

# Hybrid Renewable Energy Systems with Battery Energy Storage in Microgrids: A Review on Challenges, Optimization and Future Directions

Neha Nigam\*, Kumari Ashwini\*\*, Anil Boyal\*\*

\*M.Tech Student, Department of Electrical Engineering, Regional College for Education Research & Technology, Jaipur, Rajasthan, India

\*\* Assistant Professor, Department of Electrical Engineering, Regional College for Education Research & Technology, Jaipur, Rajasthan, India

## ABSTRACT

Renewable energy-based microgrids are gaining significant importance due to their potential to provide sustainable, reliable, and decentralized power solutions. However, the inherent intermittency and variability of renewable sources such as solar photovoltaic (PV) and wind energy pose critical challenges in maintaining stability and efficiency. Hybrid Renewable Energy Systems (HRES), coupled with Battery Energy Storage Systems (BESS), offer a viable solution to overcome these limitations. This review provides an in-depth study of the status of HRES and BESS integration, optimization algorithms for efficient energy dispatch, challenges in implementation, and the future research scope with particular emphasis on India's growing energy landscape.

**Keywords** — Hybrid power system; Optimization techniques; Particle swarm optimization; battery energy storage system (BESS).

## 1. INTRODUCTION

The global energy landscape is undergoing a rapid transition toward renewable energy sources, driven by the urgent need to mitigate climate change, reduce greenhouse gas emissions, and achieve the United Nations' Sustainable Development Goals (SDGs). Among the various solutions, microgrids have gained prominence as localized, decentralized power systems capable of integrating distributed renewable energy generation with advanced energy storage solutions. These systems not only enhance energy efficiency and reliability but also promote sustainability by reducing dependence on conventional fossil fuels.

In the context of India, the importance of microgrids is even more pronounced. The country's accelerated industrial growth, ambitious electrification initiatives, and growing rural energy requirements have created a pressing demand for affordable, resilient, and scalable energy solutions. Hybrid microgrid systems, which combine renewable energy sources such as solar, wind, and biomass with Battery Energy Storage Systems

(BESS), offer a promising pathway to address these challenges. They ensure stable power supply despite the intermittency of renewable resources, reduce transmission losses, and support grid independence in remote and underserved regions.

Furthermore, the adoption of hybrid renewable energy microgrids in India contributes to energy security, rural development, and environmental sustainability, while aligning with national policies such as the National Electricity Plan and international commitments under the Paris Agreement. As renewable energy penetration continues to grow, the integration of advanced storage and optimization techniques in microgrids will play a crucial role in shaping a reliable, sustainable, and economically viable energy future.

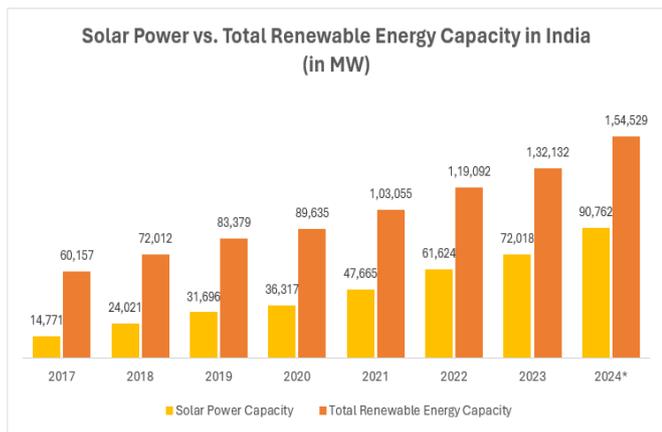


Figure 1: Growth of Solar Power vs. Renewable Energy Capacity in India (2010–2024)

## 2. RENEWABLE ENERGY POTENTIAL IN INDIA

### A. Solar Energy

India receives solar insolation between 4–7 kWh/m<sup>2</sup>/day, with over 300 sunny days annually. The government’s National Solar Mission has significantly accelerated solar deployment, aiming for 280 GW solar capacity by 2030 [1].

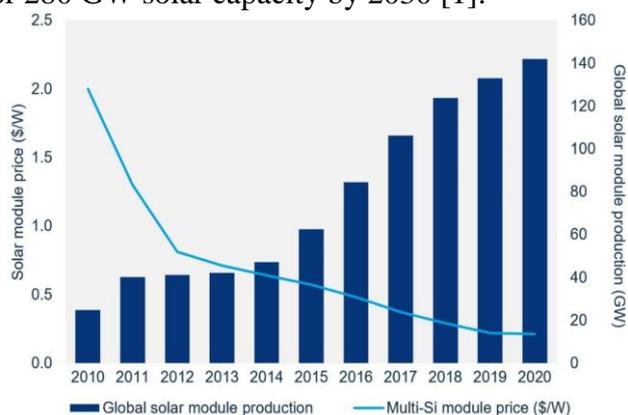


Figure 2: Solar Cell Price History (Source: Wikimedia)

### B. Wind Energy

With an estimated potential of 302 GW at 100 m hub height, wind remains a key contributor to renewable generation. However, issues such as seasonal variability, repowering of old turbines, and site-specific challenges need to be addressed [2].

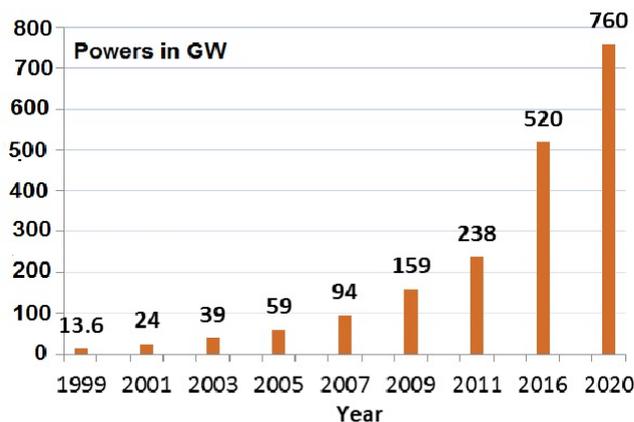


Figure 3: Global cumulative installed wind capacity 1999-2020 (Source: GWEC)

### C. Biomass and Hydro Resources

Biomass offers decentralized energy opportunities, particularly in rural areas, while small hydro systems provide steady baseload support. Together, they strengthen the hybrid system portfolio [3].

## 3. HYBRID RENEWABLE ENERGY SYSTEMS (HRES)

Hybrid Renewable Energy Systems (HRES) integrate multiple renewable energy sources with storage units to enhance system reliability and optimize power generation. By combining complementary resources, these systems are able to mitigate the inherent variability and intermittency associated with individual renewable sources [18], [19]. A typical HRES configuration incorporates solar photovoltaic (PV), wind energy, and biomass as primary generation sources, supported by Battery Energy Storage Systems (BESS). This combination ensures a continuous and stable power supply by storing excess energy during periods of high generation and discharging it during low-generation intervals. Such integration not only improves energy security but also enhances grid flexibility, making HRES an efficient and sustainable solution for modern microgrids..

### Need for Energy Storage in Hybrid Renewable Energy Systems (HRES)

**Spinning Reserve and Short-Term Backup:** In conventional energy systems, coal and oil-based power generators serve as spinning reserves, providing backup power when demand suddenly increases. However, these systems require significant start-up time and are slow to respond. In

contrast, ESS in HRES-based DG can quickly supply power within seconds to minutes making them ideal for short-term backup. This fast response capability enhances system reliability and operational flexibility.

**Load Leveling and Peak Shaving:** Renewable energy systems rely on natural resources like sunlight and wind, which may not align with peak electricity demand times. This mismatch can cause power imbalances or outages. Energy Storage Systems (ESS) help by storing excess energy generated during off-peak periods and supplying it during peak demand, thus flattening the load curve and enhancing energy efficiency. ESS also supports demand-side management by enabling consumers to monitor and optimize their energy use, leading to better planning and reduced costs.

**Integration of Renewable Energy into DG:** One of the key challenges in integrating renewable energy into DG systems is its intermittency and variability. For instance, in countries with high solar capacity, a phenomenon known as the "duck curve" occurs—where solar energy generation drops sharply in the evening while demand peaks, requiring sudden ramp-up of other power sources. ESS can help smooth this transition by storing solar energy during the day and supplying it during peak hours. This mitigates grid stress and helps maintain reliability.

**Power Quality Support:** ESS can enhance power quality by addressing issues such as voltage fluctuations, frequency deviations, and harmonics. Technologies like flywheels and supercapacitors, known for their high energy density and fast response times, are especially effective in maintaining consistent power delivery and stabilizing the grid during disturbances.

**Long-Term Energy Storage:** Historically, large-scale energy storage has been achieved through hydropower reservoirs and dams. In recent years, technologies such as thermal energy storage, compressed air energy storage, and flow batteries have emerged to store electricity for longer durations from several days to even months. These systems can reduce energy costs and ensure long-term supply continuity, particularly during seasonal fluctuations or prolonged outages.

**Auxiliary Services and Energy Arbitrage:** Grid operators rely on a range of auxiliary services such as frequency regulation, voltage control, and load following to maintain secure and stable grid operations. ESS can efficiently deliver these services. In addition, ESS enables energy arbitrage, where energy is stored during periods of low electricity prices and discharged when prices are high, thereby maximizing economic returns. While similar to peak shaving, energy arbitrage is profit-driven, focusing on trading stored energy rather than just balancing supply and demand. For these services to be financially viable, ESS technologies must be responsive and capable of delivering measurable grid benefits that justify their cost.

#### **4. ROLE OF BATTERY ENERGY STORAGE SYSTEMS (BESS)**

BESS enables:

- Smoothing fluctuations in PV and wind output
- Enhancing grid stability and flexibility
- Providing backup power during outages
- Preventing overcharging and over-discharging of batteries

The declining cost of lithium-ion batteries further strengthens the case for large-scale deployment [4].

#### **5. OPTIMIZATION TECHNIQUES FOR HRES OPERATION**

The operation of Hybrid Renewable Energy Systems (HRES) requires careful optimization to ensure reliable power supply, cost-effectiveness, and improved system stability. Since renewable energy sources are inherently intermittent, and battery storage has operational limitations such as charging/discharging efficiency and lifespan, optimization techniques are employed to strike a balance between technical performance and economic viability. Various methods have been developed to optimize generation scheduling, energy storage management, and load dispatch in microgrids.

##### **A. Heuristic Algorithms**

Heuristic methods rely on iterative search processes inspired by natural phenomena or biological behavior. These algorithms are particularly useful

in handling the nonlinear, complex, and multi-objective nature of HRES optimization problems.

- **Particle Swarm Optimization (PSO):** Inspired by the social behavior of bird flocking and fish schooling, PSO is widely used for optimal power dispatch, minimizing operational cost, and improving battery usage.
- **Genetic Algorithms (GA):** Based on the principles of natural selection and evolution, GA is effective in optimizing system sizing, component allocation, and energy scheduling in hybrid systems.
- **Ant Colony Optimization (ACO):** Inspired by the foraging behavior of ants, ACO is applied to find optimal paths in power flow and dispatch strategies, particularly in systems with multiple objectives.

### **B. Deterministic Models**

Deterministic optimization models provide mathematically exact solutions under given assumptions and constraints. They are highly effective in structured problems but may face challenges in handling uncertainties in renewable generation and load variations.

- **Mixed Integer Linear Programming (MILP):** A widely adopted approach for modeling microgrid operation, MILP can handle discrete decisions such as unit commitment and battery charging/discharging states, making it suitable for long-term planning.
- **Linear Programming (LP):** LP simplifies optimization into a linear form, often used for cost minimization and power flow management under simplified system assumptions.

### **C. Hybrid Algorithms**

To overcome the limitations of purely heuristic or deterministic methods, hybrid approaches have been introduced. These techniques combine the robustness of heuristics with the precision of deterministic models, enabling more reliable and scalable optimization.

- **Improved Particle Swarm Optimization (I-PSO):** An advanced version of PSO, I-

PSO incorporates adaptive parameters and hybrid strategies to enhance convergence speed, avoid local optima, and improve real-time energy dispatch in microgrids. This approach is particularly effective for balancing renewable generation with battery storage while maintaining voltage and frequency stability.

## **6. CHALLENGES IN HRES DEPLOYMENT**

- High capital investment and limited financing mechanisms
- Grid integration complexities
- Intermittency and forecasting uncertainties
- Lack of standardization in microgrid policies
- Recycling and sustainability concerns of large-scale battery deployment [5]

## **7. FUTURE DIRECTIONS**

Future research and deployment strategies should focus on:

- Incorporating artificial intelligence and machine learning for predictive energy management
- Expanding green hydrogen as long-term storage integrated with HRES
- Enhancing circular economy models for battery recycling
- Developing low-cost indigenous storage technologies in India
- Implementing smart grid technologies for advanced demand-side management

## **8. CONCLUSION**

Hybrid Renewable Energy Systems with BESS present a promising pathway for achieving India's energy security and sustainability goals. Optimization-based operation of microgrids ensures economic efficiency, reliability, and resilience in power supply. Addressing technical, financial, and policy-related challenges will be crucial for enabling large-scale adoption in both urban and rural contexts.

## **REFERENCES**

- [1] Ministry of New and Renewable Energy (MNRE), Govt. of India, “National Solar Mission”, 2023.
- [2] <https://www.india.gov.in/website-national-institute-wind-energy>
- [3] S. Sinha, S. S. Chandel, “Review of software tools for hybrid renewable energy systems”, *Renewable and Sustainable Energy Reviews*, vol. 20, pp. 581–597, 2013.
- [4] International Energy Agency (IEA), 'Battery Storage Trends,' 2024.
- [5] A. Kumar, et al., 'Optimization techniques for hybrid renewable energy systems: A comprehensive review,' *Renewable Energy*, vol. 146, pp. 222–235, 2020.
- [6] "India's Renewable Energy Capacity Achieves Historic Growth in FY 2024-25", Ministry of New and Renewable Energy, Delhi.
- [7] "India's Renewable Energy Capacity Hits New Milestone: Renewable energy now constitutes more than 46.3% of total capacity", Ministry of New and Renewable Energy, Delhi, 13 NOV 2024.
- [8] P. Roy, J. He, T. Zhao and Y. V. Singh, "Recent Advances of Wind-Solar Hybrid Renewable Energy Systems for Power Generation: A Review", *IEEE Open Journal of the Industrial Electronics Society*, vol. 3, pp. 81-104, 2022.
- [9] Wen-Jei Yang, Orhan Aydin, "Wind energy–hydrogen storage hybrid power generation", *International Journal of Energy Research*, 2001.
- [10] Eduard Enasel, Gheorghe Dumitrascu, "Storage solutions for renewable energy: A review", *Energy Nexus*, Vol. 17, 2025.
- [11] "Energy Storage at the Distribution Level – Technologies, Costs and Applications (A study highlighting the technologies, use-cases and costs associated with energy storage systems at the distribution network-level)", *Distribution Utilities Forum (DUF)*, September 2021.
- [12] <https://www.indiascienceandtechnology.gov.in/organisations/ministry-and-departments/ministry-new-and-renewable-energy-mnre-govt-india/national-institute-wind-energy-niwe-chennai>
- [13] Ahmed Jassim Al-Yasiri, "Global Energy Demand For Different Energy Sources: Current Status and Future Prospects", *Akkad Journal Of Contemporary Economic Studies*, Vol 1(4), pp. 186-196, 2022.
- [14] “Wind explained: History of wind power”, <https://www.eia.gov/energyexplained/wind/history-of-wind-power.php>
- [15] "The Global Wind Energy Council (GWEC)", <https://www.gwec.net/reports>
- [16] "Solar Overview", Ministry of New and Renewable Energy, Delhi, <https://mnre.gov.in/en/solar-overview/>
- [17] "Renewable Energy Sources and Climate Change Mitigation", Special Report of the Intergovernmental Panel on Climate Change. [https://archive.ipcc.ch/pdf/special-reports/srren/SRREN\\_Full\\_Report.pdf](https://archive.ipcc.ch/pdf/special-reports/srren/SRREN_Full_Report.pdf)
- [18] Neha Nigam, Kumari Ashwini, "Power Fluctuation Control in Hybrid Renewable Energy Systems Using Particle Swarm Optimization: A Comparative Study", *International Journal of Engineering Trends and Applications (IJETA) – Volume 12 Issue 4*, Jul-Aug 2025.
- [19] Zia Ul Islam, M.S. Hossain Lipu, Sheikh T. Mearaj, Abu M. Fuad, Tuhibur Rahman, Md Ashraf Islam, Mahidur R. Sarker, "Hybrid renewable energy systems towards sustainable development in Bangladesh: Configurations, optimizations, applications, challenges and future pathways", *Results in Engineering*, 2025.