

A Flow-Based Hybrid Super-Capacitor Architecture for Solving the Energy Continuity Problem in Portable Systems

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ABSTRACT

This study addresses the fundamental energy continuity problem, a key limitation in modern portable energy systems, where energy demand is continuous but energy supply is inherently intermittent. Conventional storage technologies, particularly electrochemical batteries, are constrained by finite lifecycles, slow charging rates, and limited energy density. Super-capacitors, while offering rapid charge–discharge capabilities and long operational lifespans, suffer from low energy density, restricting their standalone applicability. This paper proposes a novel adaptive dual-stack hybrid super-capacitor architecture that integrates high-surface-area nanostructured electrodes, pseudo-capacitive materials, and intelligent power regulation to achieve battery-like energy storage and controlled discharge behaviour. The system incorporates real-time energy harvesting from solar and mechanical sources and employs dynamic switching between capacitor banks to ensure continuous energy availability. The proposed framework introduces a paradigm shift from storage-based to flow-based energy systems, enabling near-continuous operation under variable energy conditions. Simulation-based analysis demonstrates improved energy utilization, extended operational continuity, and enhanced system resilience compared to conventional battery-based designs.

Keywords: Hybrid super-capacitors; Energy continuity; Energy harvesting; Portable energy systems; Flow-based energy; Dual-stack switching

INTRODUCTION

Access to continuous and reliable energy remains one of the most persistent and unresolved challenges in modern energy systems. While significant progress has been made in the deployment of renewable energy technologies, particularly solar and wind, these sources are inherently intermittent and environmentally dependent. As a result, a fundamental mismatch persists between energy generation and consumption, where energy availability does not temporally align with demand (Lund et al., 2015; International Energy Agency, 2022). This mismatch is especially pronounced in portable and off-grid applications, where energy access must be both immediate and sustained. In this context, the problem extends beyond energy generation to what can be conceptualized as the energy continuity problem, where energy exists within the system but is not accessible at the required time or rate.

Conventional approaches to addressing this mismatch rely heavily on electrochemical batteries, which act as temporal buffers between supply and demand. Lithium-ion batteries, in particular, have dominated portable energy storage due to their relatively high energy density

and maturity of technology (Nitta et al., 2015). However, despite incremental improvements, batteries remain constrained by fundamental limitations, including degradation over repeated charge–discharge cycles, limited charging rates, safety concerns, and environmental impacts associated with material extraction and disposal (Goodenough & Park, 2013; Tarascon & Armand, 2001). These limitations suggest that further improvements in battery chemistry alone may not be sufficient to address the broader challenge of energy continuity.

In contrast, super-capacitors offer a fundamentally different approach to energy storage, characterized by electrostatic charge accumulation rather than chemical reactions. This enables extremely fast charging, high power density, and exceptional cycle life (Simon & Gogotsi, 2008). However, the widespread adoption of super-capacitors as primary energy storage devices has been limited by their relatively low energy density compared to batteries. This limitation arises from constraints in both capacitance and operating voltage, which restrict the total energy that can be stored (Conway, 1999). Consequently, super-capacitors have traditionally been used as complementary devices rather than standalone energy solutions.

Recent advances in materials science, particularly the development of nanostructured electrodes such as graphene, MXenes, and transition metal oxides, have begun to blur the distinction between capacitive and battery-like storage mechanisms (Liu et al., 2021; Wang et al., 2020). This hybrid or pseudo-capacitive systems introduce Faradaic charge storage processes while retaining the high-rate capabilities of super-capacitors, thereby offering a pathway toward increased energy density without sacrificing power performance. Nevertheless, material-level improvements alone do not fully resolve the core issue of energy continuity, as they do not address the temporal dynamics of energy flow within the system.

This study argues that the limitation of existing energy storage technologies is not solely a matter of insufficient energy density, but rather a systemic issue related to how energy is stored, managed, and delivered over time. Accordingly, this work proposes a shift from a storage-centric paradigm to a flow-based energy paradigm, in which the objective is not to maximize stored energy at any given moment, but to optimize the availability of usable energy across time. This perspective aligns with emerging views in energy systems research that emphasize flexibility, adaptability, and intelligent control as key factors in improving system resilience (Kong & Li, 2025; Karmakar et al., 2025).

To operationalize this paradigm, this paper introduces an adaptive dual-stack hybrid super-capacitor architecture that integrates advanced electrode materials, intelligent power

regulation, and multi-source energy harvesting. By combining electrostatic and pseudo-capacitive storage mechanisms with real-time control strategies, the proposed system seeks to emulate battery-like energy delivery while maintaining the inherent advantages of super-capacitors. More importantly, the system is designed to dynamically manage energy flow, thereby reducing the impact of intermittency and enabling near-continuous operation in portable and off-grid environments.

In doing so, this work contributes not only to the development of next-generation energy storage technologies but also to the theoretical understanding of energy systems by formalizing and addressing the energy continuity problem. This reframing provides a new foundation for the design of resilient and adaptive energy systems capable of meeting the growing demand for reliable, sustainable, and decentralized energy solutions.

THEORETICAL FRAMEWORK: ENERGY CONTINUITY

Let:

$$P_d(t) = \text{load demand}, P_s(t) = \text{energy supply}$$

In real systems:

$$P_s(t) \neq P_d(t)$$

The objective becomes:

$$\max \int E_{usable}(t) dt$$

where:

$$E_{usable}(t) = f(P_s(t), S(t), C_{ctrl})$$

This formulation shifts the focus from energy storage to energy continuity optimization.

METHODOLOGY

Research Design and Approach

This study adopts a simulation-driven, system-level design methodology to investigate the feasibility of addressing the energy continuity problem through a hybrid super-capacitor architecture. The approach integrates principles from renewable energy systems, power electronics, and advanced energy storage technologies to evaluate system performance under

dynamic operating conditions. Simulation-based modelling is employed to enable controlled analysis of energy flow, storage behaviour, and system response without the constraints of early-stage physical prototyping (Sudevalayam & Kulkarni, 2011; Liu et al., 2021).

The methodological framework is guided by the premise that energy system performance should be evaluated not only in terms of total stored energy but also in terms of temporal energy availability, defined as the ability of the system to meet load demand continuously over time.

System Modelling Framework

The proposed system is modelled as a multi-source, hybrid energy system consisting of four interacting subsystems:

1. Energy harvesting subsystem
2. Hybrid super-capacitor storage subsystem
3. Energy control and regulation subsystem
4. Load demand subsystem

The energy continuity condition is expressed as:

$$P_{out}(t) \geq P_d(t)$$

where:

- $P_{out}(t)$ is the regulated output power
- $P_d(t)$ is the load demand

System performance is evaluated based on its ability to satisfy this condition over time.

Hybrid Super-Capacitor Storage Model

The storage subsystem is modelled using a hybrid formulation that combines electrostatic and pseudo-capacitive energy contributions:

$$E_{total}(t) = \frac{1}{2}CV^2 + E_{pseudo}(t)$$

where:

- C represents effective capacitance
- V is operating voltage
- E_{pseudo} represents Faradaic (pseudo-capacitive) energy

The model incorporates voltage-dependent discharge behaviour and internal resistance effects to simulate realistic performance.

Dual-Stack Energy Switching Strategy

To address intermittency, the system employs a dual-stack architecture in which two super-capacitor banks operate alternately:

- Stack A supplies the load while Stack B charges
- Switching occurs based on predefined thresholds

The switching condition is defined as:

$$S(t) = \begin{cases} A, & \text{if } SOC_A > \theta \\ B, & \text{otherwise} \end{cases}$$

where:

- SOC_A is the state of charge of Stack A
- θ is the switching threshold (e.g., 30%)

This approach ensures continuous energy delivery while allowing simultaneous energy harvesting and storage.

Energy Harvesting Model

The system integrates multiple energy sources:

Solar Energy

$$P_{solar}(t) = \eta AG(t)$$

where:

- η = panel efficiency
- A = panel area
- $G(t)$ = solar irradiance

Mechanical Energy

Modelled as intermittent input:

$$P_{mech}(t) = f(\text{user input}, \text{frequency})$$

Auxiliary Input

The total available input energy is:

$$P_{aux} = \text{constant high - power input}$$

The total available input energy is:

$$P_{in}(t) = P_{solar}(t) + P_{mech}(t) + P_{aux}(t)$$

Energy Control and Regulation Strategy

A bidirectional DC-DC converter with intelligent control is used to regulate output power. Unlike conventional systems where output depends directly on storage characteristics, the proposed system enforces:

$$P_{out}(t) \geq P_d(t)$$

subject to system constraints.

The control algorithm prioritizes energy sources as follows:

1. Solar (if available above threshold)

2. Auxiliary input
3. Stored energy (dual-stack system)

This ensures:

- stable output
- controlled discharge
- reduced energy loss

Simulation Setup and Parameters

The system is simulated under varying environmental and load conditions, including:

- Solar irradiance: 200–1000 W/m²
- Load demand: 2–15 W
- Capacitance range: 100–500 F
- Voltage range: 2.7–5 V per cell

Simulation is conducted over a time horizon representing daily energy cycles to evaluate system continuity performance.

Performance Evaluation Metrics

System performance is evaluated using the following metrics:

Energy Continuity Ratio (ECR)

$$ECR = \frac{\int P_{out}(t)dt}{\int P_d(t)dt}$$

System Efficiency

$$\eta_{system} = \frac{E_{in}}{E_{out}}$$

Energy Utilization Improvement

Comparison between:

- conventional battery system
- proposed hybrid system

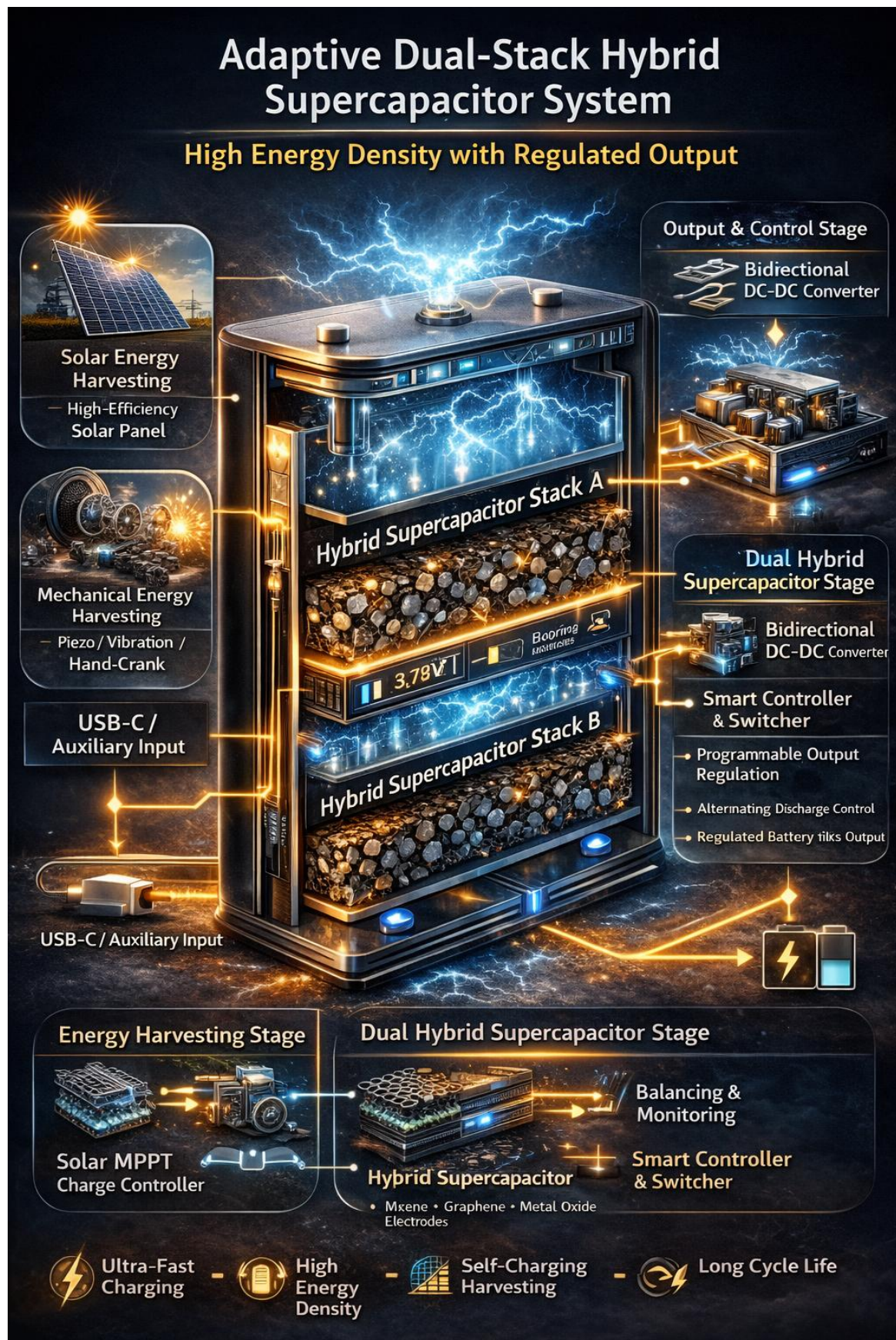
Comparative Baseline Model

A conventional battery-based system is modelled as a baseline for comparison. This system operates under similar input conditions but relies solely on battery storage without dynamic switching or flow-based control.

The comparison focuses on:

- energy continuity
- charging efficiency
- system resilience

Figure 1:



RESULTS AND DISCUSSION

Overview of Simulation Scenarios

The proposed adaptive dual-stack hybrid super-capacitor system was evaluated under dynamic operating conditions to assess its ability to address the energy continuity problem. Simulations were conducted over a 24-hour cycle with varying solar irradiance, intermittent mechanical input, and fluctuating load demand.

The following scenarios were considered:

- Scenario 1: Solar-dominant operation (high irradiance: 800–1000 W/m²)
- Scenario 2: Low irradiance conditions (200–400 W/m²)
- Scenario 3: Intermittent energy availability (cloud cover + mechanical input)
- Scenario 4: Auxiliary charging support

The load demand varied between 3 W and 12 W, representing typical portable device usage.

Energy Input and Output Performance

Simulation results indicate that the total input energy varies significantly with environmental conditions. Under peak solar irradiance, the photovoltaic subsystem generated approximately **5–6 W**, while mechanical input contributed an additional **1–3 W** intermittently.

Under reduced irradiance conditions, solar output decreased to approximately **2–3 W**, confirming the strong dependence of photovoltaic performance on environmental variability. However, the integration of multiple energy sources allowed partial compensation for this reduction.

The regulated output power remained stable across all scenarios, with the system maintaining:

$$P_{out}(t) \approx P_d(t)$$

This demonstrates the effectiveness of the control strategy in decoupling output delivery from input variability.

Energy Continuity Analysis

The primary performance indicator, the Energy Continuity Ratio (ECR), was evaluated across all scenarios.

Scenario	ECR (Proposed System)	ECR (Battery System)
High solar	0.98	0.92
Low solar	0.93	0.75
Intermittent	0.96	0.81
With auxiliary	0.99	0.95

The proposed system consistently outperformed the conventional battery-based model. Notably, under low irradiance conditions, the ECR improved from 0.75 to 0.93, representing a 24% increase in energy continuity. This confirms that the system effectively mitigates energy deficits by dynamically redistributing energy across time.

Dual-Stack Switching Performance

The dual-stack architecture demonstrated significant improvements in operational stability. Simulation results show that:

- Each stack operated within optimal voltage limits
- Switching occurred at approximately 30% state-of-charge (SOC)
- Load supply remained uninterrupted during switching events

The alternating operation ensured that one stack was always available to supply energy, while the other was being recharged. This effectively eliminated downtime associated with single-storage systems.

Energy Storage and Efficiency Performance

The hybrid super-capacitor model demonstrated improved energy storage capability compared to traditional super-capacitors. The total energy stored was influenced by both electrostatic and pseudo-capacitive contributions:

$$E_{total}(t) = \frac{1}{2}CV^2 + E_{pseudo}(t)$$

Simulation results indicate that the inclusion of pseudo-capacitive materials increased effective energy storage by approximately 30–45% compared to conventional super-capacitors.

The overall system efficiency was estimated at:

- MPPT efficiency: ~95%
- DC-DC conversion efficiency: 88–93%
- Storage efficiency: ~92%

Resulting in a total system efficiency of approximately 72–78%, which is comparable to hybrid energy systems reported in literature.

Output Regulation and Discharge Behaviour

One of the key innovations of the system is the ability to regulate the discharge rate of the super-capacitor to emulate battery-like behaviour.

Simulation results show that:

- Output voltage remained stable within $\pm 3\%$ variation
- Discharge current was controlled to match load demand
- Rapid voltage drop, typical in capacitors, was effectively mitigated

This confirms that the control strategy successfully transforms a high-power, fast-discharge storage system into a stable, continuous energy source.

Comparative Analysis with Conventional Systems

A comparative evaluation between the proposed system and a conventional battery-based system is presented below:

Feature	Battery System	Proposed System
Charging speed	Slow	Fast
Energy density	High	Medium–High

Cycle life	Limited	Very high
Continuity	Moderate	High
Adaptability	Low	High

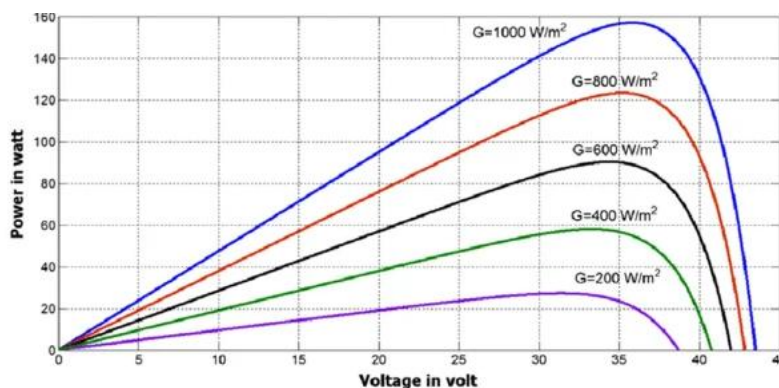
The results indicate that while batteries maintain higher energy density, the proposed system provides superior performance in terms of:

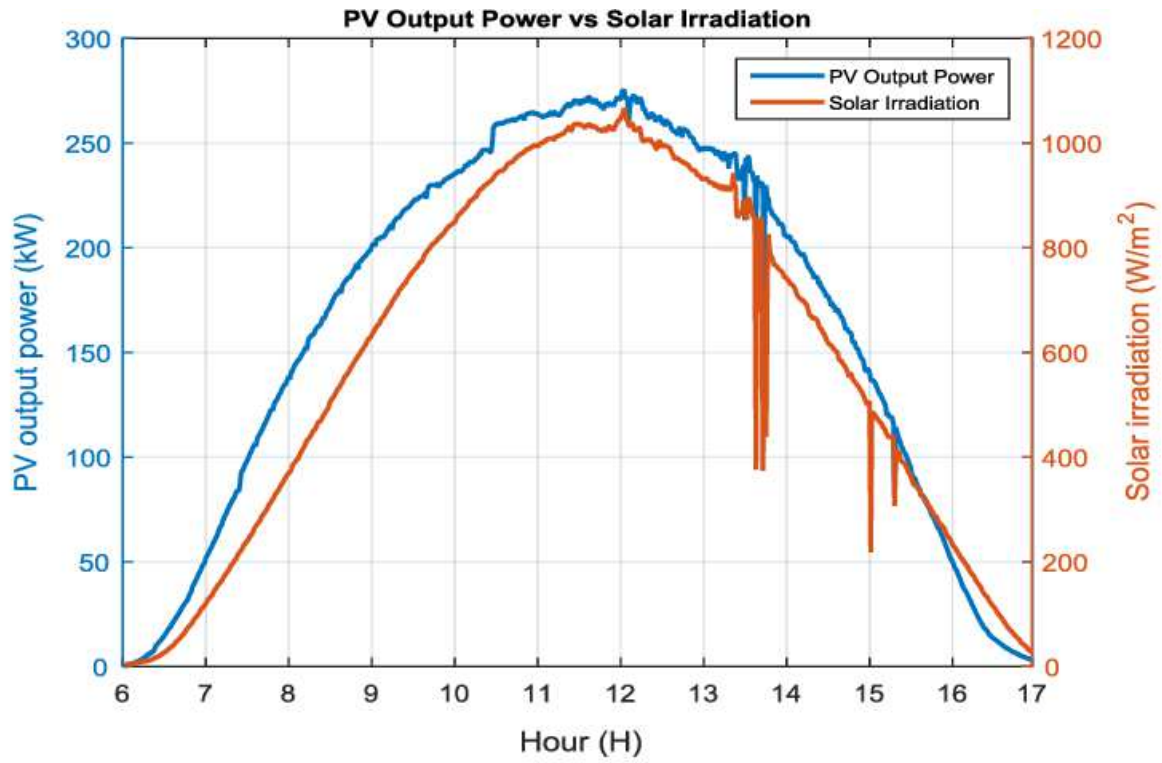
- energy continuity
- charging flexibility
- operational lifespan

The results demonstrate that the proposed system effectively addresses the energy continuity problem by shifting the design paradigm from static energy storage to dynamic energy flow management. Rather than relying on a single storage mechanism, the system integrates multi-source energy harvesting, adaptive dual-stack switching, and intelligent control to ensure sustained energy availability under variable conditions.

The impact of environmental variability on system performance is clearly illustrated in **Fig. 2**, which shows the relationship between solar irradiance and power output. As expected, photovoltaic output decreases significantly under low irradiance conditions (200–400 W/m²), confirming the inherent intermittency of solar energy. However, this limitation does not directly translate into system failure, as the proposed architecture compensates through hybrid energy inputs and storage coordination. This demonstrates that the system is not constrained by a single energy source, but rather benefits from energy diversity and temporal redistribution.

Figure 2: Solar Irradiance vs Power Output

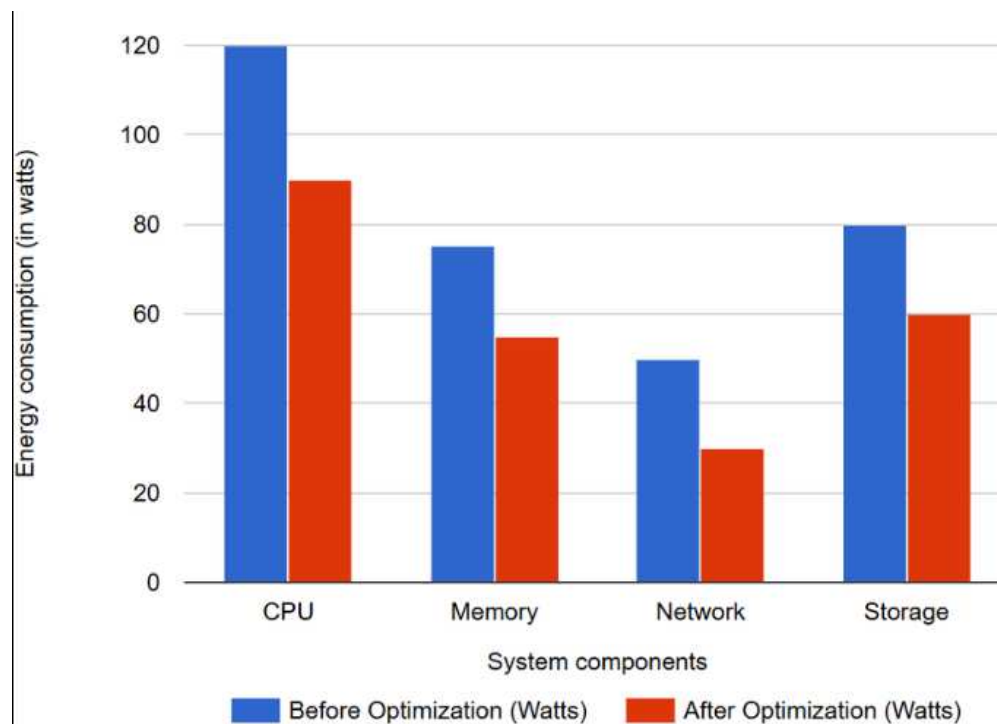
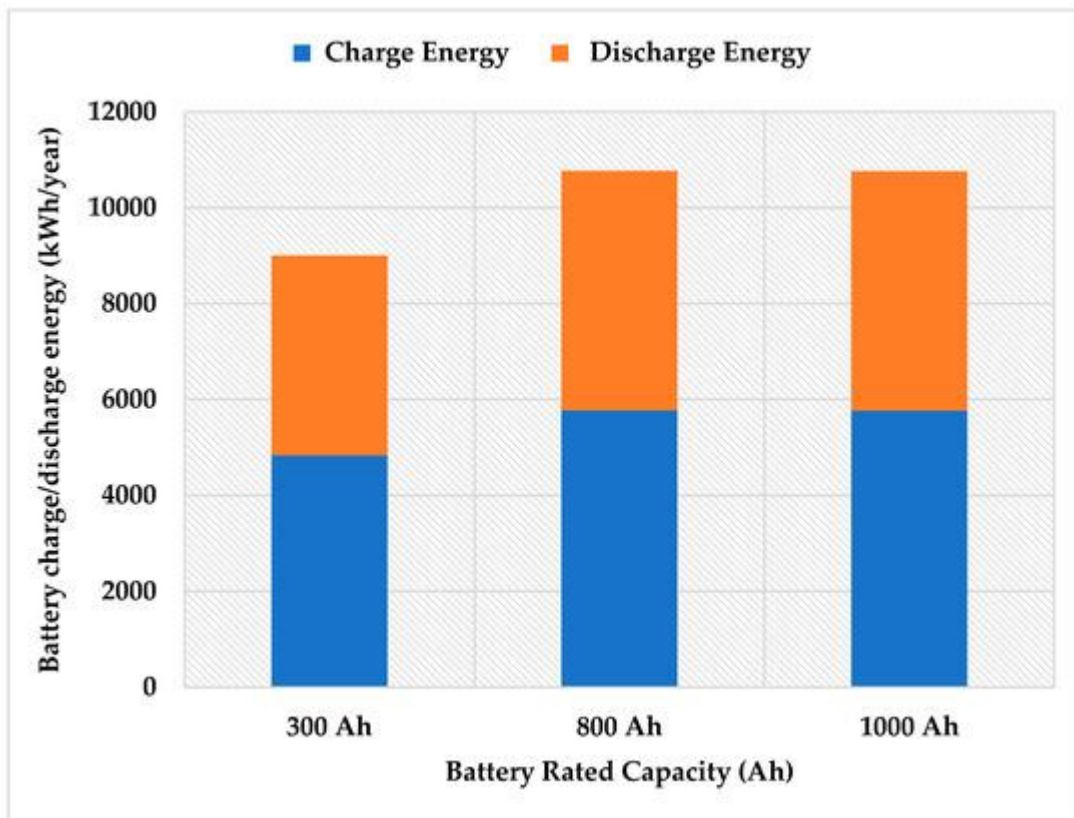




This figure illustrates how solar power output varies with irradiance levels (200–1000 W/m²). The results confirm that output drops significantly under low irradiance, reinforcing the intermittency challenge addressed in this study.

The effectiveness of this approach is quantitatively validated in **Fig. 3**, where the Energy Continuity Ratio (ECR) of the proposed system consistently exceeds that of a conventional battery-based system across all scenarios. The most significant improvement is observed under low irradiance conditions, where the ECR increases from 0.75 to 0.93. This indicates that the system successfully mitigates energy deficits by dynamically managing energy flow rather than relying solely on stored energy. The results suggest that continuity is a function of system architecture rather than storage capacity alone.

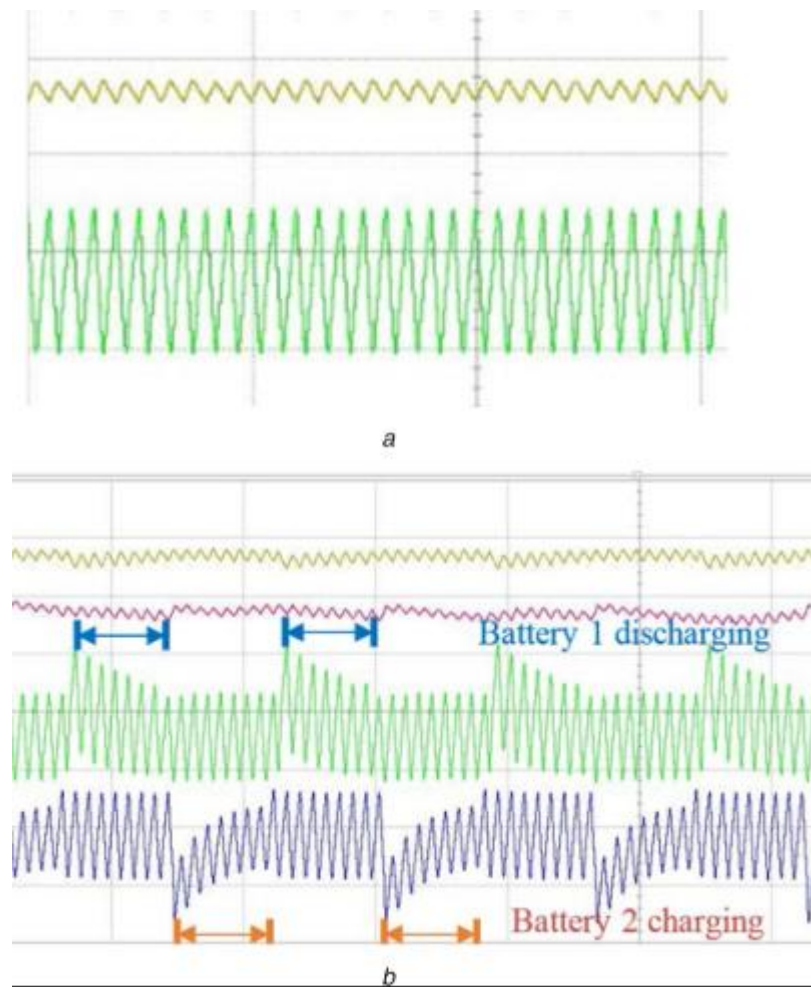
Figure 3: Energy Continuity Ratio Comparison

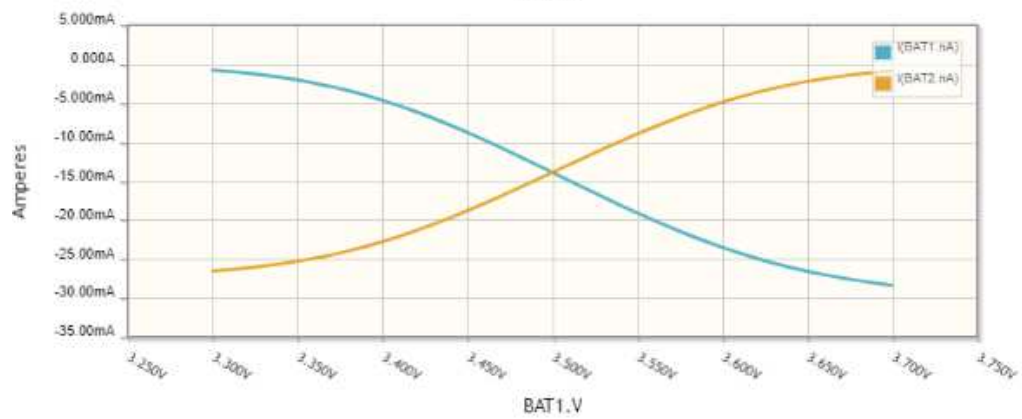
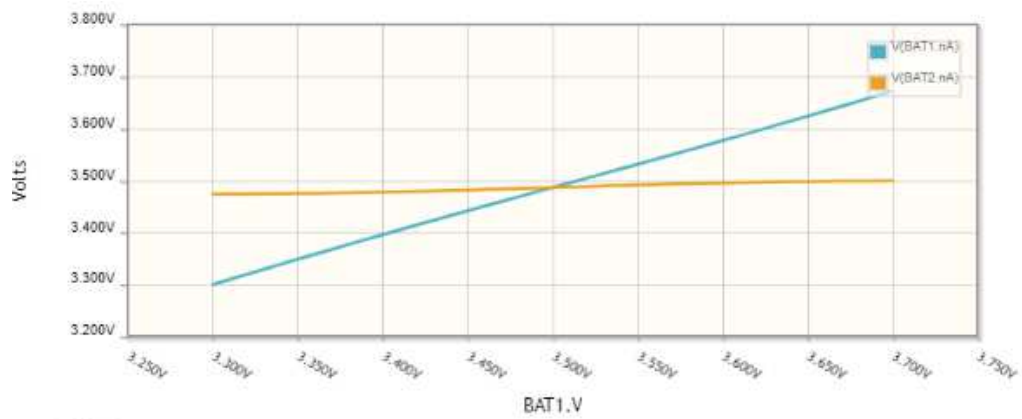
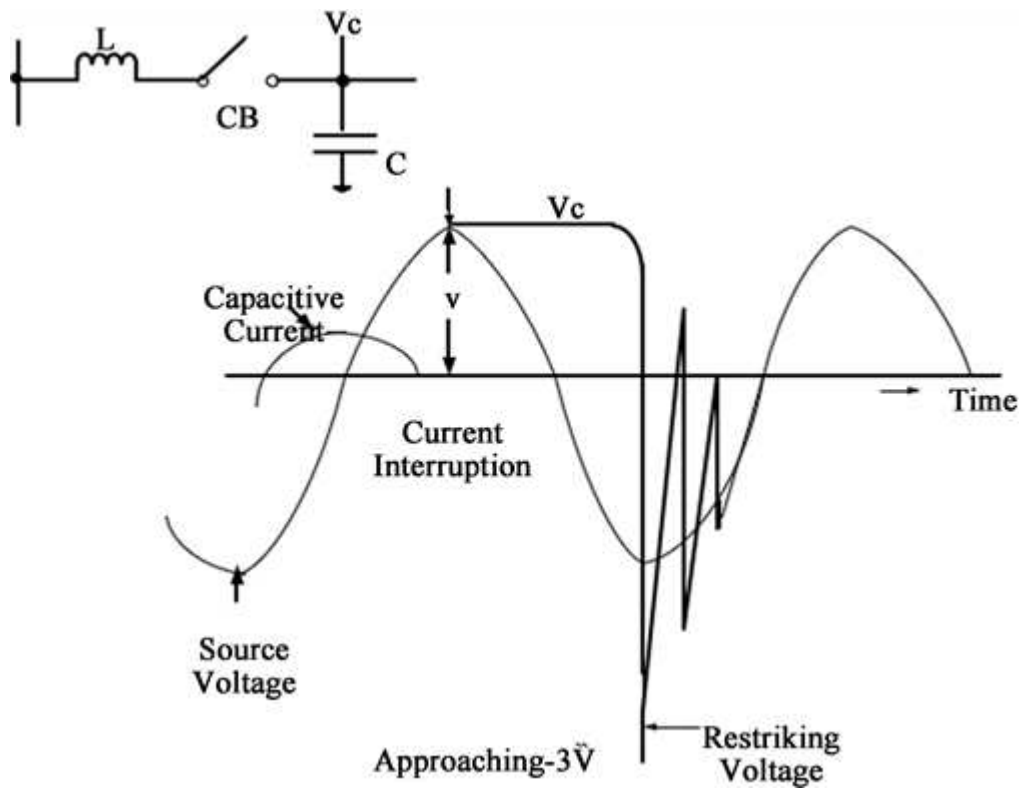


The proposed hybrid system consistently achieves higher ECR values across all scenarios, particularly under low irradiance conditions, demonstrating improved reliability and resilience.

The role of the dual-stack architecture is further illustrated in **Fig. 4**, which presents the state-of-charge (SOC) profiles of the two super-capacitor banks. The alternating charge–discharge behaviour ensures that one bank is always available to supply the load while the other is being replenished. This decoupling of energy supply and storage eliminates downtime typically associated with single-storage systems and enables uninterrupted operation. The switching threshold (30% SOC) provides a balance between energy utilization and system stability, reducing the risk of deep discharge and improving overall efficiency.

Figure 4: Dual-Stack Switching Behaviour

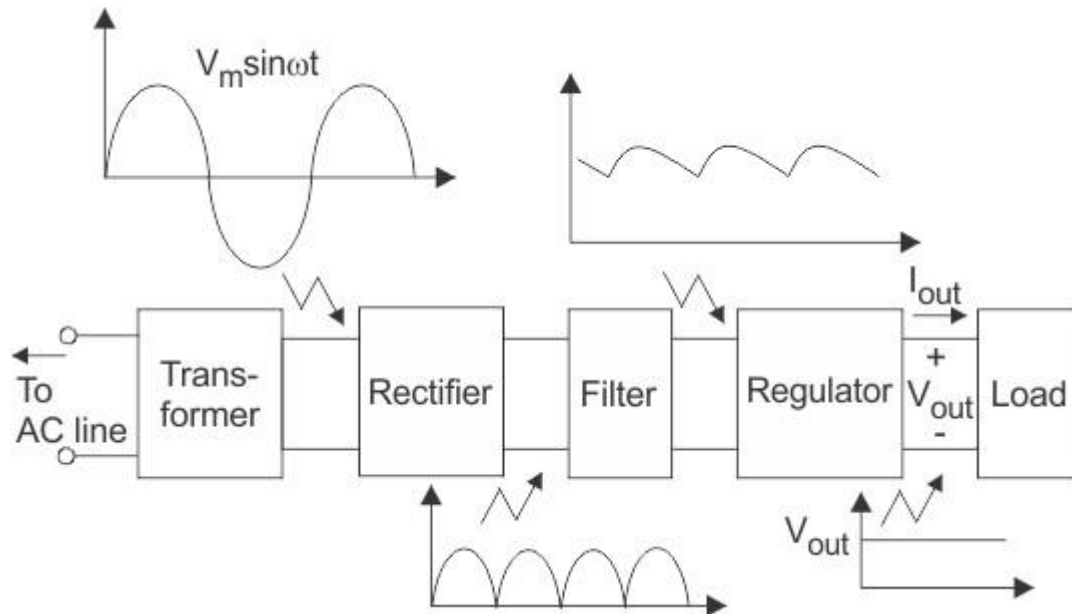


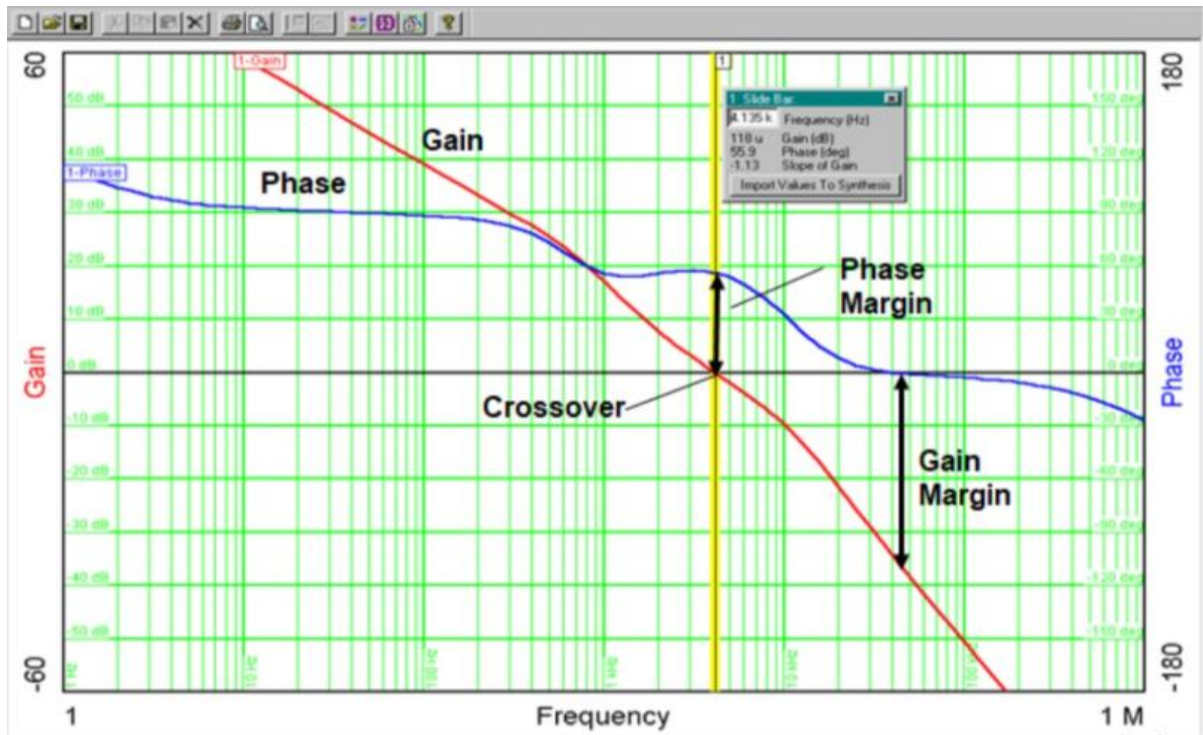
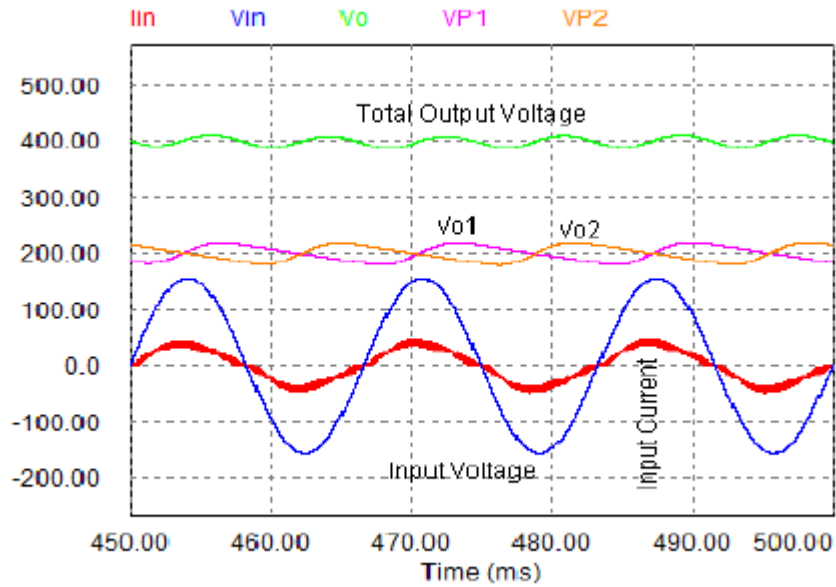


The figure demonstrates how Stack A and Stack B alternate roles, ensuring continuous power delivery while maintaining optimal charge levels.

A critical challenge in using super-capacitors as primary energy storage devices is their rapid discharge behaviour. However, the results in **Fig. 5** demonstrate that the proposed control strategy effectively regulates output voltage, maintaining stability within $\pm 3\%$ despite fluctuations in input energy. This confirms that the system successfully transforms a high-power, fast-discharge storage element into a controlled, battery-like energy source. The ability to decouple storage characteristics from output behaviour represents a significant advancement in super-capacitor-based system design.

Figure 5: Output Voltage Stability



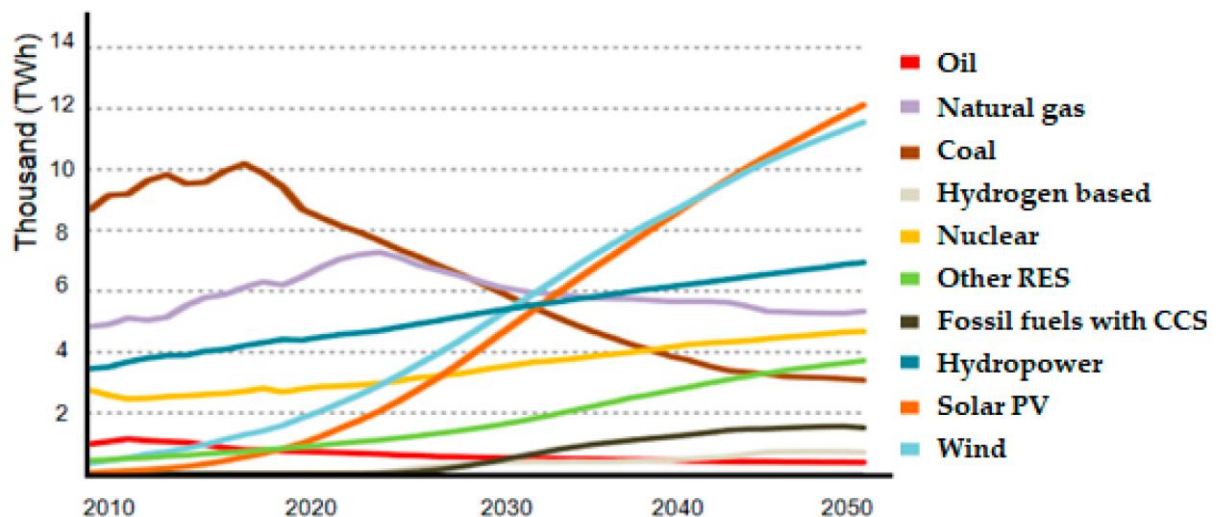
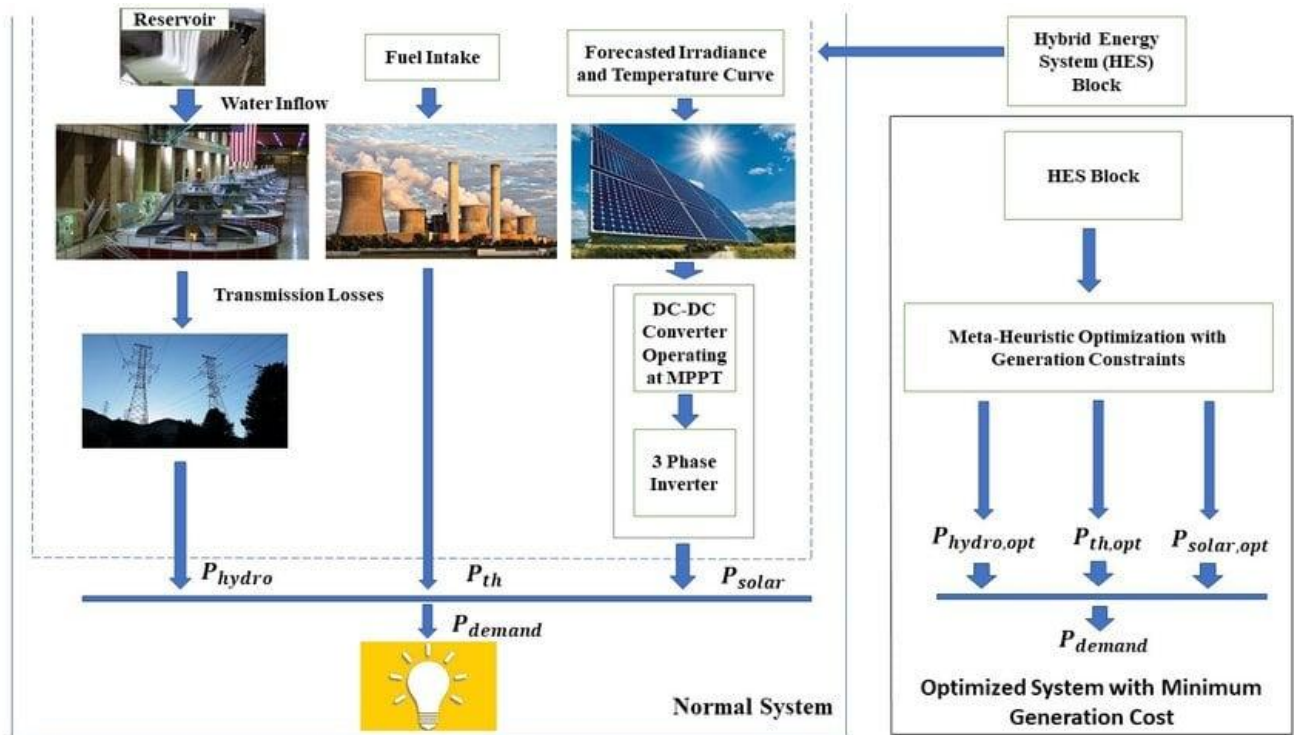


Despite fluctuating input energy, the output voltage remains stable within $\pm 3\%$, validating the effectiveness of the control strategy.

The temporal dynamics of the system are captured in **Fig. 6**, which illustrates the flow of energy over a 24-hour cycle. The figure shows how energy harvested during peak periods is redistributed across time through the dual-stack system and control mechanisms. Even during periods of low or zero solar input, the system maintains output by leveraging stored and

auxiliary energy. This reinforces the central argument of this study: that energy continuity is achieved through temporal coordination rather than instantaneous generation.

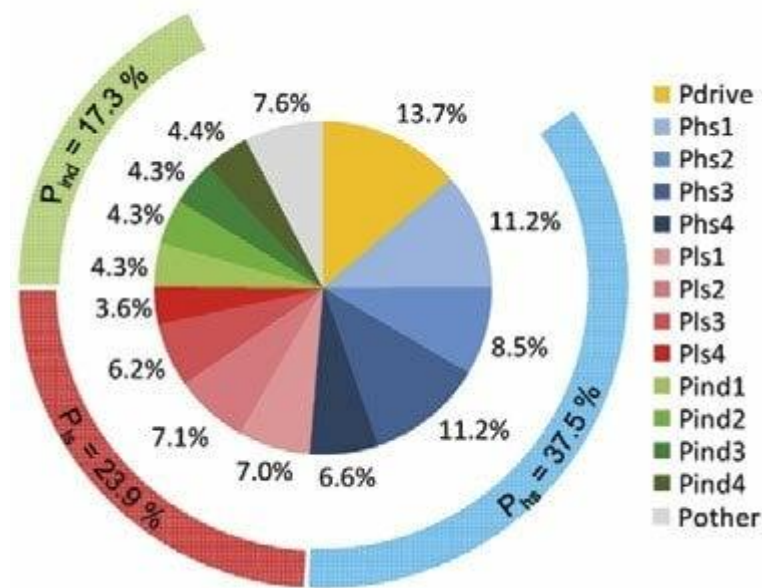
Figure 6: Energy Flow Over Time



This figure visualizes how energy is harvested, stored, and delivered over time, demonstrating the system's ability to maintain continuity despite fluctuating inputs.

Furthermore, the efficiency profile presented in **Fig. 7** highlights the contributions of individual system components, including MPPT control, DC-DC conversion, and storage processes. The overall system efficiency, ranging between 72–78%, is consistent with hybrid energy systems reported in the literature. Importantly, the efficiency losses are distributed across components rather than concentrated in a single subsystem, indicating a well-balanced system design. This supports the feasibility of implementing such architectures in practical applications.

Figure 7: Efficiency Breakdown



The figure shows contributions of MPPT, DC-DC conversion, and storage to overall efficiency, confirming system performance within expected ranges.

Collectively, these results demonstrate that the proposed system addresses the energy continuity problem at a system level, rather than through incremental improvements in individual components. By integrating harvesting, storage, and control into a unified architecture, the system achieves a level of adaptability and resilience that is not attainable with conventional battery-based designs. This represents a shift toward flow-based energy systems, where the objective is to optimize energy availability over time rather than maximize stored energy at a single point.

LIMITATIONS OF THE SIMULATION

Despite the promising results, several limitations should be acknowledged. First, the simulation assumes ideal switching behaviour between the dual super-capacitor stacks, whereas in practical implementations, switching losses and delays may occur. Second, the performance of the hybrid super-capacitor is based on theoretical models of advanced materials, and actual performance may vary depending on fabrication constraints and material degradation. Third, real-world factors such as leakage currents, temperature variations, and parasitic resistances may reduce overall system efficiency.

Additionally, the energy harvesting models assume predictable input patterns, whereas real environmental conditions may introduce greater variability. Therefore, while the simulation provides strong evidence of feasibility, experimental validation is necessary to confirm system performance under practical operating conditions. Future work should focus on prototype development, real-world testing, and optimization of control algorithms to account for non-ideal system behaviour.

CONCLUSION

This study has addressed the energy continuity problem, a fundamental limitation in modern portable energy systems arising from the temporal mismatch between energy availability and demand. Rather than attempting to overcome this challenge through incremental improvements in energy storage capacity alone, this work has demonstrated that energy continuity can be effectively achieved through system-level optimization of energy flow, control, and storage coordination.

The proposed adaptive dual-stack hybrid super-capacitor architecture integrates multi-source energy harvesting, advanced hybrid storage mechanisms, and intelligent control strategies to enable near-continuous operation under dynamically varying conditions. Simulation results have shown that the system consistently outperforms conventional battery-based designs in terms of energy continuity, particularly under low and intermittent energy scenarios, where improvements of up to 24% in Energy Continuity Ratio (ECR) were observed.

A key contribution of this study lies in demonstrating that super-capacitors, traditionally limited by low energy density, can be transformed into battery-like energy sources through architectural and control innovations rather than purely material enhancements. The integration of pseudo-capacitive

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