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Performance Analysis of a Battery-Buffered Solar Charging System for Low-Power DC Loads

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ABSTRACT

The rapid depletion of conventional energy resources and the growing demand for electrical power have increased the need for portable and sustainable charging solutions. Solar energy provides a promising renewable option for powering low-power electronic devices. This study presents the performance analysis of a battery-buffered solar charging system designed to supply regulated 5 V DC power for low-power loads. The system consists of a 12 V, 30 W solar photovoltaic panel for energy harvesting, a 12 V, 2 Ah rechargeable battery for energy storage, and a DC–DC buck converter for voltage regulation. Experimental tests were conducted under natural sunlight conditions to evaluate key performance parameters, including charging current, battery charging time, output voltage stability, and overall energy conversion efficiency. Results indicate that the solar panel delivered an average current of approximately 1.5 A under irradiance levels between 600 and 800 W/m². The battery reached full charge within about 2 hours, storing roughly 24 Wh of energy. The system maintained a regulated 5 V output with voltage variations within ±0.2 V at load currents up to 2 A. The overall system efficiency, calculated from the solar panel output to the regulated load output and accounting for losses in the charge controller, battery storage process, and DC–DC converter, was approximately 69%. These findings demonstrate that the proposed system provides a simple and reliable solution for portable low-power DC applications, particularly in off-grid environments where access to conventional electricity is limited.

Keywords: Solar-powered battery system, energy storage, low-power DC loads, performance analysis, portable charging solutions.

1. INTRODUCTION

1.1 Background and Motivation

Renewable energy solutions are increasingly gaining global acceptance, with their adoption growing rapidly in response to rising energy demand and environmental concerns. The quest for sustainable and clean energy solutions has intensified research interest in energy storage technologies, particularly due to the widespread use of mobile devices, Internet of Things (IoT) electronics, and small communication gadgets in off-grid, rural, and emergency scenarios (Ellabban et al., 2014). In many such environments, grid power is either unavailable or unreliable, while conventional energy sources are depleting at a fast rate and energy demand continues to increase. This situation has created a strong need for durable, reliable, and efficient alternative energy sources to power essential low-power electronic devices (Gabbar et al., 2021).

Among the various renewable energy options, solar energy remains one of the most reliable and efficient

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sources due to its abundance, cleanliness, and environmental friendliness. These attributes have made solar energy one of the most widely adopted renewable energy technologies worldwide. Solar photovoltaic (PV) systems convert sunlight directly into electrical energy, providing a decentralized power solution that aligns well with the needs of regions lacking access to conventional electricity infrastructure (Ukoba et al., 2024).

In recent years, advances in energy management have further promoted the integration of PV panels with energy storage systems (ESS), making such hybrid configurations a major research focus, particularly for small-scale and residential applications. A key limitation of solar energy systems is their dependence on sunlight availability, as energy harvesting is restricted to daytime operation, thereby limiting continuous power supply (Nyamathulla & Dhanamjayulu, 2024). The incorporation of rechargeable batteries for energy storage provides an effective means of mitigating this limitation by enabling energy availability during periods of low or zero solar irradiance. Furthermore, maximum power point tracking (MPPT) is widely recognized as an important technique for improving energy harvesting efficiency, given the inherent variability of solar irradiance caused by diurnal and environmental factors (Osagie et al., 2024).

Small-scale, battery-buffered solar-powered systems offer a practical solution for charging low-power DC devices such as mobile phones, light-emitting diode (LED) lamps, portable communication units, and other compact electronic loads. Most of these devices require a regulated 5 V DC supply, which is typically obtained by stepping down higher battery voltages using DC–DC conversion techniques. This work focuses on the design and performance analysis of a battery-buffered solar charging system capable of delivering a stable 5 V DC output for low-power applications. The system consists of a 12 V, 30 W solar panel for energy harvesting, a 12 V, 2 Ah rechargeable battery for energy storage, and a DC–DC buck converter for voltage regulation to the required 5 V level. The performance of the system is evaluated under real sunlight conditions, with emphasis on battery charging behavior, output voltage stability, and overall energy conversion efficiency. The results demonstrate that the proposed system can reliably supply regulated 5 V power to a range of low-power electronic devices. The design is cost-effective, simple to implement, and suitable for deployment in rural areas, emergency backup applications, and portable charging stations.

The remainder of this paper is organized as follows: Section 2 describes the system design and implementation process, outlining the key components and operating principles. Section 3 presents the experimental results and discusses the observed performance characteristics. Finally, Section 4 concludes the paper and highlights potential areas for future improvement.

1.2 Literature Review

a. Theoretical Background

In recent days, low-power applications such as mobile phones have become an omnipresent personal electronic device in people's daily lives. Users are always alert for cell phones that have advanced technology. However, the difficulty in charging a phone battery, which is commonly due to a power supply problem, has not yet been satisfactorily resolved. Despite the advanced technology of mobile phones, the battery still cannot meet the increasing power demand due to the rapidly increasing functionalities of the mobile phone. Therefore, it is highly desirable to reduce the dependency on conventional sources of energy and increase focus on renewable energy as it is reliable, durable, and also efficient.

The study by Smith and Harris (2018) explains that solar-powered charging offers a promising solution, especially in remote or off-grid areas where traditional power sources are unavailable. Solar panels convert sunlight into electrical energy, which can be stored in a battery and managed using a charge controller to optimize energy flow and prevent overcharging. MPPT technology enhances energy efficiency by adjusting to varying sunlight conditions. Therefore, the massive amount of solar energy attainable daily makes it a very attractive resource for generating electricity.

International Renewable Energy Agency (IRENA, 2019) emphasizes that global decarbonization pathways must align with long-term economic and social objectives. The transition to low-carbon energy systems requires coordinated global action and sustained investment. Power generation by fossil-fuel resources has peaked, whilst solar energy is predicted to be at the vanguard of energy generation in the near future. Moreover, it is predicted that by 2050, the generation of solar energy will have increased to 48% due to economic and industrial growth.

Sustainable energy development is defined as the development of the energy sector in terms of energy generating, distributing, and utilizing that is based on sustainability rules. Energy systems will significantly impact the environment in both developed and developing countries. Consequently, the global sustainable energy system must optimize efficiency and reduce emissions (Ellabban et al., 2014).

b. Related research work

Smith and Harris (2018) designed and implemented an intelligent battery charging circuit for hybrid electric vehicles (HEVs) in which a fuel cell served as the primary energy source, while solar PV and battery systems acted as auxiliary sources. The study employed a cascaded DC–DC converter architecture comprising a boost converter for PV power harvesting and a buck converter for battery charging. A fuzzy-logic-enhanced MPPT algorithm was integrated into the boost converter, while an optimal Proportional–Integral–Derivative (PID) controller was applied to the buck converter. The MPPT performance was evaluated under varying irradiance conditions ranging from 400 to 1000 W/m² at 25 °C. Results showed that the fuzzy-logic-based MPPT achieved a tracking efficiency between 99.06% and 99.80%, significantly outperforming conventional Perturb and Observe (P&O) and Incremental Conductance techniques.

Also, Shiau & Ma (2013) designed and compared a 1 kW asynchronous buck converter (ASBC) and a synchronous buck converter (SBC) for solar-powered battery charging in an electric vehicle (EV) rickshaw application. The experimental setup involved a DC motor–driven three-wheeler rickshaw powered by a battery bank consisting of four series-connected sub-colloid storage batteries rated at 12 V and 120 Ah each. Performance evaluation was conducted using PSIM simulation software, followed by hardware implementation. An experimental test bed incorporating a 48 V, 100 Ah battery bank with a charging current of 6 A was used. The study found that at low charging current rates (1 A), the ASBC demonstrated superior performance compared to the SBC, whereas at higher charging current rates, the SBC exhibited better efficiency and overall performance.

Gabbar et al. (2021) presented a comprehensive review of Battery Management Systems (BMS) across two major application domains: electric transportation and large-scale stationary energy storage systems. The study examined BMS functional components, system architectures, operational behaviors, testing protocols, and topological configurations. It further reviewed existing industrial standards and regulatory codes governing BMS safety and performance. Key gaps in current safety requirements and operational standards were identified, leading to the proposal of a structured framework aimed at guiding the development of improved and harmonized BMS standards for future applications.

A review of solar energy adaptation in the Global South, with a particular focus on economically disadvantaged regions across Africa, Latin America, and Asia was conducted by Ukoba et al. (2024). The study examined the historical evolution of solar energy technologies, their classification, and global deployment statistics. It also reviewed major application areas, including rural electrification, household energy supply, transportation, industrial usage, and deployment in harsh or remote environments. The review highlighted the role of solar energy in addressing energy access challenges and promoting sustainable development in low-income regions.

Osagie et al. (2024) focused on the design and implementation of a solar-powered battery charger for deployment at Yaba College of Technology, Lagos. The system utilized a 200 Ah battery for backup power and a 70 Ah battery as a sampling unit for charging and discharging tests. A 280 W monocrystalline solar panel was selected due to its high efficiency, compact size, and long lifespan of approximately 25 years. Three charging scenarios, including solar power, generator supply, and national grid electricity, were evaluated. The initial battery voltage was measured using a digital voltmeter prior to charging, and subsequent voltage readings were recorded hourly over an eight-hour period. Although the charge indicator turned green after the fifth hour, the battery voltage did not reach the fully charged level of 12.8 V until approximately 25 minutes later, indicating a delay between charger indication and actual battery state.

Nyamathulla and Dhanamjayulu (2024) provided a comprehensive review of Battery Energy Storage Systems (BESS) and BMS across a wide range of applications, with particular emphasis on electric vehicles and renewable energy integration. The review covered battery technologies, material compositions, performance characteristics, and key storage applications. It also examined core BMS functions, including voltage and current monitoring, charge–discharge control, thermal management, cell balancing, and data acquisition. Both traditional and advanced methods for estimating State of Charge (SoC) and State of Health (SoH) were critically assessed, outlining their strengths and limitations. The authors identified key design and implementation challenges and offered recommendations for improving BESS and BMS performance across diverse application scenarios.

Terkes et al. (2025) compared battery control strategies, specifically self-consumption and feed-in damping, under a minimum cost objective for residential consumers integrating battery storage with rooftop solar photovoltaic systems. The analysis considered varying load cover ratios and different fractions of energy production relative to load demand. A cost-minimizing optimization model incorporating battery aging effects was developed using Python, the Gurobi solver, and mixed-integer linear programming (MILP) techniques. The study evaluated the impact of varying PV-to-load ratios on system cost, energy curtailment, battery lifespan, carbon emissions, and overall operational performance. Results indicated that the feed-in damping strategy offered clear advantages in extending battery life, reducing system costs, and minimizing energy waste, although the authors noted that real-world validation of these findings is still required.

Lastly, Jacob and Farzaneh (2025) developed a detailed modeling and simulation framework for a hybrid off-grid microgrid system combining photovoltaic–thermal (PV/T) technology, wind turbines, and battery energy storage. Implemented in MATLAB/Simulink, the study formulated a nonlinear optimization model to determine optimal PV/T design parameters, such as flow rate and thermal–electrical sizing, under thermo-electrical constraints, with the objective of maximizing power output. A customized Simulink component (mask) representing the optimized sheet-and-tube PV/T unit was created and integrated with wind and battery subsystems. The complete hybrid system was evaluated through a 72-hour off-grid microgrid simulation, demonstrating the effectiveness of the proposed design and integration approach.

Table 1 is a comparative mapping table of the reviewed studies. The table is structured to support related works, clearly highlighting methodology and key outcomes while making research gaps visible.

Table 1: Comparative mapping table of reviewed studies

Author(s) & Year	Methodology	Findings	Identified Gaps
Smith & Harris (2018)	Simulation and hardware implementation; fuzzy-logic MPPT; PID-controlled buck converter	Fuzzy-logic MPPT achieved 99.06–99.80% efficiency, outperforming P&O and incremental conductance methods	Focused on HEV application; limited analysis of long-term battery aging and grid-connected scenarios
Shiau & Ma (2013)	PSIM simulation; hardware prototype and experimental test bed	ASBC performed better at low current (1 A); SBC superior at high charging current	Restricted to EV charging; no integration with PV system-level optimization or energy management
Gabbar et al. (2021)	Comprehensive literature review	Identified gaps in safety and operational standards; proposed framework for improved BMS standardization	Conceptual review; lacks experimental or system-level validation
Ukoba et al. (2024)	Systematic literature review	Highlighted solar energy's role in rural electrification and sustainable development	Did not provide system modeling, optimization, or performance evaluation
Osagie et al. (2024)	Experimental testing using solar, generator, and grid power	Identified delay between charger indicator and actual battery full charge	Small-scale system; no optimization or advanced battery diagnostics (SoC/SoH)
Nyamathulla & Dhanamjayulu (2024)	Comprehensive review	Provided critical assessment of traditional and advanced SoC/SoH methods and challenges	Review-based; lacks case-specific implementation or real-time validation
Terkes et al. (2025)	MILP optimization using Python and Gurobi	Feed-in damping reduced cost, extended battery life, and minimized curtailment	Results not yet validated in real-world deployments
Jacob & Farzaneh (2025)	MATLAB/Simulink modeling; nonlinear optimization	Optimized PV/T design improved system performance and integration	Short simulation horizon; no long-term operational or economic assessment

1.3 Contribution

This study contributes to the growing body of research on small-scale renewable energy systems by experimentally evaluating a battery-buffered solar charging architecture for low-power DC applications under real operating conditions. While numerous studies have investigated solar photovoltaic systems and energy storage solutions in general contexts, there remains a need for practical, experimentally validated designs that address the performance of compact, portable solar charging systems suitable for off-grid and emergency use.

The key contributions of this work are as follows:

i. The design and implementation of a simple and cost-effective solar-powered charging system that integrates a photovoltaic panel, rechargeable battery storage, and DC–DC voltage regulation to deliver a stable 5 V DC output for low-power electronic loads.

ii. An experimental performance evaluation of the proposed system under natural sunlight conditions, focusing on critical metrics such as battery charging time, output voltage stability, and system-level energy conversion efficiency.

iii. A quantitative assessment of energy losses across the charge controller, battery storage, and DC–DC buck converter, providing insight into the practical efficiency limitations of small-scale solar charging systems without advanced control techniques such as MPPT.

iv. A demonstration of the system's suitability for portable and off-grid applications, highlighting its potential use in rural electrification support, emergency backup power, and standalone charging stations for low-power DC devices.

By addressing these aspects, the study provides practical design insights and experimental evidence that can support future improvements in portable solar charging technologies, including the integration of enhanced energy management and power conditioning techniques.

2. MATERIALS AND METHODS

The methodology followed a systematic, practical approach divided into various stages, from component selection to system testing. Each phase is carefully planned to ensure the final system is practical, reliable, and efficient. The proposed system is a battery-buffered solar charging system designed to supply a regulated 5 V DC output suitable for low-power electronic loads. The overall architecture consists of four major functional units: a solar photovoltaic (PV) module for energy harvesting, a charge controller for battery protection and controlled charging, a rechargeable battery for energy storage, and a DC–DC buck converter for voltage regulation.

2.1. Component Selection and Description

a. Solar Panel: The solar panel, as shown in Figure 1, is the source of the solar-powered battery charging system. It plays a vital role by converting sunlight into electrical energy through the photovoltaic effect. This energy is used to power the system and charge the storage batteries, making the setup self-sufficient and eco-friendly. A 12V, 30W solar panel was selected due to its affordability, availability, and ability to generate sufficient power under typical outdoor sunlight conditions. During testing, the panel produced an open-circuit voltage in the range of 17–19 V and an average current of approximately 1.5 A under sunlight intensities between 600 and 800 W/m². This rating was considered adequate for charging the selected battery within a reasonable duration.

Figure 1: Image of a solar panel

b. Storage Battery (Lithium-Ion): The lithium-ion battery, as shown in Figure 2, is the energy reservoir of the system. A 12 V, 2 Ah rechargeable battery was employed to store harvested solar energy and provide power continuity during periods of low or no solar irradiance. The battery also acts as a buffer, decoupling the intermittency of solar input from the load requirements. Lithium-ion batteries offer a longer lifespan than other types, such as lead-acid batteries. These qualities make them ideal for charging applications, as they provide consistent, efficient charging.

Figure 2: Lithium-ion battery

c. PWM Charge Controller: The PWM (Pulse Width Modulation) charge controller is a smart device used to optimize the maximum energy output from the solar panel and adjust the voltage and current coming from the panel to ensure operation at the most efficient point. This results in greater energy harvesting, especially under fluctuating weather or lighting conditions. It efficiently transfers electricity from the solar panels to the lithium-ion batteries and prevents overcharging, which can degrade battery performance. By constantly monitoring and adapting to the solar panel output and battery state, the PWM controller, as shown in Figure 3, maximizes energy utilization while extending battery life. Its reliability and intelligence make it an essential component in modern solar energy systems.

Figure 3: A PWM Charge Controller

d. DC-DC Buck Converter: The DC-DC buck converter, as shown in Figure 4, plays a crucial role in voltage regulation. It was incorporated into the design to step down the battery's 12V DC output to a regulated 5V DC output suitable for device charging. The converter also helps reduce power loss and improve battery life by avoiding inefficient power delivery.

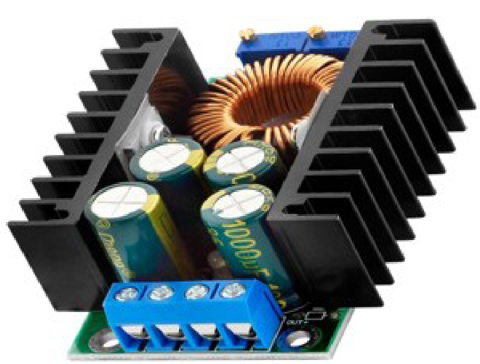

Figure 4: DC-DC Buck converter

2.2. *Block Diagram:*

Figure 5 presents the comprehensive block diagram of the system, which depicts the working process flow. The solar panel (12V, 30W) captures the sunlight and converts it into DC electrical energy. This power output depends on solar intensity, while the PWM charge controller maximizes power extraction by regulating the voltage and current from the solar panel, therefore, charging the storage battery (12V) efficiently. The storage battery stores energy to power the system even when solar input is low, providing a stable voltage source for charging. Next, the DC-DC buck converter steps down the 12V battery voltage to a stable 5V DC output, suitable for charging low-power devices.

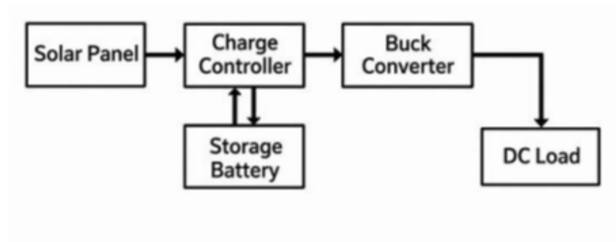

Figure 5. Block diagram of the system

2.3 *Working Principle:*

Once all components were acquired, the system was assembled according to the predefined block diagram. The solar panel was connected to the charge controller, which in turn was connected to the 12V battery for energy storage. The output terminals of the charge controller were linked to the input terminals of the DC-DC buck converter. The 5V output of the converter was then used to charge a mobile drone to simulate real charging conditions.

After the assembly, the system was tested under natural sunlight conditions. Measurements of solar panel voltage, battery voltage, charging current, and load output voltage were taken at regular intervals using a digital multimeter. Sunlight intensity was noted during testing periods to assess the effect of irradiance variations on system performance. The battery charging time from a low state of charge to near full capacity was also recorded.

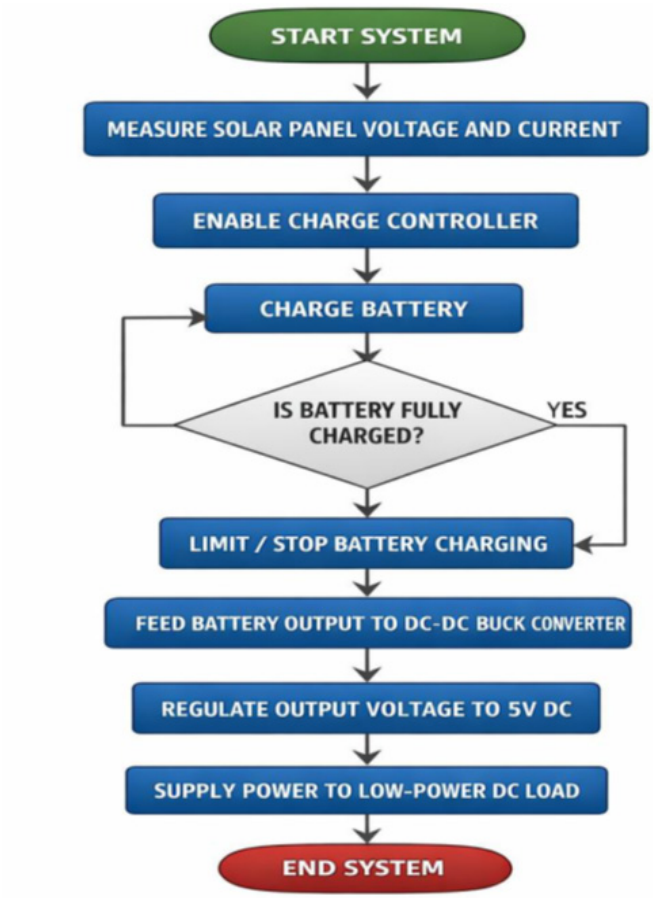

Figure 6: Flowchart illustrating the operational sequence of the system

2.4. Flowchart Description of System Operation

Figure 6 presents the flowchart illustrating the operational sequence of the system. The flowchart begins with system initialization, followed by solar irradiance detection. If sufficient sunlight is detected, the system enables battery charging through the charge controller. Once the battery reaches full charge, the controller limits further charging to prevent overvoltage. The stored energy is then passed through the DC–DC buck converter to deliver a regulated 5 V output to the load. In the absence of adequate solar energy, the system automatically switches to battery-powered operation while maintaining output voltage regulation. This process continues dynamically to ensure reliable power delivery under varying environmental conditions.

2.5. Circuit Diagram

Figure 7 shows the design of the solar-powered battery system to convert energy from the sun into a stable and usable form for charging low-voltage electronic devices. The circuit diagram is made up of several interconnected parts, each serving a unique role in the energy conversion and regulation process. The system begins with a 12V solar panel, serving as the primary source of energy. Under full sunlight, the panel typically produces around 18V at open circuit, but this value depends on the sunlight intensity and environmental conditions. The output from the solar panel is not stable and varies throughout the day, making it unsuitable to be fed directly into the battery or load.

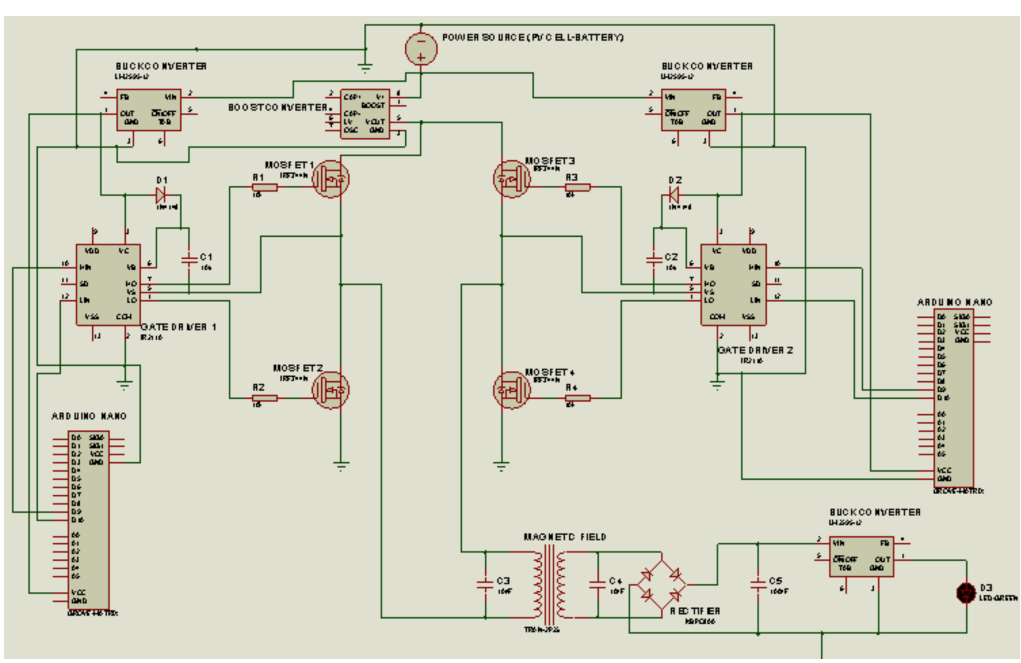

Figure 7: Circuit diagram of the system

To ensure safe charging, the solar panel is first connected to a charge controller. The charge controller regulates the incoming voltage and current, preventing the battery from being overcharged or deeply discharged. The battery is connected to the charge controller. It acts as an energy storage unit, storing excess energy generated during the day and supplying power to the load when sunlight is weak or unavailable. This storage feature ensures uninterrupted operation of the charging system.

Since many portable electronic devices operate on 5V, a buck converter is used. This converter reduces the 12V battery output to a stable 5V regulated supply. The buck converter is efficient and ensures that the output remains constant, even if the input voltage from the battery fluctuates within a certain range. Finally, the 5V output is delivered to the load via a USB port. This ensures the device receives the required voltage without the risk of damage.

3.0. RESULTS AND DISCUSSION

3.1. Battery Charging Performance

Under average sunlight, the intensities ranging between 600 W/m2 and 800 W/m2 were tested. At these levels, the 12V and 30W solar panel consistently provided an open-circuit voltage ranging from 17V to 19V and a short-circuit current of approximately 1.5A, as shown in Table 2. When the panel was connected through the charge controller, it successfully charged the 12V, 2Ah battery within an average period of 2 hours, increasing the voltage of the battery from 11.5V (partially discharged) to 12.7V (fully charged).

3.2. Output Voltage Stability at 5V Load

After charging the battery, the DC-DC buck converter was connected to the output of the battery to regulate the voltage down to 5V DC. The buck converter maintained a steady output voltage of 5.02V to 5.10V throughout the period of charging when connected to a drone. Voltage fluctuations remained within ±0.2V, indicating good voltage stability suitable for sensitive electronic devices. Table 2 shows the performance of the solar-powered battery from 0 to 120 minutes.

The gradual increase in battery voltage observed in Table 2, despite a decrease in solar panel voltage and charging current at certain intervals, can be attributed to the charging characteristics of the rechargeable battery and the cumulative nature of energy storage. During the charging process, the battery voltage increases as its state of charge (SOC) rises over time, even when the instantaneous charging current decreases due to fluctuations in solar irradiance. The energy stored in the battery can be expressed as $E = VIt$, where E represents the stored energy, V is the charging voltage, I is the charging current, and t is the charging duration. As energy accumulates in the battery, the terminal voltage gradually increases. In addition, the battery terminal voltage during charging can be approximated by $V_{bat} = V_{oc} + I_{ch}R_{int}$, where V_{oc} is the open-circuit voltage of the battery, I_{ch} is the charging current, and R_{int} represents the internal resistance of the battery. As the battery approaches full charge, the open-circuit voltage increases, contributing to the observed voltage rise. The slight variation in the regulated output voltage around the nominal 5 V level is due to the regulation characteristics of the DC–DC buck converter, which follows the relationship $V_{out} = DV_{in}$, where V_{out} is the output voltage, V_{in} is the converter input voltage (battery voltage), and D is the duty cycle of the switching converter. The measured output variation within approximately 5.02–5.10 V therefore reflects normal converter regulation tolerance and remains within the acceptable operating range for typical 5 V electronic devices.

Table 2: Performance data of the solar-powered battery charging system over time

Time (Min)	Solar Panel Votage (V)	Battery Voltage (V)	Charging Current (A)	5V Output Voltage (V)
0	18.2	11.5	1.4	–
30	17.9	11.9	1.2	5.04
60	17.7	12.3	1.1	5.05
90	17.4	12.5	1.0	5.06
120	17.2	12.7	0.9	5.07

3.3 Energy Conversion Efficiency:

The total energy generated by the solar panel during the 2-hour charging period was estimated using the measured current and voltage values. On average, 24Wh of energy was produced by the panel, and approximately 16.5Wh was effectively stored in the battery and delivered through the 5V converter. The overall system's energy conversion efficiency, including losses in the charge controller, battery, and buck converter, was calculated to be approximately 69% (68.75%). This is defined as the ratio of the useful electrical energy delivered through the regulated 5 V output to the total electrical energy generated by the solar panel during the charging period.

Discussion of Findings: Figure 8 shows the graphical representation of the performance of the system. The results obtained show that the solar-powered battery charging system successfully met its design objectives. The time it takes to charge the battery was reasonable for a 2Ah battery, given the panel's capacity and sunlight conditions. The output voltage stability at 5V remained within acceptable limits for mobile devices and other small electronics, ensuring the safety of the device during operation.

The performance characteristics observed in this study, i.e., 69% energy conversion efficiency, are consistent with previously reported results for small-scale photovoltaic charging systems incorporating battery storage and DC–DC voltage regulation. Similar studies have reported comparable voltage stability and moderate system-level efficiencies due to cumulative losses in charge control, storage, and conversion stages. These similarities indicate that the proposed system performs within the expected operational range of compact standalone solar charging architectures. The efficiency could be further improved
by integrating an MPPT-based charge controller or using higher-quality DC-DC converters in future designs.

Additionally, under fluctuating sunlight conditions, the system functioned reliably, although charging times extended slightly under lower irradiance. This highlights the dependence of solar-based systems on weather and environmental factors, which is a known limitation of off-grid renewable energy solutions. The system proves to be a cost-effective, portable, and reliable solution for 5V DC charging applications in off-grid, rural, and emergency scenarios. It provides a practical alternative to conventional power sources, contributing to sustainable energy access initiatives.

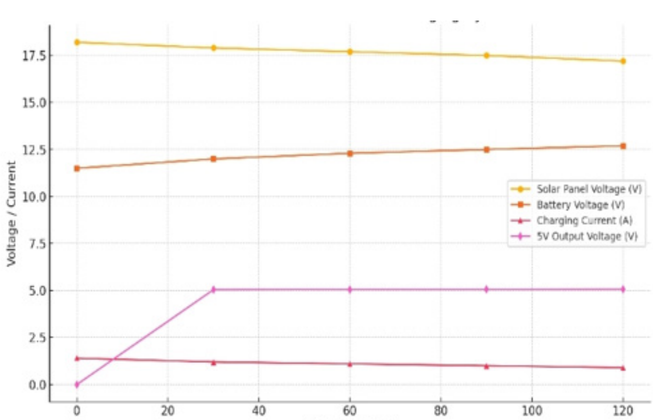

Figure 8: Graphical representation of the performance of the system

4.0. CONCLUSION

This work successfully demonstrated the design and development of a small-scale battery-buffered solar charging system capable of delivering a stable 5 V DC output for low-power electronic devices. The system, consisting of a 12 V solar panel, a rechargeable storage battery, and a DC–DC buck converter, was able to supply regulated power under natural sunlight conditions. The results indicate that the system can harvest solar energy during periods of adequate irradiance, store it in the battery, and subsequently convert it to a steady 5 V DC supply with minimal voltage fluctuations.

Experimental observations showed that under moderate sunlight conditions, the battery was charged within approximately 2 hours, while the regulated output voltage remained stable within the acceptable range for typical 5 V low-power DC loads. The overall system energy conversion efficiency was estimated to be about 69%, accounting for losses across the charge controller, battery storage process, and DC–DC conversion stage. This level of efficiency is consistent with the expected performance of small-scale photovoltaic charging systems that do not employ advanced control techniques such as maximum power point tracking (MPPT).

In terms of contribution to knowledge, this study provides a practical design and experimental evaluation of a compact solar-powered charging architecture integrating photovoltaic energy harvesting, battery-based energy buffering, and DC–DC voltage regulation. The findings offer useful insight into the operational performance of standalone solar charging systems under real sunlight conditions, particularly in terms of charging behavior, voltage regulation, and system-level efficiency.

The proposed system demonstrates that simple and cost-effective solar charging solutions can provide reliable power for low-power DC applications, making them suitable for deployment in rural areas, emergency backup scenarios, and other off-grid environments where access to a conventional electricity supply is limited.

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