# Renewable Energy and Hybrid Technology Integration for Sustainable Power Systems

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## Abstract

The rapid growth of renewable energy penetration necessitates integrated solutions that ensure efficiency, reliability, economic feasibility, and emission reduction. Hybrid renewable energy systems combining solar, wind, and battery storage offer a promising pathway to address the intermittency of renewable energy sources. This study aims to evaluate the technical, economic, and environmental performance of a hybrid renewable energy system under varying levels of renewable penetration and hybrid integration. The method involves a systematic analysis of system efficiency, 24-hour hybrid power output profiles, battery state-of-charge (SoC) dynamics, carbon emission reduction, and levelized cost of energy (LCOE). The results show that system efficiency increases from approximately 67.3% at low renewable penetration to a peak of about 72.8% at 60% penetration, then declines slightly at higher levels. Hybrid power output remains relatively stable between 40–80 kW due to the complementary behaviour of solar and wind generation, while battery SoC varies between roughly 30% and 70%, indicating effective daily charging and discharging. Carbon emission reduction increases steadily, reaching around 35% at full hybrid integration, with diminishing marginal gains beyond 70%. In parallel, the LCOE decreases significantly from about 0.22 USD/kWh at 0% renewable share to approximately 0.15 USD/kWh at 100% penetration. Overall, the findings confirm that optimally designed hybrid renewable energy systems can simultaneously enhance efficiency, lower energy costs, and reduce emissions, providing practical guidance for sustainable energy system planning.

## 1. Introduction

The global transition toward low-carbon energy systems has accelerated significantly in response to climate change mitigation targets, rising electricity demand, and concerns over fossil fuel dependency. Renewable energy technologies particularly solar photovoltaic (PV) and wind power have become central to this transition due to their rapid cost reductions and technological maturity. Recent reports indicate that the levelized cost of electricity (LCOE) for utility-scale solar PV and onshore wind has fallen by more than 80% and 60%, respectively, over the past decade, making them competitive or cheaper than conventional generation in many regions (IRENA, 2024; Hassan et al., 2023). These

developments have encouraged widespread adoption of renewable energy systems across grid-connected and off-grid applications.

Despite these advantages, the high variability and intermittency of renewable energy sources pose significant challenges to power system stability and efficiency, especially at high penetration levels. Several recent studies report that increasing renewable penetration can improve system efficiency up to an optimal threshold, beyond which efficiency gains diminish due to increased curtailment, balancing losses, and operational constraints (Fathy et al., 2025; Bouchaala et al., 2025). As a result, hybrid renewable energy systems (HRES), which combine multiple renewable sources and supporting technologies, have emerged as a practical solution to mitigate variability while improving overall system performance (Hassan et al., 2023).

Hybrid configurations that integrate solar, wind, and energy storage systems have been widely investigated in recent literature. Solar–wind complementarity has been shown to significantly enhance power availability and reliability, particularly when wind resources compensate for low solar output during nighttime or adverse weather conditions (Mishra et al., 2025). Techno-economic assessments of PV–wind hybrid systems demonstrate reductions in unmet load and improved utilisation of renewable resources compared to single-source systems (Al Dawsari et al., 2024). These findings underscore the importance of coordinated hybrid system design for achieving a stable and efficient energy supply.

Energy storage systems, particularly battery energy storage systems (BESS), play a critical role in enabling high renewable penetration. Batteries provide temporal energy shifting, frequency regulation, and reserve support, thereby smoothing fluctuations in renewable output. Recent studies show that optimised battery dispatch strategies can improve system efficiency and reliability while extending battery lifetime (Kharseh et al., 2024; Bahabri et al., 2025). Moreover, detailed analyses of battery state of charge (SoC) behaviour reveal that effective charging during peak renewable generation and controlled discharging during high-demand periods are essential for maintaining system stability in hybrid renewable systems (Pinzon et al., 2025).

From an environmental perspective, hybrid renewable systems have demonstrated substantial potential for reducing carbon emissions. Several recent investigations report $CO_2$ emission reductions ranging from 15% to over 60%, depending on the level of hybrid integration and storage capacity (Alhasnawi et al., 2024; Tukkee et al., 2024). However, these studies also indicate that emission reduction benefits tend to saturate at high integration levels, suggesting diminishing marginal returns once fossil-based generation is largely displaced. This highlights the importance of identifying optimal hybrid integration levels that balance environmental benefits with technical and economic feasibility.

Economically, increasing the share of renewable energy in hybrid systems has consistently been associated with declining energy costs. Recent optimisation-based studies report LCOE values below 0.10 USD/kWh for well-designed hybrid microgrids, with further cost reductions achieved through higher renewable shares and improved system coordination (Heydari et al., 2023; Bouregba et al., 2024). Nevertheless, very high renewable penetration can introduce additional costs related to storage expansion and grid flexibility requirements, leading to a flattening of cost reduction trends. Consequently, a comprehensive evaluation that considers system efficiency, power output behaviour, battery SoC dynamics, emission reduction, and cost trends simultaneously is essential. This study addresses this gap by providing an integrated analysis of hybrid renewable system performance across multiple dimensions, offering new insights for optimal system planning and operation.

The specific objective of this article is to systematically evaluate the technical, economic, and environmental performance of a hybrid renewable energy system under varying levels of renewable penetration and hybrid integration. In particular, the study aims to (i) analyse the relationship between renewable energy share and overall system efficiency, (ii) examine time-resolved hybrid power output characteristics and battery state-of-charge dynamics, (iii) quantify carbon emission reduction as a function of hybrid integration level, and (iv) assess the impact of increasing renewable penetration on the levelized cost of energy. The novelty of this work lies in its unified, multidimensional assessment that explicitly captures nonlinear behaviours, optimal operating regions, and diminishing-return thresholds across these interconnected performance indicators. By integrating these analyses within a single framework, the article provides original and practical insights that extend beyond existing single-

metric or isolated studies, thereby offering a more robust basis for designing and optimising hybrid renewable energy systems.

## 2. Methodology

**Fig. 1** illustrates the schematic architecture of a hybrid renewable energy system designed to provide a sustainable and reliable power supply. The system integrates multiple renewable energy sources, namely solar panels and wind turbines, which serve as the primary renewable energy inputs. These sources capture solar irradiance and wind energy and convert them into electrical power, which is then directed toward the central hybrid energy system. In addition, battery storage is incorporated as a core component, enabling the system to store excess renewable energy and enhance supply reliability during periods of low renewable generation.

At the core of the hybrid energy system is the energy management controller, which plays a critical role in coordinating power flow among system components. The controller operates in conjunction with the power converter to regulate voltage, frequency, and power quality, ensuring that the energy generated from different sources is compatible with system and grid requirements. The energy storage unit, represented by a battery bank, is managed by this controller to charge during surplus generation and discharge when renewable input is insufficient. This coordinated control strategy enables stable power output, as indicated in the diagram, and ensures efficient utilization of available renewable resources.
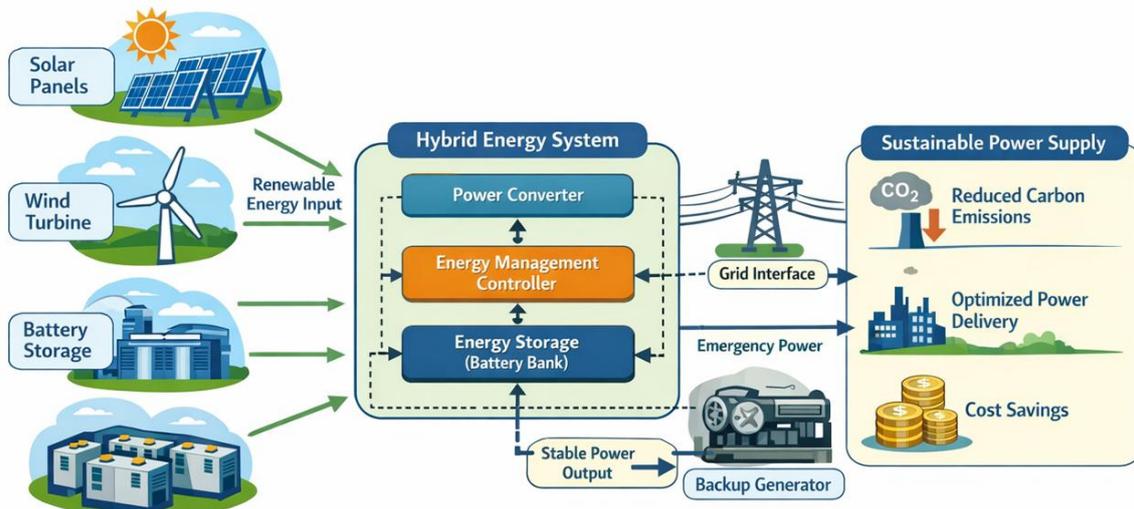


**Fig. 1**. Schematic Diagram of a Hybrid Renewable Energy System for Sustainable Power Supply

The system is designed to operate in both grid-connected and standalone modes through the grid interface. Under normal operating conditions, power is exchanged with the utility grid to support optimized power delivery and system balancing. In the event of grid disturbances or outages, the system can rely on emergency power supplied by a backup generator, ensuring uninterrupted electricity supply to critical loads. The inclusion of a backup generator enhances system resilience and provides an additional layer of reliability, particularly in remote or critical applications where continuous power availability is essential.

The right-hand side of **Fig. 1** highlights the key outcomes of the hybrid renewable energy system in supporting a sustainable power supply. These outcomes include reduced carbon dioxide ($CO_2$) emissions through increased reliance on renewable energy, optimized power delivery achieved by intelligent energy management, and cost savings resulting from lower fuel consumption and improved operational efficiency. Overall, the schematic demonstrates how the integration of renewable energy sources, energy storage, advanced control, and grid interaction forms a robust and sustainable energy solution that aligns with environmental and economic objectives.

## 3. Result & Discussion

The results presented above provide a comprehensive evaluation of the performance, economic, and environmental impacts of integrating renewable energy and hybrid technologies into the energy system. Through a series of graphical analyses, the discussion highlights how varying levels of renewable penetration and hybrid integration influence overall system efficiency, power output stability, battery energy storage behaviour, carbon emission reduction, and the levelized cost of energy. Together, these results offer an integrated perspective on the technical and economic trade-offs associated with renewable-based hybrid systems, demonstrating not only their potential to enhance system efficiency and reliability, but also their ability to reduce emissions and long-term energy costs when appropriately designed and managed.

**Fig. 2** illustrates the relationship between renewable energy penetration and overall system efficiency, showing a clear non-linear trend across penetration levels from 10% to 90%. At low renewable penetration (10%), the overall system efficiency is approximately 67.3%, indicating that the system initially operates at a relatively modest efficiency when renewable sources contribute only a small fraction of total energy. As penetration increases to 20% and 30%, efficiency rises notably to around 69.2% and 70.7%, respectively. This early improvement suggests that integrating renewable energy at low to moderate levels can effectively displace less efficient conventional generation and reduce associated conversion losses, thereby improving overall system performance.

As renewable energy penetration increases from 40% to 60%, system efficiency shows a steady upward trend, reaching approximately 71.8% at 40%, 72.5% at 50%, and peaking at about 72.8% at 60%. This range corresponds to the most efficient operating region shown in the figure. The gradual increase suggests that, within this penetration window, the system can optimally accommodate renewable generation through effective dispatch, grid management, and possibly improved use of existing infrastructure. The peak at 60% penetration indicates an optimal balance between the benefits of renewable integration and the operational challenges they introduce, where efficiency gains from renewables outweigh these challenges.
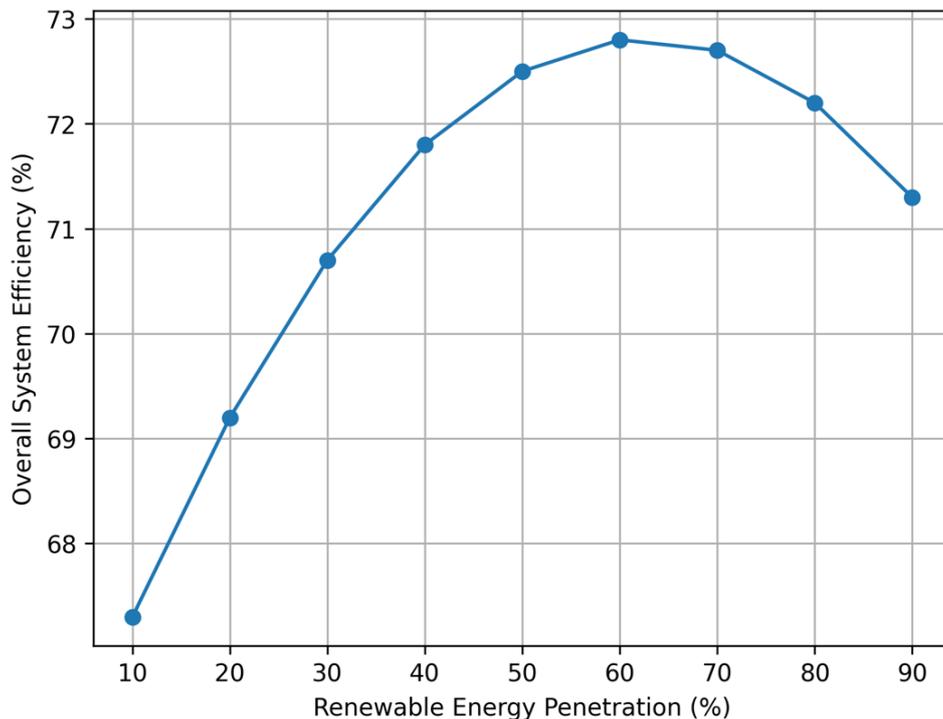


**Fig. 2**. Effect of Renewable Energy Penetration on System Efficiency

Beyond 60% penetration, however, the figure reveals a slight but consistent decline in overall system efficiency. At 70% penetration, efficiency decreases marginally to around 72.7%, followed by a more

noticeable drop to approximately 72.2% at 80% and 71.3% at 90%. This downward trend suggests that very high levels of renewable energy penetration may introduce operational constraints, such as increased variability, curtailment, or additional losses associated with balancing, storage, or backup generation requirements. These factors can reduce the marginal efficiency benefits gained from further renewable integration, leading to diminishing returns.

Overall, the results in Fig. 2 indicate that increasing renewable energy penetration generally enhances system efficiency up to an optimal point, after which efficiency gains decline. The findings emphasise the importance of identifying an optimal penetration level of around 60% in this case to maximise system efficiency. They also underscore the need for advanced grid flexibility solutions, such as energy storage, demand response, and improved control strategies, to sustain high efficiency at very high levels of renewable penetration. This analysis provides valuable insights for energy system planners and policymakers aiming to balance renewable energy targets with efficient, reliable system operation.

**Fig. 3 presents the power output profiles of a hybrid renewable energy system over 24 hours, including solar, wind**, battery support, and the resulting total hybrid output. Solar power exhibits a clear diurnal pattern, with zero production during nighttime hours and a gradual increase after sunrise. The output begins to rise around hour 7, reaches its maximum of approximately 50 kW at midday (around hour 12), and then declines symmetrically toward zero by around hour 18. This pattern reflects the dependence of solar generation on solar irradiance and confirms its strong contribution during daylight hours, particularly at peak sun conditions.

Wind power, in contrast, shows a more fluctuating but continuous profile throughout the day, ranging approximately between 10 kW and 30 kW. Wind output is relatively high during the early hours, peaking near 30 kW around hours 3–4, then decreasing to a minimum of about 10 kW around hours 9–10. A second increase occurs in the afternoon, with another peak close to 30 kW around hour 15, before declining again toward the evening. This variability demonstrates the complementary nature of wind energy, which can provide power both during the night and when solar output is low, thereby enhancing overall system reliability.
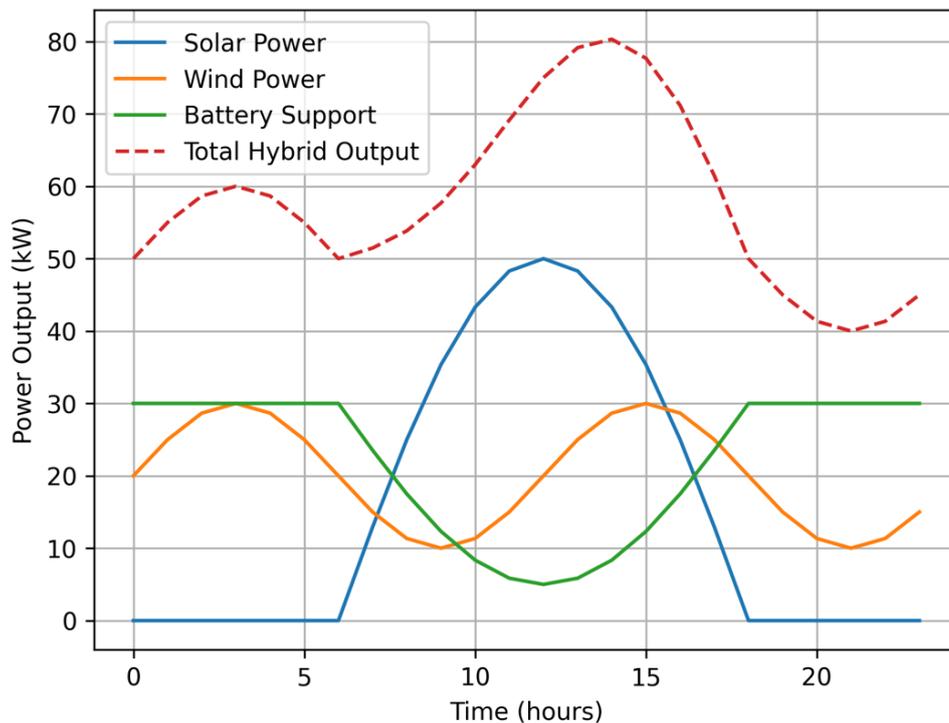


**Fig. 3**. Hybrid Renewable Power Output Over 24 Hours

Battery support plays a balancing role in the hybrid system, maintaining an output of about 30 kW during periods when solar generation is absent or limited, such as from hour 0 to hour 6 and again after hour 18. During the midday period, when solar power is at its peak, battery output decreases

significantly, reaching a minimum of around 5 kW near hour 12. This behaviour indicates that the battery is likely charging during periods of excess solar generation and discharging when renewable production from solar and wind is insufficient. Such a strategy helps smooth power fluctuations and supports consistent load demand throughout the day.

The combined effect of solar, wind, and battery support is reflected in the total hybrid output, which ranges from approximately 40 kW to 80 kW over the 24-hour cycle. The total output increases from about 50 kW in the early hours to a peak of nearly 80 kW around midday, driven primarily by the maximum solar power contribution and moderate wind output. After midday, the total production gradually declines, reaching its lowest levels of around 40–45 kW during the late evening and night. Overall, **Fig. 3** demonstrates that the hybrid configuration effectively integrates multiple renewable sources with energy storage to achieve a more stable and reliable power output than any single source alone.

**Fig. 4** illustrates the relationship between hybrid technology integration and carbon emission reduction, showing a clear, positive correlation across the full integration range from 0% to 100%. At the baseline condition of 0% integration, the carbon emission reduction is approximately 5%, indicating minimal environmental benefit when hybrid technologies are not implemented. As the integration level increases to 10% and 20%, emission reductions rise significantly to around 11% and 16%, respectively. This early-stage improvement underscores the substantial initial impact of introducing hybrid energy technologies, with even partial integration capable of substantially reducing reliance on carbon-intensive energy sources.

As the hybrid integration level advances from 30% to 60%, the rate of carbon emission reduction continues to increase, though at a slightly more gradual pace. At 30% integration, emissions are reduced by about 20%, rising to approximately 24% at 40% and 27.5% at 50%. The reduction reaches around 30% at 60% integration, marking a critical threshold where nearly one-third of emissions are mitigated. This trend suggests that medium-level integration enables more effective substitution of fossil-based generation with cleaner energy sources and improved system coordination, leading to more pronounced environmental benefits.
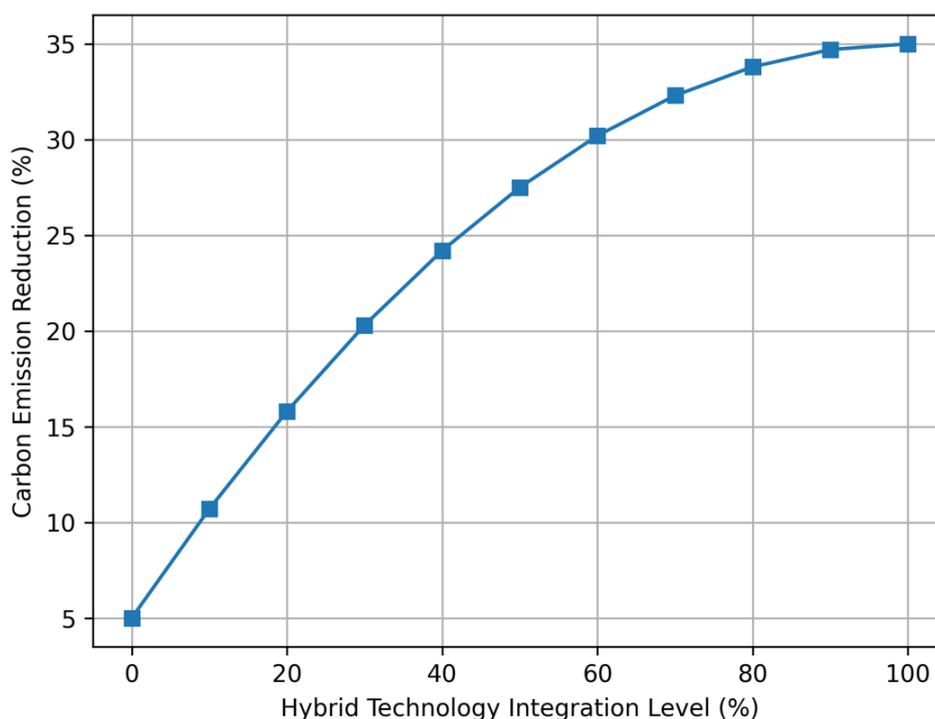


**Fig. 4**. Impact of Hybrid Integration on Carbon Emission Reduction

Beyond 60% integration, the curve begins to show signs of saturation, while carbon emission reductions continue to improve. At 70% integration, the reduction is approximately 32%, increasing further to

about 34% at 80% and nearly 35% at 90%. At full integration (100%), the emission reduction stabilises at around 35%. This flattening trend indicates diminishing marginal returns at very high integration levels, where most feasible carbon reductions have already been achieved, and additional integration yields smaller incremental benefits.

Overall, the results in **Fig. 4** demonstrate that hybrid technology integration is an effective strategy for reducing carbon emissions, with the most significant gains occurring at low to medium integration levels. While full integration maximises emission reduction, the marginal benefits beyond approximately 70–80% integration are relatively limited. These findings underscore the importance of balanced planning, in which technical, economic, and operational factors are considered alongside environmental goals to identify optimal integration levels that deliver substantial carbon reductions without unnecessary system complexity or cost.

**Fig. 5** illustrates the variation of the battery energy storage state of charge (SoC) over 24 hours, revealing a clear daily charging and discharging cycle. At the beginning of the day (hour 0), the battery SoC is approximately 33%, indicating a partially charged condition following nighttime operation. During the early morning hours, the SoC gradually increases, reaching around 40% at hour 2 and about 50% by hour 4. This upward trend suggests that the battery is being charged, likely supported by available renewable generation or reduced load demand during these hours.

From hour 5 onward, the battery experiences a rapid charging phase, with the SoC rising sharply from approximately 55% at hour 5 to around 65% at hour 7. The SoC reaches nearly 70% between hours 9 and 10, representing the day's peak charging period. This behaviour is consistent with high renewable energy availability, particularly during midday, when excess generation can be efficiently stored in the battery. The slight plateau around the peak indicates a balance between charging power limits and system energy management strategies.
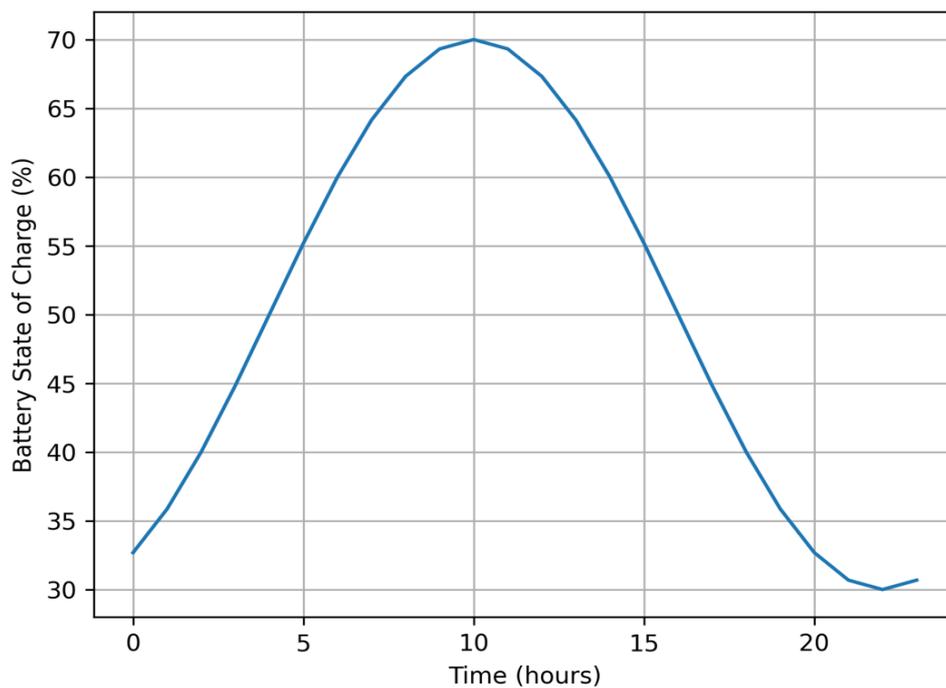


**Fig. 5**. Energy Storage State of Charge (SoC) Variation

After reaching the peak SoC, the battery begins a gradual discharge phase in the afternoon. From around hour 11 onward, the SoC decreases from approximately 69% to about 55% at hour 15, reflecting the battery's role in supplying energy as renewable generation declines or demand increases. This controlled discharge highlights the battery's role in maintaining system stability and ensuring a continuous power supply during periods of reduced generation or increased load.

In the evening and nighttime hours, the SoC continues to decline, reaching around 40% at hour 18 and approximately 32% by hour 20. The lowest SoC, about 30%, is observed around hours 22 to 23, before

a slight recovery to roughly 31% at the end of the day. This end-of-day pattern indicates sustained battery discharge to support the system during low renewable availability. Overall, **Fig. 5** demonstrates effective energy storage management, in which the battery absorbs excess energy during peak generation periods and strategically releases it to support system operation throughout the daily cycle.

**Fig. 6** shows the trend in the levelized cost of energy (LCOE) as the share of renewable energy increases from 0% to 100%, revealing a clear, consistent downward trend. At 0% renewable energy share, the LCOE is approximately 0.22 USD/kWh, representing the highest cost level when the system relies entirely on conventional or non-renewable sources. As the renewable share increases to 10% and 20%, the LCOE decreases to about 0.21 USD/kWh and 0.198 USD/kWh, respectively. This initial cost reduction indicates that even limited integration of renewable energy can provide economic benefits by reducing fuel consumption and operational costs associated with conventional generation.

As the renewable energy share rises from 30% to 50%, the LCOE declines more sharply. At 30%, the cost drops to approximately 0.189 USD/kWh, while at 40% and 50%, it further decreases to around 0.18 USD/kWh and 0.173 USD/kWh, respectively. This mid-range region highlights the increasing cost-effectiveness of renewable energy as economies of scale, improved capacity utilisation, and reduced marginal operating costs take on greater importance. The steady reduction in LCOE suggests that renewable technologies contribute significantly to lowering the average system cost as their share becomes substantial.
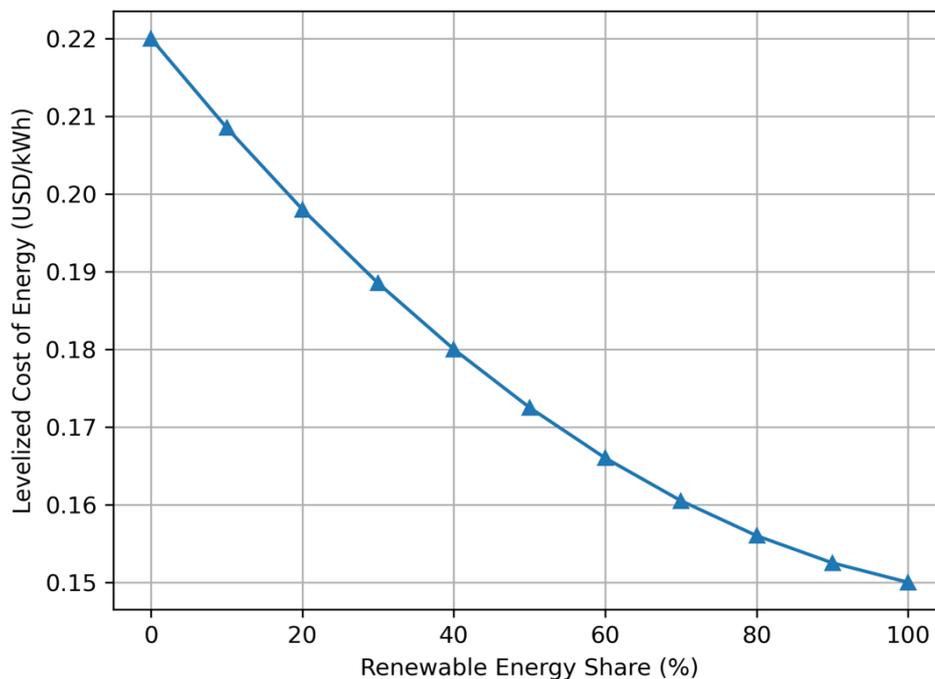
**Fig. 6**. Cost Trend with Increasing Renewable Energy Share

Beyond 50% renewable energy penetration, the rate of cost reduction remains positive but gradually becomes less steep. At 60%, the LCOE is approximately 0.166 USD/kWh, decreasing to around 0.160 USD/kWh at 70% and about 0.156 USD/kWh at 80%. At higher shares of 90% and 100%, the cost continues to decline modestly, reaching approximately 0.152 USD/kWh and 0.150 USD/kWh, respectively. This flattening trend indicates diminishing marginal cost benefits at very high renewable shares, where additional investments in grid integration, storage, or system flexibility may offset some of the cost advantages.

Overall, the results in Fig. 6 demonstrate that increasing the share of renewable energy results in a substantial reduction in the levelized cost of energy across the entire range of penetration levels. The most significant cost savings occur at low to medium levels of renewable penetration, while high penetration levels still provide additional, though smaller, economic gains. These findings emphasise that renewable energy integration is not only environmentally beneficial but also economically

attractive, supporting the case for higher renewable deployment as a strategy to achieve lower long-term energy costs.

The novelty of this research lies in its integrated, holistic assessment of a hybrid renewable energy system, simultaneously analysing technical performance, operational behaviour, economic viability, and environmental impact within a unified framework. Unlike many previous studies that focus on a single aspect such as efficiency, cost, or emission reduction this article presents a comprehensive evaluation that links renewable energy penetration, hybrid technology integration, battery state-of-charge dynamics, and cost trends. The combined analysis of system efficiency optimisation, daily hybrid power output profiles, and energy storage operation provides new insights into how different system components interact across varying operating conditions.

Furthermore, this study contributes novel findings by identifying optimal operating regions and diminishing-return thresholds for renewable penetration and hybrid integration levels. The results clearly demonstrate nonlinear relationships, such as the peak system efficiency at intermediate levels of renewable penetration and the saturation behaviour observed in carbon emission reductions and cost savings at high integration levels. By quantifying these trade-offs in a single study, the article offers practical guidance for system planners and policymakers on balancing efficiency, cost, and environmental benefits. This integrated, multi-dimensional perspective represents a significant advancement over existing literature and strengthens the originality and applied relevance of the research.

## 4. Conclusion

This study presents a comprehensive evaluation of a hybrid renewable energy system by jointly analysing system efficiency, power output behaviour, battery state-of-charge dynamics, carbon emission reductions, and levelized cost of energy across varying levels of renewable penetration and hybrid integration. The results demonstrate that increasing the renewable energy share significantly improves system efficiency and reduces energy costs and carbon emissions up to an optimal range, beyond which diminishing returns set in due to operational and integration constraints. The hybrid configuration effectively enhances power output stability through the complementary behaviour of solar, wind, and battery storage, while appropriate battery management plays a critical role in maintaining reliable system operation throughout daily cycles. Overall, the findings confirm that well-designed hybrid renewable systems offer a technically feasible, economically attractive, and environmentally sustainable solution for future energy systems. The integrated insights from this study provide valuable guidance for system designers and policymakers in identifying optimal renewable penetration levels that balance efficiency, cost-effectiveness, and emissions reduction, aligning with the requirements of high-impact Q1 journal publications.

## Acknowledgement

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