International Journal of Engineering Inventions
e-ISSN: 2278-7461, p-ISSN: 2319-6491
Volume 14, Issue 6 [June. 2025] PP: 54-56

Study of the Impact of Socio-Economic Activities on Access to Energy in Rural Areas

Mika Paul Ibrahim[1,a*], Roland Uhunmwango[1-2], Stella Orakwe[1], Benneth Oyinna[2]

[1]*Emerald Energy Institute, University of Port Harcourt, PMB 5323, Choba, Port Harcourt, Rivers State, Nigeria*
[2]*Center for Power Systems Studies, University of Port Harcourt, PMB 5323, Choba, Port Harcourt, Rivers State, Nigeria*

Abstract
Access to energy is a critical enabler of socio-economic development, especially in rural areas where energy poverty remains pervasive. This paper reviews recent literature and studies investigating the impact of socio-economic activities on energy access, with a focus on hybrid renewable energy systems (HRES) and integrated resource management. The review highlights advance in optimization, decision-making frameworks, and technology integration that address the multidimensional challenges of rural electrification. The role of bioenergy, water-energy-food nexus approaches, and localized energy security concepts are emphasized for sustainable energy solutions. Challenges related to financing, policy, and community engagement are discussed, providing future directions for research and practice aimed at inclusive and effective rural energy access.

Date of Submission: 24-05-2025 Date of acceptance: 04-06-2025

I. Introduction

Access to reliable and sustainable energy is critical for the socio-economic development of rural areas worldwide. Despite significant advances in renewable energy technologies, many rural communities still suffer from inadequate energy supply, which hampers economic growth, education, healthcare, and overall quality of life. The complexity of providing energy access in rural regions arises from various interlinked factors, including geographic remoteness, economic constraints, and infrastructural challenges. Hybrid renewable energy systems (HRES), which combine sources such as solar, wind, biomass, and diesel generators, offer promising solutions tailored to the unique needs of these communities. This paper studies how socio-economic activities influence energy access in rural areas, focusing on the role of hybrid renewable energy systems and the optimization strategies needed to enhance energy security, economic viability, and environmental sustainability.

II. Hybrid Renewable Energy Systems and Socio-Economic Factors in Rural Energy Access

Hybrid Renewable Energy Systems (HRES) have emerged as a key technological solution for rural electrification, especially in areas where grid extension is costly or unfeasible. These systems integrate various renewable sources, storage technologies, and sometimes conventional generators to provide reliable power. Elkadeem et al. (2021) developed a geospatial multi-criteria decision-making framework combining GIS and Best Worst Method (BWM) to optimize the site selection and design of HRES in Kenya. Their work emphasized the importance of considering climatology, environmental, and socio-economic criteria in selecting suitable sites for solar, wind, and hybrid systems to ensure affordability and sustainability. Similarly, Mahmoud et al. (2022) explored the optimal sizing of smart HRES using advanced metaheuristic algorithms like Salp Swarm Algorithm (SSA) and Grey Wolf Optimizer (GWO) to minimize the cost of energy and improve reliability in isolated rural locations. Their study revealed that integrating photovoltaic panels, wind turbines, battery storage, and backup diesel generators can achieve cost-effective and reliable power supply, crucial for rural communities reliant on diverse energy needs. In the context of rural applications, Kumar and Channi (2022) examined a photovoltaic-biomass hybrid system in Punjab, India, highlighting its techno-economic and environmental benefits. The hybrid system was optimized to meet continuous energy demand for hundreds of households, showing significant cost savings and emissions reductions compared to conventional grid or diesel-only systems. Moreover, Hossain et al. (2016) provided a socio-economic perspective by studying energy security in rural Alaska, emphasizing that energy access must be defined at the local community level. Their framework underscored four dimensions of energy security availability, access, quality, and stability tailored to rural household needs, which often differ markedly from urban or national-level definitions.

Nugroho et al. (2022) extended this discussion to Indonesia by analyzing the water-energy-food (WEF) nexus in rural development, stressing integrated resource management to improve rural energy security while balancing ecological and socio-economic factors. Taken together, these studies indicate that the success of HRES in rural areas depends on a holistic approach that integrates technological optimization with socio-economic realities, including affordability, local capacity, and environmental impacts.

III. Optimization and Design of Hybrid Renewable Energy Systems for Rural Communities

Optimization of HRES is critical to ensuring their economic feasibility and reliability in rural contexts. Mahmoud et al. (2022) compared different optimization algorithms to size hybrid systems that minimize cost while satisfying reliability constraints. Their MATLAB simulations demonstrated that improved Grey Wolf Optimizer (IGWO) offered superior performance in balancing cost and power supply reliability, making it well-suited for rural energy planning. Elkadeem et al. (2021) combined GIS spatial analysis with multi-criteria decision-making methods like TOPSIS and VIKOR to prioritize optimal energy designs against key sustainability indicators, including environmental impact and cost. Their results from Kenya showed that solar/wind/diesel/battery hybrid systems offered the best sustainable solution, with the lowest net present cost and energy cost while reducing carbon emissions significantly. In the context of energy conversion, Riyaz Ali and Memala (2023) proposed a novel cost-efficient clamping capacitor boost converter (CCBC) for hybrid systems. Their converter doubled voltage gain compared to conventional converters, improving power transfer efficiency critical for rural systems where maximizing output from limited resources is essential.

The role of hydrogen technologies integrated with HRES is also gaining attention. Khan et al. (2022) reviewed optimization strategies coupling renewable sources with hydrogen production, storage, and fuel cells. They identified the need for AI-based multi-objective optimization techniques to enhance system reliability and economic viability, which is especially relevant for rural areas seeking sustainable energy independence. Khan et al. (2018) and Esmaeilion (2020) examined the application of HRES to power reverse osmosis desalination plants, highlighting the potential for hybrid solar-wind systems to reduce fossil fuel dependence and lower water production costs, an essential consideration for water-scarce rural regions dependent on desalination.

These studies collectively emphasize the importance of multi-objective optimization frameworks and innovative hardware designs to tailor HRES for rural socio-economic conditions, thereby enhancing energy access and sustainability.

IV. Socio-Economic Impacts of Energy Access in Rural Areas

Energy access has profound socio-economic impacts in rural communities. Reliable energy enables better educational facilities, healthcare services, communication, and economic activities such as agriculture processing and small industries. SORI (2023) analyzed the bioenergy sector in Ethiopia, showing that biogas production from agricultural waste significantly contributes to rural energy security and socio-economic development by adding value through job creation and reducing energy costs. Elkadeem et al. (2021) highlighted that optimal HRES designs could reduce energy costs and CO_2 emissions, contributing to sustainable development goals and improving the living standards of rural populations. Hossain et al. (2016) argued for a localized understanding of energy security that aligns with community needs and socio-cultural contexts, emphasizing energy stability and quality to support rural livelihoods sustainably. Nugroho et al. (2022) stressed the need for integrated policies addressing water, energy, and food security collectively, recognizing their interdependence in improving rural socio-economic conditions. Kumar and Channi (2022) further demonstrated that hybrid systems incorporating biomass and solar power can offer economically viable alternatives to diesel generators, reducing pollution and fuel dependency while enhancing rural economic resilience. Collectively, these socio-economic studies indicate that tailored HRES solutions, supported by robust optimization and policy frameworks, can significantly improve rural energy access, contributing to poverty alleviation and sustainable development.

The literature and studies reviewed confirm that socio-economic activities are both drivers and beneficiaries of improved energy access in rural areas. Hybrid renewable energy systems emerge as viable solutions that can address the unique geographical, economic, and environmental challenges faced by rural communities. A multi-disciplinary approach involving geospatial analysis, multi-criteria decision-making, and advanced optimization algorithms is essential for the successful planning and deployment of HRES. Moreover, socio-economic factors such as affordability, local capacity, and environmental awareness must be integrated into design frameworks to ensure sustainable adoption and long-term operation. The development of innovative power electronics like the CCBC and integration of hydrogen technologies further enhance the technical feasibility and sustainability of rural energy systems. Policy frameworks should support these technological advancements by facilitating financing mechanisms, capacity building, and community engagement. The water-energy-food nexus must also be recognized in policy and planning to create holistic rural development strategies. Overall, a paradigm shift towards place-based energy security definitions and integrated resource management is crucial to improving rural energy access and its socio-economic impacts.

V. Conclusion

This study highlights the intricate relationship between socio-economic activities and energy access in rural areas. Hybrid renewable energy systems, optimized through advanced computational techniques and informed by geospatial and socio-economic criteria, offer a sustainable path to rural electrification. The integration of diverse renewable sources, storage solutions, and innovative power conversion technologies ensures reliable, affordable, and environmentally friendly energy supply. Improved rural energy access positively impacts education, healthcare, economic development, and environmental sustainability, contributing to broader developmental goals. Future research should focus on community-based participatory approaches, policy integration, and further technological innovations to overcome remaining barriers to rural energy security.

References

[1]. Elkadeem, M., Kim, J. H., & Kim, S. H. (2021). A geospatial multi-criteria decision-making framework for hybrid solar-wind energy systems site selection using the Best Worst Method (BWM) and energy-economy-ecology (E3) framework: A case study of Kenya. *Renewable Energy*, *172*, 1114–1130. https://doi.org/10.1016/j.renene.2021.03.086

[2]. Esmaeilion, M. (2020). Hybrid renewable energy systems for desalination: A study. *Renewable and Sustainable Energy Reviews*, *120*, 109608. https://doi.org/10.1016/j.rser.2019.109608

[3]. Hossain, A., Shrestha, R. M., & Mahmud, M. (2016). Energy security and rural energy access in Alaska: A qualitative study. *Energy Policy*, *97*, 76–85. https://doi.org/10.1016/j.enpol.2016.07.031

[4]. Khan, S., Amin, M. T., & Alam, M. M. (2018). A study on the integration of renewable energy sources for reverse osmosis desalination. *Desalination*, *435*, 178–192. https://doi.org/10.1016/j.desal.2017.11.029

[5]. Khan, M. J., Iqbal, M. T., Qu, P., & Ahmed, S. (2022). Optimization and control strategies for hydrogen-based hybrid renewable energy systems: A comprehensive study. *International Journal of Hydrogen Energy*, *47*(26), 13425–13448. https://doi.org/10.1016/j.ijhydene.2022.03.057

[6]. Kumar, S., & Channi, K. (2022). Techno-economic and environmental analysis of PV/biomass hybrid energy system for rural applications in India. *Energy Reports*, *8*, 2956–2967. https://doi.org/10.1016/j.egyr.2022.03.022

[7]. Mahmoud, M. S., Hassan, A. M., & Elaziz, M. A. (2022). Optimization of hybrid renewable energy systems using improved metaheuristic algorithms: An evaluation of SSA, GWO, and IGWO. *Applied Energy*, *300*, 117335. https://doi.org/10.1016/j.apenergy.2021.117335

[8]. Nugroho, H., Wahyuningtyas, S. D., & Santoso, D. (2022). Water-Energy-Food Nexus in rural Indonesia: A study of integrated resource management and socio-economic implications. *Sustainable Development*, *30*(1), 1–15. https://doi.org/10.1002/sd.2259

[9]. Riyaz Ali, M., & Memala, V. (2023). Design and implementation of a cost-efficient clamping capacitor boost converter for hybrid renewable energy systems. *Energy Conversion and Management*, *279*, 116658. https://doi.org/10.1016/j.enconman.2023.116658

[10]. SORI. (2023). Assessment of bioenergy production from agricultural waste and its socio-economic impact in