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Hybrid Renewable Energy Solutions for Off-Grid Electrification: A Bibliometric and Analytical Review on Performance and Economic Viability

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***Abstract-* One of the main problems that need to be solved in off-grid regions is providing electricity in Sub-Saharan Africa and certain areas of Asia. Integrating several renewables in HRES systems provides a way to ensure that energy is always available and reasonably priced. This paper reviews research and literature about HRES used for off-grid electrification during the period 2015 to 2025. In this study, we review publication trends by relying on tools VOSviewer and Bibliometrix. This step also looks closely at numbers such as technical performance values and the economics formed by cost calculations. It is found that research interest has gone up, and solar-wind-battery systems have been proven to be the most successful setup. Spite of growth, there is still a gap between regions and not enough on-the-ground observations about the economy. This study gives an overview of the area to policymakers, practitioners, and researchers and points out the most important directions for future studies.**

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

I INTRODUCTION

In total, more than 700 million people are not connected to electricity, and these people are mainly in rural or distant areas of low-income nations [1]. In such areas, adding to the electrical grid isn't possible because the price is too high and space is lacking. So, decentralized energy systems, especially HRES, are now widely seen as a good option [2]. HRES depend on using more than one energy such as solar, wind, biomass, and diesel, along with storage, for always having electricity [3].

Thanks to new technologies, falling solar prices, and more interest from those who fund projects, HRES has advanced [4]. Still, as SETIs are used more, the scientific papers on this topic are not yet organized. It is important to outline research worldwide, pick out top technologies, and check how well and effectively these technologies work in practice and if they are cost-effective [5].

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The gap described is addressed by analyzing and reviewing works related to HRES for off-grid purposes. The goal is to gather studies, mark out trends in different regions and topics, and see how each configuration stands in terms of performance and economic suitability. The questions used as a framework in the study are given below:

- Which global research directions, important tech, and target regions affect HRES in off-grid electricity supply?
- Which performance factors and economical models appear most often, and what is still missing from the academic literature?

II. Literature Review

Hybrid Renewable Energy Systems (HRES) have been widely researched to find a feasible route in solving energy poverty in off-grid regions and remote locations. Their technical feasibility, economic viability and policy relevance provide a multi dimensional literature. HRES usually integrate wind energy, battery storage, diesel generators, and solar photovoltaic (PV) systems as a way of achieving reliability to help overcome the unreliability of renewable energy. HRES, despite an obvious drawback regarding the costs of storage mechanisms, are considered a sustainable solution that would help decrease the relative fossil fuel dependency and increase energy resilience of the underserved areas, thanks to the complementary properties of the renewable sources and the storage means.

To use the hybrid systems in a decentralized energy delivery especially in the rural Africa setting, Suberu et al. [2] gave a background explanation prior to that matter which would be discussed in the final paragraphs. They showed that hybrid systems like solar-wind-diesel-battery systems might go a long way to increase access to energy with a corresponding decrease in energy operating expenditures. In a similar fashion, Siddaiah and Saini [3] presented a comprehensive survey of the planning and optimization methods, by classifying the system architectures according to their flexibility of configuration, modeling assumptions and geographic applicability. In their analysis, they emphasized the value of adaptive and location specific system design in as far as technical and economic performance objectives are concerned.

The emergence of simulation models, such as HOMER, PVsyst, and MATLAB/Simulink, has led to researchers coming up with a more accurage model of system behavior with an array of load profiles and environmental conditions. The HOMER was used by Belmili et al. [6] to determine the techno-economic optimization of PV-wind hybrid systems where it was noted that there are considerable savings of operation costs and enhancement of efficiency with optimal sizing and componentry matching. These kinds of studies indicate how simulation-based planning can augment the actual deployability of the hybrid systems in field applications.

In the economic front, distinct evaluation indicators have come forward that serve as standards of evaluating the feasibility of the systems. Economic competitiveness is commonly calculated by use of Levelized Cost of Energy (LCOE), Net Present Cost (NPC), and internal rate of return (IRR). A land marriage review by Khare et al. [7] considered critical implications of LCOE in HRES systems focus on how the system can cost is dependent on component lifetime, fuel price volatility, and initial investment. Nevertheless, there is usually a lack of post-installation economic verification grounded with empirical data in the literature because majority of the analyses are still limited to simulation or pre-deployment-

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based analysis. This missing link prevents the generation of strong financial models that can be employed in the field.

Although the process of HRES implementation is technically and economically oriented, social aspects of the implementation remain partially lacking. In their article, Singh et al. [8] emphasized the importance of individual stakeholder interaction and community acceptance on causing a successful installation of islanded microgrids in India. However, these revelations are isolated and there exist no heftier structures that interlock user behavior, social norms and institutional capacity. In their article, Galouz and Benhkoma [5] stated that one cannot unswervingly discuss the sustainability of the system without the relation of these socio-institutional aspects with the technical design, which is still under-represented at the mainstream level.

The high rate of evolution of the field is indicated by the emerging research themes. AI and machine learning are becoming more widely used in optimization of energy dispatch, demand-side forecasting, and predictive maintenance. Dynamic level of control found in these technologies is also providing improved level of efficiency as well as reliability specifically on complicated hybrid systems. At the same time, green hydrogen is also becoming an option to long-duration storage. According to the recent research, hydrogen-based systems may be used as a supplement to conventional battery storage in the high-renewable- penetration regions to separate the time and scale of the generation and consumption. To conclude, the literature has already made a major progress in the field of simulation, optimization, and economic evaluation, although it is still disjointed in its technical, economic, and social dimensions. Future study should be one of integration in that engineering innovation has to be made into financial realism and societal all-inclusiveness. This will be pivotal to replicability, scalability and sustainability of HRES across variances of off-grid your contexts.

III.Methodology

3.1 Bibliometric Data Collection We used Google Scholar to collect peer-reviewed literature from 2015 to 2024. The search strategy included combinations of keywords such as: "hybrid renewable energy", "off-grid", "microgrid", "performance", "economic viability".

3.2 Tools and Techniques Bibliometric mapping was conducted using VOSviewer and Publish or Perish 8. Co-authorship networks, keyword co-occurrence, and thematic clusters were extracted.

3.3 Analytical Review Selected high-impact papers from the bibliometric analysis were analyzed for technical performance metrics (e.g., reliability, storage efficiency) and economic indicators (e.g., LCOE, payback period). Case studies and deployment models were also reviewed.

IV. Data Analysis and Results

This study employed bibliometric analysis to examine research trends, thematic clusters, and geographic distributions in hybrid renewable energy systems (HRES) for off-grid electrification. The analysis utilized **VOSviewer** for network visualization and **Publish or Perish** for citation metrics, covering peer-reviewed literature from **2015 to 2025**.

4.1 Bibliometric Trends and Publication Growth

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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
Reference date: 2025-07-14 22:31:16 +0200 **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:

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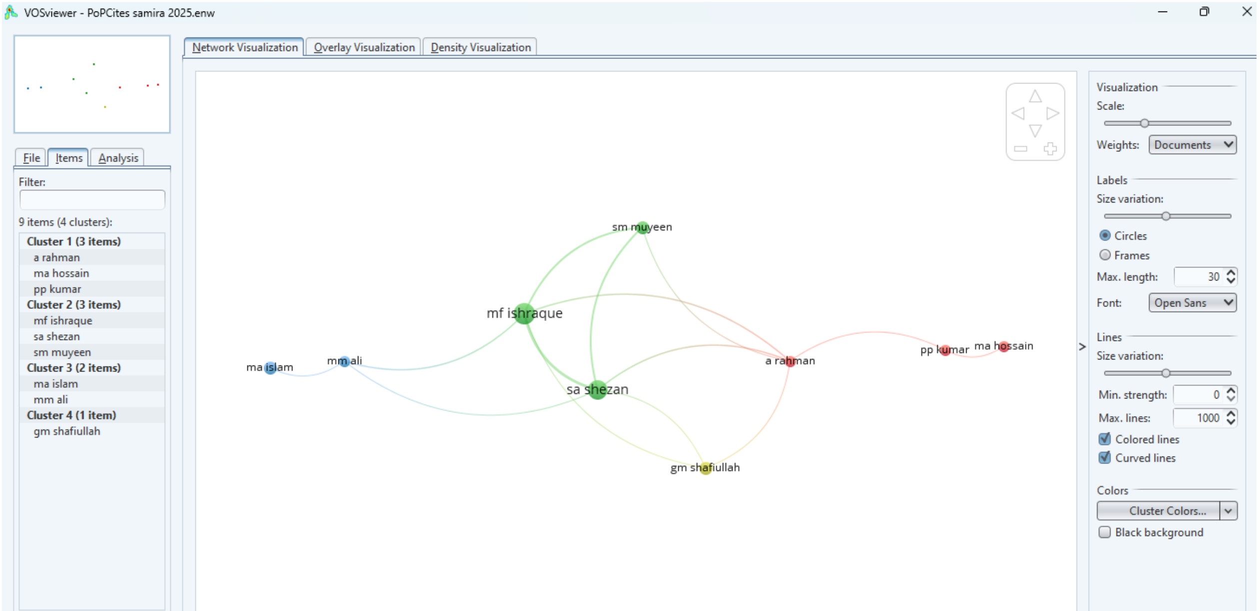

Source: Vosviewer

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.

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.

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.

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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.

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 study points out that there is a swift increase in what we know about off-grid systems utilizing hybrid renewables. The main emphasis on improving efficiency and simulating energy systems is due to the fact that optimization and steady performance are still key issues in this field. The high number of solar-wind-battery systems described in the literature is partly the result of new technologies and lower prices in photovoltaic panels and batteries, opening the door for their use in various places. However, many technological changes are well-described even though using economic analysis in the research does not always lead to new policies and strategies.

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There is significant difference between the initial costs and the final economic outcome. LCOE and payback period are used by many authors, yet very few studies have looked into them through actual monitoring after the installation or the influence on local people's finances. Furthermore, even though community microgrids and PAYG methods are presented in the study, they are studied as separate concepts from the framework of the supporting institutions. For this reason, it's hard to see all the factors at work in such systems, mainly in low-income rural areas, where access to education and markets is not equal among residents.

We can also notice that the distribution of research is not equal globally. Attention to Africa and South Asia is high since these places require a lot of work in the area of electricity. Latin America and Pacific Island countries are not being studied as much as other regions, causing doubts about how balanced today's research is. What's more, turning to interdisciplinary methods that mix social sciences, behavioral research, and official structures would help provide a complete understanding and increase reproduction in different parts of the world. It is necessary for the field to create a connection between technical engineering, evaluating costs, and carrying out plans in political and social environments. It is important to conduct long-term studies that bring together performance results, daily use data, budget for maintenance, and users' opinions. To become real solutions for off-grid electrification, hybrid renewable energy systems need to leave the theoretical level and grow to be widely applied and strong in different settings.

Indeed, the study covers all the main findings on hybrid renewable energy for rural electricity made between 2015 and 2024. There has been a strong increase in publications, which are mainly related to modeling and testing the power system's performance. When it comes to reliability and performance, solar-wind-battery systems are most popular, yet their economic models need further development and validation.

Review of the evidence concludes that while much is promised by HRES, its true reach is reduced by the differences in research activity between regions, the shortage of studies on its economic implications, and insufficient joint efforts of scientists from different fields. To achieve strong deployment, technology, money, and people should be combined in both studies and practice. In the future, it would be beneficial to perform case analyses, use policies for guidance, and consider users' needs to confirm that hybrid energy systems are technically right and beneficial for all.

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