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A Study of Hybrid Renewable Energy Systems Integrated with Mechanical Energy Storage Technologies for Sustainable Power

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ABSTRACT

The increasing demand for reliable, efficient, and environmentally sustainable energy has encouraged the development of hybrid energy systems that combine renewable energy sources with mechanical energy technologies. This study evaluates hybrid energy systems integrating solar, wind, hydropower, biomass, and geothermal resources with mechanical technologies such as flywheel energy storage, pumped-hydro storage, compressed-air energy storage, turbines, generators, and kinetic-energy recovery systems. The study focuses on the technical, economic, environmental, and operational performance of these integrated systems. Major evaluation parameters include system efficiency, energy-storage capacity, response time, power quality, reliability, operating cost, maintenance requirements, greenhouse-gas emissions, and overall system stability. The study also examines the role of energy-management systems, sensors, power-conversion devices, and advanced control technologies in coordinating generation, storage, and electricity demand. The analysis indicates that mechanical storage technologies can reduce renewable-energy fluctuations, improve frequency and voltage stability, store surplus electricity, and maintain power supply during periods of low renewable generation. Hybrid energy systems also have the potential to reduce dependence on fossil fuels, minimise emissions, improve energy security, and support rural and remote-area electrification. However, high initial investment, complex system design, geographical limitations, conversion losses, maintenance requirements, and component-sizing difficulties remain important challenges. The study concludes that properly designed hybrid energy systems can provide a flexible, reliable, and sustainable solution for future energy requirements.

Keywords: *Hybrid Energy Systems, Renewable Energy, Mechanical Energy Storage, Sustainable Power*.

1. INTRODUCTION

The increasing demand for reliable, efficient, and environmentally sustainable energy has encouraged the development of hybrid energy systems that combine mechanical technologies with renewable energy sources. Traditional energy systems based mainly on fossil fuels have contributed significantly to greenhouse gas emissions, environmental degradation, and the depletion of natural resources. As a result, renewable energy sources such as solar, wind, hydropower, biomass, and geothermal energy have become important alternatives for meeting future energy needs. However, renewable energy generation is often intermittent and dependent on climatic and geographical conditions. Solar energy production varies with sunlight intensity, while wind power depends on changing wind speed and weather patterns. These variations can affect power quality, system stability, and the continuous supply of electricity. Hybrid energy systems provide an effective solution by integrating different energy resources and technologies so that the limitations of one component can be compensated for by the strengths of another. Mechanical energy technologies, including flywheel energy storage, pumped-hydro storage [1], compressed-air energy storage, turbines, mechanical transmission systems, and kinetic energy recovery systems, can play a major role in improving the performance of renewable energy systems. These technologies can store excess energy, regulate power output, support frequency control, and provide energy during periods when renewable resources are unavailable. For example, a wind energy system may be combined with a flywheel to reduce short-term fluctuations and improve power stability. Similarly, solar power can be integrated with pumped-hydro or compressed-air storage to store excess electricity generated during peak sunlight hours and release it when demand increases or solar radiation decreases. The integration of mechanical and renewable energy technologies can therefore improve energy efficiency, reliability, flexibility, and operational continuity. Evaluating such hybrid systems requires a comprehensive assessment of their technical, economic, environmental, and operational performance. Technical evaluation involves examining energy conversion efficiency, storage capacity, response time, reliability, power quality, system losses, and equipment lifespan. Economic evaluation includes capital investment, operation and maintenance costs, replacement expenses, payback period, and the overall cost of generated energy. Environmental evaluation considers greenhouse gas reduction, land use, resource consumption, noise, waste generation, and ecological effects [2]. Operational assessment focuses on energy management, system control, load variation, component coordination, and interaction with the electrical grid. Advanced technologies such as artificial intelligence, machine learning, predictive control, and real-time monitoring can further improve the operation of hybrid energy systems by forecasting energy demand, predicting renewable generation, optimising storage use, and detecting system faults. Despite their benefits, these systems also face challenges such as high initial costs, complex design, energy losses during conversion, maintenance requirements, geographical limitations, and difficulties in selecting the appropriate size and combination of components. Therefore, a systematic evaluation is necessary to determine the most suitable hybrid configuration for specific applications. The study of hybrid energy systems integrating mechanical and renewable technologies is important for developing cleaner, more stable, and cost-effective energy solutions for industries, transportation, rural electrification, smart grids, and future sustainable communities [3].

1.1 Background and Need for Sustainable Energy Systems

Energy is one of the most essential requirements for economic development, industrial growth, transportation, agriculture, communication, healthcare, education, and the daily functioning of modern society. The rapid growth of the world population, increasing urbanisation, expansion of industries, technological advancement, and rising living standards have resulted in a continuous increase in global energy consumption. Traditionally, this growing demand has been met mainly through conventional energy resources such as coal, petroleum, and natural gas. Although these fossil fuels have supported economic and industrial development for many decades, their excessive use has created serious environmental, economic, and social problems. Fossil fuels are finite resources that cannot be replenished within a short period, and their reserves are gradually declining. Their extraction, transportation, processing, and combustion also contribute to air pollution [4], water contamination, land degradation, greenhouse-gas emissions, and climate change. The conventional energy sector is one of the major contributors to carbon dioxide and other harmful emissions. The burning of coal and petroleum products releases pollutants such as sulphur dioxide, nitrogen oxides, particulate matter, and carbon monoxide into the atmosphere. These pollutants negatively affect human health, reduce air quality, damage ecosystems, and increase the risk of respiratory and cardiovascular diseases. Greenhouse-gas emissions also contribute to rising global temperatures, irregular rainfall, melting glaciers, sea-level rise, droughts, floods, and extreme weather events. Therefore, continued dependence on fossil fuels is environmentally unsustainable and presents a serious threat to present and future generations.

The unequal distribution of conventional energy resources creates additional challenges related to energy security. Many countries depend heavily on imported oil, natural gas, or coal to meet their domestic energy requirements. Changes in international fuel prices, political conflicts, transportation disruptions, and supply shortages can affect national economies and the reliability of energy supply. Rural and remote areas may also remain without adequate electricity because the expansion of conventional power grids is expensive and technically difficult. These conditions highlight the need for decentralised, affordable, reliable, and locally available energy solutions. Sustainable energy systems have emerged as an important response to these challenges. A sustainable energy system meets present energy requirements without reducing the ability of future generations to meet their own needs. It promotes the efficient use of natural resources, reduces environmental damage, ensures long-term energy availability, and supports social and economic development. Renewable resources such as solar, wind, hydropower, biomass, geothermal, tidal, and wave energy are central to sustainable energy development because they are naturally replenished and generally produce fewer emissions than fossil fuels. However, the variable and intermittent nature of renewable energy creates difficulties in maintaining a continuous balance between generation and demand. Solar energy is unavailable at night and varies with weather conditions, while wind power depends on changing wind speed. Therefore, renewable technologies must be supported by suitable energy storage, control, and backup systems [5]. Hybrid energy systems offer an effective solution by integrating multiple renewable sources with mechanical, electrical, thermal, or electrochemical technologies. Mechanical technologies such as flywheels, pumped-hydro storage, compressed-air storage, turbines, and kinetic-energy recovery systems can store surplus renewable energy and supply it when generation is insufficient. Consequently, the development of sustainable hybrid energy systems is essential for improving energy efficiency, reliability, affordability, environmental protection, and long-term energy security.

1.2 Concept and Components of Hybrid Energy Systems

A hybrid energy system refers to an integrated energy arrangement that combines two or more energy-generation, conversion, or storage technologies to provide a reliable, efficient, and continuous supply of power. The main purpose of such a system is to use the complementary characteristics of different energy sources. Renewable sources such as solar, wind, hydropower, biomass, and geothermal energy are environmentally friendly, but their output may vary according to weather and geographical conditions. Mechanical storage and backup technologies can maintain power availability when renewable generation is insufficient. By coordinating different resources, a hybrid energy system can improve energy security, reduce dependence on fossil fuels, minimise greenhouse-gas emissions, stabilise power output, and enhance overall operational performance. These systems can be connected to the electrical grid or operated independently in remote areas. Their effectiveness depends on proper component selection, system sizing, energy management, and control strategies [6].

Major Components of a Hybrid Energy System

- **Renewable Energy Generation Units:** Renewable energy generation units produce electricity from naturally replenished resources. These units may include solar photovoltaic panels, wind turbines, small hydropower plants, biomass systems, and geothermal technologies. They reduce dependence on conventional fossil fuels and support environmentally sustainable power generation. Their output may vary according to weather, location, and resource availability.

- **Mechanical Energy Technologies:** Mechanical energy technologies support the conversion, transmission, and storage of energy within the hybrid system. They include flywheels, turbines, pumped-hydro storage, compressed-air energy storage, generators, gears, and kinetic energy recovery devices. These technologies can respond quickly to changes in power demand and generation. They also help improve the stability, flexibility, and efficiency of the overall system.
- **Energy-Storage Systems:** Energy-storage systems store excess energy produced when renewable generation is higher than demand. The stored energy is released during low generation, peak demand, or power interruptions. Common storage options include batteries, flywheels, hydrogen systems, pumped-hydro storage, and compressed-air storage. These systems improve reliability and ensure a more continuous and balanced supply of electricity.
- **Power-Conversion Devices:** Power-conversion devices regulate and convert electricity into the form required by various components and loads. Inverters convert direct current into alternating current, while rectifiers perform the reverse process. Converters and transformers adjust voltage and current levels according to system needs. These devices maintain suitable power quality, frequency, and voltage throughout the hybrid system.
- **Energy-Management and Control System:** The energy-management and control system coordinates the operation of all generation, storage, and distribution components. It continuously monitors renewable output, storage level, load demand, and grid conditions. The system determines when energy should be generated, stored, supplied, or obtained from a backup source. Effective control reduces energy losses, operating costs, and unnecessary dependence on conventional power.
- **Sensors and Communication Devices:** Sensors collect real-time information about voltage, current, temperature, speed, pressure, energy production, and equipment conditions. Communication devices transmit this information to controllers and monitoring systems for analysis. They support fault detection, performance evaluation, remote operation, and preventive maintenance. Accurate sensing and communication are essential for the safe and efficient functioning of hybrid energy systems.
- **Electrical Loads and Backup Supply:** Electrical loads are the appliances, machines, equipment, and processes that consume the energy generated by the system. Their demand may change according to time, application, and operating conditions. A grid connection, diesel generator, or another auxiliary source may be included as a backup supply. The backup source maintains continuity when renewable generation and stored energy are insufficient [7].

1.3 Role of Renewable Energy Technologies

Renewable energy technologies play a central role in hybrid energy systems by providing clean, sustainable, and naturally replenished sources of power. Technologies such as solar photovoltaic panels, wind turbines, small hydropower plants, biomass systems, and geothermal units reduce dependence on fossil fuels and minimise greenhouse-gas emissions. Their integration with mechanical technologies and energy-storage systems helps ensure a more reliable and continuous energy supply. The major roles of renewable energy technologies are explained below:

- **Clean Energy Generation:** Renewable technologies generate electricity with significantly lower emissions than conventional fossil-fuel-based systems. Solar, wind, hydro, and geothermal resources produce energy without continuously releasing harmful pollutants. Their use contributes to cleaner air and a healthier environment. They also support national and international efforts to reduce carbon emissions.

- **Reduction in Fossil-Fuel Dependence:** The use of renewable energy decreases reliance on coal, petroleum, and natural gas. This helps conserve limited fossil-fuel reserves and reduces exposure to changing fuel prices. It also strengthens energy independence by using locally available natural resources. Consequently, countries can reduce fuel imports and improve energy security.
- **Diversification of Energy Sources:** Renewable technologies allow hybrid systems to use multiple energy resources rather than depending on a single source. Solar energy may be available during the day, while wind or hydropower may contribute at different times. This complementary operation improves the continuity of power generation. Energy-source diversification also reduces the risk of complete system failure.
- **Support for Energy Storage:** Renewable units can produce excess energy during periods of high resource availability and low demand. This surplus energy can be stored in batteries, flywheels, pumped-hydro systems, hydrogen units, or compressed-air storage. The stored energy can later be supplied during peak demand or low renewable generation. This arrangement improves the utilisation of renewable resources.
- **Improvement in System Reliability:** Combining different renewable sources with storage and mechanical technologies improves system reliability. When one source becomes unavailable, another source or storage device can continue supplying electricity. Proper coordination reduces power interruptions and output fluctuations. This is particularly important for remote areas and essential services.
- **Reduction in Environmental Impact:** Renewable energy technologies help reduce greenhouse-gas emissions, air pollution, and environmental damage associated with fuel extraction and combustion. They generally consume fewer non-renewable resources during operation. Properly designed renewable systems can support long-term environmental protection. However, their land use and ecological effects must also be carefully managed.
- **Rural and Remote-Area Electrification:** Renewable technologies can provide electricity in areas where extending the central grid is difficult or expensive. Solar panels, small wind turbines, biomass systems, and micro-hydropower plants can operate as local energy sources. When combined with storage, they can offer a stable supply for households, schools, healthcare centres, and small businesses. They therefore support rural development and social welfare.
- **Economic and Sustainable Development:** Renewable energy systems create employment opportunities in manufacturing, installation, operation, maintenance, and research. Their operating costs may remain relatively stable because sunlight, wind, and flowing water do not require fuel purchases. They also encourage technological innovation and local investment. Thus, renewable technologies contribute to environmentally responsible and economically sustainable development [8].

1.4 Integration of Mechanical and Renewable Energy Systems

The integration of mechanical and renewable energy systems refers to the coordinated combination of renewable energy sources with mechanical technologies for energy conversion, storage, transmission, and regulation. Renewable resources such as solar, wind, hydropower, biomass, and geothermal energy provide clean and sustainable power, but their output may fluctuate because of changing weather and environmental conditions. Mechanical technologies such as flywheels, turbines, pumped-hydro storage, compressed-air energy storage, generators, gear systems, and kinetic energy recovery devices help manage these variations and maintain a stable energy supply. For example, excess electricity produced by solar panels or wind turbines can operate pumps that transfer water to an elevated reservoir. When renewable generation becomes insufficient, the stored water can flow through turbines to generate electricity. Similarly, surplus renewable energy can compress air and store it in underground or high-pressure facilities. The compressed air can later be expanded through a turbine to produce power during periods of high demand. Flywheel systems store energy in the form of rotational motion and can release it rapidly to control short-term power fluctuations, voltage variations, and frequency disturbances. Effective integration also requires power-conversion devices and an intelligent energy-management system to coordinate generation, storage, and consumption. Sensors and controllers continuously monitor renewable output, mechanical storage levels, load demand, and grid conditions. Based on this information, the control system determines when energy should be stored, released, supplied directly to loads, or obtained from the grid or a backup unit. Such integration improves the reliability, flexibility, efficiency, and stability of the overall energy system. It also reduces renewable energy wastage, dependence on fossil fuels, operating costs, and greenhouse-gas emissions. However, successful integration depends on appropriate system design, component sizing, control strategies, geographical conditions, maintenance planning, and economic feasibility. Therefore, combining mechanical and renewable energy technologies provides an effective approach to developing sustainable hybrid energy systems for residential, industrial, transportation, rural electrification, and smart-grid applications [9].

1.5 Benefits and Challenges of Hybrid Energy Systems

Hybrid energy systems offer several technical, economic, and environmental benefits by combining renewable energy sources with mechanical storage and conversion technologies. One of their main advantages is improved reliability because the limitations of one energy source can be compensated for by another. For example, when solar or wind power generation decreases, stored energy from flywheels, pumped-hydro systems, compressed-air storage, or batteries can be used to meet electricity demand. These systems also improve energy efficiency by storing excess renewable power that might otherwise be wasted. The integration of multiple technologies helps reduce dependence on fossil fuels, greenhouse-gas emissions, and conventional grid electricity. Hybrid systems can also improve voltage regulation, frequency stability, load management, and overall power quality. They are particularly useful for rural and remote areas where extending the main electricity grid may be technically difficult or economically expensive. Furthermore, the use of locally available renewable resources can strengthen energy security, reduce fuel transportation costs, support local employment, and contribute to sustainable economic development.

Despite these benefits, hybrid energy systems also face several challenges. Their initial installation cost may be high because they require multiple generation units, storage technologies, power-conversion devices, sensors, and advanced control systems. Designing and sizing the components is complex because renewable generation and electricity demand continuously change. Incorrect sizing may cause excessive costs, insufficient power supply, or underutilisation of equipment. Energy losses can also occur during the conversion, storage, and transmission processes. Mechanical technologies such as turbines, pumps, compressors, gears, and flywheels may require regular inspection and maintenance because of wear, friction, vibration, and mechanical stress. Some technologies are also limited by geographical conditions. Pumped-hydro systems require suitable elevation and water availability, while compressed-air storage may need appropriate underground structures. The integration of different technologies further requires compatible communication standards and intelligent energy-management strategies. Skilled personnel are needed for system design, installation, operation, and maintenance. Environmental concerns, including land use, noise, visual impact, water consumption, and effects on local ecosystems, must also be considered. Therefore, careful planning, technical assessment, cost analysis, environmental evaluation, and advanced control are necessary to ensure the successful and sustainable operation of hybrid energy systems [10].

1.6 Significance of the Study

The study of hybrid energy systems integrating mechanical and renewable energy technologies is significant because it contributes to the development of reliable, efficient, and environmentally sustainable energy solutions. Renewable energy sources such as solar, wind, hydropower, biomass, and geothermal energy can reduce dependence on fossil fuels, but their variable nature may create difficulties in maintaining a continuous power supply. Mechanical technologies, including flywheels, turbines, pumped-hydro storage, compressed-air energy storage, and kinetic energy recovery systems, can help regulate, store, and deliver energy when renewable generation becomes insufficient. Therefore, evaluating their combined operation is important for understanding how different technologies can complement one another.

The study is also significant from a technical perspective because it examines system efficiency, reliability, power quality, storage capacity, response time, energy losses, and component compatibility. It can help identify suitable combinations of renewable and mechanical technologies for different applications. From an economic perspective, the study supports the assessment of capital investment, operating cost, maintenance requirements, payback period, and long-term financial feasibility. Such analysis can guide investors, industries, policymakers, and energy planners in selecting cost-effective hybrid configurations. From an environmental perspective, the study highlights the potential of hybrid systems to reduce greenhouse-gas emissions, air pollution, fossil-fuel consumption, and energy wastage. It can also identify possible environmental concerns related to land use, water consumption, noise, and ecological disturbance [11]. The study is particularly useful for rural and remote areas where grid extension may be expensive or technically difficult. Hybrid systems can provide electricity for households, schools, healthcare centres, agricultural activities, and small industries.

Furthermore, the study supports the development of intelligent energy-management and control strategies. It can contribute to better renewable-energy forecasting, storage scheduling, load management, and fault detection. The findings may also assist researchers, engineers, government agencies, and technology developers in improving system design and policy planning. Overall, the study is significant because it promotes energy security, technological innovation, sustainable development, and the transition toward cleaner and more resilient energy systems.

2. RELATED REVIEW

Maryadi and Arifah (2026) addressed the growing need for efficient and sustainable energy systems by developing Hybrid Renewable Energy Systems (HRES) that integrated multiple renewable energy sources with advanced storage technologies. The authors stated that such integration had helped overcome the challenges of intermittency and reliability associated with renewable energy generation. The study employed a quantitative modelling and simulation approach using secondary data related to renewable resources, load demand, and component specifications. Simulation tools, including HOMER Pro and MATLAB, were used to evaluate different system configurations. A multi-objective optimisation framework based on metaheuristic algorithms, particularly Particle Swarm Optimisation and Non-dominated Sorting Genetic Algorithm II, was applied to identify optimal configurations. The findings revealed that hydrogen-based systems had provided the highest reliability and lowest emissions, whereas biomass-based systems had offered lower costs but produced greater environmental impacts. The sensitivity analysis further indicated that fuel prices, load demand, and renewable resource availability had significantly influenced system performance. The authors emphasised the importance of combining diverse storage technologies and adopting comprehensive optimisation approaches that considered techno-economic, environmental, and resilience-related factors. They concluded that the proposed framework had effectively improved HRES design by generating realistic and optimal solutions for sustainable and resilient energy systems.

Dwier and Go (2026) examined the development and optimisation of hybrid energy storage systems in Malaysia in response to the growing challenges of climate change and increasing energy demand. The authors reported that renewable energy sources had become essential and were projected to contribute approximately 63% of the global primary energy supply by 2050, compared with 14% in 2015. They explained that advancements in energy storage technologies had been necessary to address the intermittent nature of renewable energy resources. The study analysed five system scenarios and conducted a sensitivity analysis to identify the most suitable configuration. The findings revealed that the optimal system had comprised a grid-connected solar photovoltaic and hydropower arrangement using SunPower E20-327 panels and a zinc bromide flow battery. This configuration had achieved a renewable fraction of 82.8%, a levelised cost of energy of USD 0.057 per kWh, a return on investment of 4.4%, and a payback period of 12.1 years. The authors further found that the photovoltaic-only system had reduced carbon dioxide emissions by 5,918 kg annually, whereas the optimised photovoltaic-battery system had reduced carbon dioxide, sulphur dioxide, and nitrogen oxide emissions by 6,797 kg, 29.5 kg, and 14.4 kg per year, respectively. The study concluded that hybrid renewable energy and storage systems had been technically, economically, and environmentally feasible for supporting Malaysia's Energy Target 2050.

Başhan et al. (2026) examined the reliability of hybrid renewable energy systems and reported that their dependable operation had largely depended on the effective identification and management of potential failure modes. The authors employed a fuzzy-based BWM–MARCOS approach to systematically analyse and prioritise failures in wind–solar hybrid systems. The study considered four major risk parameters, namely the severity of failure effects on the system and personnel, the probability of failure occurrence, the effort and ease associated with detecting failure causes, and the economic consequences of failure. The findings revealed that SP1, representing cell damage; ESS1, referring to battery degradation; and WT11, indicating battery fire, had emerged as the most critical failure modes because of their serious effects on system performance and operational safety. Sensitivity analysis had confirmed that the rankings remained stable under different parameter weights. Furthermore, validation through fuzzy TOPSIS, SAW, and MARCOS methods had produced high correlation coefficients, thereby supporting the reliability of the results. The authors proposed advanced diagnostic techniques, durable materials, and robust monitoring systems as suitable mitigation measures. They further suggested that future studies should incorporate real-world operational data and machine learning techniques to improve predictive capability and dynamic risk management.

Taghizad-Tavana et al. (2025) reviewed Hybrid Renewable Energy Systems (HRESs) and reported that such systems had emerged as practical solutions for supplying reliable and low-carbon electricity to off-grid and remote communities. The authors systematically compared electrochemical, mechanical, thermal, and hydrogen-based energy storage technologies in terms of their technical performance, lifecycle costs, operational limitations, and environmental impacts. They synthesised evidence from implemented off-grid projects across different countries and assessed real-world indicators such as renewable energy fraction, expected energy not supplied, lifecycle cost, and operation and maintenance requirements. Particular attention was given to hydrogen, which was identified as a promising long-term and cross-sector energy carrier, although its large-scale deployment had remained constrained by technical, regulatory, and financial barriers. The review also examined practical experiences from off-grid HRES projects and highlighted important lessons for system design and policy development. Furthermore, the authors observed that recent metaheuristic optimisation algorithms had improved planning efficiency, reliability, and cost-effectiveness. They concluded that future research would require systematic quantitative analysis, long-term field validation, and the development of AI-driven energy management systems within broader socio-technical and economic frameworks.

Samatar et al. (2025) evaluated the feasibility and performance of a hybrid renewable energy system designed to meet the electricity requirements of Hobyo Seaport in Somalia. The authors reported that integrating renewable energy into electricity generation had enhanced sustainability, reduced greenhouse gas emissions, improved energy security, lowered operational costs, and supported development in remote and underserved regions. The proposed system had incorporated photovoltaic panels, wind turbines, a diesel generator, pumped hydro energy storage, and a battery energy storage system. Four alternative configurations had been analysed using HOMER Pro and MATLAB to optimise system capacity and assess their technical, economic, and environmental performance. The findings revealed that the PV/WT/PHES configuration had emerged as the most efficient option, achieving a 100% renewable energy fraction. It had recorded a net present cost of $619,720, the lowest levelised cost of electricity at $0.03845 per kWh, and a simple payback period of 0.31 years. The system had also reduced approximately 1,029 tonnes of carbon monoxide emissions annually and had generated potential carbon-credit benefits valued at $20,593. Over a 20-year period, the configuration had reduced cumulative cash flow costs by 97.1% compared with a diesel-based system. The authors concluded that the proposed hybrid renewable energy system had provided a cost-effective, sustainable, and environmentally beneficial solution for strengthening energy infrastructure at Somali seaports and similar coastal locations.

Maliat et al. (2024) investigated the critical challenge of developing a robust and sustainable energy infrastructure through the integration of renewable energy sources in Makkovik, Newfoundland and Labrador. The researchers evaluated the technical and economic viability of a hybrid renewable energy system comprising wind turbines, photovoltaic solar panels, battery storage, and backup diesel generators. They reported that HOMER Pro software had been used to model and optimise the proposed system with the objectives of reducing fossil-fuel dependency, lowering carbon emissions, and minimising operational costs. The findings indicated that most of Makkovik’s energy requirements could be fulfilled through the proposed renewable energy configuration. The authors further observed substantial reductions in greenhouse gas emissions and improvements in cost efficiency over the projected lifespan of the system. They concluded that the hybrid system had offered an environmentally sustainable and technically feasible solution for improving energy resilience in isolated communities. The study also highlighted that the integration of multiple renewable energy sources had created significant opportunities for emission reduction, operational cost savings, and long-term energy security in remote regions.

Pawar et al. (2024) stated that the transition towards renewable energy sources had been essential for addressing the challenges posed by climate change and the depletion of fossil fuel reserves. The authors explained that renewable energy hybridisation, which involved combining multiple renewable energy sources with energy storage technologies, had offered a promising approach for improving the efficiency, reliability, and sustainability of power-generation systems. The study comprehensively reviewed integration strategies for hybrid renewable energy systems, with particular emphasis on the combined use of solar, wind, hydro, biomass, and other renewable sources alongside suitable energy-storage solutions.

It further examined various technological, economic, and regulatory integration approaches to identify the critical factors that had influenced the successful deployment of such systems. Through case studies and real-world examples, the authors illustrated the major advantages and challenges associated with different integration strategies. The study concluded by recommending that policymakers, researchers, and industry stakeholders should strengthen their coordinated efforts to accelerate renewable energy hybridisation and support the development of a more sustainable energy future.

Dash et al. (2023) conducted a comprehensive analysis of the energy, economic, and environmental performance of different battery and mechanical energy-storage systems under various dispatch strategies. The study evaluated lead-acid batteries, lithium-ion batteries, vanadium redox-flow batteries, flywheels, and pumped-hydro storage by applying cycle-charging, load-following, and generator-order strategies. The authors used HOMER Pro software to examine the feasibility of hybrid power generation in the Andaman and Nicobar Islands, which were not connected to the main electricity grid. The study uniquely incorporated tidal power, wind turbines, and bio-diesel generators with different storage technologies and dispatch strategies in the Indian context. The findings revealed that lithium-ion batteries had performed better than lead-acid batteries and mechanical storage systems. The wind, bio-diesel generator, tidal, and lithium-ion battery configuration under the cycle-charging strategy had recorded the lowest net present cost and cost of energy at $1.30 million and $0.263, respectively. The authors further reported that lithium-ion batteries had required only 250 units, which was approximately 46% fewer than the lead-acid batteries needed to meet the same load. Lithium-ion batteries had also demonstrated superior performance in terms of lifespan, energy losses, energy production, and state of charge. Furthermore, SWOT and sensitivity analyses had been conducted by considering fuel prices and wind speed. Various techno-economic and environmental indicators, including renewable fraction, return on investment, payback period, internal rate of return, cash flow, electrical performance, and pollutant emissions, had also been compared across the storage combinations.

Farghali et al. (2023) reviewed the global transition from a fossil fuel-based society to an electricity-based society and noted that this shift had generally been regarded as an environmentally beneficial development. However, the authors highlighted that the electrical power industry had remained a major source of carbon dioxide emissions and that the integration of renewable energy technologies could also produce certain adverse environmental effects. They observed that, despite the growing volume of research on renewable energy, the environmental implications of renewable energy consumption had not been adequately understood. The study examined the integration of renewable energy into the electricity sector from social, environmental, and economic perspectives. The findings indicated that the implementation of solar photovoltaic systems, battery storage, wind energy, hydropower, and bioenergy could generate approximately 504,000 jobs by 2030 and 4.18 million jobs by 2050. The authors further reported that photovoltaic, wind, and battery storage systems supported by diesel generators could reduce water desalination costs by 69% and adverse environmental impacts by 90% compared with fully fossil fuel-based systems. They found that carbon-emission reductions had increased with higher shares of renewable energy sources. The photovoltaic–wind–hydroelectric system had emerged as the most effective configuration for addressing climate change, while hybrid energy systems had demonstrated greater reliability and resilience than single-source energy systems.

Nasser et al. (2022) presented a techno-economic assessment of a hybrid renewable energy system combining wind turbines and photovoltaic panels for hydrogen production and storage under the climatic conditions of five Egyptian cities. The authors reported that electricity generated by actual PV panels and wind turbines had been used to operate the water electrolyzer and hydrogen compressor. They developed a transient mathematical model of the complete system and solved it using MATLAB/Simulink. The study evaluated system performance in terms of electricity generation, hydrogen storage, efficiency, and production cost. The findings revealed that annual electricity production had varied considerably across Cairo, Aswan, Asyout, El Arish, and Mersa Matruh, with Mersa Matruh recording the highest output. The researchers observed that the combined PV–wind system had been suitable for hydrogen production in most of the selected cities, although wind energy had not been recommended for El Arish. They further found that the compressor had consumed approximately 3.13%–3.30% of the generated electricity. Annual hydrogen production had ranged from 1,196 kg in El Arish to 1,972 kg in Mersa Matruh. The study concluded that overall system efficiency had ranged from 7.69% to 9.37%, while hydrogen production costs had varied between $4.54 and $7.48 per kilogram.

Homa et al. (2022) reviewed the emerging challenges faced by the energy sector, particularly the large-scale transition towards renewable energy sources and the increasing adoption of distributed generation through small-scale energy systems. The authors explained that hybrid polygeneration systems integrating multiple renewable sources had offered an effective solution for producing different forms of energy and useful substances, such as fresh water and hydrogen. They observed that such systems had addressed several operational limitations associated with single-source systems based solely on solar, wind, or biomass energy. The study further indicated that integrated hybrid systems had been capable of meeting the diverse energy demands of different users. Although previous studies had mainly focused on medium- and large-scale installations, the authors noted that increasing attention had been directed towards small-scale configurations and applications. The review comprehensively examined the technologies, operational features, performance, economic aspects, energy storage options, modelling approaches, assessment tools, and methodologies related to small-scale hybrid and polygeneration renewable energy systems. The authors concluded that the field had considerable scope for further development in terms of system configuration, hybridisation, technological integration, and practical applications.

Rashid et al. (2021) aimed to develop hybrid energy systems by incorporating biomass energy sources and to determine an optimal configuration for Kukri Mukri Island, a southern suburban area of Bhola District in Bangladesh. The authors also examined the techno-economic feasibility of different hybrid energy system configurations for rural electrification. They estimated the available renewable energy resources, determined the optimal component sizes, and analysed the economic performance of the proposed systems using HOMER Pro software to meet peak-load demand. Various configurations, including PV/diesel, PV/wind, PV/diesel/wind, V/wind/diesel/biomass, and wind/diesel systems, were evaluated and compared. The systems were optimised on the basis of net present cost and levelised cost of energy. The findings indicated that solar photovoltaic energy was the most suitable primary energy source because of the limited availability and increasing cost of wind energy, while batteries and diesel generators served as storage and backup sources, respectively. The study revealed that the PV/wind/diesel/biomass configuration produced a comparatively lower levelised cost of energy of USD 0.142/kWh than the other configurations. The authors further reported that the genetic algorithm approach generated more sustainable and cost-effective outcomes than the HOMER-based optimisation process.

3. CONCLUSION

The study concludes that the integration of mechanical and renewable energy technologies provides an effective approach to developing reliable, efficient, and environmentally sustainable energy systems. Renewable energy sources such as solar, wind, hydropower, biomass, and geothermal energy [13] offer cleaner alternatives to fossil fuels, but their variable and intermittent nature can affect the continuity and stability of electricity supply. Mechanical energy technologies, including flywheels, pumped-hydro storage, compressed-air energy storage, turbines, and kinetic-energy recovery systems, can reduce these limitations by storing excess energy, regulating power fluctuations, and supplying electricity during periods of insufficient renewable generation. The evaluation of hybrid energy systems shows that their performance depends on proper component selection, appropriate system sizing, advanced control strategies, and effective coordination between generation, storage, conversion, and load-demand units. These systems can improve energy efficiency, voltage regulation, frequency stability, system reliability, power quality, and renewable-energy utilisation. They can also reduce fossil-fuel consumption, greenhouse-gas emissions, energy wastage, and dependence on conventional electricity grids. Despite their advantages, hybrid energy systems face challenges such as high installation costs, complex design procedures, energy-conversion losses, maintenance requirements, geographical restrictions, and the need for skilled personnel. Environmental concerns relating to land use, water consumption, noise, and ecological disturbance must also be carefully considered. Therefore, comprehensive technical, economic, environmental, and operational assessments are necessary before implementing a hybrid system. Overall, hybrid energy systems integrating mechanical and renewable technologies represent a promising solution for industries, transportation, rural electrification, smart grids, and sustainable communities. Continued technological development, supportive government policies, improved storage systems, and intelligent energy-management strategies can further enhance their affordability, reliability, and long-term contribution to global energy sustainability.

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