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COMPREHENSIVE PERFORMANCE ASSESSMENT OF HYBRID RENEWABLE ENERGY SYSTEMS FOR RESIDENTIAL BUILDING APPLICATIONS

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Abstract: This study evaluates the performance of hybrid renewable energy systems (HRES) in residential buildings with respect to energy efficiency, environmental impact, and economic feasibility. The analysis highlights the effectiveness of integrated systems combining solar technologies, hydrogen storage, advanced thermal storage, and biomass-based solutions in reducing primary energy consumption and carbon emissions. The findings indicate that well-optimized HRES configurations significantly enhance operational reliability and support the development of near-zero energy buildings, demonstrating their critical role in sustainable residential energy systems.

Keywords: hybrid renewable energy systems, residential buildings, energy efficiency, near-zero energy building, carbon emission reduction, sustainable heating, energy storage.

The residential building sector remains one of the most energy-intensive components of the built environment, accounting for a substantial proportion of global energy demand and associated carbon emissions. The persistent dependence of conventional heating systems on fossil-based energy sources underscores the critical necessity for transitioning towards low-carbon and sustainable heating solutions. Within this framework, the systematic assessment and optimization of hybrid renewable energy systems for residential building heating emerge as a highly relevant research domain, as such systems offer enhanced operational stability, improved energy efficiency, and significant potential for mitigating environmental impacts while supporting the development of near-zero energy buildings.

Hybrid Renewable Energy Systems (HRES) are generally characterized by the integration of multiple renewable power sources, frequently supplemented by both thermal and electrical energy storage technologies to enhance system stability and operational reliability. A comprehensive investigation conducted by Mehrjerdi et al. [1] proposed a dynamic modelling framework that considers diurnal and seasonal variations of renewable energy supply, system uncertainty, and the coordinated operation of diverse renewable generators together with storage mechanisms. In their study, a near-zero energy building was supplied entirely through a renewable-based energy configuration, incorporating hydrogen-based storage to balance fluctuations in energy availability. Seasonal energy demand disparities were effectively managed through the combined operation of solar and water-based cogeneration systems. This integrated approach demonstrated a substantial environmental and economic benefit, achieving a marked reduction in carbon dioxide emissions and lowering overall operational costs by nearly 50%.

Billardo et al. [2] evaluated the capability of a solar-driven cooling system to satisfy the summer energy requirements of a building situated within a Mediterranean climatic zone. In their research, a dynamic simulation-based model was developed to assess the system's energy performance, which was subsequently benchmarked against conventional cooling technologies. Furthermore, a comprehensive economic assessment was carried out, incorporating capital investment, energy consumption, as well as operation and maintenance expenditures associated with the solar cooling configuration. The simulation outcomes demonstrated that the proposed mathematical model enabled a substantial reduction in primary energy demand, achieving a decrease of approximately 48%. In parallel, the renewable energy contribution factor was significantly enhanced, reaching a value of 83%, thereby confirming the high efficiency and sustainability potential of the solar cooling system.

Violidakis et al. [3] conducted a comparative analysis of two photovoltaic-powered latent heat storage technologies designed to provide thermal and/or electrical energy in building applications. The first configuration involved a low-temperature phase change material thermal energy storage system (LT-TES), primarily intended to meet residential space heating demands. The second configuration incorporated an ultra-high temperature thermal energy storage system (UHT-TES), implemented at the building scale to support both electricity generation and heating requirements. When benchmarked against a conventional air-to-water heat pump heating system, the results indicated that the UHT-TES configuration demonstrated superior performance specifically in terms of electricity supply efficiency. Conversely, the LT-TES system exhibited greater technical effectiveness, particularly with respect to its suitability and operational performance for residential heating applications. These findings highlight the importance of selecting storage technologies based on the specific functional priorities of building energy systems.

Elghamry et al. [4] examined the performance of an integrated building energy system combining a Trombe wall with renewable energy sources for space heating, ventilation, and electricity generation purposes. Their investigation demonstrated that the implementation of renewable-based heating technologies significantly altered indoor air exchange dynamics, increasing the daily air change rate from 26 to 58 cycles, while simultaneously elevating the indoor temperature by up to 14°C. The proposed innovative system exhibited a high potential for simultaneously providing thermal comfort and effective ventilation through the utilization of renewable energy resources. These findings highlight the system's capability to enhance indoor environmental quality while reducing dependency on conventional energy sources, thus supporting the development of energy-efficient and sustainable building designs.

Lamagna et al. [5] performed a simulation-based assessment of the implementation of reversible solid oxide cell systems under multiple operational scenarios. Their study highlighted both the technological advantages of this emerging solution and its potential applicability within civil building environments. The system was evaluated across three representative building typologies-an office, a hospital, and a hotel-using a comprehensive framework that incorporated three economic indicators alongside three environmental performance metrics. The energy performance analysis revealed a substantial reduction in emissions, accompanied by a notable enhancement in energy self-sufficiency, with improvements ranging from a minimum of 29% up to 58%. Furthermore, the economic evaluation indicated that the payback period of the proposed system was initially comparable to the expected lifespan of the investment. However, projections for future technological advancements suggest that this period could potentially be reduced to as little as three years, thereby reinforcing the long-term viability and competitiveness of reversible solid oxide cell technology in building energy applications.

Kallio et al. [6] highlighted the critical importance of integrating hybrid configurations within renewable energy systems for building applications. In their study, a hybrid renewable energy system (HRES) incorporating energy storage was developed, combining solid biomass-fuelled micro combined heat and power (micro-CHP) units with solar-based technologies. The proposed dynamic system was subjected to multi-objective optimization using real meteorological data to evaluate its operational performance under realistic conditions. The findings revealed that an effective configuration should involve the integration of advanced systems, particularly photovoltaic-thermal (PVT) technologies, in order to adequately satisfy building demands for electricity, space heating, and domestic hot water. Furthermore, the authors emphasized the necessity for expanded empirical performance data on HRES operation and the implementation of advanced energy management strategies employing stochastic optimization techniques to enhance system reliability and efficiency.

Klemeš et al. [7] presented a comprehensive analysis focused on enhancing heat transfer performance and upgrading heat exchanger network configurations. Their study provided a critical evaluation of strategies aimed at achieving economically viable, cash-flow-positive solutions while simultaneously addressing challenges related to operational reliability, emission reduction, system flexibility, and process control. The authors identified a significant gap in the availability of robust and adaptable tools capable of effectively translating optimization outcomes into practical applications for industrial stakeholders. They emphasized the necessity of developing flexible and efficient communication frameworks to facilitate the successful implementation of process modernization strategies and to ensure the industrial-scale feasibility of optimization solutions.

Wang et al. [8] introduced an innovative turbine damper ventilator designed to enhance energy conservation performance in building ventilation systems. This device contributes to regulating and stabilizing air exchange rates in order to maintain indoor air quality in compliance with minimum ventilation standards. Long-term field experiments conducted under real operational conditions demonstrated that the proposed ventilator effectively minimizes excessive exhaust airflow, particularly during periods of elevated wind speeds. In comparison with conventional turbine ventilators, the new system significantly reduces unnecessary ventilation-induced heat losses, thereby improving overall building energy efficiency and thermal performance.

Conclusion. Hybrid renewable energy systems offer an effective solution for improving the energy performance of residential buildings while reducing environmental impacts. The integration of multiple renewable technologies with advanced storage systems enhances system stability, lowers operational costs, and significantly decreases carbon emissions. These systems represent a viable and strategic pathway toward achieving sustainable, low-carbon and near-zero energy residential buildings.

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