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# BESS-Integrated Hybrid Wind–Solar Energy Systems in Kerala: Stakeholder Perspectives and Implementation Framework

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## Abstract

The integration of renewable energy technologies with energy storage systems has emerged as a key strategy for ensuring grid stability, improving renewable energy utilisation, and enhancing energy security. This study examines the feasibility and sustainability of Battery Energy Storage System (BESS) integrated hybrid wind–solar energy systems in Kerala, India, through the perspectives of multiple stakeholders. By utilising a mixed-methods research design, this study investigates the viability of hybrid wind-solar systems integrated with Battery Energy Storage Systems (BESS) across Kerala's key energy corridors, including Palakkad, Idukki, and Ramakkalmedu. Through a combination of statistical surveys and thematic qualitative interviews, the research highlights that while these hybrid technologies significantly resolve issues of power intermittency and grid instability, their large-scale deployment is currently stifled by high upfront costs, land scarcity, and a lack of aggressive policy incentives. To navigate these challenges, the study introduces an integrated implementation framework that balances technological innovation with active stakeholder collaboration. Ultimately, these findings serve as a strategic roadmap for policymakers and developers seeking to transition toward sustainable energy while protecting the unique ecological integrity of regions like Kerala.

**Keywords:** Hybrid Renewable Energy, Wind–Solar Systems, Energy Storage, Sustainability, Policy, Energy Transition

## Introduction

Renewable energy is now at the forefront of contemporary power generation due to the shift to a low-carbon energy system. In addition to their positive effects on the environment, technologies like solar and wind energy are now widely acknowledged for their ability to provide energy security and lessen reliance on fossil fuels (Carlsen & Bruggeman, 2021; Blanco, 2008). However, because their output is dependent on environmental factors, these energy sources are intrinsically unpredictable. In areas with little grid flexibility, this fluctuation frequently makes it difficult to maintain a steady and continuous power supply (Belyaev et al., 2017). The creation of hybrid renewable energy systems, which integrate various energy sources like sun and wind, is one workable solution to this problem. Integrating these resources helps lessen variations in energy production because they frequently exhibit complementary patterns. By storing extra energy and releasing it when required, battery storage increases system dependability even more. However,

legislative backing, economic viability, and stakeholder coordination are just as important to the success of such systems as technology solutions (Adeyeye et al., 2020; Falani et al., 2020). Due to national-level initiatives and supportive policies, renewable energy capacity in India has increased gradually over time. Kerala's condition is still somewhat limited despite these advancements. Despite the state's favourable wind corridors and solar potential, land scarcity, environmental sensitivity, regulatory delays, and infrastructure constraints have all hindered development (Lakhanpal, 2019; Sharma & Sinha, 2019). These difficulties show that having resources on hand is not enough to guarantee a project's effective execution.

Additionally, the development of renewable energy projects is greatly influenced by the involvement of local communities and institutional cooperation. Concerns regarding land usage, the impact on the environment, and the allocation of benefits among stakeholders are frequently associated with delays (Adeyeye et al., 2020). This implies that more participatory planning procedures and improved communication between local people, authorities, and developers are required. Investor uncertainty can also be decreased by streamlining approval processes and enhancing departmental communication. More efficient integration of renewable energy can be supported by bolstering grid infrastructure and encouraging decentralised energy systems, which will increase the system's overall stability and adaptability (Purohit & Purohit, 2009). To reduce greenhouse gas emissions, mitigate climate change, and provide long-term energy security, renewable energy has emerged as a key component of international policies (Carlsen & Bruggeman, 2021). Kerala's grid management and energy dependability can be greatly enhanced by the use of BESS in hybrid wind-solar systems. Energy storage devices can lessen curtailment, support peak load control, and lessen variations in renewable energy output. Furthermore, hybrid renewable energy systems can enhance rural electrification, reduce dependency on fossil fuels, and contribute to sustainable economic development.

From a governance standpoint, the successful deployment of hybrid renewable energy systems necessitates efficient coordination between a number of stakeholders, including local communities, government agencies, regulatory bodies, investors, renewable energy developers, and environmental organisations. In order to solve environmental issues, guarantee community acceptance, and enhance project sustainability, stakeholder engagement is crucial. Wind energy has become one of the most developed, scalable, and economical renewable energy sources, making a substantial contribution to international efforts to reduce carbon emissions (IRENA, 2023; Blanco, 2008). Hybrid renewable energy systems combined with energy storage technologies have received little attention in Kerala's current research on renewable energy, which has mostly concentrated on wind and solar resources separately. By analysing stakeholder viewpoints on BESS-integrated hybrid wind-solar systems and creating an implementation strategy appropriate for Kerala's particular environmental and socioeconomic setting, this study fills this research vacuum.

This study's main goal is to investigate the critical elements influencing Kerala's adoption of hybrid wind-solar energy systems with battery storage. The study specifically focuses on the technological, social, economic, environmental, and policy-related factors that influence the creation and application of such systems. Kerala has a lot of potential for renewable energy, particularly solar and wind power, but its use is still restricted. For example, there is a significant disparity between potential and actual development because the state's wind energy potential is estimated to be over 2,000 MW, while the installed capacity is now only about 70 MW. Similar to this, solar energy capacity has been growing, but large-scale deployment is still hampered by issues

with infrastructure and land availability. The study also seeks to propose a practical framework based on stakeholder perspectives, which can support decision-makers and energy developers in planning and promoting sustainable renewable energy initiatives within the state. This becomes particularly important as Kerala aims to achieve long-term goals such as carbon neutrality and a fully renewable energy-based power system in the coming decades. In addition, the growing need for a reliable and continuous power supply highlights the importance of hybrid systems integrated with battery storage, especially in a state that depends significantly on power imports to meet its energy demand. By addressing these interconnected factors, the study intends to contribute to a more practical and locally relevant approach for advancing renewable energy adoption in Kerala.

## Materials and Methods

This study follows a mixed-methods research design, combining quantitative and qualitative approaches to examine stakeholder perspectives on Battery Energy Storage System (BESS)-integrated hybrid wind–solar energy systems in Kerala. This approach was selected to capture both measurable patterns in stakeholder responses and detailed insights into practical challenges and experiences associated with renewable energy implementation. The study was carried out in a few Keralan areas that are known for having a comparatively high potential for renewable energy, such as Palakkad, Idukki, and Ramakkalmedu. One of the best places in the state for wind energy production is the Palakkad Gap, a natural gap in the Western Ghats that promotes steady wind flow. In a similar vein, Ramakkalmedu in the Idukki district has strong winds all year round, while the average sun radiation in several areas of Kerala is between 4.5 and 5.5 kWh/m²/day. Despite these favourable circumstances, site limitations, legal restrictions, and infrastructure difficulties continue to restrict the use of renewable resources in these areas (Shukla et al., 2023).

Primary data collection involved a structured questionnaire survey administered to 200 respondents. The respondents were selected to represent a wide range of stakeholders, including renewable energy developers, engineers, government officials, residents, landowners, environmental groups, and energy consultants. A combination of purposive and convenience sampling techniques was used to ensure that participants had relevant knowledge or experience related to renewable energy projects. The questionnaire was designed using a five-point Likert scale, ranging from “strongly disagree” to “strongly agree,” to measure perceptions across key dimensions such as environmental impact, social acceptance, economic feasibility, technological reliability, and policy effectiveness. Additional sections included questions on grid integration challenges, intermittency issues, energy storage adoption, cost barriers, and investment risks. The survey instrument was pre-tested with a small group of respondents to improve clarity and reliability before final data collection.

In addition to the survey, 30 semi-structured interviews were conducted with selected stakeholders to obtain more detailed qualitative insights. Participants included project developers, policy experts, engineers, and representatives from local communities located near renewable energy installations. These interviews focused on practical issues such as land acquisition challenges, environmental concerns, regulatory approvals, and the role of local participation in project success. Field visits were carried out at selected wind and solar project sites to observe physical and operational conditions. These observations included assessment of land use patterns, site accessibility, environmental sensitivity, turbine placement, and grid connectivity infrastructure. Such on-site observations helped to validate survey responses and provided a better understanding

of real-world implementation challenges. Secondary data were collected from various sources, including government publications, policy documents, renewable energy reports, and academic studies related to hybrid systems and energy storage technologies. Reports from national and state agencies were also reviewed to understand trends in renewable energy capacity, policy developments, and infrastructure status.

Statistical tools, such as descriptive statistics to summarise replies and inferential methods like regression analysis and correlation to look at links between important variables, were used to analyse quantitative data. Standard metrics like Cronbach's alpha were used to evaluate the data's reliability. Thematic analysis was used to analyse qualitative data from field notes and interviews, grouping responses into common themes on implementation issues, sustainability, and stakeholder participation. The study guarantees a more thorough and fair understanding of the elements driving Kerala's adoption of BESS-integrated hybrid renewable energy systems by integrating these approaches. By cross-verifying data from several sources, this integrated strategy also increases the validity of the conclusions.

**Results and Discussions**

The findings of this study reveal that battery energy storage system (BESS) integrated hybrid wind–solar energy systems have significant potential to enhance renewable energy generation and improve electricity reliability in Kerala. The findings of this study indicate a strong positive perception among stakeholders toward the adoption of hybrid wind–solar energy systems integrated with battery energy storage. Respondents widely recognised that combining wind and solar resources helps reduce variability in energy generation, while battery storage improves the reliability and continuity of power supply. Compared to standalone renewable systems, hybrid configurations were perceived as more efficient and capable of supporting stable electricity delivery under varying climatic conditions. Environmental sustainability emerged as a major factor influencing stakeholder acceptance. Most respondents agreed that hybrid renewable energy systems can significantly reduce greenhouse gas emissions and dependence on fossil fuels (Belyaev et al., 2017). In addition, such systems produce minimal air pollutants compared to conventional thermal power generation, contributing positively to climate mitigation efforts. However, concerns were raised regarding land use changes and ecological sensitivity, particularly in regions such as the Western Ghats. Stakeholders emphasised that large-scale installations must be supported by detailed environmental impact assessments and continuous monitoring to avoid adverse effects on biodiversity and fragile ecosystems (Falani et al., 2020).

Social factors also played a crucial role in shaping project acceptance. The results show that projects with higher levels of community engagement and transparency tend to experience fewer conflicts and greater local support. Participation of local communities in planning and decision-making processes was identified as a key element for long-term project success (Adeyeye et al., 2020). Respondents highlighted employment generation as an important benefit, especially in installation, maintenance, and support services. At the same time, lack of communication and limited stakeholder involvement were identified as major reasons for resistance in certain project locations. Economic considerations were identified as both an opportunity and a constraint. On one hand, hybrid renewable energy systems contribute to regional economic development by creating jobs and encouraging technological innovation within the energy sector (Kumar & Majid, 2020). They also support local supply chains and small-scale industries. On the other hand, the high initial investment required—particularly for battery energy storage systems—remains a major barrier to

widespread adoption. Stakeholders emphasised the need for financial support mechanisms such as subsidies, low-interest financing, and policy incentives to improve project feasibility and attract private investment.

The complementary nature of solar and wind energy resources made hybrid systems extremely advantageous from a technology standpoint. While wind energy availability frequently rises in the evening and during certain seasons, solar generation usually peaks during the day. A more balanced energy production is produced as a result of this combination. By storing extra energy and supplying it during times of high demand or low generation, battery storage integration improves system performance even further. Hybrid systems are better suited for areas with erratic renewable resources because of this capability, which also lessens power fluctuations and increases grid stability (Carlsen & Bruggeman, 2021). Another important advantage identified in the study is improved utilisation of renewable energy. In conventional systems, surplus electricity generated during peak production is often curtailed due to grid limitations. With battery storage, this excess energy can be stored and used later, thereby reducing energy losses and improving overall system efficiency. This not only enhances economic returns but also maximises the use of available renewable resources. Stakeholders also noted the role of hybrid systems in managing peak electricity demand. Battery storage allows energy generated during off-peak periods to be used during high-demand periods, reducing dependence on expensive peak power generation from conventional sources. This contributes to improved grid efficiency and helps stabilise the electricity supply.

**Table 1- Conceptual Framework for Hybrid Wind–Solar BESS Study**

| Parameter | Wind Energy | Solar Energy | Hybrid Wind–Solar + BESS |
|---|---|---|---|
| Energy Availability | Seasonal / wind dependent | Daytime only | More stable due to complementary generation |
| Grid Stability | Moderate variability | High daytime variability | High stability with storage support |
| Energy Storage Need | Medium | High | Optimised through BESS integration |
| Reliability | Moderate | Moderate | High reliability |
| Environmental Impact | Low emissions | Low emissions | Lowest emissions with optimised generation |
| Future Potential | High | Very high | Very high with smart grids and storage |

In the context of Kerala, hybrid renewable energy systems can also strengthen energy security. As the state relies partly on imported electricity, increasing local renewable energy generation can reduce external dependence and improve system resilience. In addition, decentralised hybrid systems can support microgrid development in remote or less-connected regions, providing a

reliable electricity supply where grid infrastructure is limited. It is anticipated that technological developments will increase the viability of hybrid systems. Innovations in digital monitoring tools, smart grid systems, and battery technologies can boost long-term system performance, lower operating costs, and increase efficiency. The use of hybrid renewable energy systems is expected to rise as these technologies become more widely available. Finally, policy and regulatory factors were identified as the most critical determinants of project success. Stakeholders emphasised the importance of a clear and stable policy environment to encourage investment and reduce uncertainty. Simplifying approval procedures through streamlined mechanisms, ensuring transparent tariff structures, and providing clear guidelines for grid connectivity and energy storage integration were identified as essential steps for promoting hybrid renewable energy development.

In addition, targeted financial incentives for energy storage systems, along with stable and transparent power purchase agreements, can play a crucial role in improving the feasibility of hybrid renewable energy projects. Supportive and consistent renewable energy policies are equally important for creating a favourable investment environment. At the same time, better coordination among government departments, regulatory authorities, and renewable energy developers is necessary to reduce delays and ensure smoother project implementation in Kerala. The study's overall conclusions show that hybrid wind-solar systems combined with battery energy storage provide significant benefits in terms of the environment, society, economy, and technology. These systems could lessen reliance on traditional energy sources, increase grid stability, boost local economic growth, and increase the dependability of renewable energy. However, effective stakeholder collaboration, transparent and encouraging policy frameworks, continuous technical advancements, and significant community engagement are all necessary for their successful implementation.

## Conclusion

The substantial potential of BESS-integrated hybrid wind-solar energy systems in assisting Kerala's shift to a more dependable and sustainable energy system is highlighted in this study. In a situation where demand-supply gaps and peak load changes are frequent, the integration of wind and solar resources with battery storage can increase supply consistency, improve grid stability, and enable better utilisation of renewable energy. Kerala receives an average solar radiation of 4.5–5.5 kWh/m²/day and has an estimated wind energy potential of about 2,000 MW, but the current level of utilisation is still relatively low, suggesting significant room for hybrid system development. However, the successful implementation of such systems depends on addressing several practical challenges, including high initial investment costs—especially for battery storage—limited land availability, environmental sensitivity of regions such as the Western Ghats, and procedural delays in project approvals. The findings underline the importance of adopting a stakeholder-oriented approach that integrates the perspectives of developers, policymakers, and local communities. Supportive policy measures such as financial incentives for energy storage, simplified approval mechanisms, and improvements in grid infrastructure are essential to accelerate adoption. Kerala’s dependence on power imports further strengthens the case for expanding local renewable energy generation through hybrid systems. In addition, transparent community engagement and benefit-sharing mechanisms are necessary to improve social acceptance and reduce project-level conflicts. Technological advancements in battery systems, smart grids, and digital monitoring tools are expected to improve efficiency further and reduce long-term costs. In conclusion, BESS-integrated

hybrid renewable energy systems offer a practical and sustainable pathway for Kerala's energy transition. With coordinated policy support, stakeholder collaboration, and technological innovation, Kerala has the potential to emerge as a model for renewable energy development in environmentally sensitive regions.

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