Hybrid Renewable Energy Systems for Off-Grid Electrification: A Bibliometric Analysis of Performance, Economic Viability, and Emerging Technologies

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Abstract*- Connecting off-grid areas, particularly in the Sub-Saharan part of Africa and parts of Asia, is a burning problem, and over 700 million people lack access to reliable electricity. Hybrid Renewable Energy Systems (HRES) have been seen as one of the possible solutions to this inadequacy, where different renewable energies converge, including solar, wind, as well as biomass, together with energy storage technologies to provide reliable as well as affordable energy. This article provides a bibliometric analysis of HRES utilized to electrify off-grid, research paths, technology advancement, and economies of 2015 to 2025. Utilizing the tools of analysis, including VOSviewer, the study maps global directions of research, outlines the key performance indicators, and questions the economic functionality of various HRES designs. These empirical data indicate some significant advances in technical optimization, especially in solar-wind-battery systems; however, it also shows the current lack of success in post-installation economic analysis and acceptance in the society. The paper, therefore, highlights the need to conduct additional research on the topic of community engagement, evidence-based economic modeling, and the exploration of emerging technologies, such as green hydrogen and AI-enhanced optimization. Comprehensively, this review provides invaluable information to the policy makers, researchers, and practitioners working in off-grid electrification programs, thus creating a strong base of future developments in the field of endeavor.

***Keywords*: Hybrid renewable energy, Off-grid electrification, Economic viability, Bibliometric analysis, Performance metrics**

ISSN: 2961-6603

I INTRODUCTION

Overall, over 700 million individuals on earth lack access to electricity and these are predominantly the rural or remote areas of low-income countries [1]. Such areas are faced with massive challenges of increasing conventional grid infrastructure due to prohibitive cost and space. An example of this is that it is frequently economically impractical to add new transmission lines to remote regions and that the level of demand in the remote regions does not justify the massive investments in capital in such facilities. As a result, off-grid electrification has become a critical priority towards an all-encompassing access to energy, especially in the areas like Sub-Saharan Africa, South Asia, and some parts of Latin America.

Such a scenario has led to the development of a feasible solution in the form of decentralized energy systems especially Hybrid Renewable Energy Systems (HRES). HRES will combine various renewable energy sources, including solar energy, wind energy and biomass, with energy storage technologies to supply constant and dependable energy. These systems are capable of providing an alternative to the traditional energy grids, not only in a sustainable and cost-efficient manner, but also in assisting in decreasing the dependence on the expensive and harmful fossil fuels [2]. HRES can ensure consistent energy supply even during the periods when single sources are not continuously available or uninterrupted due to their complementary nature to one another.

The last ten years have witnessed a surge in the design of HRES due to a surge in the pace of technological improvements, mass decreases in the price of solar and storage equipment, and interest among project financiers and policy makers. Specifically solar power has undergone radical prices cuts that have made it more affordable in large and small scale use in off-grid communities [3]. Combination of wind, solar and storage solutions have resulted to be a solution that has worked quite well in most off the grid sites and has provided a form of energy security, lowered energy bills and has also led to a shift to cleaner energy systems [4]. However, in spite of these developments, the research on the subject of HRES is still disjointed, and scientific articles on this subject are not always structured properly. There is a strong necessity to offer an international research on HRES synthesis, to point out the most popular technologies, and to evaluate their effective application in various geographical and economical settings.

This paper seeks to fill such gaps by a review and analysis of the literature on HRES, especially on off-grid electrification. In this analysis we aim to point out the new trends, technologies and regional differences in the development of HRES. The research questions are to respond to the following main questions:

1. What are the world research trends, valuable technology and target markets shaping HRES development in off-grid electricity delivery?

2. What are the most often debated performance aspects and economic models, and what are the areas of HRES deployment that have not been well addressed in the scholarly literature?

The answers to these questions in this study will offer a general understanding of the prevailing state of HRES, and will recommend future research to further claim the effective implementation of these systems in underserved areas.

ISSN: 2961-6603

II. Literature Review

1.1 Historical Foundations of Hybrid Renewable Energy Systems (HRES)

It is possible to trace the idea of having multiple energy sources combined to guarantee a stable and sustainable supply to the concept of a soft energy path expressed by Amory B. Lovins in the 1970s. Lovins assumed that the society must abandon the centralized fossil-fuel-powered system of power and adopt the decentralized renewable sources of energy, including solar power, wind energy and small hydro-electric power plants. This shift formed the premise of modern hybrid renewable energy systems (HRES) with its emphasis on the need to diversify energy to increase its security and sustainability, especially in remote and off-grid locations [1].

The early studies of HRES were mainly conducted to explore how renewable technologies can be connected to conventional backup systems, the diesel generators. These hybrid forms were considered viable solutions to the issue of intermittency with renewable energy sources such as wind and solar. Research in the 1990s and early 2000s identified the benefits of incorporating solar, wind, and storage technologies in unloading the unreliability of each individual source of renewable power. Other scholars opined that the hybrid systems were able to provide a reliable supply of energy by integrating complementary sources [2]. This initial development led to more complex systems that could be disconnected to a main grid and would be used in remote areas, particularly in Sub-Saharan Africa, South Asia, and rural Latin America.

1.2 Hybrid Renewable Energy Systems Growth and Development.

In the last two decades, the development of HRES has been driven by technological progress in the photovoltaic (PV) and wind energy as well as the decreasing cost of energy storage solutions. With the maturation of the renewable technologies, their combination with storage systems became a point of focus. The comparison of solar and wind energy with the presence of battery storage has turned out to be effective in assuring the reliability in electricity provision in off-grid and rural areas.

Recent literature proves that hybrid settings of PV-wind-battery systems have significant potential in terms of reliability, cost-effectiveness, and sustainability. As an example, a study by Bajpai et al. (2012) evaluates hybrid PV-wind-diesel systems, noting that the sizing of each of the elements must be optimized to reduce the operational budget and improve the efficiency of the whole system [3]. The addition of energy storage systems e.g. lithium-ion and flow batteries enhanced performance further since they were able to capture energy when generating power was high and also maintained power when it was low [4]. Such innovations have made HRES changeable options to off-grid electrification, which can create opportunities to become independent of energy and achieve long-term sustainability.

In addition to the advances in technology, the usage of smart grid technologies and optimization approaches has significantly improved the HRES performance. Higher order modeling systems, such as HOMER and MATLAB/Simulink allow researchers and engineers to model, simulate, and optimization of hybrid systems in various applications. Genetic algorithms and metaheuristic algorithms are currently widely used as optimization tools to reduce the costs of production and maximize the reliability of the system [5].

ISSN: 2961-6603

1.3 Current Trends, Future, and Problems.

The new trends and technologies are integrated into the current development of the sphere of HRES. Another area of salient improvement is the introduction of the use of green hydrogen as a storage medium in hybrid systems. Green hydrogen, which is generated through the electrolysis of water with the help of renewable energy, storing surplus energy over a long duration makes it a feasible solution in areas with high renewable penetration. In the article by Tezer et al. (2022), the authors analyzed hydrogen-based storage, which is combined with solar and wind systems and showed that it can supply stable energy during the times when renewable power production is low [6].

The other new direction is the use of artificial intelligence (AI) and machine learning (ML) to streamline HRES functioning. The technologies support energy management, predictive maintenance, and demand-side forecasting, which improves the efficiency of resources and increase the system reliability. There is also AI-based optimization that helps to handle the complicated relations between various renewable sources, storage facilities, and grid infrastructure [4].

These advances notwithstanding, there are still a few challenges. Another key issue is economic viability; in as much as HRES will help to lessen fossil-fuel contribution and enhance energy accessibility, the initial expenditure of capital to deploy it is high at least in remote locations that do not have a sound financial network. Furthermore, there is a considerable data void on long-term performance, that is, maintenance expenses, system depreciation, and local acceptance of the system in the communities. In post- installation monitoring, the application of empirical studies reveals that it is essential to ensure that the simulation results are verified and the actual implementation is optimized [5].

Despite these advancements, studies are recommended to focus on improving the integration of HRES into the current grid infrastructure, investigating hybrid systems that can be used in off-grid and grid-connected systems. Also, social-economic issues, such as community participation, policy facilitation, and funding systems, need to be incorporated to guarantee mass implementation and effectiveness of HRES in underserved areas [2] [4].

III.Methodology

This paper is a bibliometric research on the literature review of the hybrid renewable energy system (HRES) as applied to off-grids between 2015 and 2025. Google Scholar was used to access peer-reviewed articles using the search strategy that included a combination of key words that included: hybrid renewable energy, off-grid, microgrid, performance, and economical viability. To obtain important information, such as co-authorship networks, keyword co-occurrence and thematic clusters, bibliometric mapping was conducted using VOSviewer and Publish or Perish 8. The papers that had high impact based on this analysis were then evaluated to determine technical performance indicators, namely reliability and storage efficiency, and economic indicators, namely Levelised Cost of Energy (LCOE) and payback period. Also, the deployment models and case studies were analyzed to clarify the practical consequences and real life usage of HRES in different regions.

IV. Data Analysis and Results

ISSN: 2961-6603

In the current research article, the literature sources were used to examine the paths of research, clusters of themes, and spatial patterns of hybrid renewable energy systems (HRES) that are related to off-grid electrification. VOSviewer was used to create network diagrams to analyze the data, and Publish or Perish was used to compute aggregated citation data, which included peer-reviewed data published between 2015 and 2025.

4.1 Bibliometric Trends and Publication Growth

The dataset comprised **370 publications**, with an average of **57.96 citations per paper**, indicating strong academic interest in the field. Research output exhibited exponential growth, rising from fewer than **100 articles in 2015** to over **340 by 2023**, peaking around global policy milestones such as the **UN Sustainable Development Goal 7 (SDG7) updates** and **COP climate conferences**. The **h-index of 77** further underscores the field's influence, with seminal works like **Khare et al. (2016)** and **Olatomiwa et al. (2016)** receiving **966 and 743 citations**, respectively.

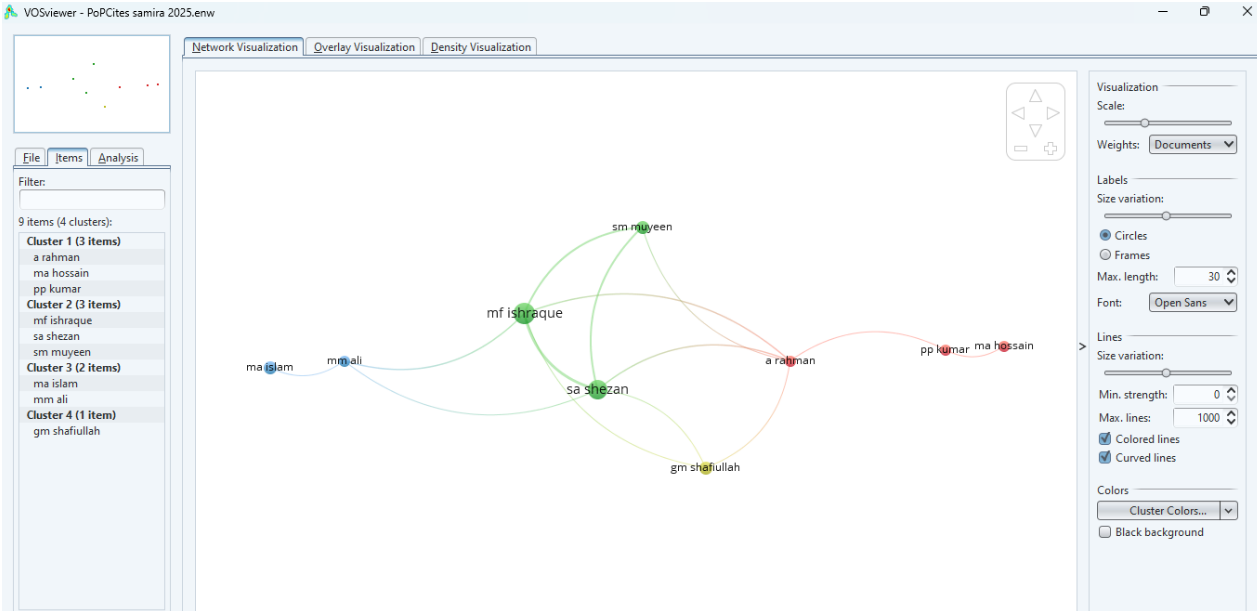
Metrics
Publication years: 2015-2025 **Citation years:** 10 (2015-2025) **Papers:** 370 **Citations:** 21446 **Citations/year:** 2144.60 (acc1=362, acc2=346, acc5=280, acc10=189, acc20=91) **Citations/paper:** 57.96 **Citations/author:** 7273.31 **Papers/author:** 124.16 **Authors/paper:** 3.57/4.0/4 (mean/median/mode) **Age-weighted citation rate:** 5519.76 (sqrt=74.30), 1831.00/author **Hirsch h-index:** 77 (a=3.62, m=7.70, 14351 cites=66.9% coverage) **Egghe g-index:** 132 (g/h=1.71, 17471 cites=81.5% coverage) **PoP hI,norm:** 41 **PoP hI,annual:** 4.10 **Fassin hA-index:** 36

Source: publish and perish

4.2 Thematic Clusters and Research Focus

Network visualization using **VOSviewer** identified **four dominant clusters**, reflecting key research themes:

ISSN: 2961-6603



Source: Vosviewer

1. **Technical Optimization (Cluster 1)**

The first thematic cluster focused on technical optimization and system design. Research within this cluster emphasized modeling and simulation, particularly using the HOMER software platform to evaluate component efficiency and overall system configuration. Authors such as Kumar, Raiman, and Hotaria were prominent in this domain, often advocating for solar-wind-battery configurations due to the continued decline in photovoltaic panel prices and improvements in storage technologies. These studies underline the technical feasibility of hybrid systems and their adaptability to varying energy demands and geographic conditions.

Technical optimization Technological modeling and simulation software such as HOMER has led to the literature on technical optimization and hybrid systems; where different combinations of renewable energy sources (solar, wind) and storage systems (batteries, hydrogen) are simulated to make a judgment on the most efficient system. Nevertheless, the limitations are a bit few and should be examined further:

- Model Assumptions and Real-World Applicability: A significant number of these studies are based on the assumptions of the performance of the components under an ideal environment. Although the insights that the HOMER and others can give are useful, they are prone to miss the real-life difficulties that exist like local grid behavior, microgrid limits, and long-term maintenance requirements. The existing literature assumes that the risk of model-optimized systems doing less-than-optimal after deployment is low because of these dynamic variables. As an example, a system that was technically good in simulation can prove not to work as well in reality in case of battery degradation or of less than optimal maintenance practices.
- Component Interdependency and Sizing: In simulations, it is suggested by many studies to use oversized components (e.g., batteries, inverters) and thus predicts artificially low LCOE. There are several issues, like space constraints, regulatory restrictions, and cost differences in the country, which should be considered in the real implementation. Also, much of the optimal sizing is usually based on the assumption that the energy consumption levels are consistent throughout the year, which does not take into consideration the seasonal and intermittent demand differences. Recent researches focus on the relevance of matching the component sizing to the local demand profiles, which may differ considerably depending on different geographies.

ISSN: 2961-6603

- Diversification Beyond Wind-Solar-Battery: There is an emerging trend towards more hybrids, such as such combinations as solar-wind-hydrogen or solar-battery-biomass, to solve the problem of intermittency in generation.

2. **Economic Assessment (Cluster 2)**

The second cluster revolved around economic assessment, with studies exploring financial metrics such as the Levelized Cost of Energy (LCOE), capital expenditure (CAPEX), and payback periods. Scholars including Islangue, Shezan, and Moyeen contributed significantly to this area, often employing financial modeling to forecast the economic viability of HRES. However, a recurrent limitation across this body of work is the lack of empirical data from post-installation monitoring, which hinders validation of the proposed economic models and limits insights into long-term sustainability and investment planning.

The financial suitability of Hybrid Renewable Energy Systems (HRES) is commonly measured with the help of such metrics as LCOE, CAPEX, payback period. Nevertheless, there are some key points that are not studied thoroughly:

- Absence of Post-Installation Data: This is one of the major limitations since empirical data are not obtained after the installation to prove the simulation models. Although research is indicating promising values of LCOE (in many cases below $0.30/kWh), these estimations hardly consider actual operational challenges associated with LCOE, including maintenance costs, degradation of individual components, and the cost of long-term operation. Due to the fact that the literature mostly deals with theoretical models, it is a big gap in terms of understanding how such systems will work once installed and after several years.
- External Factors: Economic feasibility also depends on a chain of external factors such as the sources of finances, regulatory encouragement and grid infrastructure. The economic research does not consider these factors, and its evaluations are overly optimistic, failing to represent the problems which practitioners meet in the field. The importance of LCOE and such factors as the availability of financing and subsidies, especially in countries with low income where the cost of upfront capital is a major obstacle to implementation, is critical.
- Scaling and Regional Variability: The other vital problem is that in most cases economic studies are regional. When the HRES area is expanded globally, it is evident that the models created in a particular region may not be suitable in other areas because of the disparities in resource supply, the financial models and energy policies.

3. **Storage and Reliability (Cluster 3)**

The third cluster addressed issues related to storage and reliability, delving into topics like battery sizing, hybrid system stability, and efficient energy management strategies. Notably, the works of Islam and Af highlighted the importance of robust storage systems for ensuring uninterrupted power supply in off-grid settings. Recent trends in this cluster point to growing interest in lithium-ion and hydrogen-based storage solutions, reflecting a broader move toward integrating more advanced and sustainable technologies within HRES frameworks.

The trustworthiness of HRES systems and more so the energy storage is crucial to the stability of the power supply. Nevertheless, new problems connected with storage technologies which are not adequately covered by the existing studies are emerging:

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- Battery Degradation and Efficiency Losses: The other important aspect that contributes to the reliability of the hybrid system is the diminution of energy storage systems, especially lithium-ion batteries. Research has noted that a lot of models fail to consider the long-term patterns of degradation which may seriously compromise the reliability of a system in the long run. The significance of battery life, and predictive algorithms that will be required to handle storage health, are emerging as the focus of future research. Moreover, hydrogen storage with a longer cycle than battery-based systems has not been extensively explored in hybrid systems, particularly in rural microgrids.
- Hybrid storage solution complexity: Recent research holds that on complexities of battery-to-hydrogen or battery-to-flywheel hybrid systems, which often seem safer and easier to manage than strictly battery systems, these solutions are generally harder to design. Such complicated structures demand highly sophisticated control measures to manage the load requirements, generation and storage levels effectively resulting in increased operation cost. However, their capability to be reliable in long term in remote or off-grid could justify the increased complexity.
- Sustainability and Environmental Impact of Storage: The other area that has not been well studied is the ecological impact of mass battery manufacturing, specifically the lithium-ion batteries. The higher the requirement to be stored, the greater the necessity to learn more about the lifecycle effects of battery systems - the extraction of resources to the disposal. The problems of sustainability in terms of lithium and cobalt availability (as raw materials) and recycling of battery at the end of life are an issue of study.

4. **Field Applications (Cluster 4)**

The final cluster examined field applications, with a focus on case studies in rural electrification efforts, particularly in regions such as Bangladesh and Kenya. These empirical investigations, often led by researchers like Shafullah, provided practical insights into the deployment and operational challenges of HRES in diverse socio-economic contexts. Nonetheless, the literature remains skewed towards Sub-Saharan Africa and South Asia, with limited attention given to Latin America and the Pacific Islands. This regional imbalance highlights the need for broader geographic coverage and context-specific analyses to inform inclusive and globally relevant energy solutions.

The practice of Hybrid Renewable Energy Systems (HRES) in a real field of application is often characterized by the recognition of the intricacy of the process of transforming theoretical literature into the operational reality. There are a number of challenges that are not well tackled as noted in the literature:

- Geographic and Socio Economic Bias in Case Studies: Although there is a plethora of case studies available on South Asia and Sub-Saharan Africa, the rest of the world, including Latin America and the Pacific Islands, is grossly underrepresented. Such a geographical bias restricts the generalizability of the results; what may be the case in one part of the world may not necessarily be the same in other parts of the world, especially when considering the different renewable energy resource endowments, socio-economic status, and regulatory climates that are found all over the globe.
- Community Involvement/Capacity Building: HRES functions effectively in field locations, which in most cases depends on local capacity building, active community involvement and widespread technical training. The long-term sustainability does not only rely on the installation of technology, but the community should be equipped with the necessary capabilities and resources to sustain and manage the systems. There is scanty empirical evidence on the structure of governance, the definition and division of roles, and roles in these communities, particularly in remote and marginalized places.

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- Policy and Regulatory Barriers: There has been a common theme in the field applications of implementing innovative HRES designs with lack of alignment between newer designs and existing policies. Lack of favorable policy, no clarity in regulations, and high taxes levied on the renewable equipment in most developing areas pose significant barriers to massive implementation. In this regard, governments should address these shortcomings by creating regulatory conditions that will enable adoption of HRES as recommended by scholars.

4.3 Geographic and Institutional Distribution

HRES research is led by institutions and scholars from India, China, the United States, and Nigeria, reflecting their active engagement in addressing off-grid energy challenges. Prominent academic institutions such as IIT Delhi, MIT, and the University of Cape Town have emerged as key contributors. While around 60% of the reviewed case studies focus on Sub-Saharan Africa and South Asia, only a small fraction approximately 8% address Latin America, underscoring a regional bias in research output. This disparity calls for targeted efforts to diversify geographic representation and enhance the applicability of findings to underexplored regions.

4.4 Citation and Impact Analysis

The most frequently cited works, such as Khare et al. (2016) and Singh et al. (2016), have shaped scholarly discourse through comprehensive reviews on solar-wind hybrid systems and islanded microgrid feasibility. These publications, with citation counts of 966 and 527 respectively, emphasize the importance of techno-economic optimization. However, there remains a noticeable gap in addressing socioeconomic implications and community engagement. The scarcity of studies exploring the role of local stakeholders, behavioral dynamics, and institutional frameworks signifies an area ripe for future investigation.

4.5 Keyword Co-Occurrence and Emerging Trends

Keyword analysis indicates a dominant focus on terms such as "hybrid renewable energy," "off-grid," "microgrid," and "economic viability." Despite this, critical elements like "social acceptance," "maintenance costs," and "policy governance" are underrepresented. From 2023 onwards, a marked shift toward advanced technologies is evident, particularly the integration of artificial intelligence for system optimization and the use of green hydrogen as an energy storage medium. These developments signal the emergence of next-generation HRES models that prioritize both technological sophistication and environmental sustainability.

V. Discussion & Conclusion

The growing pace of research in the off-grid systems using hybrid renewable energy (HRES) is showing significant move towards more sustainable and resilient energy systems. The ever-growing literature base demonstrates a great focus on the efficiency improvement, optimizing system configurations, and energy system simulations. Still, the maximization of performance and the stability of constant reliability are critical issues in the field. The most commonly researched and broadly used configurations are the hybrid ones, especially the solar-wind-battery systems. The driving force behind this increased interest is largely due to the developments in the technology, specifically, the decreasing price of photovoltaic (PV) modules and battery storage technologies and making such systems more accessible to various geographic environments [5], [4]. New technologies have enabled the introduction of such systems to varied environmental locations as remote rural locations to island archipelagos. In spite of these developments,

ISSN: 2961-6603

many technological innovations studies fail to look at economic effects of technology in the long-term, especially where economic assessments frameworks like the Levelized Cost of Energy (LCOE) and payback period has been used [6]. Despite these models being widely used, they often overlook actual operational data in the real world which may confirm their predictions and this creates an information gap in understanding the entire economic effect on the local communities, and in particular in the low-income areas.

One of the problems that are constant in the implementation of HRES is the inequalities between the initial costs of installation and the subsequent economic benefits in the long run. Although LCOE and payback periods are commonly referred to as the performance indicators in the academic literature, little studies have been tracking these measures after the installation, or determining the impact of these types of technologies on the economic and social life of the communities impacted. The lack of longitudinal data erodes the plausibility of such economic models and further supports the need to conduct empirical case studies that support the findings of the theory [3]. In addition, despite the proposed community-based solutions like microgrids and Pay-As-You-Go (PAYG) frameworks being considered as possible solutions to off-grid environment, they are frequently considered within the context of isolated situations with regard to the overall institutional, social and economic environments in which these systems exist. As a result, there arises partial understanding of the working reality of such arrangements especially in the rural settings where there is unequal distribution of market access, educational access and the provision of financial services [2].

Moreover, there is an apparent geographic unequal distribution of HRES scholarship. The region of Latin America and the Pacific Island nations have relatively little scholarly coverage as Sub-Saharan Africa and South Asia represent the greatest focal points because of their highly pronounced energy access shortages. Such a regional difference raises questions about the externalizability and generalizability of the available research findings. To counter these shortcomings, it would be important to have a more comprehensive approach to the investigation that would entail the consideration of areas with diverse socio-economic and environmental backgrounds. A more interdisciplinary approach including not just engineering and technical evaluations, but also the social sciences, behavioral research, and policy analysis would provide a more holistic picture about HRES. This holistic approach may make HRES models more scalable and replicable in different environments and guarantee that these systems efficiently meet the needs on a local scale [7].

Throughout the dealings with local imbalances, there is a need to make amends in how technical solutions, economic analysis, and the political and social milieu in which systems of hybrid renewable energy (HRES) are implemented are interrelated. This reconciliation would require the reconciliation of the system performance measures with the maintenance budgets, day to day utilisation data and feedback of users. The ongoing examination of the empirical functioning of the hybrid system and the socio-economic environment of the community in which the system is served, carried out longitudinally, is essential in the context of improving the efficiency of the system and ensuring its sustainable effectiveness. The real ability of HRES to help alleviate the off-grid electrification problem will be limited until these instruments can be transformed into real-world testing in a variety of environments [8].

In general, despite the significant developments that have been made in the development and implementation of hybrid renewable energy systems to electrify rural areas, it is possible to say that the full potential of these systems is hindered by various critical gaps in the research and practice. Such gaps

ISSN: 2961-6603

include the lack of validation of economic models with empirical evidence, the fragmented community-based strategy, and lack of studies addressing regional variation in the implementation of HRES. To achieve mass implementation on HRES, it is vital that technological advancement should be harmonised with the right financial systems, social culture issues, and institutional backup, thus generating a holistic and sustainable means of energy to the off-grid areas. Future research programs must focus on longitudinal case studies, incorporate policy models, and assess the requirements and preferences of end-users to support the technical feasibility and advantage of hybrid energy systems to communities, and especially rural and underserved areas [9].

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Note:
The list of 370 references cited in this article has been extracted from the *Publish or Perish* database and has been used extensively in the analysis. This compilation provided a robust foundation for evaluating current trends, gaps, and developments in Hybrid Renewable Energy Systems (HRES) research.

ISSN: 2961-6603