International Journal of Electrical and Computer Engineering (IJECE)
Vol. 16, No. 1, February 2026, pp. 111~120
ISSN: 2088-8708, DOI: 10.11591/ijece.v16i1.pp111-120

Efficiency enhancement of off-grid solar system

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Article Info

Article history:

Received Apr 8, 2025
Revised Oct 25, 2025
Accepted Nov 23, 2025

Keywords:

AT- mega controller
IoT based supply controller
Load scheduling and efficiency enhancement
Solar panel

ABSTRACT

This paper presents the design and implementation of a sensor-enabled off-grid solar charge controller aimed at maximizing the utilization of renewable energy. The proposed system integrates solar and load power sensors to minimize solar energy wastage. A microcontroller is employed to efficiently monitor and regulate battery voltage, solar power generation, and load demand. This system is designed to optimize solar energy usage, reduce dependency on the electrical grid, and lower electricity bills. Additionally, a main supply controller board with a display is introduced, along with a smart scheduler for appliance management. Prior to deployment, total solar power wastage was recorded at 93.1 watts per day. After implementing the proposed solution, wastage was reduced to 13.1 watts per day—reflecting an 85.92% reduction. These results confirm the system's effectiveness in reducing energy loss, increasing self-consumption, and promoting energy sustainability in off-grid environments. It is important to note that this value may vary based on factors such as temperature, cloud cover, fog, and irradiation levels.

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1. INTRODUCTION

The world is currently facing significant energy challenges due to the depletion of fossil fuel reserves and their rising prices. These fuels also contribute to environmental pollution, ozone layer depletion, and global warming. Rural electrification is crucial for organized rural development. Energy is a fundamental requirement for developing countries, playing a central role in the interconnected economic and social progress of their populations. A country like India recognizes the importance of energy, and its utilization must be carefully managed to prevent accelerated environmental damage, increased inequality, and jeopardized economic growth. Solar energy is one of the most economical forms of renewable energy. It is naturally abundant and environmentally friendly. Photovoltaic cells are uniquely effective in harvesting solar energy, being pollution-free and having a reliable, long lifespan. This makes it one of the fastest-growing renewable energy alternatives.

The paper addresses the problem of solar energy wastage in off-grid solar systems due to inefficient charge controllers and lack of intelligent energy management. Specifically, it investigates how to maximize the utilization of renewable solar energy by minimizing energy losses in off-grid setups. In many off-grid solar PV systems, a significant portion of the generated solar energy goes unused, especially when battery storage reaches capacity or when there is no smart mechanism to balance load and generation. Traditional charge controllers are often not equipped to handle real-time monitoring and adaptive load scheduling. This inefficiency leads to increased dependency on the electrical grid and higher electricity costs. With the global push for renewable energy adoption, especially in remote or rural areas, there's a growing need for intelligent systems that can efficiently manage solar power generation, storage, and usage. The objective is to design a smart solar charge controller using sensors, microcontrollers, and a decision-making algorithm. The system uses real-time data to manage battery charging, load scheduling, and energy discharge. It combines low-cost hardware with adaptive control logic to improve off-grid solar efficiency. Solar power plants can be broadly categorized based on grid connectivity: on-grid, off-grid, and hybrid. On-grid PV systems are grid-connected and do not require batteries for power storage. These systems are connected to the electrical grid and can feed excess energy back into it. However, they are not suitable for household use during mains failures, as power generation ceases. Off-grid PV systems are not connected to the grid and require batteries for excess power storage. Hybrid PV systems combine on-grid and off-grid features, allowing for both grid connection and energy storage. Most solar systems in rural areas, where mains power availability is limited, are installed in off-grid mode. On-grid PV systems do not generate power during grid outages, which can lead to wasted solar power and reduced overall system efficiency. Extensive research is being conducted to improve the efficiency of off-grid solar systems.

Research efforts are exploring diverse demand-side management (DSM) strategies for the residential sector [1]. These include comprehensive reviews of DSM potential, the development of fully automated systems using Open ADR 2.0b and building energy management systems to optimize energy usage and reduce peak demand, and the application of nature-inspired algorithms for smart grid environments to balance energy demand and enhance grid efficiency. These approaches collectively aim to improve energy conservation, load shifting, and demand response through intelligent automation [2], [3]. On the supply side, Galarza *et al.* [4] proposed a novel trade-off approach for photovoltaic power smoothing to mitigate output variability, contributing to enhanced grid stability. In a related direction, Draoui *et al.* [5] introduced a global maximum power point tracking (MPPT) technique using the Flamingo Search Algorithm, which performed better under partial shading conditions. Enhancing estimation precision in economic analysis, Sahrin *et al.* [6] presented an improved energy import estimation model for rooftop grid-connected PV systems. For intelligent MPPT control, Salem *et al.* [7] combined perturb and observe (P&O) methods with neural networks, improving tracking speed and responsiveness. Wireless energy transfer techniques have also gained attention, as Irwanto *et al.* [8] investigated power transfer efficiency via magnetic relays at standard grid frequency. Hybrid and off-grid systems also feature prominently. Fennane *et al.* [9] 9assessed a PV-wind-diesel-battery microgrid and demonstrated its viability for rural electrification. Jusoh *et al.* [10] developed a rule-based control scheme for battery energy storage systems (BESS), enabling better hourly power dispatch in PV systems. Likewise, Jafar *et al.* [11] applied fuzzy logic to enhance P&O MPPT, resulting in faster convergence and greater accuracy. Jaoide *et al.* [12] combined MPPT with space vector modulation in quasi-Z-source inverters to improve both voltage regulation and efficiency in grid-tied PVs. Complementing these control strategies, Yu and Jung [13] developed a simulation-based dynamic performance evaluation platform to assess PV behaviour under transient conditions. Efforts to improve power quality are also evident. Mishra et al [14] used filters and compensation methods to enhance the quality of power delivered by grid-tied PV systems. Ouahab *et al.* [15] proposed a temperature-based fast MPPT detection method, effective under rapidly changing environmental conditions. Singh [16] employed a unified power quality conditioner (UPQC) for hybrid renewable systems to reduce voltage fluctuations and harmonic distortion. Torabi *et al.* [17] introduced a hybrid MPPT technique combining fuzzy logic with P&O, achieving optimized tracking under varying irradiance. Additionally, Mensik *et al.* [18] examined the interplay between energy storage sizing, control strategies, and system reliability in hybrid configurations.

Several studies explore the application of IoT in optimizing energy usage and promoting sustainability. Zhao *et al.* [19] focuses on low-energy building design in dense urban areas, utilizing IoT to monitor and control energy consumption for improved efficiency and reduced costs. Studies [20] and [21] developed IoT-based systems for real-time solar energy monitoring, optimizing generation and consumption, and enabling remote management to enhance efficiency and detect faults. Finally, Ahmadzadeh *et al.* [22] reviews communication aspects of demand response management in 5G IoT-based smart grids, highlighting how advanced communication technologies enhance real-time data exchange and grid management. Several research efforts have explored advanced techniques for energy management. Specifically, Pal *et al.* [23] developed an IoT-based real-time energy management system for virtual power plants using PLCs within a transactive energy framework, emphasizing enhanced operational efficiency and control. Similarly, Saleem *et al.* [24] designed and implemented an IoT-based smart energy management system to monitor and control energy consumption, aiming for improved management and sustainability. In the context of smart grids, Saleem *et al.* [25] designed and evaluated an IoT-based system for demand-side management, focusing on optimizing energy use and balancing demand. To address residential energy optimization, Singaravelan *et al.* [26] applied the two-phase simplex method (TPSM) to reduce peak demand and consumer costs. Furthermore, Han *et al.* [27] proposed a deep learning framework for intelligent energy management in IoT networks, facilitating smarter and more adaptive energy management. Research also extends to solar energy systems, where Badoni *et al.* [28] proposed a grid-tied solar PV system with quality enhancement using an adaptive generalized maximum versoria criterion, improving power quality and grid integration. recently, Mukherjee *et al.* [29] focused on optimizing solar power for home lighting, highlighting smart control and energy storage solutions for enhanced reliability and efficiency. This article presents an innovative approach to enhance the efficiency of off-grid solar systems by minimizing energy wastage through an adaptive solar charging controller and retrofit. A key feature is the integration of sensors for real-time monitoring and quantification of unused solar energy. By analyzing surplus energy generated by the photovoltaic (PV) system, the proposed design strategically discharges the battery during nighttime hours using a load-priority mechanism. This ensures optimal utilization of available solar energy the following day, thereby continuously mitigating energy wastage. The system maximizes solar energy usage, minimizes grid power reliance, and results in significant reductions in electricity costs, ultimately improving overall solar system efficiency.

In this section, Introduces the issue of solar energy wastage in off-grid systems and the need for smart energy management. In section 2, Describes the architecture of the proposed system including sensors, microcontroller, smart scheduler, and control board, explains how the system is built, integrated, and configured in a real-world setup. In section 3, Presents pre- and post-installation data (e.g., daily wastage reduced from 93.1W to 13.1W) and discusses the improvement in efficiency. Analyzes contributing factors like weather, temperature, and their impact on performance; discusses system advantages and limitations. Finally, section 4 summarizes findings and emphasizes the potential for future scalability and broader implementation. This manuscript fits the journal's scope on renewable energy, power electronics, and intelligent control. It presents a practical, sensor-based solution for reducing solar energy wastage in off-grid systems. Its low-cost, adaptive approach makes it highly citable for future work in smart grids and energy optimization. The paper offers a validated, interdisciplinary solution to energy loss in solar systems. It is technically robust, socially relevant, and well-suited to the journal's focus on innovative and practical renewable energy research.

In the hardware design and implementation of the proposed off-grid solar system prototype is designed to prevent battery overcharging and to ensure maximum utilization of renewable energy. The system employs a sensor-based control architecture that dynamically switches between solar and mains power based on real-time monitoring of battery state of charge (SOC), load demand, and solar energy availability.

Figure 1 depicts the block diagram of the proposed off-grid solar system prototype, designed to prevent battery overcharging and maximize renewable energy utilization. When solar power is available and the battery's state of charge (SOC) is below 60%, the decision-making unit signals the mains retrofit load to be powered by the mains supply, while the battery charges from both solar and mains power, When the battery's state of charge exceeds 60%, the system disconnects the retrofit from the mains power supply, and the load is powered by solar energy. Conversely, if solar power is available, the battery is fully charged, and the load's power consumption is less than the solar power generation, excess solar energy is produced. This excess is quantified by measuring the solar current and voltage. Based on the accumulated data of this wasted solar power and the load's power demand patterns, a decision-making unit determines if and when to disconnect the retrofit from the mains power supply before sunrise. This controlled battery discharge effectively reduces solar power wastage. The algorithm is illustrated in the flowchart shown in Figure 2.

The electrical load's power consumption is measured using a PZEM-004T-100A module. An arithmetic logic unit (ALU) manages the load priority device. A Python-based integrated development environment (IDE) is used for data analysis. An AC energy meter, integrated with the inverter, monitors the load's energy consumption. To minimize solar power wastage, a load priority device is implemented. A DC energy meter measures the solar system's generated and wasted energy. An AC energy meter measures the load's power consumption. The load priority device strategically discharges the battery before sunrise by an amount equivalent to the estimated wasted solar power.

This preemptive discharge ensures that the battery has capacity to absorb more energy the following morning, thereby optimizing solar energy utilization. This system aims to maximize solar power utilization and minimize wastage through continuous monitoring of solar power generation, demand, and wastage. The system design comprises three stages:

- Total power generated by Solar PV: The energy generated by the solar PV system in a day is measured using a DC energy meter (PZEM-003/017 DC communication module).
- Total load demand: The energy consumed by the load connected to the inverter is also measured.
- Calculation of solar wastage power: When the power supply from the solar PV is interrupted, the wastage power is calculated.

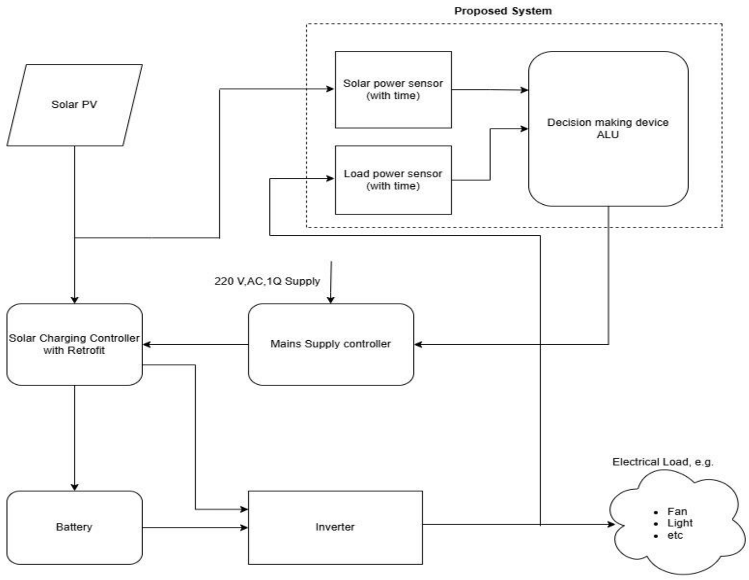

Figure 1. Block Diagram of off- grid solar system with IoT based system

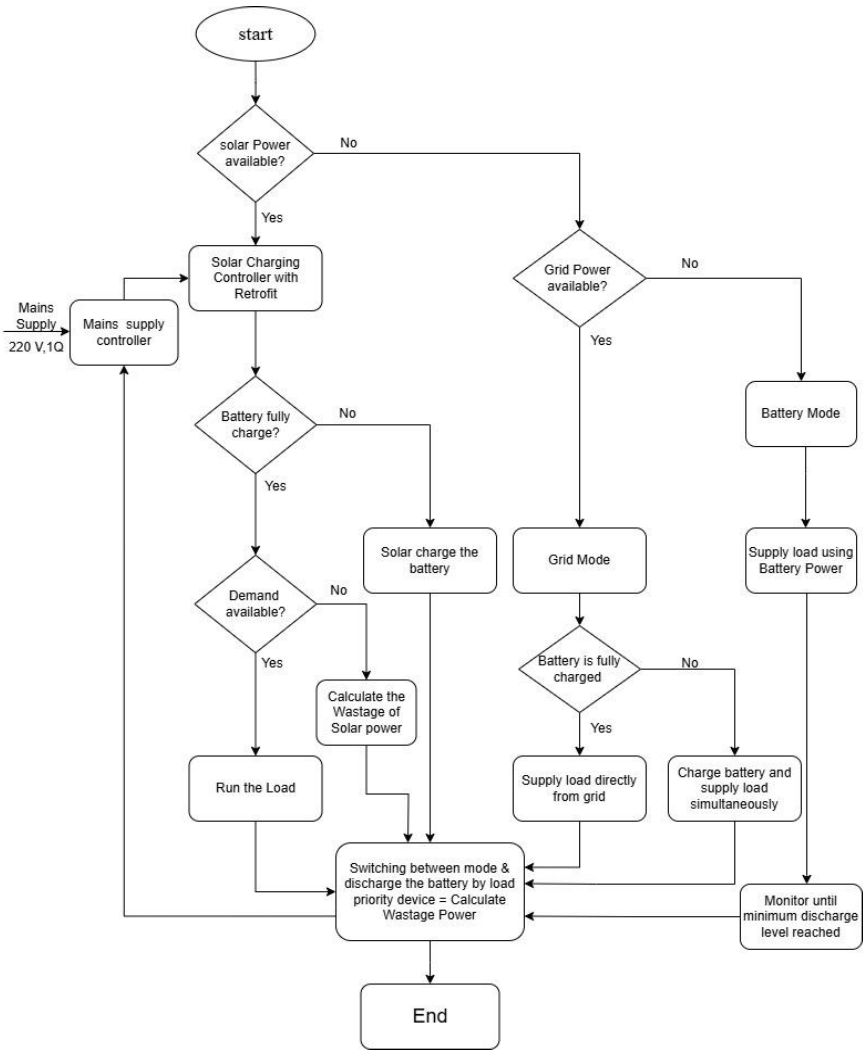

Figure 2. Flowchart of the entire process

The wastage power P waste calculated as follow:

$$P_{waste} = P_{Solar} - P_{Load}$$

Where:
P_{waste} = Solar energy wasted (Wh/day)
P_{Solar} = Total solar energy generated (Wh/day)
P_{Load} = Total energy consumed by the load (Wh/day)
By implementing this monitoring framework, the system ensures that any underutilization of solar energy is identified, quantified, and addressed through intelligent load scheduling and energy management.

2. RESULTS AND DISCUSSION

Figure 3 illustrates the hardware implementation of the proposed system. The prototype model, used for data collection, incorporates a 55-watt monolithic photovoltaic (PV) panel, a 500 VA, 12-volt inverter, and a 28 Ah battery. Table 1 and Figure 4 present the solar power wastage data collected before implementing the proposed system. Maximum power wastage was observed between 13:00 and 16:00 hours, occurring when the battery was fully charged and the load power demand was minimal. Existing solar charging systems or retrofits typically disconnect the inverter's mains power only during daylight hours and when the battery's charge level exceeds 60%. Consequently, if the load power demand is less than the solar power available after the battery is fully charged, solar power is wasted. Table 2 and Figure 5 show the measured data after implementing the proposed system, designed to minimize this wastage. Our proposed adaptive solar charging controller cum retrofit efficiently reduces wasted solar power by continuously calculating the daily solar power wastage. Based on this data, the system disconnects the inverter's mains power supply prior to sunrise, thereby minimizing wastage. The total daily power wastage before implementing the proposed system was 93.1 watts in Table 1. After implementation, this was reduced to 13.1 watts, resulting in an 85.92% reduction in wasted solar power.

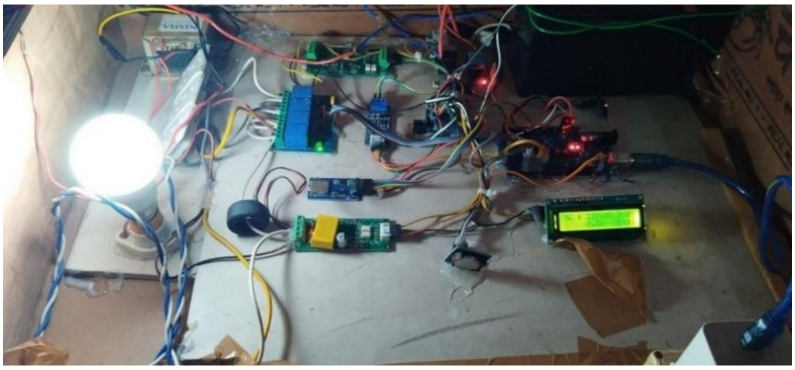

Figure 3. Prototype model, off- grid solar system with IoT

Compared to traditional off-grid systems, which typically use basic charge controllers without forecasting or load management features, this approach represents a notable advancement. Previous studies have acknowledged the problem of energy wastage in off-grid solar systems due to overcharged batteries and mismatched load profiles, but few have implemented automated feedback loops with real-time sensing and scheduled discharge. This system builds upon such findings and introduces a practical, low-cost solution using widely available modules like the PZEM-004T, DC/AC energy meters, and a Python-based IDE for data processing and visualization

To this improvement was the intelligent battery management mechanism. By introducing a load-priority discharge strategy before sunrise, the system created space in the battery for fresh solar energy the next morning. The integration of sensors for real-time measurement of solar voltage, current, and load demand enabled the controller to make data-driven decisions that minimized energy overflow and idle charging conditions. This proactive discharge of the battery allowed more solar energy to be stored and used effectively the following day, reducing both energy loss and dependence on grid power.

Table 1. Wastage solar power data before implementation of proposed system

Time	Solar Power (W)	Load Power (W)	Battery charging Power by solar (W)	Wastage Power (W)
00:00-01:00	0	0	0	0
01:00-02:00	0	0	0	0
02:00-03:00	0	0	0	0
03:00-04:00	0	0	0	0
04:00-05:00	0	0	0	0
05:00-06:00	0	0	0	0
06:00-07:00	9.5	10	0	0
07:00-08:00	30.75	23	7.75	0
08:00-09:00	39.65	23	16.65	0
09:00-10:00	40.7	23	17.7	0
10:00-11:00	42.1	17	25.1	0
11:00-12:00	42.4	10	32.4	0
12:00-13:00	42.4	10	32.4	0
13:00-14:00	42.1	0	27.65	14.45
14:00-15:00	40.7	0	0	40.7
15:00-16:00	37.95	0	0	37.95
16:00-17:00	19.05	23	0	0
17:00-18:00	4.9	23	0	0
18:00-19:00	0.9	29	0	0
19:00-20:00	0	27	0	0
20:00-21:00	0	22	0	0
21:00-22:00	0	19	0	0
22:00-23:00	0	22	0	0
23:00-00:00	0	19	0	0

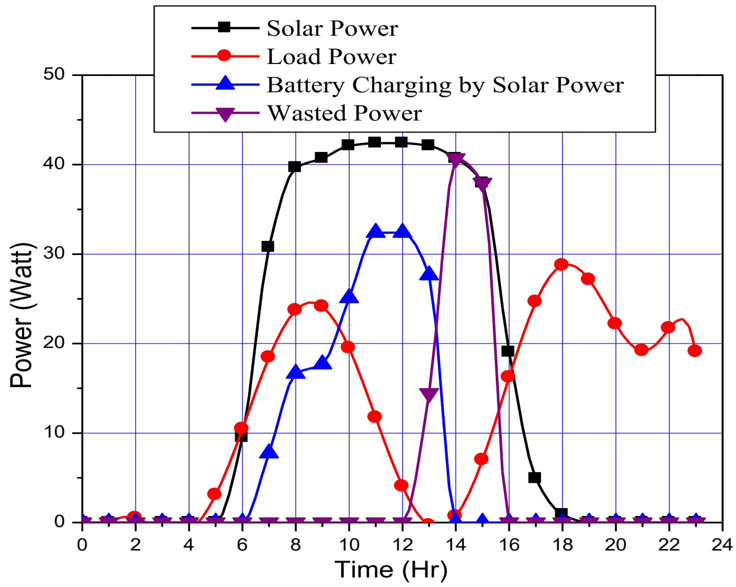

Figure 4. Wastage solar power data before implementation of proposed system

The study emphasizes the role of smart retrofit disconnection based on battery SOC and load conditions. For instance, when the battery SOC was below 60%, the retrofit ensured battery charging from both solar and mains sources. Once the SOC exceeded 60%, the system intelligently disconnected the mains power and prioritized solar power for load usage. This dual-source strategy, coupled with the selective discharge mechanism, enhanced energy flow control and reduced unnecessary grid reliance.

An adaptive charge controller with integrated sensor feedback and load-priority logic can significantly improve the performance of off-grid solar systems. This work contributes new insights into energy-aware scheduling and intelligent discharge management, offering a scalable solution for rural electrification and decentralized energy systems. The proposed system bridges the gap between raw energy generation and efficient utilization, ensuring that the potential of solar PV systems is fully harnessed without expensive or complex infrastructure. It's important to note that this percentage may fluctuate depending on environmental factors such as temperature, cloud cover, fog, and solar irradiation.

Table 2. After the successful implementation of off grid solar inverter

Time	Solar Power (W)	Load Power (W)	Battery Charging Power (W)	Wastage Power (W)
00:00-01:00	0	0	0	0
01:00-02:00	0	20	0	0
02:00-03:00	0	20	0	0
03:00-04:00	0	20	0	0
04:00-05:00	0	20	0	0
05:00-06:00	0	0	0	0
06:00-07:00	9.5	10	0	0
07:00-08:00	30.75	23	7.75	0
08:00-09:00	39.65	23	16.65	0
09:00-10:00	40.7	23	17.7	0
10:00-11:00	42.1	17	25.1	0
11:00-12:00	42.4	10	32.4	0
12:00-13:00	42.4	10	32.4	0
13:00-14:00	42.1	0	42.1	0
14:00-15:00	40.7	0	40.7	0
15:00-16:00	37.95	0	37.95	13.1
16:00-17:00	19.05	23	0	0
17:00-18:00	4.9	23	0	0
18:00-19:00	0.9	29	0	0
19:00-20:00	0	27	0	0
20:00-21:00	0	22	0	0
21:00-22:00	0	19	0	0
22:00-23:00	0	22	0	0
23:00-00:00	0	19	0	0

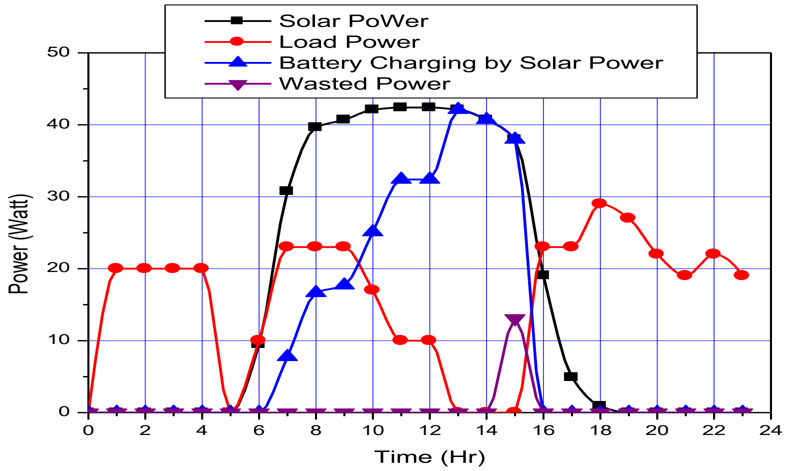

Figure 5. Data comparison of After the successful implementation of off grid solar inverter

3. CONCLUSION

In conclusion, this paper successfully demonstrates the effectiveness of a sensor-enabled off-grid solar charge controller in significantly reducing energy wastage and enhancing the efficiency of solar power utilization. By integrating real-time monitoring of solar and load power through strategically placed sensors, the system optimizes battery management and load distribution, particularly through a load-priority based nighttime discharge mechanism. The empirical results, showcasing an 85.92% reduction in daily energy wastage from 93.1 watts to 13.1 watts, validate the proposed approach. This optimized system not only minimizes reliance on the electrical grid and lowers electricity costs but also contributes to a more sustainable energy consumption model. The inclusion of a main supply controller with a display and a smart scheduler further enhances user control and appliance management.

This work advances the field by introducing real-time, proactive energy management in off-grid solar systems. It validates a method that reduces daily solar wastage by 85.92% through smart battery discharge and adaptive control. While environmental factors such as temperature, cloud cover, and irradiation can influence performance, the system's adaptive design effectively addresses the core challenge of maximizing renewable energy utilization in off-grid solar systems. This research highlights the potential of intelligent, sensor-driven solutions in improving the viability and efficiency of solar energy applications, particularly in remote or grid-constrained environments.

ACKNOWLEDGMENTS

The authors would like to acknowledge Integral University for providing the necessary support (Article MCN no IU/ R&D/2025-MCN0003483).

FUNDING INFORMATION

This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors.

AUTHOR CONTRIBUTIONS STATEMENT

This journal uses the Contributor Roles Taxonomy (CRediT) to recognize individual author contributions, reduce authorship disputes, and facilitate collaboration.

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Anil Kumar Singh	✓				✓				✓	✓	✓			
Deepak Gangwar	✓				✓				✓	✓	✓			

C : **C**onceptualization
M : **M**ethodology
So : **So**ftware
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I : **I**nvestigation
R : **R**esources
D : **D**ata Curation
O : Writing - **O**riginal Draft
E : Writing - Review & **E**diting
Vi : **Vi**sualization
Su : **Su**pervision
P : **P**roject administration
Fu : **Fu**nding acquisition

AUTHOR CONTRIBUTIONS STATEMENT

All authors contributed equally to the conception, design, analysis, and writing of this manuscript. All authors have read and approved the final version of the manuscript.

CONFLICT OF INTEREST STATEMENT

The authors declare that there is no conflict of interest regarding the publication of this paper.

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