitoring. Rawat (2024) reported that IoT integration enhances photovoltaic efficiency through precise real-time data analysis, a principle reflected in the Blynk application's ability to provide accurate voltage, current, and power readings. Similarly, Rao (2023) highlighted the potential of IoT to optimize solar energy systems, noting improvements in energy capture through adaptive control mechanisms. The dual-axis tracking system, driven by light-dependent resistors (LDRs) and servo motors, corroborates Mithil (2024), who emphasized the importance of precise sun-tracking for maximizing energy output. The servo adjustments, ranging from 46° to 175° for Servo 1 and 16° to 38° for Servo 2, effectively optimized panel orientation, contributing to peak power outputs of 37.64W under sunny conditions.

The system's sensitivity to weather conditions, with power output dropping to 0.125W during rainy periods, highlighted a key challenge also noted by Himri (2024), who discussed the impact of environmental variability on solar performance. This variability underscores the need for robust system enhancements, such as weather-resistant housing, to ensure reliability across diverse conditions. The Blynk application's remote monitoring and control capabilities proved instrumental, enabling real-time adjustments to servo positions and system parameters. This functionality aligns with Razzak (2023), who demonstrated that IoT-based monitoring systems enhance operational flexibility and responsiveness in solar applications.

The study's findings have significant implications for the Philippines' renewable energy landscape, where high electricity costs and abundant solar resources create a compelling case for efficient solar systems (Morales, 2023). The system's scalability and adaptability make it a viable model for residential and commercial applications, supporting the national goal of achieving 20,000 MW of solar capacity by 2040. By integrating IoT with dual-axis tracking, the prototype bridges traditional solar technology with modern automation, offering a sustainable solution that reduces reliance on fossil fuels (Altieri, 2024).

Despite its successes, the study faced limitations. Sensor inaccuracies, particularly in the uncalibrated system, contributed to high initial error rates, suggesting the need for more robust calibration protocols. Funding constraints restricted the scope of testing, limiting the range of environmental conditions evaluated. These challenges echo Badole (2022), who noted that resource limitations often hinder comprehensive testing of IoT-based solar systems. Additionally, the system's reliance on Wi-Fi for Blynk integration introduces potential vulnerabilities in areas with unstable internet access, a concern Yacine (2024) raised regarding IoT reliability.

Future improvements could address these limitations. Implementing a dust-cleaning system, as suggested by Badole (2022), would mitigate efficiency losses caused by debris accumulation. Upgrading to higher-capacity servo motors could enhance tracking precision, particularly for larger panels. Adding a battery percentage display and weather-resistant housing would further improve usability and durability, aligning with Rawat's (2024) recommendations for resilient solar systems. These enhancements would strengthen the system's applicability in diverse settings, from rural households to urban commercial installations.

In conclusion, the IoT-based solar power generation system demonstrated high accuracy and adaptability, validating the potential of IoT and dual-axis tracking in renewable energy applications. While minor limitations exist, the system's performance supports its role in advancing sustainable energy solutions in the Philippines, bridging technological innovation with environmental imperatives.

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