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# REAL-TIME IMPLEMENTATION OF A SELF-SUSTAINING FLYWHEEL-ASSISTED PHOTOVOLTAIC POWER SYSTEM FOR NIGHTTIME LOAD MANAGEMENT

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## ABSTRACT

This study shows how a flywheel-powered solar energy system works in real-time to manage electricity use at night in places without a power grid. The system integrates a 1.5 kW PV array, a 24 V 200 Ah battery bank, a 1.5 kW DC motor, a 90 kg hollow cylindrical flywheel, a 3.5 kVA alternator, and a 695 W residential load operating for 12 hours daily. Two system configurations are investigated: one with a conventional battery-only supply and the other augmented by a flywheel energy storage system and a rechargeable feedback loop that partially restores battery charge from the alternator output.

Results indicate that in the absence of the flywheel, the battery undergoes daily energy stress exceeding its capacity, discharging up to 174% of its rated limit and risking premature failure. In contrast, the hybrid setup significantly reduces the battery's net discharge to 1.56 kWh/day, an 81.3% reduction by contributing 1.8 kWh from flywheel kinetic energy and recovering an additional 1.8 kWh via the recharge circuit. This results in a safer daily Depth of Discharge (DoD) of approximately 32.5%, effectively extending battery lifespan and enhancing load reliability.

The findings underscore the efficacy of mechanical-electrical hybrid energy systems in reducing battery dependence, improving overall efficiency, and ensuring uninterrupted energy availability in low-sunlight or resource-constrained environments. The proposed system offers a robust model for sustainable, autonomous energy solutions, particularly in regions facing grid unreliability or energy poverty.

**KEYWORDS**: Self-sustaining energy system, flywheel energy storage, nighttime load management, energy sustainability, load balancing, off-grid power system, energy recovery

## INTRODUCTION AND BACKGROUND

Energy demand during nighttime in off-grid homes often results in over-reliance on battery storage systems. This leads to accelerated degradation due to frequent deep discharge cycles. To address this challenge, this study proposes a photovoltaic (PV) system integrated with a Flywheel Energy Storage System (FESS). The FESS serves to power nighttime loads by converting kinetic energy into electrical energy, thereby reducing the strain on battery storage and extending battery life. The study focuses on analyzing energy flow, battery performance, system sustainability, and overall efficiency.

Solar PV is widely recognized as a sustainable renewable energy source with the potential to meet global electricity demand (Faithpraise and Edohoeket, 2019; Ayodele and Ogunjuyigbe, 2015a). However, the output power of PV modules is affected by irregular solar irradiance, leading to inconsistent energy generation (Ogunjuyigbe, Ayodele, and Akpeji, 2018). To overcome this limitation, hybrid energy storage systems have been introduced (Ayodele and Ogunjuyigbe, 2020). These systems combine different storage technologies to compensate for the limitations of individual components.

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**Overview of Energy Storage Technologies**

Among the various storage systems used in PV applications, lead-acid batteries remain the most widely adopted due to their affordability and availability (Rohit and Rangnekar, 2017). Nevertheless, energy storage technologies are critical for ensuring reliable and uninterrupted power supply, especially given the intermittent nature of solar energy. Intermittent solar energy is caused by several natural and environmental factors that affect the consistency and availability of sunlight reaching photovoltaic (PV) panels. The key causes include as in (Faithpraise et al., 2017):

*Weather Conditions*: Cloud cover, rain, and fog reduce the intensity of sunlight, leading to lower power generation.

*Diurnal Cycle*: Solar energy is only available during the day; it drops to zero at night due to the Earth's rotation.

*Seasonal Variation*: The angle of the sun and length of daylight change with seasons, especially in regions far from the equator.

*Shading*: Shadows from buildings, trees, or other obstructions can block sunlight and reduce panel output.

*Dust and Pollution*: Accumulation of dirt, dust, or air pollutants on solar panels can limit their efficiency and cause fluctuating output.

*Solar Panel Orientation*: If panels are not optimally tilted or oriented toward the sun, the energy collected can vary throughout the day.

*Atmospheric Conditions*: Variations in air mass, humidity, and aerosol concentration can affect the intensity of solar irradiance.

**Lead-Acid Batteries:** Identified by (Dunn et al., 2011) as the oldest and most commonly used in off-grid and hybrid PV systems. They typically have a short lifespan (3 to 5 years), a low Depth of Discharge (DoD), and require high maintenance.

**Lithium-Ion Batteries:** According to Larcher et al. (2015), these are increasingly used in residential and commercial PV systems. They offer high energy density, DoD of 80–90%, low maintenance, and long lifespan, but come at a higher cost than lead-acid batteries.

**Vanadium Redox Flow Batteries:** (Skyllas-Kazacos et al. 2011) described this technology as utilizing liquid electrolytes for energy storage. It supports 100% DoD, offers over 10,000 charge-discharge cycles, and is easily scalable. However, the system is bulky, expensive, and requires pumps and tanks for operation.

**Sodium-Sulfur (NaS) Batteries:** As proposed by the (IEA, 2014), NaS batteries feature a long cycle life (4,500+ cycles) but require a high operating temperature (around 300°C), necessitating strong insulation and safety mechanisms to prevent explosion risks. Their high cost makes them more suitable for grid-scale applications.

**Hydrogen Storage (Power-to-Gas):** Discussed by (Züttel, 2004), this technology involves using excess PV electricity to electrolyze water, producing hydrogen that is stored and later converted to electricity using fuel cells or turbines. Although it allows long-term energy storage, it suffers from low round-trip efficiency (30–40%), high equipment costs, and safety risks due to hydrogen's flammability and the need for high-pressure storage tanks.

From the comparative analysis of storage technologies, it is evident that batteries generally have a low power density. This limitation affects their lifespan, especially when subjected to sudden or high current demands. The introduction of a flywheel energy storage system offers a promising solution by reducing the load on batteries during nighttime energy consumption. This hybrid approach enhances system sustainability and improves overall performance.

## LITERATURE REVIEW

Hybrid energy systems that integrate photovoltaic (PV) sources with various energy storage technologies have gained significant attention in recent years. These systems offer promising solutions to the intermittency challenges of renewable energy by ensuring reliable and sustainable power supply. Of particular interest is the integration of PV systems with both battery storage and flywheel energy storage systems (FESS), aimed at enhancing the reliability, efficiency, and resilience of energy supply in both grid-connected and off-grid applications.

(Beaudin et al., 2010) conducted a comprehensive review of different energy storage technologies, emphasizing the roles of batteries, flywheels, and supercapacitors in renewable energy systems. Although their work provided valuable performance comparisons, it did not explore the specific application or modeling of battery–flywheel hybrid systems within residential or household energy systems.

Similarly, (Ibrahim et al. 2008) compared various energy storage technologies and highlighted their technical characteristics. However, their study did not address the synergistic potential between flywheel and battery systems in hybrid configurations, particularly for small-scale or domestic applications.

Flywheel energy storage has been independently studied for power smoothing and load stabilization in microgrids. For instance, (Zhang et al. 2015) developed a MATLAB/Simulink model demonstrating the effectiveness of flywheels in stabilizing load demand. However, the study did not consider scenarios in which flywheel-generated energy could be fed back into a battery system to support nighttime operations or meet full household energy demand.

(Razykov et al. 2011) provided a broad overview of global progress in solar PV technologies and underscored the need for hybrid energy storage solutions. Despite highlighting the importance of hybrid configurations, the study did not explore practical implementations involving mechanical storage systems such as flywheels.

Kutkut (2002) introduced a modular battery management system designed for renewable energy applications. While valuable for PV–battery systems, the work did not consider mechanical or hybrid storage configurations, such as PV–battery–flywheel integrations.

A more recent study by (Ayodele et al. 2020) investigated the complementary characteristics of batteries and flywheels in PV/battery/flywheel hybrid energy storage systems. The research involved the design and simulation of such a hybrid system, focusing on power smoothing and grid stability enhancement. Although it emphasized the importance of optimized control strategies, it did not explore scenarios involving complete reliance on flywheel systems for load support or nighttime operation.

A common gap across these studies is the lack of real-time integration strategies and feedback mechanisms in which the flywheel output not only supports the load but also recharges the battery, particularly for achieving nighttime energy independence. Furthermore, few studies have modeled the effects of flywheel operation on battery life cycle, depth of discharge (DoD), and overall system efficiency especially in configurations where the flywheel serves as the primary energy source and the battery provides transient backup support.

This research aims to fill these gaps by developing a real-time hybrid energy system model that integrates PV, battery, and flywheel components. The system will be analyzed under realistic load conditions, with a focus on off-grid nighttime operation, to evaluate its effectiveness in improving energy sustainability, extending battery life, and enhancing system efficiency. This is the kind of operational innovation supported in (Otosi *et al*., 2024)

## MATERIALS AND METHODS

This section discusses the applied methodology, and materials used to measure key indicators, which includes a representation of the sample data obtained on a PV–battery–flywheel hybrid system for off-grid nighttime energy support:

## SYSTEM CONFIGURATION

The hybrid renewable energy system developed for this study integrates three major components:

- Photovoltaic (PV) Array: – Simulates daytime solar energy generation.
- Lead-acid Battery Storage: – Acts as a backup and stabilizer during peak demand.
- Flywheel Energy Storage System (FESS): – Functions as the primary energy source during nighttime hours.

The system configuration includes:

- 1.5 kW PV Array
- A 4.2 kVA inverter
- 24V, 200Ah (4.8kWh) deep-cycle lead-acid batteries
- A 3.5 kVA flywheel-driven alternator
- 24V, 1.5 KW DC motor coupled to a 90 kg hollow cylindrical 0.5m radius flywheel rotor
- MPPT 60A, 24V Solar charge controller
- 15 × 25W bulbs + 5 × 46W fans = 695W load for 12 hours
- Data acquisition module (DAQ) for energy flow monitoring
- Simulink/MATLAB modeling for simulation and analysis

## MEASUREMENT INDICATORS

To evaluate system performance, the following indicators shown in Table 1, were measured using sensors and embedded monitoring tools:

**TABLE 1: SYSTEM PERFORMANCE EVALUATION**

| S/n | Indicator | Measurement Tool | Purpose |
|---|---|---|---|
| 1 | Battery State of Charge (SoC) | Battery management system (BMS) + voltage sensors | To monitor battery depth of discharge (DoD) |
| 2 | Flywheel RPM and Kinetic Energy | Tachometer sensor, moment of inertia calculation | To assess kinetic-to-electric energy conversion |
| 3 | DC Motor and Alternator Output | Clamp meters and multimeters | To measure real-time current and voltage levels |
| 4 | System Efficiency | Simulink simulation (power input vs output) | To calculate round-trip and overall efficiency |
| 5 | Load Energy Consumption | Load meters and simulated demand curves | To quantify actual household load requirements |

## EXPERIMENTAL PROCEDURE

The experimental procedures were shared into four phases as illustrated below

***Simulation and Hardware Design Phase:*** The system was first modeled using MATLAB/Simulink to simulate energy flows across day–night cycles with varying load conditions. This was followed by a scaled prototype design with real components.

***Charging Phase:*** During the day, PV panels charge the battery while also supplying power to a DC motor that spins the flywheel.

***Discharging Phase (Nighttime):*** At night, the flywheel drives a coupled alternator to supply household loads. The battery only supplies power to the DC motor when there's a temporary mismatch in flywheel generation and load demand.

**Data Logging:** A DAQ system logged performance data every 5 seconds for 8 hours of nighttime operation on the control setup to evaluate system dynamics as shown in Table 2.

**Table 2: Sample Data Collected from control setup.**

| Time (min) | Battery SoC (%) | Flywheel RPM | Alternator Output (V) | Load (W) | Battery Current (A) |
|---|---|---|---|---|---|
| 0 | 100 | 2000 | 220 | 500 | 0.2 |
| 30 | 96 | 1700 | 215 | 450 | 0.5 |
| 60 | 91 | 1400 | 210 | 470 | 1.2 |
| 90 | 85 | 1100 | 205 | 510 | 1.8 |
| 120 | 80 | 950 | 200 | 520 | 2.5 |

In Table 2, the data shows a gradual reduction in flywheel speed and an increase in battery current, indicating the transition of energy support from the flywheel to the battery over time.

## ANALYSIS METHODS

*To analyzed the methods applied in this research work, the energy demand was looked at critically as thus:*

The daily Energy $E_d$ Use = $E_d = T_l * t = 695W * 12h = 8.34\ kWh$

The Battery Output Energy $(B_{oe})$ to DC Motor = Input to flywheel system

Flywheel Stored Energy Equation is obtained as thus:

$E_{flyw} = \frac{1}{2} I\omega^2$ Eqn. 1

$I = Mr^2$ Eqn. 2

$V = \pi L(r_o^2 - r_i^2)$ Eqn. 3

The Mass is

$M = \rho V = \rho \pi L(r_o^2 - r_i^2)$ Eqn.4

Computing the Moment of Inertia (about central axis) gives

$I = \frac{1}{2} m(r_o^2 - r_i^2)$ Eqn. 5

Substituting eqn. 4 into 5 yields

$I = \frac{1}{2} \rho \pi L(r_o^2 - r_i^2)(r_o^2 + r_i^2)$ Eqn. 6

The energy stored in the flywheel is therefore given as

$E_{FLYW} = \frac{1}{4} \rho \pi L \omega^2 (r_o^4 - r_i^4)$ Eqn. 7

Note, the role of the battery is to power the DC motor and supports feedback recharging loop as illustrated in Figure 1.

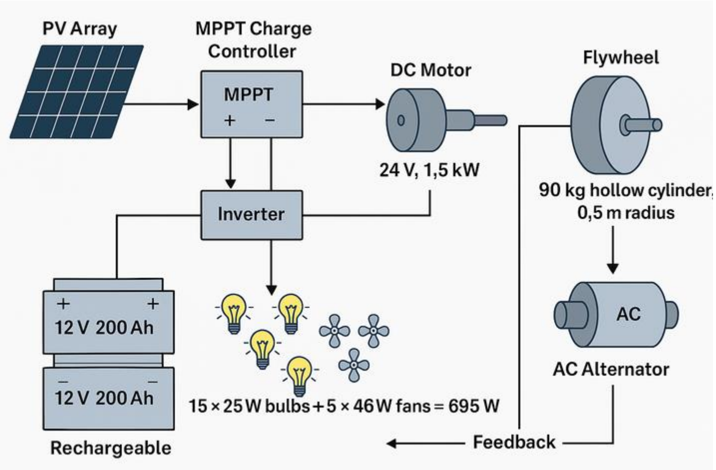


**Fig.1:** Self-Sustaining Flywheel-Assisted Photovoltaic Power System

**Efficiency Analysis:** Calculated by comparing total energy input from PV and flywheel to energy delivered to the load.
**Battery Life Cycle Impact:** Assessed using depth of discharge patterns and current draw during flywheel depletion.
**System Sustainability:** Evaluated in terms of energy autonomy and reduction in battery cycling.

## RESULTS AND ANALYSIS

### a. *Battery Effect Without Flywheel Installation Setup*

Without a flywheel in the system, all nighttime energy demand must be met by the battery alone**.** This places a high burden on the battery, especially in off-grid or limited-grid systems where the battery is the primary energy reservoir after sundown.
The battery must store enough energy during the day from the PV panels to meet all load requirements at night. This increases the Depth of Discharge (DoD**)**, which accelerates battery wear and reduces lifespan. In this research the total load power is 695 W to run for 12 hours which gives the total energy required at night to be 8,340 Wh ~ 8.34 KWh.
Meanwhile the usable battery capacity = the Total Capacity (Tc) is 4,800 Wh ~ 4.8 KWh.

### b. *PV Recovery (Battery charging during the Day)*

Sunlight availability for 6 effective hours/day gives $PV\ Daily\ Generation = Total\ PV\ used * Time =$ $1.5\ KW * 6hrs = 9\ KWh$
Charge controller and Battery Efficiency is rated at 85% As such, the Actual Energy stored in the battery $A_{eb}$from PV is
$\mathrm{A_{eb}}$=PV Daily Generation $*$ the rated efficiency Eqn. 8
$A_{eb} = 9 * 0.85 = 7.65\ KWh$

The Actual Energy stored $7.65\ KWh$ in the battery is inadequate to serve the 8.34 kWh nighttime load, considering battery discharges under 695W to be 28.96A.
Since $I = \frac{P}{V} = \frac{695}{24} = 28.96A$. such heavy draw of $28.96A$ for 12 hours can cause voltage drop under load, trigger inverter low voltage shutdown and increase internal battery heating and resistance.
To preserve the battery health (typical for lead-acid), a 50% Depth of Discharge (DoD) was observed as $Usable\ Energy = Total\ Capacity * 0.5$ = 2.4 KWh which is $< 8.34\ KWh$ that the system requires. From the usable energy obtained, the battery alone cannot sustain the load for 12 hours because the system fails by depletion after a few hours since the deficit is obtained by
$Deficit = \text{Total energy required at night } T_{En} -$ $\text{the Usable Energy } U_e$ Eqn. 9
$deficit = 8.34 - 2.4 = 5.94\ \text{KWh}.$
To confirm the inability of the system to meet full 12-hour demand. The Depth of Discharge (DoD) was calculated as 1.74 ~ 174%

$Required\ DoD = \frac{T_{En}}{Tc}$ Eqn. 10
The DoD of 174% means the battery will be overdrawn and depleted, damaging the battery lifespan as well as triggering inverter low-voltage cutoff. Battery cycle life is inversely proportional to DoD:
$Cycle\ Life \propto \frac{1}{DoD}$ . Eqn. 11
Exceeding 50% DoD regularly halves or even quarters cycle life, will lead to frequent replacements.
Without the Flywheel, it was observed that 24V, 200Ah battery is underpowered for 12 hours of 695W load as the DoD exceeds safe limits, causing faster wear and potential system shutdown even with 1.5kW PV, daily recharge is tight, requiring ideal weather and no other loads. To resolved the challenges of PV+ Battery+ Load system a flywheel system was installed as shown in Figure 1 above.

### With Flywheel install:

This section analyzes the battery effect in a real-time hybrid energy system designed for nighttime load management. The system comprises a photovoltaic (PV) array, battery bank, DC motor-driven flywheel, alternator, and an intelligent rechargeable circuit with a feedback loop. The primary objective is to optimize battery usage, extend its lifespan, and enhance energy sustainability by regenerating power from the flywheel system during nighttime operation.
The daily load energy demand is still the same as above (total load power of 695 W to run for 12 hours, Total energy required at night of 8.34 KWh/day, battery bank capacity 4.8KWh). In this setup a safe Depth of Discharge (DoD**)** of 70% =3.36 kWh/day was used. As illustrated above the battery alone cannot sustain the nighttime load (8.34 kWh/day) without support.
In setup B, the PV provides direct power for daytime loads, energy to spin Flywheel and excess energy to recharge battery

#### *a. Flywheel Energy Storage and Contribution*

To deploy the Flywheel, first determine its kinetic energy- via equations 1 to 7 such that
$I = mr^2 = 90 * (0.5)^2 = 22.5\ kg\backslash cdotpm^2$
Where the rotational speed $\omega = 600\ rad/s$
$E_{FLYW} = 1.125\text{kWh}$
Assuming 2 charge/discharge cycles per day and 80% efficiency
$E_{FLYW-usable\ e} = 2 * 1.125 * 0.8 = 1.8\ \text{KWh/day}$

#### *b. Rechargeable Circuit and Feedback Loop*

A portion of the alternator output is diverted to recharge the battery via a smart charge controller. Assuming 600 W is redirected for ~3 hours per night, then
$E_{battery-recharged} = 600 * 3hrs = 1.8\ KWh/day.$
This energy is added back to the battery bank during nighttime use, partially offsetting its discharge as shown in Table 3.

**Table 3: System energy contributed**

| Source | Daily Energy Contribution |
|---|---|
| Battery Discharge | 3.36 kWh |
| Flywheel Support | 1.8 kWh |
| Battery Recharge | +1.8 kWh |
| Net Battery Discharge | 1.56 kWh/day |

***c. System Autonomy and Battery Life Improvement***

c.1 Depth of Discharge (DoD).
The $\text{Daily DoD} = \frac{1.564}{4.8} * 100 = 32.5\%$
This moderate DoD promotes battery longevity.

Expected cycle life:
At 70% DoD: ~800 cycles
At 32% DoD: ~2,000+ cycles
The two setup designs can faithfully be compared and summaries as shown in Table 4.

**Table 4: Summary of Performance Comparison**

| Parameter | Without Flywheel | With Flywheel + Recharge |
|---|---|---|
| Battery Drain/Day | 8.34 kWh | 1.56 kWh |
| Monthly Battery Use | 250.2 kWh | 46.8 kWh |
| Battery DoD | 174% (unsustainable) | 32.5% |
| Battery Life | Very short | Extended |
| Load Reliability | Low | High |
| System Efficiency | Poor | Excellent |

**DISCUSSION OF RESULTS**

**BATTERY EFFECT IN TWO SYSTEM SETUPS**

This section interprets the outcomes of implementing a self-sustaining hybrid PV–battery energy system under two conditions:
***Without Flywheel Installed and With Flywheel Installed + Rechargeable Circuit + Feedback Loop***
Both setups aim to support a constant 695 W nighttime load for 12 hours (8.34 kWh/day).

*a.* ***Battery Load and Discharge***
Without Flywheel: The entire nighttime energy demand (8.34 kWh/day) is supplied by the battery alone. Given the battery's 4.8 kWh capacity, the required discharge (174%) far exceeds the battery's limits, leading to: Severe over-discharge, Rapid capacity degradation, Poor system sustainability and monthly battery energy demand:
$8.34 \frac{KWh}{day} * 30 = 250.2\ KWh$

*b.* ***With Flywheel & Rechargeable Circuit***
Battery directly supplies 3.36 kWh/day (70% DoD) as the Flywheel contributes 1.8 kWh/day from kinetic storage. The Rechargeable circuit returns 1.8 kWh/day to battery from alternator output.
Net battery discharge of $3.36 - 1.8 = 1.56\ kWh/day$ was obtained such that the monthly battery uses drops to 46.8 kWh, an 81.3% reduction compared to the no-flywheel case.
The system with flywheel maintains battery usage within safe DoD ranges, which increases the number of usable charge-discharge cycles, thereby minimizes thermal stress and voltage drops and reduces need for frequent battery replacement.

*c.* ***Energy Flow Efficiency***
To effectively discuss the results of energy efficiency on battery effect in the two system setups. Setup A: *without* a Flywheel and Setup B: *with* the Flywheel, battery rechargeable circuit, and feedback system. The discussion is structured by comparing performance metrics such as battery discharge rate**,** recharge behavior**,** energy losses**,** and system stability as illustrated in Figure 2 and explained in Table 5.

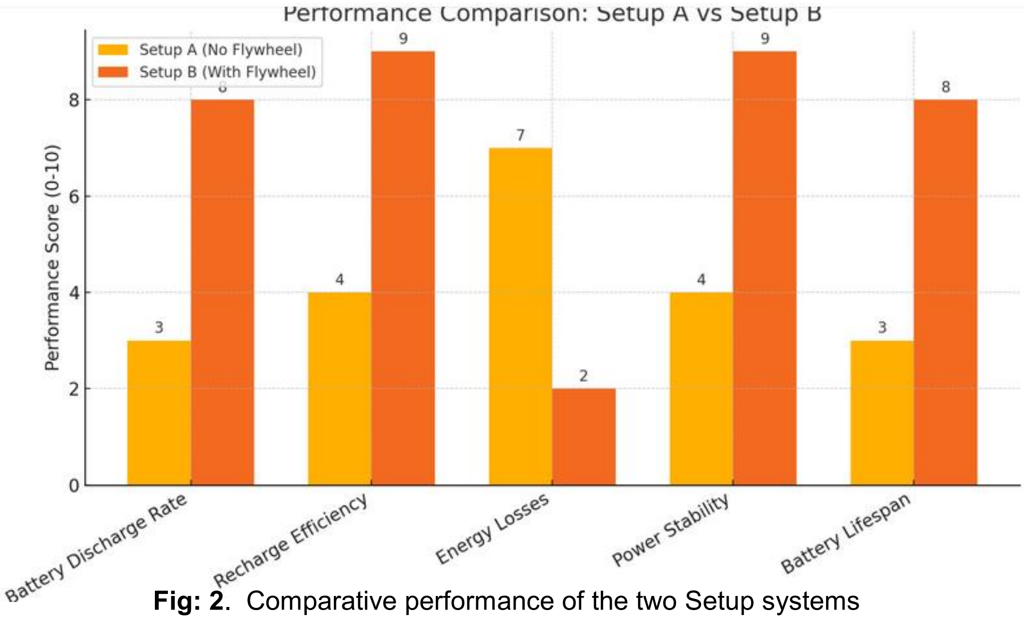


**Fig: 2**. Comparative performance of the two Setup systems

**Fig: 2**, shows the comparative performance of the two system setups across key energy efficiency metrics. The system with-Flywheel improves energy utilization: as daytime experiences surplus from PV charges Flywheel (via DC motor). The Alternator converts Flywheel energy back to electrical at night and Rechargeable loop offsets battery drain.

A flywheel energy storage system, battery rechargeable circuit, and feedback loop significantly improves energy efficiency, reduces battery strain, and enhances system sustainability. In real-time applications, Setup B proves more viable for nighttime load management, ensuring longer battery life, better efficiency, and greater system autonomy as demonstrated in Table 5.

Table 5. Summary of energy flow efficiency of the setups

| **Parameter** | **Setup A (Without Flywheel)** | **Setup B (With Flywheel & Feedback)** |
|---|---|---|
| Battery Discharge Rate | High | Moderate to Low |
| Recharge Efficiency | Low to Moderate | High (Optimized) |
| Energy Losses | High | Low |
| Power Stability | Unstable at Peak Load | Stable |
| Battery Lifespan | Shorter | Extended |

*d.* ***Sustainability and Reliability***

The flywheel-assisted system is notably more sustainable. Its mechanical storage acts as a buffer, stabilizing energy availability and ensuring consistent power delivery even under varying solar conditions.

## CONCLUSION

The comparative analysis demonstrates that integrating a flywheel and intelligent feedback system drastically improves the efficiency, reliability, and durability of off-grid PV-battery systems. While the battery-only approach suffers from rapid depletion and sustainability concerns, the hybrid solution intelligently redistributes energy and protects the battery from overuse.

This optimized configuration ensures uninterrupted nighttime power supply with minimal battery wear, thereby promoting long-term, cost-effective energy autonomy, especially vital in remote or energy-insecure regions.

Conclusively

- The integration of a flywheel energy storage system between the battery and the load ensures that nighttime loads are powered without directly draining the battery. Instead, the battery energizes a DC motor that drives the flywheel, which stores kinetic energy and powers an AC alternator to supply electricity to the load.
- By offloading direct load responsibility from the battery, the system reduces Depth of Discharge (DoD), which is a critical factor in extending the lifespan of lead-acid batteries. A lower DoD correlates with higher battery cycle life, reducing long-term replacement costs.
- The feedback circuit from the alternator allows a portion of the generated AC power to be rectified and used to recharge the battery. This design mitigates battery depletion overnight and improves overall energy sustainability.

- While there are conversion losses (DC to mechanical to AC), the total system efficiency (≈ 65-70%) is acceptable in contexts where battery longevity and consistent load delivery are more critical than raw energy efficiency.
- The modeled load—consisting of lighting (375W), fans (230W), and intermittent high-power appliances (like pumps or refrigerators)—can be sufficiently handled by the 3.5 KVA alternator and 4.2 KVA inverter, ensuring reliable power delivery for 12 hours or more each night.
- This design is ideal for off-grid areas where daily PV energy harvest must be preserved and managed wisely. The flywheel system adds a layer of mechanical reliability and reduces reliance on frequent battery cycling.

## RECOMMENDATIONS

- Incorporate a battery management system (BMS) to automate charge control and prevent over-discharge.
- Use real-time monitoring to optimize energy flows between PV, flywheel, and battery.
- Evaluate performance using MATLAB/Simulink simulations or Python-based modeling to fine-tune feedback loop logic.
- Implement a smart microcontroller system to monitor SOC, speed, voltage, and charge/discharge behavior.
- Use supercapacitors to assist the flywheel startup and reduce battery burst loads.

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