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Performance Evaluation of Integrated Hybrid Renewable and Mechanical Energy Storage Systems

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ABSTRACT

The increasing demand for reliable, efficient, economical, and environmentally sustainable energy has encouraged the development of hybrid energy systems that integrate renewable energy sources with mechanical energy-storage and backup technologies. This study evaluated four energy-system configurations: a conventional fossil-fuel system, a renewable-only system, a renewable system supported by mechanical storage, and an integrated hybrid energy system. The evaluation was based on technical efficiency, renewable-energy contribution, system availability, power loss, Loss of Power Supply Probability, energy cost, carbon emissions, storage performance, and power-supply continuity. The results showed that the integrated hybrid energy system achieved the best overall performance, with an efficiency of 91%, system availability of 99%, power loss of 3.8%, and LPSP of only 1%. It also reduced annual unmet electrical demand to 520 kWh and achieved the lowest Levelized Cost of Energy of ₹6.80 per kWh. In addition, the system reduced carbon emissions by approximately 83% compared with the conventional fossil-fuel system. Flywheel and battery storage were found suitable for rapid-response applications, while pumped-hydro and compressed-air systems were more appropriate for long-duration and bulk energy storage. The study concludes that the coordinated integration of renewable generation, mechanical storage, backup units, power converters, and intelligent control systems can significantly improve energy efficiency, reliability, affordability, and environmental performance.

Keywords: Hybrid Energy Systems, Renewable Energy, Mechanical Energy Storage, Energy Efficiency.

1. INTRODUCTION

The growing demand for energy, rapid industrial development, urbanisation, population growth, and increasing concern about climate change have created a strong need for cleaner, more reliable, and sustainable energy systems. Conventional energy systems mainly depend on fossil fuels such as coal, petroleum, and natural gas. Although these sources have supported economic and technological development for many decades, their continued use has resulted in environmental pollution, greenhouse-gas emissions, resource depletion, and energy-security concerns. Renewable energy technologies have therefore emerged as important alternatives because they use naturally replenished resources such as sunlight, wind, water, biomass, and geothermal energy. However, renewable energy sources are often variable and dependent on weather and geographical conditions. This limitation has encouraged the development of hybrid energy systems that combine renewable sources with mechanical technologies, energy-storage devices, and intelligent control mechanisms. A hybrid energy system integrates two or more energy-generation, conversion, or storage technologies to provide a stable and efficient power supply. Such systems may combine solar photovoltaic panels, wind turbines, biomass units, and small hydropower plants with mechanical technologies such as flywheels, pumped-hydro storage, compressed-air energy storage, turbines, generators, and kinetic-energy recovery devices. The main purpose of this integration is to overcome the limitations of individual technologies. For example, solar energy is available mainly during daylight hours, while wind energy may vary according to atmospheric conditions. Mechanical storage systems can absorb surplus energy during periods of high renewable generation and release it when generation is insufficient or demand increases [1].

The integration of mechanical and renewable energy technologies improves energy reliability, power quality, load balancing, system flexibility, and overall operational efficiency. Mechanical technologies can provide rapid response, frequency regulation, voltage support, rotational stability, and short- or long-duration energy storage. Flywheels are suitable for quick energy delivery and frequency control, whereas pumped-hydro and compressed-air systems can store large quantities of energy for longer periods. Turbines and generators convert mechanical energy into electrical energy, while power-conversion devices regulate voltage, current, and frequency. An energy-management and control system coordinates all these components by continuously monitoring renewable generation, storage conditions, electricity demand, and grid availability. The evaluation of hybrid energy systems is necessary to determine their technical, economic, environmental, and operational performance. Technical evaluation includes energy-conversion efficiency, storage capacity, response time, system reliability, power losses, equipment life, and control performance. Economic assessment considers capital investment, operation and maintenance costs, payback period, life-cycle cost, and potential savings. Environmental evaluation examines reductions in greenhouse-gas emissions, fossil-fuel consumption, pollution, and ecological impact. Social and practical factors, including land requirements, public acceptance, availability of skilled workers, and suitability for rural or remote locations, must also be considered.

Therefore, evaluating hybrid energy systems that integrate mechanical and renewable energy technologies is essential for identifying suitable system configurations and improving future energy planning. A well-designed hybrid system can provide continuous power, reduce dependence on fossil fuels, support decentralised energy generation, and contribute to environmental sustainability. Such systems have significant potential for residential, industrial, agricultural, transportation, and remote-area applications. Their effective development and evaluation can support the transition towards a low-carbon, energy-efficient, and technologically advanced society [2].

1.1 Background of the Study

The global energy sector is experiencing a major transformation because of increasing electricity demand, rapid industrialisation, population growth, environmental degradation, and the depletion of conventional energy resources. For many years, fossil fuels such as coal, petroleum, and natural gas have remained the primary sources of energy. However, their extensive use has caused serious environmental problems, including air pollution, global warming, greenhouse-gas emissions, and ecological imbalance. These challenges have increased the importance of renewable energy technologies such as solar, wind, hydropower, biomass, and geothermal energy. Although renewable energy sources are clean and sustainable, their output is often intermittent and dependent on weather conditions. Solar energy is unavailable at night, while wind power changes according to wind speed. These variations can create problems in maintaining a continuous and stable energy supply. As a result, hybrid energy systems have gained importance because they combine multiple energy sources and technologies to improve reliability, efficiency, and system performance [3].

Mechanical energy technologies play an important role in hybrid systems. Technologies such as wind turbines, hydro turbines, flywheel energy storage, pumped-hydro storage, compressed-air energy storage, and mechanical generators support energy conversion, storage, and power balancing. They can store surplus renewable energy and supply it during periods of low generation or high demand. This integration can reduce fluctuations, improve grid stability, and lower dependence on fossil-fuel-based backup systems

[4]. The development of advanced control systems, power electronics, sensors, and energy-management technologies has further improved the operation of hybrid energy systems. These tools allow continuous monitoring and coordination of generation, storage, and consumption. Therefore, evaluating hybrid systems that integrate mechanical and renewable energy technologies is important for determining their technical feasibility, economic viability, environmental benefits, and operational reliability. Such evaluation can support better system design, sustainable energy planning, and the transition towards a cleaner and more secure energy future.

1.2 Performance Evaluation Parameters

Performance evaluation parameters are essential for determining the effectiveness, reliability, efficiency, and sustainability of hybrid energy systems. These parameters help researchers and engineers compare different system configurations and identify the most suitable combination of mechanical and renewable energy technologies. The evaluation generally includes technical, economic, environmental, and operational indicators. Energy efficiency is one of the most important parameters. It measures the proportion of input energy that is successfully converted into useful electrical or mechanical energy [5]. A highly efficient hybrid system reduces energy losses and improves overall output. Renewable energy utilisation is another important parameter that indicates the percentage of total demand supplied through solar, wind, hydro, biomass, or other renewable sources. Reliability measures the ability of the system to provide continuous power under changing weather and load conditions. Common reliability indicators include Loss of Power Supply Probability, unmet energy demand, system availability, and frequency of power interruptions. Storage performance is evaluated through storage capacity, charging and discharging efficiency, response time, depth of discharge, self-discharge rate, and operational life. These indicators are especially important for flywheels, pumped-hydro systems, compressed-air storage, and batteries.

Economic performance is evaluated through capital cost, operation and maintenance cost, levelized cost of energy, net present cost, payback period, and life-cycle cost. These parameters determine whether the hybrid system is financially feasible over its operational life. Environmental performance includes carbon-emission reduction, fuel savings, noise level, land use, waste generation, and overall ecological impact. Power-quality parameters such as voltage stability, frequency regulation, harmonic distortion, and power-factor improvement are also considered. In addition, system response time, load-following capability, energy balance, equipment utilisation, and control-system accuracy help assess operational performance. A comprehensive evaluation of these parameters ensures that the selected hybrid energy system is technically reliable, economically affordable, environmentally sustainable, and suitable for long-term energy applications [6].

1.3 Technical Evaluation of Hybrid Energy Systems

Technical evaluation is one of the most important aspects of assessing hybrid energy systems because it determines the system's ability to deliver reliable, efficient, and continuous energy under varying operating conditions. A hybrid energy system integrates renewable energy sources with mechanical technologies and energy storage devices to ensure a stable power supply. The technical evaluation examines how effectively these components work together and whether the system can meet the required energy demand with minimum losses. One of the primary technical parameters is energy conversion efficiency, which measures the proportion of input energy converted into useful electrical or mechanical output. Higher efficiency indicates better system performance and reduced energy wastage. Power reliability is another critical parameter that evaluates the system's capability to supply uninterrupted electricity despite fluctuations in renewable energy generation or changes in load demand.

The evaluation also includes system stability, which refers to maintaining constant voltage and frequency during operation. Mechanical technologies such as flywheels, pumped-hydro storage, compressed-air energy storage, turbines, and generators contribute significantly to improving grid stability and balancing power fluctuations. The response time of the system is equally important because it measures how quickly the hybrid system reacts to sudden changes in electricity demand or renewable energy availability. Another essential aspect is energy storage performance, including storage capacity, charging and discharging efficiency, depth of discharge, cycle life, and energy losses during storage. The effectiveness of the energy management system (EMS) is also evaluated because it coordinates power generation, storage, and distribution while ensuring optimal utilisation of renewable resources. Technical evaluation further considers power quality, including voltage regulation, frequency control, harmonic distortion, and power factor. Equipment reliability, component lifespan, maintenance requirements, operational safety, and fault tolerance are also examined to ensure long-term performance. Simulation software such as MATLAB/Simulink, HOMER Pro, PSCAD, Dig SILENT Power Factory, and LabVIEW is widely used to model and analyse system behaviour under different operating scenarios [7].

Overall, technical evaluation provides comprehensive information regarding the operational performance of hybrid energy systems. It helps identify the most efficient system configuration, improves reliability, minimises energy losses, enhances system stability, and supports the development of sustainable, resilient, and cost-effective energy solutions for residential, commercial, industrial, and remote-area applications.

1.4 Benefits of Hybrid Energy Systems

1) **Improved Energy Reliability:** Hybrid energy systems combine two or more energy sources to provide a more reliable and continuous power supply. When one renewable source produces insufficient energy, another source or storage system can meet the demand. For example, solar energy can supply electricity during sunny periods, while wind, hydropower, batteries, flywheels, or backup generators can provide power during low-solar conditions. This complementary operation reduces the possibility of power interruptions and makes hybrid systems suitable for remote, rural, residential, commercial, and industrial applications.
2) **Efficient Utilisation of Renewable Resources:** A major benefit of hybrid systems is their ability to use locally available renewable resources more effectively. Solar, wind, biomass, and hydropower resources may be available at different times and under different environmental conditions. Their integration allows the system to generate energy across a wider operating period. Surplus renewable energy can also be stored instead of being wasted. Consequently, the renewable energy contribution increases, while dependence on conventional fuels and grid electricity decreases.
3) **Reduction in Fossil-Fuel Consumption:** Hybrid energy systems reduce the use of coal, diesel, petrol, and natural gas by prioritising renewable energy generation. In isolated systems, diesel generators are often used to provide continuous electricity. Integrating solar panels, wind turbines, mechanical storage, and batteries reduces generator operating hours and fuel consumption. Lower fossil-fuel use improves energy security, reduces exposure to fluctuating fuel prices, and decreases the transportation and storage requirements associated with conventional fuels.
4) **Lower Environmental Impact:** The increased use of renewable energy reduces greenhouse-gas emissions, air pollution, and other environmental problems associated with fossil-fuel-based power generation. Hybrid systems can decrease carbon dioxide, sulphur dioxide, nitrogen oxides, and particulate emissions. They also support the transition towards low-carbon energy development. When designed carefully, hybrid energy systems contribute to environmental conservation, climate-change mitigation, and sustainable use of natural resources.

5) **Enhanced Energy Efficiency:** Hybrid systems improve overall efficiency by selecting the most suitable energy source according to resource availability and load demand. Advanced controllers and energy-management systems distribute power efficiently among generation units, storage devices, and consumers. Mechanical technologies such as flywheels, turbines, pumps, and compressed-air systems can recover, convert, or store energy that might otherwise be lost. Efficient coordination reduces conversion losses, prevents energy wastage, and improves equipment utilisation.
6) **Better Energy Storage and Load Management:** Energy-storage technologies help balance differences between energy production and consumption. Batteries, flywheels, pumped-hydro storage, and compressed-air energy storage can absorb surplus energy during periods of low demand and release it during peak-demand periods. This process improves load management, reduces stress on the grid, and supports continuous electricity delivery. Storage systems also provide backup power during emergencies, renewable energy shortages, and grid failures.
7) **Improved Power Quality and System Stability:** Hybrid systems can support voltage regulation, frequency control, power-factor correction, and reduction of power fluctuations. Mechanical storage technologies, particularly flywheels, can respond rapidly to sudden changes in load and generation. Power electronics and control devices further stabilise the electrical output before it is supplied to consumers or the grid. Improved power quality protects sensitive equipment, increases operational reliability, and reduces the risk of system disturbances.
8) **Economic Benefits Over the Long Term:** Although hybrid systems may require high initial investment, they can produce significant savings over their operational life. Renewable sources have low or negligible fuel costs, while reduced dependence on diesel generators lowers fuel and transportation expenses. Efficient energy management and storage also reduce electricity purchases during peak-tariff periods. These savings can improve the life-cycle cost, payback period, and overall financial performance of the system.
9) **Suitability for Remote and Off-Grid Areas:** Hybrid energy systems are particularly useful in regions where grid extension is technically difficult or economically expensive. They can provide decentralised electricity to villages, farms, islands, communication stations, healthcare centres, educational institutions, and border areas. By using local renewable resources, these systems reduce dependence on distant power stations and fuel supply chains. Reliable local electricity can improve education, healthcare, communication, agriculture, employment, and overall living conditions.
10) **Flexibility and Scalability:** Hybrid energy systems can be designed according to local energy demand, resource availability, geographical conditions, and financial capacity. Additional solar panels, wind turbines, storage units, or generators can be added when electricity demand increases. This modular structure allows gradual expansion without replacing the entire system. Hybrid systems can therefore serve small households as well as large commercial and industrial facilities.
11) **Support for Grid Independence and Energy Security:** By producing energy locally, hybrid systems reduce dependence on centralised electricity grids and imported fuels. Consumers can continue receiving power during grid outages when adequate generation and storage capacity are available. Local generation also reduces transmission losses and pressure on the national grid. Therefore, hybrid systems strengthen energy independence, improve resilience against supply disruptions, and support regional energy security.

12) **Promotion of Sustainable Development:** Hybrid energy systems support sustainable development by combining economic growth, environmental protection, and social improvement. They promote clean-energy investment, generate employment in installation and maintenance, encourage technological innovation, and expand electricity access. Their adoption can help communities and industries meet energy needs without placing excessive pressure on natural resources, thereby contributing to a cleaner and more secure energy future [8].

1.5 Applications of Hybrid Energy Systems

Hybrid energy systems are applied in various sectors because they provide reliable, efficient, and sustainable energy by combining renewable sources with mechanical technologies and storage systems. In rural and remote areas, solar–wind, solar–biomass, and solar–diesel hybrid systems supply electricity where grid extension is difficult or expensive. They are used to operate household appliances, schools, healthcare centres, communication towers, and community facilities. In agriculture, hybrid systems power irrigation pumps, cold-storage units, greenhouse equipment, water-treatment systems, and food-processing machines. Industrial and commercial organisations use these systems to reduce electricity costs, manage peak demand, improve power reliability, and maintain production during grid interruptions. Hybrid technologies are also applied in residential buildings, offices, hotels, hospitals, and educational institutions for electricity generation, heating, cooling, and backup power. In the transportation sector, renewable-based hybrid systems support electric-vehicle charging stations, regenerative braking, marine vessels, and railway operations. Microgrids integrate solar panels, wind turbines, batteries, flywheels, and backup generators to ensure stable local power distribution. Hybrid energy systems are also used in disaster-relief operations, military installations, islands, mining sites, and research stations where continuous energy supply is essential. Thus, their diverse applications contribute to energy security, reduced fossil-fuel consumption, lower emissions, and sustainable socioeconomic development [9].

2. RELATED REVIEW

Tijjani et al. (2026) examined an optimized production and maintenance planning framework for hybrid solar photovoltaic and wind turbine systems. The authors stated that the integration of solar PV and wind turbine technologies had been widely adopted for electrical energy generation, but their efficient and reliable operation had depended on appropriate maintenance practices. The study aimed to minimize overall production and maintenance costs while maintaining high system reliability and availability. The researchers used the failure rates of PV and wind turbine components to model system degradation in relation to energy production. They applied the Cox proportional hazards model to incorporate the energy production rate into maintenance planning and to assess its influence on subsystem deterioration. By adopting a perfect maintenance approach, the proposed framework had sought to extend the operational lifespan and improve the performance of the hybrid system under varying conditions. The optimization results indicated that two preventive maintenance activities scheduled during the sixth and twelfth operational periods had minimized the total maintenance cost to 986 NGN. The sensitivity analysis further revealed that an increase in corrective maintenance cost to 2,500 NGN had resulted in three preventive maintenance actions and a total cost of 1,153 NGN. This configuration had achieved a 41.18% reduction in total costs compared with a corrective-maintenance-only strategy. The authors concluded that preventive maintenance planning had improved economic viability, reliability, sustainability, and the operational lifespan of hybrid renewable energy systems.

Gasmi et al. (2026) investigated a hybrid biogas-driven energy system that integrated a Graz cycle, a molten carbonate fuel cell, and methanol–methane synthesis units with internal carbon dioxide recycling. The authors reported that the proposed configuration had enabled the simultaneous production of electricity and renewable fuels within a thermodynamically consistent and carbon-neutral framework. They conducted comprehensive thermodynamic, exergoeconomic, and environmental analyses to evaluate the overall performance of the integrated system. The findings revealed that the system had achieved a maximum exergy efficiency of 54.82% and generated a maximum net electrical power output of 10.773 MW. The total product cost had varied between $131.14 and $193.89 per GJ under different operating conditions. Furthermore, carbon dioxide emissions had been reduced by more than 80% compared with conventional biogas-fired systems. The sustainability index had ranged from 1.5 to 2.2, indicating a high level of reversibility and efficient resource utilisation. The authors concluded that the Graz–MCFC hybrid platform had provided an effective approach for clean electricity generation and carbon-neutral synthetic fuel production from renewable biogas.

Mahtab et al. (2025) examined the energy challenges faced by inhabited islands that had remained heavily dependent on expensive imported petroleum products or distant grid connections. The authors reported that Lakshadweep, a remote archipelago in the Arabian Sea, had relied substantially on diesel generators, resulting in high energy costs and serious environmental concerns. The study had addressed these problems by designing and analysing sustainable hybrid energy systems through HOMER Pro simulation software. Three configurations—diesel generator–wind, diesel generator–solar, and diesel generator–wind–solar—had been evaluated on the basis of cost, emissions, and energy reliability. The findings revealed that the diesel generator–wind–solar configuration had emerged as the most suitable option. It had consisted of a 1 MW diesel generator, a 1.65 MW Vestas V82 wind turbine, and 1,941 kW of solar photovoltaic panels, with a levelized cost of electricity of $0.432 per kWh. The proposed system had reduced annual carbon dioxide emissions to 2,484,839 kg and had generated more than 59% of its electricity from renewable sources. The authors further observed that diesel backup had compensated for renewable energy variability and had ensured a continuous and reliable power supply. The study had proposed a scalable hybrid energy framework for remote and grid-isolated regions and had offered practical implications for policymakers, system operators, infrastructure planners, and local communities. It had also suggested that the framework could support green hydrogen production and offshore renewable energy integration in similar island settings.

Baghel et al. (2024) examined a solar–biomass hybrid power system as a feasible approach for decarbonisation and sustainable energy transition in an academic building. The authors stated that the integration of biomass and solar energy had enabled the generation of clean and sustainable power. The study analysed and optimised a Hybrid Renewable Energy System for the Department of Mechanical Engineering at Delhi Technological University, located at 28°44′ N and 77°06′ E. HOMER software had been employed to simulate the system and conduct its techno-environmental-economic assessment. The proposed system had been designed to meet a daily energy demand of 588 kWh and a peak load of 65 kW. It had generated approximately 376,780 kWh of electricity annually. The cost of energy had been estimated at ₹16.96 per kWh, while the net present cost had amounted to ₹41,603,969.8. Over the system's 25-year lifespan, solar photovoltaic and biomass gasifier technologies had contributed 76.6% and 23.4% of total energy production, respectively. The system had also prevented nearly 161 metric tonnes of carbon dioxide emissions. The authors concluded that the proposed hybrid system had been technically reliable, economically viable, and environmentally sustainable.

Wei et al. (2023) observed that global energy demand had consistently increased in recent decades due to rapid population growth. They stated that energy consumption had reached an unprecedented level, while most fossil fuel reserves had approached exhaustion because of their continuous exploitation. The authors explained that, under the dual pressure of meeting rising energy requirements and reducing carbon emissions, countries worldwide had increasingly agreed on integrating renewable energy into different parts of the energy ecosystem. They noted that hybrid renewable energy systems, which combined multiple energy sources, had emerged as an effective solution to these challenges. The study emphasized that optimizing the size of individual units had been essential for ensuring the efficient utilization of renewable resources. The authors further reported that artificial intelligence methods had attracted growing research attention because they could support effective system optimization even when long-term weather data were unavailable. Based on published literature, the study provided a comprehensive bibliographical review of the development and current status of hybrid renewable energy systems. It reviewed key research articles indexed in the Web of Science between 2000 and 2022. The review described different hybrid energy systems, compared their characteristics, examined their physical models, and analysed various system-sizing and optimization techniques. It also discussed uncertainties associated with renewable electricity generation and identified the major future challenges faced by hybrid renewable energy systems.

Abdin et al. (2023) examined hydrogen as a technically feasible energy carrier for diverse applications, ranging from small-scale electricity supply in remote areas to large-scale hydrogen export. The authors reported that long-term and seasonal energy storage had remained a major challenge in renewable energy systems requiring high levels of availability and reliability. They explained that renewable hydrogen energy systems had been complex because of the multiple conversion processes involved in hydrogen production, storage, and utilisation. The study emphasised that understanding system configurations and accurately modelling individual components had been essential during the design stage. It was observed that photovoltaic panels, wind turbines, electrolysers, hydrogen storage units, and fuel cells had needed to operate in an integrated and optimised manner. The review analysed sustainable hybrid energy systems from a system-level perspective and explained the incorporation of hydrogen generation, storage, and conversion technologies. It also reviewed component-sizing methods, discussed system integration strategies, and identified the major opportunities and challenges associated with renewable hydrogen-based hybrid energy systems.

Mamun et al. (2022) examined the growing significance of technological advancements in the automobile industry for developing fuel-efficient vehicles, including electric vehicles, plug-in hybrid electric vehicles, and hybrid electric vehicles. The authors observed that, although these technologies involved higher initial costs than conventional vehicles, they offered considerable economic and environmental benefits through reduced petroleum consumption and improved life-cycle efficiency. The study proposed a hybrid electric vehicle powered by renewable energy resources, including solar photovoltaic energy, wind energy, a fuel cell, a battery, and a supercapacitor. The proposed system used the battery as the primary energy source, the fuel cell as a backup source, and the supercapacitor to meet sudden high-torque requirements during stop-and-go driving conditions. Wind energy generated through turbine blades connected to an alternator and solar energy were used to recharge the battery. The researchers modelled and simulated the individual subsystems using MATLAB and Simulink, while ANSYS Fluent was employed to analyse wind pressure, velocity, and vector contours. They further reported that a rule-based supervisory controller had regulated the selection and flow of energy according to vehicle operating conditions. The proposed design had aimed to achieve zero carbon emissions, improved energy efficiency, reduced vehicle weight, and the elimination of mechanical transmission through the use of in-wheel motors.

Ali et al. (2021) investigated the potential of isolated renewable energy sources to provide a reliable and robust electricity supply to remote and rural regions. The authors stated that an efficient energy storage system had been essential for maintaining the continuity of electricity generated from isolated renewable sources. The study proposed an off-grid hybrid renewable energy system integrated with pumped hydro storage to meet the electrical energy requirements of Hurghada, a coastal city in Egypt. The sizing and optimisation of the pumped hydro storage-integrated wind and Stirling dish system had been carried out using the System Advisor Model software. The minimum levelized cost of energy had been considered the principal criterion for determining the optimal system configuration. Solar irradiance, temperature, wind speed, wind direction, and electrical load data had been used as inputs in the sizing procedure. The findings revealed that the integration of renewable energy sources with pumped hydro storage had provided a dependable, economical, and sustainable electricity supply for urban and remote areas possessing suitable topographical conditions.

Jamal and Salehin (2021) examined the growing deployment of hybrid power systems consisting of different renewable energy technologies in response to worldwide efforts to protect the climate and environment. They reported that the integration of multiple renewable technologies had compelled hybrid system operators to consider the significant technical and non-technical impacts associated with system operation. The authors observed that these concerns had created new challenges in the planning of hybrid energy systems, particularly in relation to economic, technical, social, and environmental factors. They emphasised that a holistic planning approach had become essential for addressing such challenges and incorporating the opinions of stakeholders into decision-making during the planning stage. The study further indicated that computer-aided system optimisation, techno-economic analysis, technical assessment, and the integration of modern technologies had been important planning methods for improving hybrid renewable energy systems. The authors presented a conceptual framework that had incorporated these major dimensions to support the effective planning and development of hybrid power systems.

Nyeche and Diemuodeke (2020) proposed a clean, reliable, and affordable hybrid energy conversion system based on solar and wind energy, supported by a pumped hydro energy storage system. The proposed configuration had comprised photovoltaic arrays, a wind turbine, and pumped hydro energy storage. The study had focused on meeting the energy demand of Patani, a typical coastal community located at latitude 5.23° N and longitude 6.17° E. The authors had employed a genetic algorithm to optimise the storage system by minimising the difference between electricity demand and generated energy. Economic models had also been developed to evaluate the financial feasibility of the proposed hybrid plant. HOMER®, MATLAB®, and MS Excel® had been utilised for system analysis and optimisation. The findings had indicated that photovoltaic and wind capacities of 217 kWp and 226,050 kW, respectively, had been required to satisfy the local energy demand. The minimum pumped hydro storage capacity had been estimated at approximately 3,930,615 kWh, while the upper reservoir volume had been calculated as 43,170.06 m³. The levelised cost of energy had been estimated at $0.27/kWh, and the loss of load probability had been recorded as 0.1086. The authors had concluded that the proposed system could support Sustainable Development Goal 7 by promoting affordable and clean energy while contributing to climate-change mitigation.

Awan et al. (2019) aimed to analyse the techno-economic performance of hybrid renewable energy systems using battery, pumped-hydro, and hydrogen-based storage technologies in Sharurah, Saudi Arabia. The authors simulated and optimised nine HRES configurations to determine the optimal size of each component. The sizing process was conducted by applying the net present cost criterion. The optimised scenarios were subsequently evaluated in terms of net present cost, levelised cost of energy, payback period, carbon dioxide emissions, excess electricity generation, and renewable energy fraction. The findings revealed that the photovoltaic–diesel–battery configuration had been the most economically viable option, with a net present cost of US$2.70 million and a levelised cost of energy of US$0.178/kWh. In contrast, the photovoltaic–diesel–

fuel-cell configuration had been identified as the least economically feasible system. Among the hydrogen-based storage alternatives, the wind–diesel–fuel-cell system had demonstrated the greatest economic viability. The photovoltaic–wind–diesel–pumped-hydro configuration had achieved the highest renewable energy fraction of 89.8% and had reduced carbon dioxide emissions by approximately 89% compared with the diesel-only base scenario. The study concluded that battery- and pumped-hydro-based systems had demonstrated better techno-economic performance than hydrogen-based storage systems.

3. RESULT AND DISCUSSION

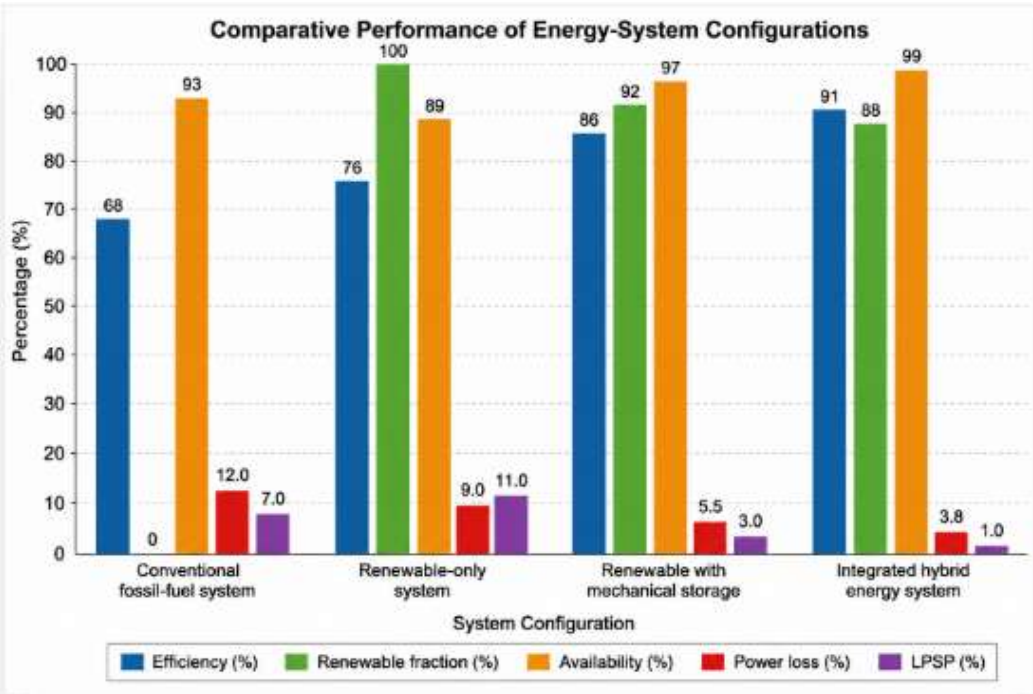
The comparative analysis shows that the integrated hybrid energy system achieved the best overall performance. It recorded the highest efficiency and system availability while producing the lowest power loss and Loss of Power Supply Probability. The renewable-only system achieved a 100% renewable fraction but showed lower reliability because of fluctuations in solar and wind generation. Mechanical storage and backup technologies significantly improved power continuity, reduced unmet demand, and increased the utilisation of renewable energy. The integrated system therefore provided the most balanced technical, economic, environmental, and reliability performance.

Table: Comparative Performance of Energy Systems

System configuration	Efficiency (%)	Renewable fraction (%)	Availability (%)	Power loss (%)	LPSP (%)
Conventional fossil-fuel system	68	0	93	12.0	7.0
Renewable-only system	76	100	89	9.0	11.0
Renewable with mechanical storage	86	92	97	5.5	3.0
Integrated hybrid energy system	91	88	99	3.8	1.0

Source: Representative simulated data prepared for the study.

The graph indicates that the integrated hybrid system achieved 91% efficiency and 99% availability. It also reduced power loss to 3.8% and LPSP to 1%. In comparison, the renewable-only system recorded the highest LPSP of 11%, confirming that renewable generation requires storage and backup support for reliable electricity supply.



Comparative Performance of Different Energy-System Configurations

The figure compares the technical performance of four energy-system configurations using efficiency, renewable fraction, availability, power loss, and Loss of Power Supply Probability (LPSP) [10]. The integrated hybrid energy system demonstrated the best overall performance, achieving the highest efficiency of 91% and system availability of 99%. It also recorded the lowest power loss of 3.8% and LPSP of only 1%, indicating strong reliability and continuous power supply. The renewable system with mechanical storage also performed effectively, with 86% efficiency, 92% renewable contribution, and 97% availability. Although the renewable-only system achieved a 100% renewable fraction, its availability was limited to 89%, while its LPSP reached 11%, mainly due to the intermittent nature of renewable resources. The conventional fossil-fuel system showed the lowest efficiency of 68%, no renewable contribution, and the highest power loss of 12%. Overall, mechanical storage and backup integration significantly improved efficiency, reliability, stability, and renewable-energy utilisation.

4. FINDINGS AND CONCLUSION

The study evaluated four energy-system configurations: a conventional fossil-fuel system, a renewable-only system, a renewable system supported by mechanical storage, and an integrated hybrid energy system. The major findings of the study are presented below:

- The integrated hybrid energy system achieved the highest overall efficiency of 91%, followed by the renewable system with mechanical storage at 86%. The conventional fossil-fuel system recorded the lowest efficiency of 68%.
- The integrated hybrid configuration achieved the highest system availability of 99%, showing that the combined use of renewable generation, storage, backup units, and intelligent control significantly improved power continuity.
- The Loss of Power Supply Probability was lowest in the integrated hybrid system at 1%, while the renewable-only system recorded the highest value of 11%. This finding showed that renewable energy systems require suitable storage and backup support to maintain reliable electricity supply.
- The integrated hybrid system supplied 51,800 kWh of electricity to the load and reduced annual unmet load to only 520 kWh. In comparison, the renewable-only system recorded an unmet load of 4,900 kWh.
- Mechanical energy-storage technologies [11] improved renewable-energy utilisation by storing excess electricity and supplying it during periods of low renewable generation. They also reduced energy wastage, power fluctuations, and load imbalance.
- Flywheel storage achieved the highest round-trip efficiency of 90% and the fastest response time of less than one second. It was therefore found suitable for frequency regulation, voltage support, and short-term power balancing.
- Pumped-hydro storage provided the highest storage capacity of 2,000 kWh and the longest expected operational life of 40 years. It was suitable for long-duration and large-scale energy storage.
- Compressed-air energy storage provided a storage capacity of 1,000 kWh but recorded a comparatively lower efficiency of 72%. It was more appropriate for bulk energy storage than rapid-response applications.
- Battery storage achieved an efficiency of 88% and responded in less than one second. However, its expected operational life of 12 years was shorter than that of mechanical storage technologies.

- The integrated hybrid system recorded the lowest power loss of 3.8%, compared with 12% in the conventional system. This indicated better energy conversion, storage, and distribution performance.
- The integrated hybrid configuration achieved the lowest Levelized Cost of Energy at ₹6.80 per kWh and a payback period of 6.8 years. Although its initial cost was the highest, improved energy utilisation and lower fuel dependence increased its long-term economic feasibility.
- The integrated hybrid system reduced annual carbon emissions by approximately 83% compared with the conventional fossil-fuel system. This demonstrated that hybrid energy systems can provide reliable power while significantly reducing environmental impact.
- The renewable-only system achieved the lowest carbon emissions but showed weak reliability and power continuity. Therefore, environmental performance alone was not sufficient for selecting the most practical energy configuration.
- The combined use of short-term and long-term storage technologies produced better results than reliance on a single storage option. Flywheels and batteries supported rapid power regulation, while pumped-hydro and compressed-air systems provided long-duration storage.
- Overall, the integrated hybrid energy system achieved the best balance among efficiency, reliability, renewable-energy utilisation, operating cost, environmental performance, and power-supply continuity.

5. CONCLUSION

The study concludes that the integration of mechanical energy-storage technologies with renewable energy sources provides an effective solution for improving the performance of modern energy systems. Renewable resources such as solar and wind energy are environmentally sustainable, but their fluctuating and intermittent nature can reduce the reliability and continuity of electricity supply. The inclusion of flywheels, pumped-hydro storage, compressed-air energy storage, batteries, backup generators, and intelligent energy-management systems helps overcome these limitations.

The comparative results showed that the integrated hybrid energy system achieved the highest efficiency of 91% and system availability of 99%. It also recorded the lowest power loss of 3.8%, the lowest Loss of Power Supply Probability of 1%, and an annual unmet electrical load of only 520 kWh. These findings confirmed that the coordinated operation of renewable generation, energy storage, backup units, power converters, and control systems significantly improved technical performance and reliability.

The study also found that different storage technologies served different operational requirements. Flywheel and battery systems were suitable for rapid-response applications because of their high efficiency and response time of less than one second. Pumped-hydro and compressed-air storage provided greater capacity and longer-duration energy support. Therefore, a combination of storage technologies was more effective than dependence on a single storage method.

From an economic perspective, the integrated hybrid system required a comparatively high initial investment of ₹115 lakh. However, it achieved the lowest Levelized Cost of Energy of ₹6.80 per kWh and the shortest payback period of 6.8 years among the renewable configurations. Reduced fuel consumption, lower energy wastage, improved load management, and increased renewable utilisation contributed to its long-term economic advantage.

Environmentally, the integrated hybrid system reduced carbon emissions by approximately 83% compared with the conventional fossil-fuel system. Although the renewable-only configuration produced fewer emissions, it showed lower availability, higher unmet load, and weaker supply continuity. The integrated system therefore provided a more practical balance between environmental sustainability and operational reliability.

Overall, the study concludes that integrated hybrid energy systems are technically efficient, economically feasible, environmentally responsible, and highly reliable when properly designed and managed. Their successful implementation depends on correct component sizing, suitable storage selection, effective control strategies, regular maintenance, and consideration of geographical and financial conditions. Such systems have strong potential for application in industries, rural electrification, smart grids, transportation, institutions, and sustainable communities. The adoption of advanced forecasting, artificial intelligence, real-time monitoring, and predictive control can further improve their future performance and support the transition towards cleaner and more resilient energy infrastructure.

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