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The Application of Hybrid Renewable Energy Systems

Catherine Ivana, Mia Galina*, Iksan Bukhori, and Tetuko Kurniawan

***Abstract* – Hybrid Renewable Energy Systems (HRES) integrate solar, wind, and other renewable energy to deliver more sustainable, dependable, and affordable energy for rural, urban, and industrial areas. Based on 20 articles/journal from 2020–2025 that were taken from Google Scholar, IEEE Xplore, and Scopus, this paper evaluates HRES applications, technologies, barriers, and future development. Storage will increase to 204.47 GW, when solar and wind power dominate with capacities increased by 937% and 118% throughout 2014 to 2020. Optimization tools like HOMER Pro and Particle Swarm Optimization (PSO) can reach up to 1.10% error in energy predictions. HRES can reduce costs and emissions by 86% (solar) and 61% (wind) by prioritizing renewable energies usage. Regulatory loopholes, intermittency, and high initial costs are some of the challenges in the application of HRES. MATLAB visualizations show capacity trends and cost reductions, which supports economic viability. Examples that demonstrate sustainability and highlight reliability include mining activities in Iran and microgrids in Makkovik, Canada. This paper identifies HRES based on the literature, AI, IoT, and policy incentives. Future advancements must go beyond technical constrains and standardize regulations to scale HRES for global energy transformations, smart cities, mining industries, and resilient communities.**

Keywords— Hybrid Renewable Energy Systems, Solar Energy, Wind Energy, Energy Storage, Optimization.

I. Introduction

The global energy crisis, shows by the rising usage and the impact on environment of fossil fuels, has raised the urgency for more sustainable energy solutions. Hybrid Renewable Energy Systems (HRES) offers more promising results by delivering more reliable and low-cost energy, this innovation combines solar, wind, and other renewable sources [1]. These systems are increasingly important for various applications, from microgrids for off-grid communities to industrial sectors such as mining, where they increase sustainability and energy security [2], [3].

HRES help overcome the critical challenge of intermittency inherent in renewable energies, making them important to smart cities and eco-friendly industries. For example, wind-solar-storage microgrids in Makkovik, Canada, are very reliable [2], while Implementation of HRES in Iranian mines demonstrates their role in sustainable industrial processes [3]. Despite many application successes, HRES still face significant barriers, such as technical limitations like limited battery life and higher initial cost [4], as well as having difficulties in getting high renewable fractions due to grid integration challenges [5].

This systematic review draws on evidence from 20 peer-reviewed paper published from 2020 to 2025 to examine the primary applications of HRES, the technologies enhancing their performance, the challenges to their adoption, and future advancement for optimizing their application [6]. By analyzing capacity and cost data from 2014–2020 and using MATLAB visualizations, this study helps quantifies trends to inform people who makes policy and other researchers [7]. The review has intentions to deliver suggestions of actions to advance HRES as a cornerstone of global sustainable energy transitions, particularly in smart cities, mining industries, and resilient communities [8].

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II. Related Works

The previous studies of HRES highlights various applications and technologies. The first studies are by Maliat et al. [2] which evaluate a wind-solar-storage of HRES in Makkovik and achieved great reliability. The second studies, Pérez Uc et al. [9] tells us that using designs optimized by HOMER Pro, there are 47% of HRES studies focus more on rural areas. The third studies, Talaat et al. [10] studies tell us that 1.10% error of microgrid prediction is using PSO and ANN. The fourth studies, Hosen et al. [11] found that solar-wind-biomass systems helps reduce emissions in South Africa. Then the fifth, Pouresmaieli et al. [3] explored more in innovation of HRES in mining, emphasizing planning for energy sustainability. The sixth studies, Khosravani et al. [5] explained about the challenges in achieving high renewable fractions, specifically in storage and grid integration issues. The seventh studies, Jurasz et al. [8] by citing metrics of system design, it reviewed complementarity of renewable sources. The eighth studies, Kumawat et al. [7] highlighted control techniques of power quality that are still growing, and finally, Eltamaly et al. [1] proposed the use of IoT for HRES in the implementation of smart campus. These past researches define the scope of the review, which emphasize the potential and limitations of HRES.

III. Methodology

This paper analyzed the recent 20 studies from 2020 to 2025, based on Scopus, IEEE Xplore, and Google Scholar using keywords "HRES", "solar Energy", wind Energy", "Energy Storage", and "optimization." Criteria that are included needs to be peer-reviewed studies on HRES applications. Recent data on applications, metrics, technologies, locations, and challenges were extracted into an Excel file. The results of the thematic analysis were divided into three categories which is barriers, technologies, and applications. The theoretical framework includes Levelized Cost of Energy (LCOE):

$$LCOE = \frac{\sum_{t=0}^{n}\frac{I_t+M_t+F_t}{(1+r)^t}}{\sum_{t=0}^{n}\frac{E_t}{(1+r)^t}} \quad (1)$$

where I_t is investment expense, M_t is maintenance and operation cost, F_t is fuel cost, E_t is energy output, r is discount rate, and n is life of the system [12].

IV. Result

A systematic review of 20 peer-reviewed studies from 2020-2025 on Hybrid Renewable Energy Systems (HRES) provides a role in providing sustainable energy across rural electrification, micro-grids, educational institutions, and industrial areas such as mining. HRES meet diverse energy needs by integrating solar, wind, storage and other renewables, ranging from off-grid communities to high-energy industrial processes. Table I summarizes key case study data extracted from the reviewed studies, highlighting specific metrics and their impact.

TABLE 1. HRES Case Study Data from reviewed studies.

No	Application	Year	Metric	Value	Location
1	Rural Electrification	2020 [5]	Solar Capacity	462.44 GW	Global
2	Rural Electrification	2020 [5]	Wind Capacity	209.14 GW	Global
3	Rural Electrification	2020 [5]	Cost Reduction	86% (solar)	Global
4	Rural Electrification	2020 [5]	Cost Reduction	61% (wind)	Global
5	Microgrid	2023 [10]	Forecasting Error	1.10% NMSE	Not Specified
6	Educational	2023 [13]	System Design	HOMER Pro	Oakland, USA
7	Rural Electrification	2024 [9]	Study Focus	47% of studies	India
8	Microgrid	2024 [2]	Reliability	47% of studies	Makkovik, Canada

Figure 1 highlights the various applications of HRES, giving a strong emphasis on rural electrification and microgrids applications, with some emerging attention directed into offshore/coastal and regional systems, followed by interest in education and industry, illustrating the broad relevance of HRES in different global environments [2], [3], [9], [14], [15], [16]. Figure 1 shows the significant capacity contributions of various HRES applications, where because of significant solar and wind advancement the Rural Electrification will dominates, and Microgrids utilize considerable energy capacities to ensure reliability, as supported by global data trends [2], [5]. Figure 1, obtained from a thorough data analysis, further highlights the research focus on HRES applications, where due to Rural Electrification and microgrids taking the critical role in global energy access, in addition to increasing attention on specialized applications such as Offshore/Coastal and Regional Systems [2], [5], [15], [16]. Figure 1, which uses global data of capacity from 2020, highlights the significant contributions of solar, wind, and storage to HRES applications, supporting their widespread use in areas like rural electrification, micro-grids, and educational institutions [5], [14], [16].

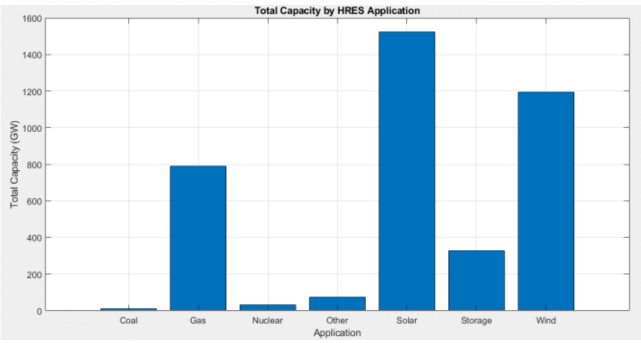

FIGURE 1. Performance improvements across HRES applications.

Further analysis of some studies provides more quantitative input into the performance of HRES. Reference [5] reports a growth in global solar capacity by 937% (44.56 GW to 462.44 GW) and growth in wind capacity by 118% (95.88 GW to 209.14 GW) from 2014 to 2020, along with the increase of storage capacity to 204.47 GW, which covers the energy demands reflecting the scalability of HRES. HRES have made economy better by reducing cost of 86% for solar and 61% for wind systems, particularly for rural electrification, where 47% of studies focus, notably in India [5], [9]. Though they face challenges like harsh conditions and intermittency, they extend applications to marine environments, such as offshore and coastal HRES, integrating solar, wind, and wave energy [14]. Reference [10] in microgrid energy forecasting using Particle Swarm Optimization (PSO) and Artificial Neural Networks (ANN) achieved up to 1.10% Normalized Mean Square Error (NMSE), make it to able to manage energy precisely. Reference [2] demonstrates high reliability of a wind-solar-storage microgrid in Makkovik, Canada, and [13] highlights usages of HOMER Pro to optimized HRES designs for educational campuses [15].

Technological improvement is important to the success of HRES. Optimization tools such as HOMER Pro, as used in reference [9] and [13], showing more precise sizing system and design with less cost for rural and educational applications. In addition, advanced forecasting algorithms, such as PSO and ANN in [10] are more accurate (1.10% NMSE) and can improve energy dispatch further for microgrids. Artificial neural networks further enhance energy prediction in HRES, supporting efficient energy management despite computational challenges [16]. Energy storage systems, emphasized in [5], mitigate intermittency, and by 2020 the storage capacity increased to 204.47 GW. Strategic planning for renewable energy application, as discussed in [3], helps with sustainability in high-energy mining operations. Complementarity metrics for balancing renewable sources enhance to design the system and mitigate intermittency [8].

Challenges still has some significant effect. As cited in [4], high initial costs and limited battery life are creating economic and technical barriers. Intermittency and grid integration challenges, as highlighted in [5], making it hard to achieving high fraction of renewable energy. The gaps on regulation, as discussed in [7], require standardized policies to facilitate HRES scale. These challenges need a continuous innovation and policy adjustment to maximize HRES potential.

V. Discussion

HRES shows great potential for sustainable energy, especially for rural electrification and industry, from 2014 to 2020 solar and wind capacities has been increasing rapidly by 937% and 118%, with the reductions of cost by 86% for solar and 61% for wind [5], [11]. Previous studies, such as Makkovik's microgrid and HRES in Iranian mining operations, highlighting the role of storage, aligning with Maliat et al. and Pouresmaieli et al.'s findings [2], [3]. Optimization tools like HOMER Pro and algorithms like PSO, as stated by Talaat et al. [10], improving system efficiency in various sectors as well as achieved high forecasting accuracy (1.10% NMSE), ranging from rural India to educational institutions such as Oakland University [9], [13].

However, there are still some challenges to achieve high renewable fractions, with 70% of the studies identifying barriers such as high initial costs, intermittency, and gaps in regulations [5], [7], [17]. The problem of both intermittency and grid integration, as highlighted by [5], require improved storage technologies, while strategic planning, as noted by Pouresmaieli et al. [3], is really important for sectors with high-energy like mining. Complementarity metrics, as discussed by Jurasz et al. [8], faces computational complexity in real-time applications to help balance renewable sources [18]. HRES efficiency applications in regional scale is improved by fine-scale optimization of wind-solar combinations, which further reduces renewable energy fluctuation [19]. Technologies such as AI and IoT, proposed by Eltamaly et al. [1], improve energy management, but their implementation is expensive, thus requiring innovation to balance economic and technical feasibility.

To overcome these challenges requires integrating technological advancements with some policy adjustment. Policy support, as highlighted by Hosen et al. [11], can accelerate HRES application adoption through subsidies and standardized frameworks, especially in industrial areas [3]. The literature validates HRES's ability to reduce emissions and enhance energy security, but overcoming technical and regulatory barriers, especially for high renewable fractions, is very critical to know their full potential in smart cities, mining industries, and other applications [5], (Obuseh, Eyenubo, Alele, Okpare, & Oghogho, 2025), [20].

VI. Conclusion

Hybrid Renewable Energy Systems (HRES) will revolutionize global energy systems, thanks to significant growth in solar, wind, and storage capacities, with reductions in cost. Their applications are to demonstrate versatility in reducing emission and enhancing reliability, especially in rural electrification, educational institutions, commercial sectors, urban systems, and mining industries. Efficiency is enhancing through optimization tools and AI-based algorithms, and IoT enhances real-time management. Despite these advancements, challenges such as high initial costs, intermittency, and gaps in regulation, particularly in achieving high renewable fractions. These are met with sophisticated storage technologies, long-term planning, and new technologies like quantum computing. In order to ensure that HRES propel resilient, smart cities with low carbon, sustainable industries, and communities globally, this review highlights the crucial part HRES plays in sustainable energy transitions and calls for future research to standardize regulations, scale AI and IoT applications, and promote international collaboration to overcome obstacles.

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Author Contributions

Catherine Ivana: Conceptualization, Methodology, Writing – First Draft;

Mia Galina: Project Supervision, Methodology;

Iksan Bukhori: Writing – Review & Editing.

Conflict of Interests

There are no conflicts of interest related to the research, authorship, or publication of this article.

Ethics Statements

Ethical approval was not applicable to this research since it did not involve human participants, animals, or sensitive data.

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