**Abstract**. Solar energy utilization in places like Dhulikhel, Nepal, is often obstructed by unpredicted environmental factors and existing technological barriers. The challenges often result in fluctuating energy outputs, hindering the transition to greener energy solutions. To tackle these issues, this study introduces a custom-designed Maximum Power Point Tracking (MPPT) controller, seamlessly incorporated into a microcontroller-based battery charging system. This approach seeks to enhance the efficiency of photovoltaic (PV) systems, aligning with the global shift towards renewable energy systems. The research's primary objective is to enhance PV module power yield by employing MPPT techniques, thereby reducing dependency on non-renewable energy sources. Key goals include real-time MPP tracking for optimal power extraction from PV modules and the integration of a real-time monitoring mechanism for PV and battery states. Leveraging a coordinated interplay of sensors measuring temperature, voltage, and current, vital metrics are fed to the microcontroller. This, in turn, generates a precise Pulse Width Modulation (PWM) signal, fine-tuning the voltage regulation of the buck-boost converter Metal Oxide Semiconductor Field Effect Transistor (MOSFET) for optimal operation. The adopted approach emphasizes monitoring environmental metrics, overseeing power outputs, and generating PWM signals to manage the buck-boost converter MOSFET voltage adeptly. The system also prioritizes balanced load alignment to boost power transfer and improve charging efficiency. An integrated LCD screen provides clear data visualization, allowing users to oversee and fine-tune the system's performance. Concurrently, data is transmitted hourly to the ThingSpeak cloud platform, facilitating real-time monitoring capabilities showcasing the potential of this system as a sophisticated IoT application. As a result of these integrations, an efficiency improvement of approximately 37.28% on average was observed. This research underscores the profound impact of merging advanced technologies within the renewable energy sector, offering a robust blueprint for enhancing energy stability and productivity. Building on the innovations and approaches introduced in this project, it's anticipated that it will set the stage for ground-breaking developments in renewable energy, guiding toward a greener and more sustainable future. Moreover, this study lays the groundwork for infrastructural advancements and encourages community participation in embracing green solutions, especially in regions similar to Dhulikhel.

## 1. Introduction

Renewable energy plants, particularly solar power plants, are becoming more prevalent worldwide due to their eco-friendliness and the availability of solar radiation. Furthermore, the modular design of photovoltaic (PV) plants makes them versatile and adaptable for various power needs, making them a widely utilized solution in both industrial power generation and small-scale power supply systems [1, 2]. The maximum efficiency achievable by a solar panel is limited to around 25%. Nevertheless, solar cells exhibit a commendable ability to generate power. Maximum Power Point Tracking (MPPT) is a technique used in photovoltaic (PV) systems to optimize the voltage and current levels. MPPT is employed to get the maximum output from a PV system [3, 4].

In a study conducted by Randriamanantenasoa et al., a comparative analysis of various Maximum Power Point Tracking (MPPT) techniques was undertaken. These techniques included Perturbation and Observation (P&O), Fuzzy Logic Controller (FLC), Artificial Neural Network and PI controller (ANN-PI), and Artificial Neural Network & Sliding Mode (ANN-SM). PV cell characteristics (I-V or V-P) are nonlinear and change with insolation and temperature. The study found that Perturbation and Observation (P & O) were less suitable for managing dynamic changes in weather conditions. In contrast, the Artificial Neural Network (ANN) technique, particularly ANN-SM (Sliding Mode), demonstrated greater suitability for efficiently adapting to dynamic weather changes in the context of MPPT [5]. A recent study demonstrated that Model Reference Adaptive Control (MRAM) for MPPT surpasses the traditional Perturb and Observe (P&O) method in terms of efficiency, voltage and current ripple reduction, error rates, and convergence speed. The MRAM-based controller achieves an average tracking efficiency of 99.77% under varying temperatures and 99.69% in changing radiation conditions, while rapidly reaching the Maximum Power Point (MPP) in just milliseconds [6]. The paper titled 'An Improved MPPT Control Strategy Based on Incremental Conductance' by Liqun Shang et al. emphasizes the importance of PV power generation in solar energy due to environmental concerns. Given the drawbacks of conventional methods, ensuring efficient MPPT is essential. These constraints are addressed in the research by introducing an improved incremental conductance technique that improves accuracy, speed, and stability. Its performance is rigorously assessed using MATLAB simulations, with an emphasis on monitoring efficiency and responsiveness to environmental changes. The paper also explores the function of institutional investors in PV systems. The simplicity and accuracy of this method increase tracking effectiveness and practical utility under a variety of circumstances [7].

This paper focuses on the design and implementation of a microcontroller-based battery charge controller with Maximum Power Point Tracker (MPPT) for photovoltaic (PV) power systems, aiming to improve efficiency and extend battery lifespan. The MPPT charge controller based on the Incremental Conductance (IC) technique [8] is designed to operate the PV module at the peak power point, delivering maximum power to the batteries. The Constant Voltage MPPT method [9], maintains a constant PV voltage output but is inefficient for considering the effect of temperature and solar irradiance. The Incremental Conductance Method involves calculating the rate of change of conductance concerning voltage in a PV module, helping determine whether to increase or decrease the operating voltage to reach the maximum power point [10, 11]. A DC-DC Buck Boost converter [12] was designed to adjust the PV module voltage accordingly the powers generated by a solar panel can vary substantially during the day, regardless of whether Maximum Power Point Tracking (MPPT) technology is employed. These variations are primarily attributable to a range of factors, including alterations in solar conditions like sunlight angle, shading, weather, and the sun's position in the sky [13].

To assess how well MPPT technology performs, the power output from a solar panel was examined with and without MPPT for 24 hours in Dhulikhel, Nepal. The effectiveness of MPPT was observed in variations of weather conditions, including both sunny and cloudy days which were found to have a substantial impact on the performance of the solar MPPT system. The system operated at its highest efficiency during sunny days, generating a maximum output power of 26.8W. Conversely, its performance was considerably diminished during cloudy days, yielding a maximum output of 20.15W. The acquired data was transferred into a cloud-based storage system, enabling remote monitoring and analysis. This research paper lies in its contribution to the development of efficient solar energy systems in Nepal, which has a high potential for solar energy generation. The scope of the research paper is limited to the examination of the power output of a solar energy system with and without the use of MPPT and the impact of irradiance levels on the system's power output.

## 2. Materials and Methods

Maximum Power Point Tracking (MPPT) system is essential for optimizing the efficiency of solar panels when connected to batteries or the utility grid. It ensures the solar panels operate within their appropriate voltage and current values to maximize energy extraction under varying conditions [14, 15]. MPPT solar charge controllers are crucial in solar systems with batteries, as they regulate voltage between solar panels and batteries, enhancing battery life, and systematic protection and promoting longer lifespan of batteries. Moreover, grid-tied inverters also incorporate MPPT tracking system to extract maximum power from PV arrays.

In this study, a 40-watt solar panel was utilized which generates power depending on factors such as its efficiency factor, irradiance, and temperature. The temperature sensor was utilized to measure ambient atmospheric temperature which directly affects the power output of the panel. Likewise, panel output was monitored by voltage and current sensors. The data from those sensors were fetched to the microcontroller; which was then further processed using the incremental conductance method. Subsequently, the required PWM signal was generated and transmitted to the MOSFET gate pin of the buck-boost converter for regulation of voltage level. Load impedance was adjusted to match the panel's impedance so that maximum power transfer was ensured. Harvested optimal power was supplied to a 12-volt battery with the adjusted voltage and current level. Battery voltage was sensed and fed back to the microcontroller which in turn utilized it to regulate the charging process. Information from various sensors, such as voltage, temperature, and current, along with battery status, maximum power point data, and current, was displayed on an LCD screen and also securely transmitted to the ThingSpeak cloud platform [16]. This cloud-based repository allows remote real-time monitoring and analysis exploring the IoT applications of such systems.

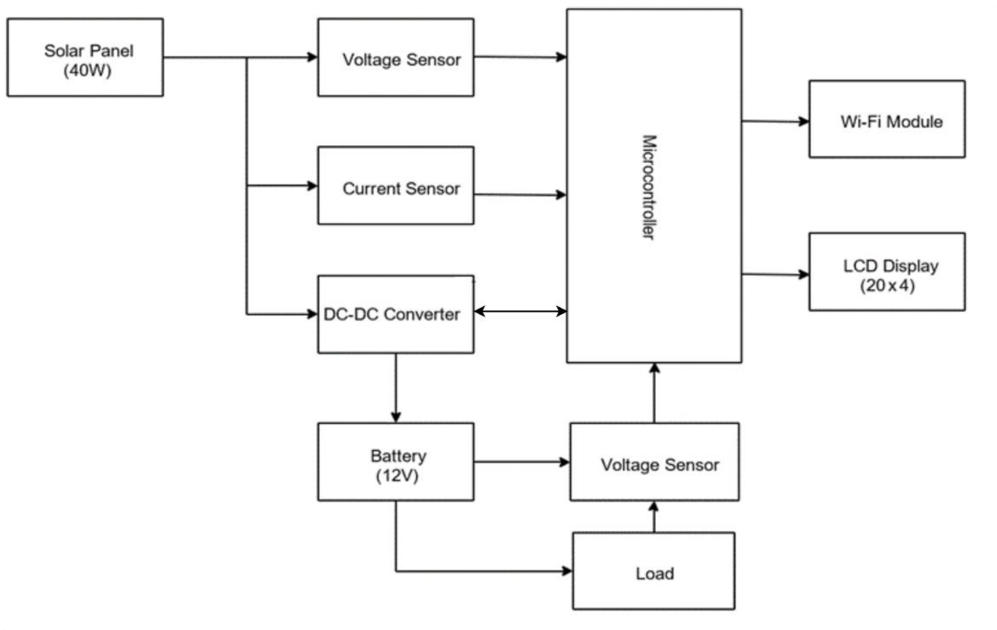


**Figure 1.** Block diagram of the experimental setup.

*2.1. MPPT Algorithm (Incremental Conductance Method)*

The incremental conductance (IC) method is a maximum power point tracking (MPPT) algorithm that tracks the maximum power point (MPP) of a photovoltaic (PV) array by comparing the incremental conductance (dI/dV) to the negative of the conductance (-I/V) [17].

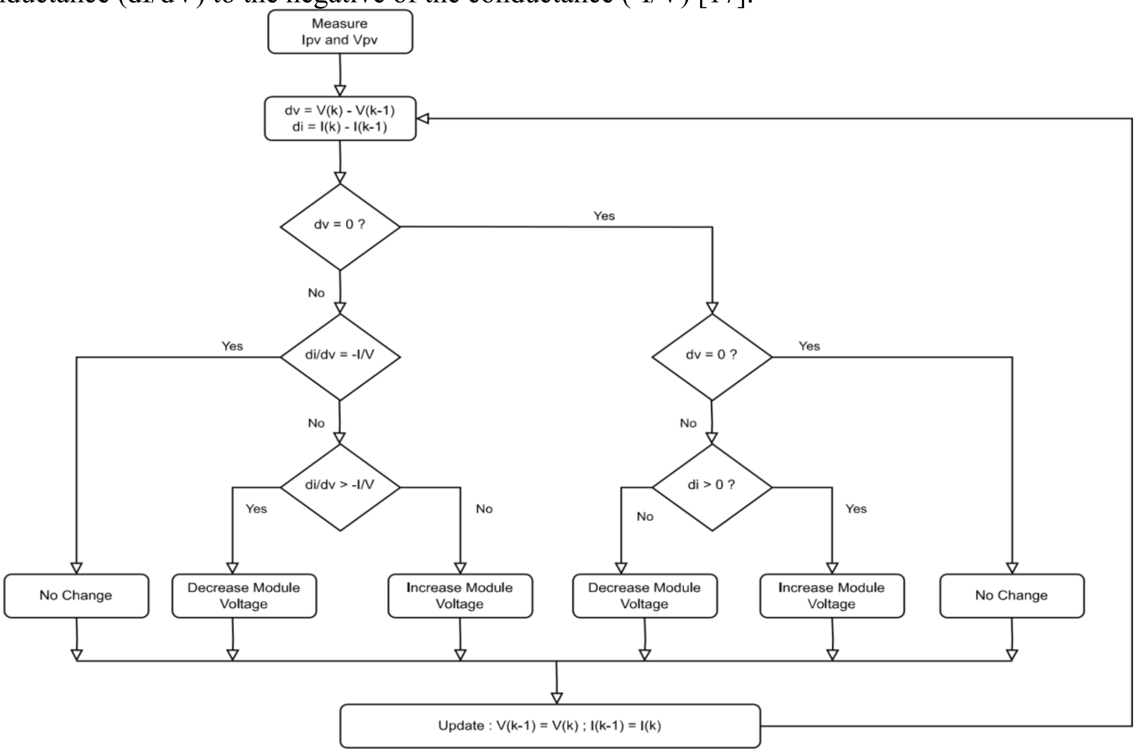

**Figure 2.** MPPT algorithm schematics.

The IC method is based on the principle that the MPP is the point on the PV curve where the incremental conductance is equal to the negative of the conductance [18].
This can be expressed mathematically as follows:

$$\frac{I}{V} = -\frac{dI}{dV} \tag{1}$$

The IC method works by continuously measuring the PV voltage and current and calculating the incremental conductance. If the incremental conductance is greater than the negative of the conductance, the MPPT controller increases the PV voltage. If the incremental conductance is less than the negative of the conductance, the MPPT controller decreases the PV voltage. This process continues until the MPP is reached [19].

### 2.2. Buck Converter

The buck converter, also known as a step-down converter, is a switching topology that transforms a DC input voltage, $V_{in}$, into a smaller DC output voltage, $V_{out}$. This conversion occurs in two phases: when the switch is on and when it's off. During the "on" phase, when the MOSFET or switch is active, it supplies current to the load. Initially, the current flow to the load is limited because energy is stored in the inductor (L)[20]. Consequently, the load current and the charge on the output capacitor ($C_{out}$) gradually increase during this "on" period.

Additionally, throughout this phase, the diode experiences a significant positive voltage, causing it to be reverse-biased. When the MOSFET or switch is turned off, the energy stored in the magnetic field around the inductor is released back into the circuit. The voltage across the inductor now reverses polarity compared to its voltage during the "on" period. Sufficient stored energy remains in the circuit to sustain current flow during this "off" period.

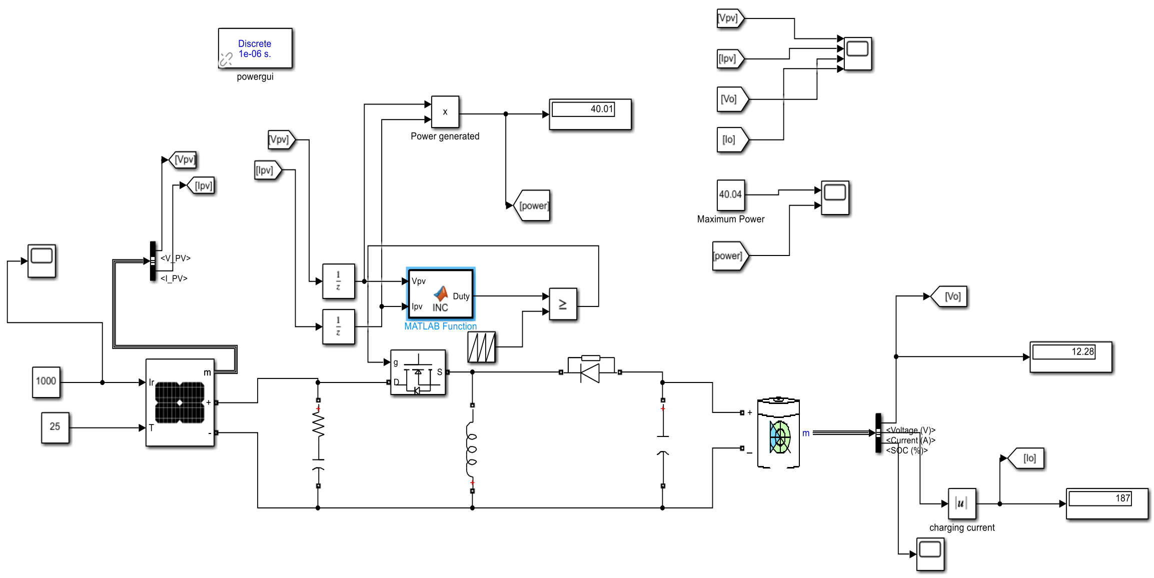


**Figure 3.** Schematics of a buck converter with MPPT in Simulink.

Calculation of Converter Design:
Maximum power of solar panel: 40W
Input voltage = 18.2V
Output voltage =12V
Switching frequency = 50Khz

$I_{ripple} = 20\%$
$V_{ripple} = 2\%$
Output Current = 3.33A
Current ripple = 10 % of 3.33A = 0.33A
Voltage ripple = 1% of 12V = 0.12V

$$L = \frac{Vop(Vip - Vop)}{FSW * Irp * Vrp} = 33H$$
$$C = \frac{Irp}{8 * FSW * Vrp} = 250\mu F$$

When a load is directly connected to a solar cell, the operating point of the panel seldom aligns with its peak power. The impedance encountered by the panel primarily dictates this operating point. Properly adjusting the impedance ensures that the panel operates at peak power.

Referring to the circuit diagram illustrated in Figure [3], MPPT is realized in Simulink using the Incremental Conductance method. The primary inputs to the PV panel are irradiance and temperature, both of which significantly influence the panel's output. The Incremental Conductance method is employed to identify the optimal voltage required to achieve maximum power for a given irradiance level. The output of this algorithm, expressed in terms of duty cycle, is then relayed to the buck converters. This facilitates the charging of the battery at its maximum potential power.

*2.3. Interfacing the Solar Panel with a Load in the Absence of MPPT*

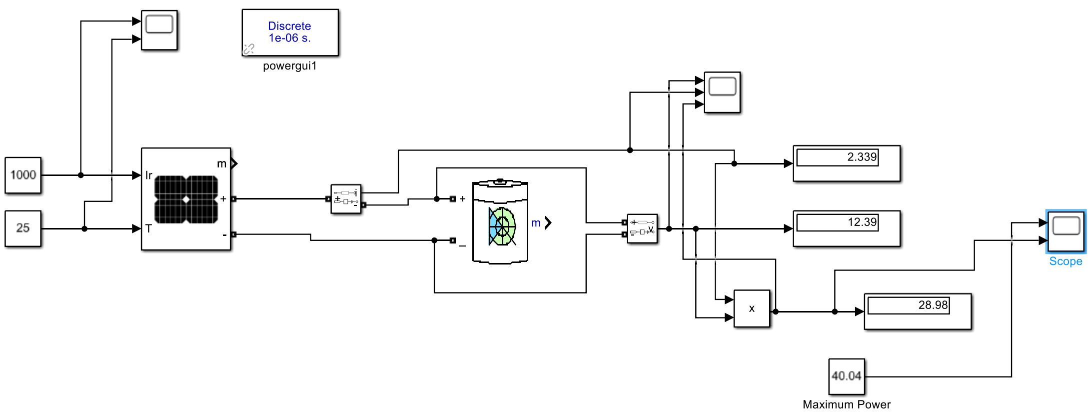


**Figure 4.** PV panel with load without MPPT.

In this setup, the solar panel is directly connected to the battery without incorporating the MPPT circuit. Given that the input parameters of the solar panel, specifically irradiation and temperature, are held constant, the output from the solar panel remains consistent over the observed time frame.

*2.4. Circuit simulation of the system*

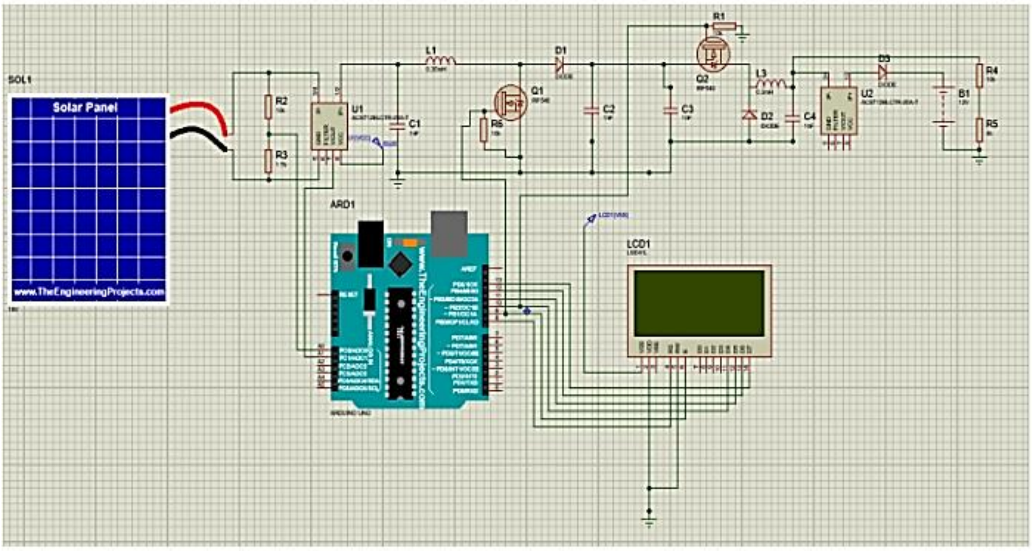

**Figure 5.** Schematic of the circuit on Proteus.

The circuit schematic shown in Figure [5], created in Proteus, represents our design blueprint. This simulation served as the foundation for our hardware implementation, ensuring a seamless transition from our digital design to the physical system.

## 3. Results and Discussions

In this study, our primary objective was to assess and optimize the efficiency and output power of a photovoltaic (PV) system under two distinct scenarios: with and without the implementation of the Maximum Power Point Tracking (MPPT) circuit. Implementing the buck/boost converter alongside the incremental conductance method algorithm, we were able to simulate the behaviour of the PV system under these conditions. Specifically, we plotted graphs for irradiance levels of 1000w/m$^2$ and 500w/m$^2$ in MATLAB for research purposes. Our findings, as depicted through these MATLAB-generated graphs as well as output generated by our hardware product, reveal a tangible disparity in the power generated by the PV panel in the presence versus the absence of MPPT. This section delves into a comprehensive analysis of these results and their implications on the potential efficiency gains associated with the use of MPPT in solar applications.

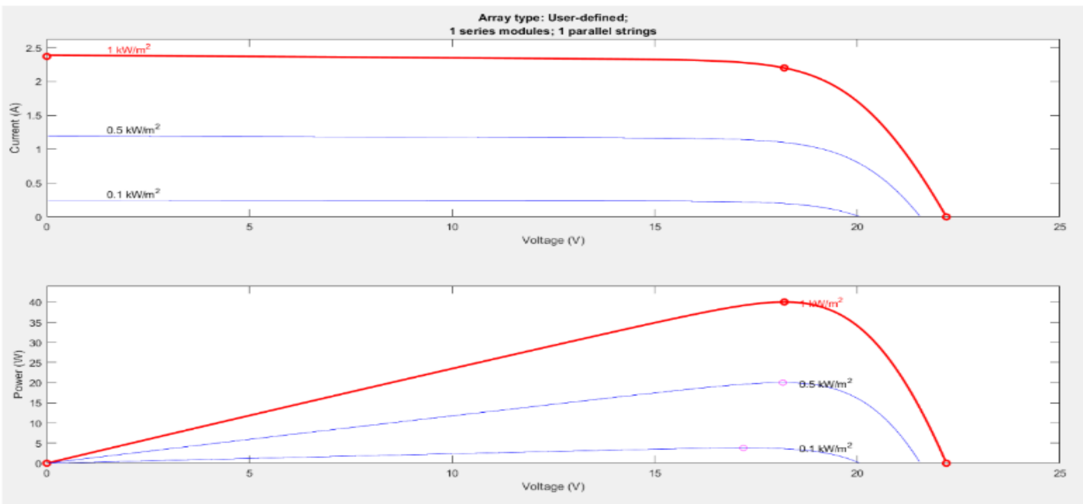


**Figure 6.** Variation of current and voltage with irradiance.

From the above-mentioned graph, it is evident that the maximum power achievable at an irradiance of 1000w/m$^2$ is at a voltage of 18.2V. By employing the MPPT circuit, this maximum power voltage can be harnessed; however, without the MPPT, the battery charges at a suboptimal power level, reducing the system's overall competence.

### *3.1. Response of the system with MPPT*

The system's power output is examined both with and without the use of MPPT. As illustrated in Figure [7], the expected maximum power at a specific irradiance level (i.e., 1000w/m$^2$) is 40W, represented by the black dotted line. The orange dotted line demonstrates the system's power output without the MPPT. With the incorporation of MPPT, there is a noticeable increase in the system's power output, as depicted by the red line in the plot, where the power incrementally rises to reach 40W. The power output of a solar energy system is intricately tied to the level of irradiance it receives, as depicted in Figure [7].

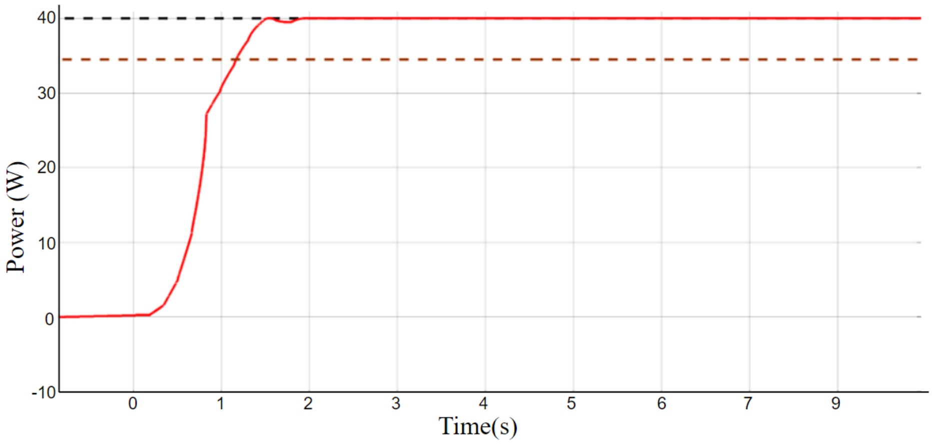


**Figure 7.** The power output of the system with MPPT.

When the sun's rays are intense, leading to high irradiance levels, solar panels capture more energy and thus deliver a higher power output. Conversely, during periods of reduced irradiance, such as on cloudy days or at specific times of the day, the panels receive less radiant energy. This results in a decrease in the system's maximum power generation capacity. The output of the panel with varying irradiance is shown in the Figure [8, 9].

### *3.2. IV parameters with varying irradiance*

All the system voltages and currents also vary according to the variation of the input factor (i.e., irradiance, temperature) of the solar panel. System output under an irradiance of 1000w/m$^2$ is realized with the help of MATLAB Simulink is shown the Figure [8].

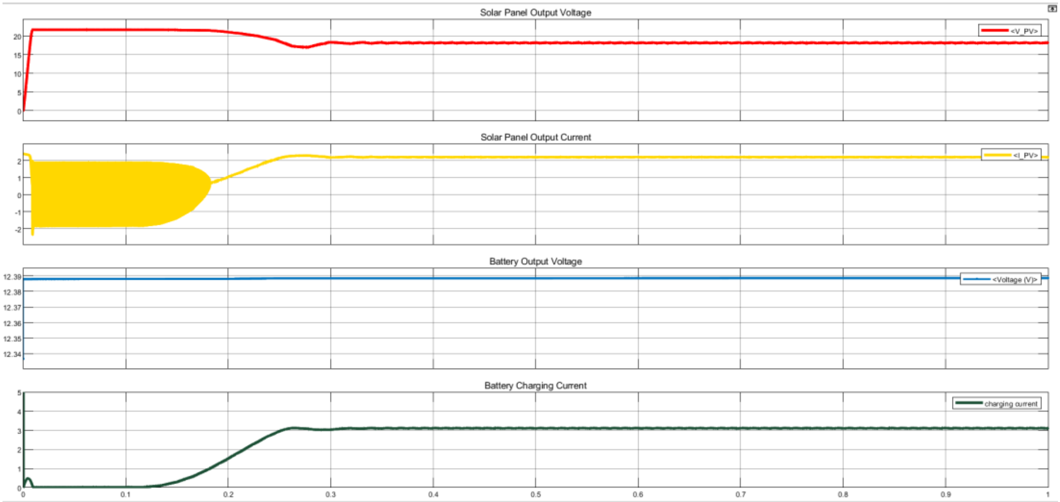


**Figure 8.** System output with irradiance 1000 w/m$^2$.

The output current of the solar panel is significantly influenced by irradiance levels. As irradiance increases, the solar panel's output current rises, enabling a greater power supply to charge the battery. Conversely, when irradiance decreases, the solar panel's output current diminishes, resulting in a reduced current available for battery charging. Referring to Figure [8], with an irradiance of 1000w/m$^2$, the solar panel's output current stands at approximately 2.1A, while the battery's charging current is 3A. Now if the irradiance is decreased to 500 w/m$^2$, both the output current of the PV panel and the battery's charging current will see a corresponding reduction. The solar output current is reduced to 1A and the battery charging current is reduced to 1.5A when the irradiance is decreased from 1000 w/m$^2$ to 500 w/m$^2$ shown in the Figure [9].

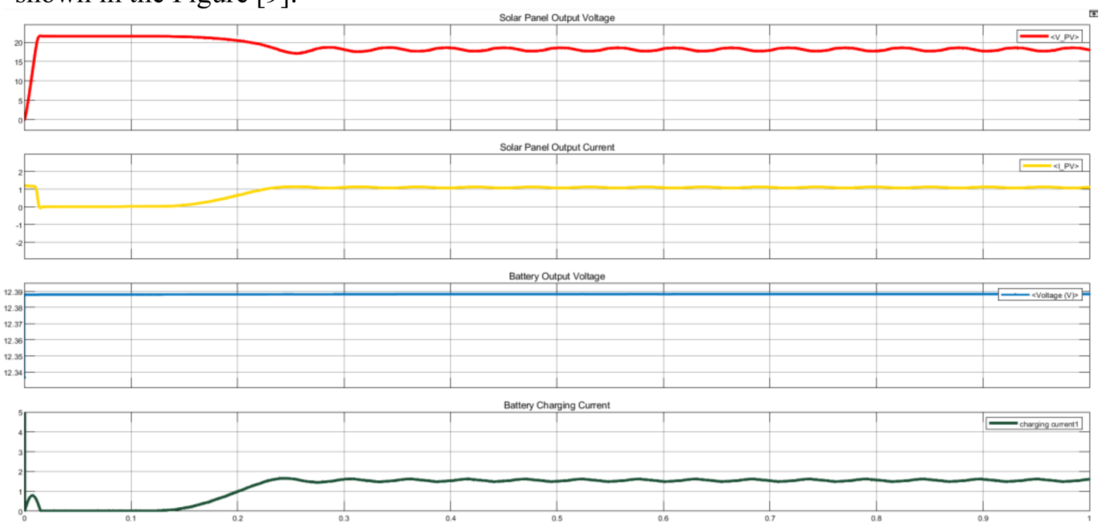


**Figure 9.** System output with irradiance 500 w/m$^2$.

Now if the charging current of the battery is high battery will charge at a higher speed and if the charging current is low battery will charge at a lower speed. The behavior of the battery charging is also analyzed using the scope block of Simulink.

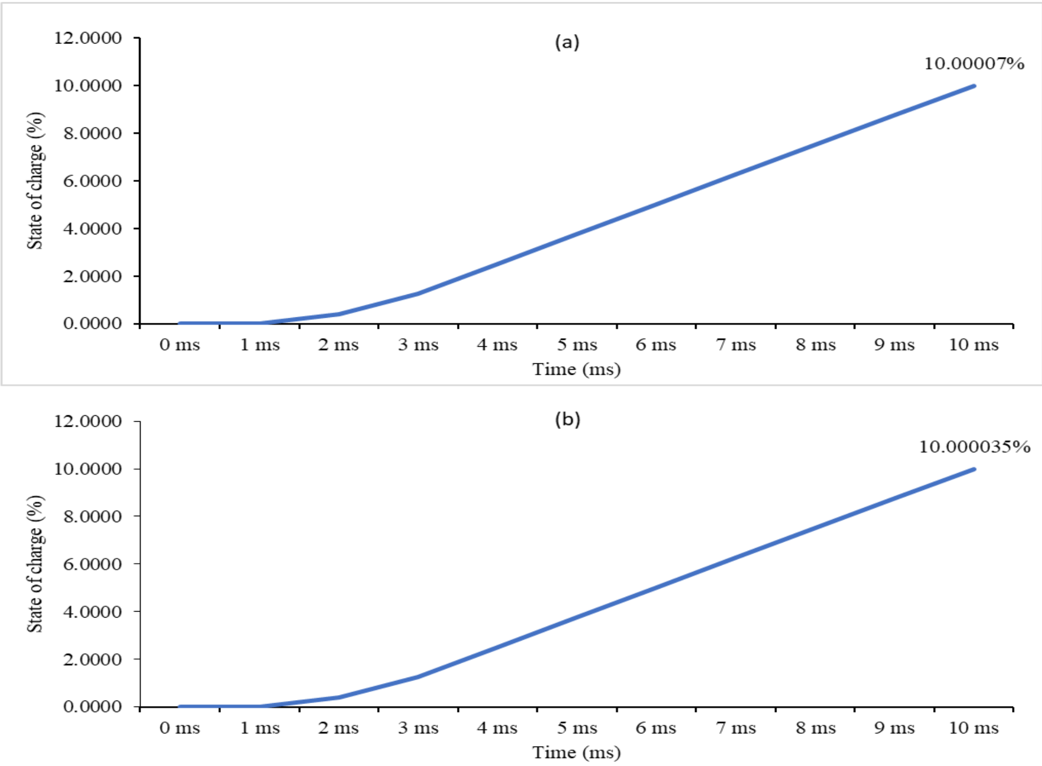


**Figure 10.** Comparison of battery charging varying irradiance. (a) State of charge with an irradiance of 1000w/m$^2$. (b) State of charge with an irradiance of 500w/m$^2$.

From Figure [10], it is evident that with an irradiance of 1000 w/m$^2$, the battery's charge increases from 10% to 10.00007% in just 1 second. Similarly, when the irradiance drops to 500 w/m$^2$, the charge rises from 10% to 10.000035% in the same duration of 1 second. If the charging current remains constant at 3A, the battery will be fully charged in 10 hours. However, with a reduced current of 1.5A, the charging duration extends to 20 hours, given the battery's capacity of 30Ah.

### *3.3. Hardware Prototype*

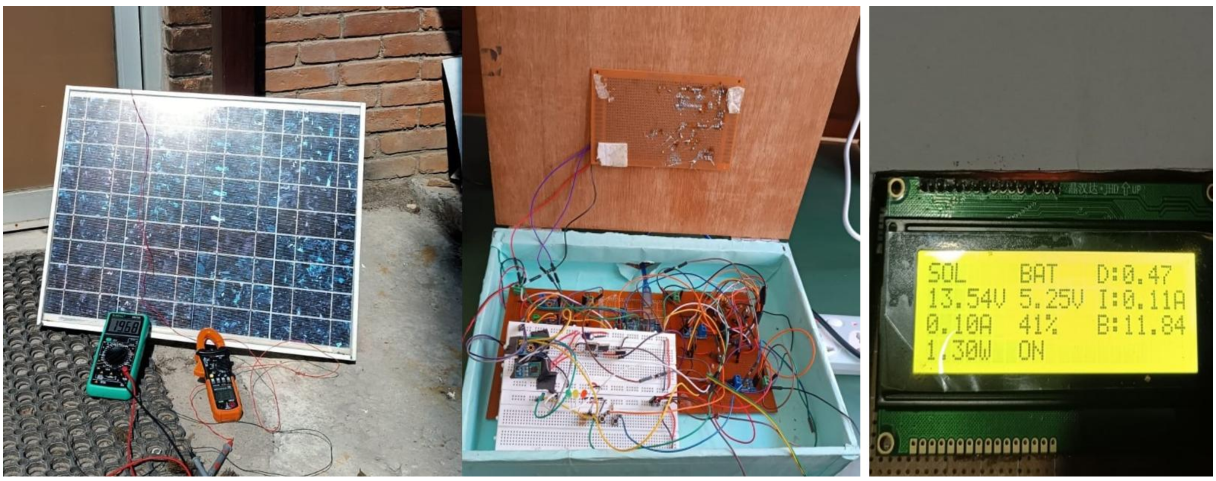


**Figure 11.** Hardware implementation and LCD for real-time monitoring.

The LCD interface, Figure [11] shows comprehensive data of photovoltaic (PV) arrays data including values of current, voltage, and power generation. Likewise, it provides detailed insights into the battery system, including its charging voltage, state of charge, and whether it was presently activated. Moreover, the screen provides critical information regarding the duty cycle, battery status voltage, and current level.

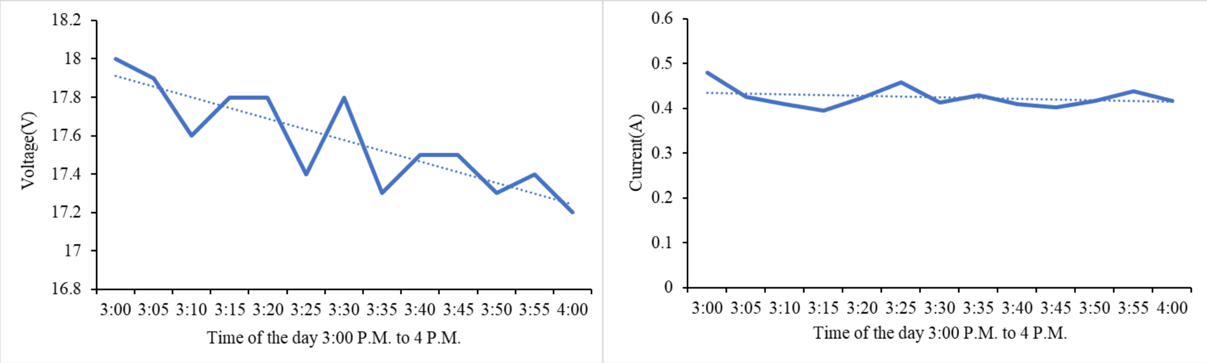


**Figure 12.** Trends in current and voltage over time.

Figure [12] presents the current and voltage measurements recorded at five-minute intervals over an hour, starting at 3 p.m. and ending at 4 p.m. The current shows some fluctuation, starting at a high of 0.48 amperes and dropping to a low of 0.395 amperes at 3:15, before peaking again at 0.459 amperes at 3:25. Following this, the current stabilizes around 0.41 to 0.42 amperes range towards the end of the session. In contrast, the voltage begins at 18 volts and demonstrates a gradual declining trend over the hour, with minor fluctuations but ultimately lowering to 17.2 volts by 4:00. This overall downward trend in voltage, coupled with the variations in current, suggests a system experiencing changes in electrical load or possibly some form of regulation affecting the power supply or consumption over the period observed.

### *3.4. Power output from the hardware designed*

Table [1] shows the hourly recorded power levels yielded by the PV panel in both scenarios including with MPPT integration and without MPPT integration on a sunny day in Dhulikhel, Nepal.

**Table 1.** The power output of the solar panel with and without MPPT on a sunny day.

| Time | Without MPPT Power Generation (W) | With MPPT Power Generation (W) |
|---|---|---|
| 06:00 | 4 | 6 |
| 07:00 | 6.2 | 8.56 |
| 08:00 | 9.6 | 14.1 |
| 09:00 | 13.2 | 18.216 |
| 10:00 | 17 | 23.46 |
| 11:00 | 17.5 | 24.15 |
| 12:00 | 18 | 26.8 |
| 13:00 | 14 | 19.32 |
| 14:00 | 10.2 | 17.2 |
| 15:00 | 8.7 | 10.7 |
| 16:00 | 6.8 | 8.5 |
| 17:00 | 5.7 | 7.2 |

| | | |
|---|---|---|
| 18:00 | 4 | 6.1 |

Figure [13] illustrates power generation from a solar panel system with and without MPPT technology over a sunny day. Power production gradually rises throughout the day in both scenarios (with and without MPPT), reaching its highest point at noon with 26.8W for MPPT and 18W without MPPT. Across all hours, MPPT consistently outperforms the non-MPPT system, demonstrating its efficacy in enhancing solar panel power output under changing sunlight conditions.

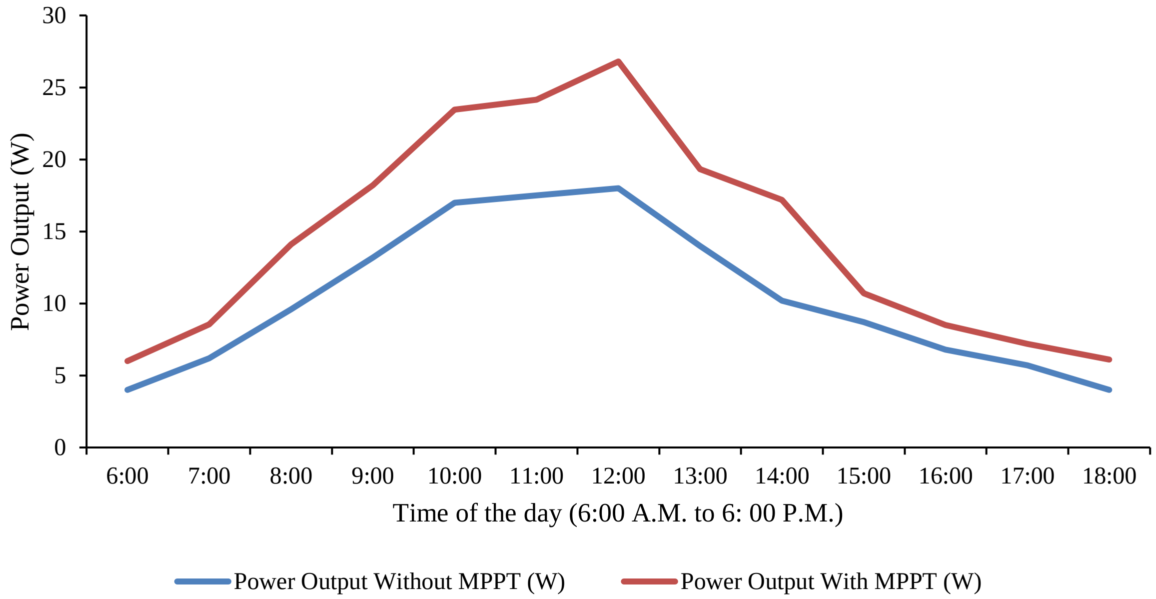


**Figure 13.** PV Solar Panel output during a sunny day.

Table [2] shows the hourly recorded power levels yielded by the PV panel in both scenarios including with MPPT integration and without MPPT integration on a cloudy day.

**Table 2.** The power output of the solar panel with and without MPPT on a cloudy day.

| Time | Without MPPT Power Generation (W) | With MPPT Power Generation (W) |
|---|---|---|
| 06:00 | 4.1 | 5.617 |
| 07:00 | 4.4 | 5.72 |
| 08:00 | 8.6 | 11.954 |
| 09:00 | 10.8 | 14.796 |
| 10:00 | 14 | 20.16 |
| 11:00 | 15.3 | 20.349 |
| 12:00 | 16 | 21.6 |
| 13:00 | 13.9 | 20.155 |
| 14:00 | 8.7 | 12.615 |
| 15:00 | 7.4 | 10.138 |
| 16:00 | 5.5 | 7.645 |
| 17:00 | 4.8 | 6.576 |

| | | |
|---|---|---|
| 18:00 | 4.6 | 6.44 |

Figure [13] illustrates power generation from a solar panel system with and without MPPT technology over a cloudy day. Power production gradually rises throughout the day in both scenarios (with and without MPPT), reaching its highest point at noon with 21.6 W for MPPT and 16W without MPPT. Across all hours, MPPT consistently outperforms the non-MPPT system. Although it outperforms the non-MPPT system its output is significantly low compared to that of a Sunny Day with the MPPT.

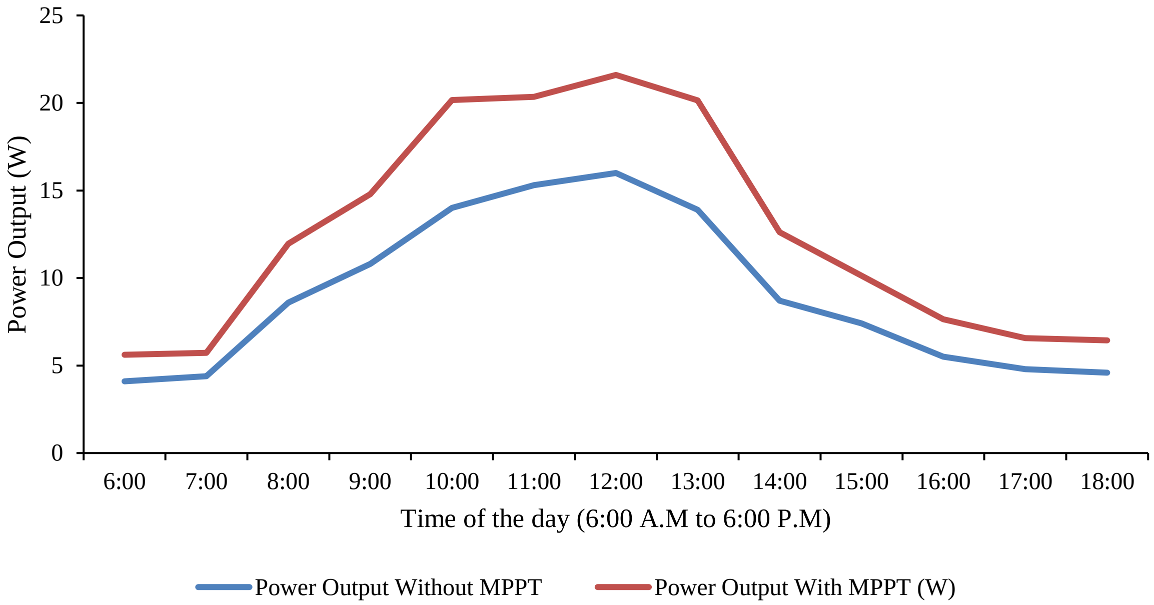


**Figure 14.** PV Solar Panel output during a cloudy day.

Furthermore, the power output from the system was uploaded every hour to the Thingspeak cloud platform to demonstrate the IoT integration in such systems. This crucial integration enables the accessibility of the data, i.e., power yielded in practical scenarios remotely for further analysis and the potential applicability can be extended to remote monitoring of PV power plants.

## 4. Conclusion

In conclusion, this research addresses pivotal challenges in the adoption of solar energy, particularly in regions like Dhulikhel, Nepal, where environmental and technological barriers often limit its efficacy. Our study introduces a robust Maximum Power Point Tracking (MPPT) controller integrated into a microcontroller-based battery charging system, aiming to significantly enhance the efficiency of photovoltaic (PV) modules. Employing a sophisticated interplay of sensors and real-time tracking also with the exploration of possible IoT applications, the study observed a notable improvement in efficiency by approximately 37.28% on average. This work not only serves as a blueprint for elevating energy stability and productivity but also advocates for a greener and more sustainable future. The study's findings extend beyond mere energy generation, stimulating infrastructural development and galvanizing community engagement in renewable energy initiatives. By melding advanced technologies and rigorous methodology, we contribute to the burgeoning field of renewable energy, pointing the way for future innovations.

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