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Hybrid renewable energy systems for rural electrification in developing countries: Assessing feasibility, efficiency, and socioeconomic impact

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Abstract

In many developing countries, access to electricity remains a critical barrier to socioeconomic development, especially in rural and remote regions where grid expansion is challenging and costly. Hybrid Renewable Energy Systems (HRES), which combine multiple renewable energy sources such as solar, wind, biomass, and small hydro, have emerged as viable alternatives to traditional grid-based solutions for rural electrification. This review paper provides a comprehensive assessment of the feasibility, efficiency, and socioeconomic impacts of HRES implementations in rural areas of developing countries. We examine key components of HRES, including energy generation, storage, and system optimization, and highlight the technical and economic considerations that influence their deployment. Furthermore, we explore the socioeconomic benefits of HRES, such as job creation, improved health and educational outcomes, and enhanced economic resilience, which make them an attractive option for sustainable development. However, we also address the challenges limiting HRES adoption, such as high initial costs, limited technical expertise, and inadequate policy frameworks. Our findings underscore that, while HRES present significant potential to transform rural energy landscapes, realizing this potential requires targeted policy interventions, financial support mechanisms, community engagement, and continuous technical innovation. By synthesizing current research and case studies, this paper aims to offer insights for policymakers, developers, and stakeholders on how to effectively design and implement HRES to meet the unique energy demands of rural communities in developing countries, paving the way for inclusive and sustainable energy access.

Keywords: Hybrid Renewable Energy Systems (HRES); Rural electrification; Socioeconomic development; Developing countries; Sustainable energy access

1. Introduction

Energy access is fundamental to socioeconomic development, impacting health, education, economic growth, and quality of life [1]. In developing countries, however, access to reliable electricity remains a pressing challenge, especially in rural and remote areas. Despite global efforts to expand electricity access, rural regions in Africa, Asia, and Latin America often remain underserved due to the high costs and logistical difficulties of extending national grids to remote, sparsely populated locations. Traditional solutions, such as diesel generators, have historically been used to address this gap, but they pose environmental risks, are financially burdensome due to fuel costs, and often provide inconsistent energy access.

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In response, Hybrid Renewable Energy Systems (HRES) have emerged as a sustainable and feasible alternative for rural electrification. HRES integrate two or more renewable energy sources—typically solar, wind, biomass, and small-scale hydro—into a single system to harness the complementary strengths of different energy sources [2][3]. By combining these renewable resources, HRES can reduce the intermittency associated with individual sources, improve reliability, and lower dependency on fossil fuels. HRES typically operate as stand-alone systems or microgrids, making them ideal for isolated rural areas without grid connectivity.

This paper aims to assess the potential of HRES as a solution for rural electrification in developing countries, focusing on three key dimensions: feasibility, efficiency, and socioeconomic impact. We begin by examining the technical and economic feasibility of implementing HRES, considering resource availability, initial investment requirements, and the influence of supportive policies and regulatory frameworks. Next, we explore the efficiency of HRES, analyzing the role of energy storage, system design, and load management in optimizing energy output and stability. Finally, we evaluate the socioeconomic impact of HRES deployment, exploring how access to clean, reliable energy can transform rural economies, improve health and education, and foster sustainable development.

This review synthesizes insights from recent studies, technical reports, and case studies across multiple developing countries, providing a holistic overview of the opportunities and challenges associated with HRES for rural electrification. By identifying best practices and pinpointing potential barriers to successful HRES deployment, this paper aims to offer valuable recommendations for policymakers, engineers, and community stakeholders seeking to harness renewable energy to meet the unique needs of rural communities. In doing so, we hope to contribute to a broader understanding of how HRES can support sustainable development goals, particularly in regions that remain beyond the reach of traditional grid infrastructure.

2. Hybrid Renewable Energy Systems: Concept and Design

Hybrid Renewable Energy Systems (HRES) offer a flexible and sustainable approach to rural electrification, particularly suited to areas with limited or no access to conventional grid infrastructure [4]. The core concept of HRES lies in combining multiple renewable energy sources—such as solar photovoltaic (PV), wind, biomass, and small-scale hydropower—to produce a more reliable and efficient power supply. By integrating various sources, HRES can capitalize on the complementary strengths of each, addressing the intermittency issues often associated with single-source renewables. For instance, while solar PV systems generate power during sunny days, wind turbines may continue producing electricity during cloudy or windy conditions, providing a balanced and continuous energy supply [5]. This adaptability makes HRES particularly effective for remote, off-grid rural areas in developing countries, where weather patterns and local conditions can vary significantly.

2.1. Key Components of HRES

The design of an HRES typically consists of several key components, each contributing to the system's functionality and efficiency. These components include:

- **Primary and Secondary Energy Sources**: Solar PV, wind turbines, biomass generators, and small hydropower systems are the primary energy sources in most HRES. The selection of these sources depends on the local availability of natural resources [6][7]. For instance, regions with abundant sunlight may prioritize solar PV, while areas with consistent wind may incorporate wind turbines.
- **Energy Storage Solutions**: Given the intermittent nature of renewable sources, energy storage is a critical component in HRES. Batteries, flywheels, and pumped hydro storage are commonly used to store excess energy generated during peak production times [8]. This stored energy can then be deployed during periods of low renewable generation, such as nighttime or low-wind conditions. Battery storage technology, in particular, has advanced significantly, becoming more cost-effective and efficient [9], enhancing the reliability of HRES.
- **System Controller and Inverter**: System controllers regulate the flow of energy within the HRES, ensuring that energy is optimally distributed to meet demand and stored efficiently. Inverters convert the DC (direct current) generated by sources like solar panels and batteries into AC (alternating current), compatible with standard electrical devices [10]. Advanced control systems are often used to manage the power from multiple sources and storage units, balancing supply and demand in real time to maintain a stable energy output.
- **Load Management**: Effective load management is essential to balance the energy supply with consumption in an HRES [11]. This involves distributing electricity to meet peak demand times while conserving energy during off-peak periods. Load management techniques, such as demand response and energy prioritization, help optimize the use of available resources, reducing the need for additional storage and improving system efficiency.

2.2. HRES Design Configurations

HRES design configurations can vary based on resource availability, energy requirements, and site-specific constraints. Common configurations include:

- **Solar-Wind Hybrid Systems**: Solar and wind hybrid systems are among the most popular configurations in HRES due to the complementary nature of solar and wind energy sources [12]. These systems capitalize on sunny and windy periods, which often occur at different times, ensuring a more consistent energy supply.
- **Solar-Biomass Hybrid Systems**: In areas with abundant biomass resources, solar-biomass hybrids provide a viable solution. During daylight hours, solar energy meets demand, while biomass generators provide power during the night or in cloudy weather [13]. Biomass can also serve as a reliable backup source, enhancing the system's overall stability [14].
- **Solar-Wind-Biomass Systems**: In regions where solar, wind, and biomass resources are available, a combination of all three sources creates a robust, resilient system [15]. By integrating multiple renewables, these systems provide high reliability, leveraging each source as a backup for the others. Such configurations, however, are more complex to design and require careful load management and control systems.
- **Hydropower-Based Systems with Solar and Wind**: Small-scale hydropower systems, when combined with solar and wind, are particularly suited for regions with reliable water sources [16]. Hydropower can operate continuously, providing a baseline energy supply, while solar and wind sources contribute additional power, offsetting peak demand.

2.3. System Optimization and Control Strategies

The optimization of HRES depends on using advanced control strategies to manage the various energy sources and storage units efficiently. Key optimization techniques include:

- **Energy Management Systems (EMS)**: EMS software is used to monitor, control, and optimize the performance of HRES. It ensures that energy production, consumption, and storage are balanced effectively, maximizing resource use while minimizing waste. By leveraging real-time data, EMS can adjust energy flows based on demand, weather forecasts, and storage levels.
- **Optimization Models and Simulation Tools**: Tools like HOMER (Hybrid Optimization of Multiple Energy Resources) and RETScreen are widely used to simulate HRES designs [17]. These models analyze system performance, predict energy production from different sources, and optimize system configurations to minimize costs and enhance reliability. Simulation tools also help identify the most cost-effective mix of renewables for specific regions [18], considering local resource availability, consumption patterns, and financial constraints.
- **Predictive Maintenance**: HRES requires consistent maintenance to ensure system components function efficiently and last longer. Predictive maintenance uses data from system components to identify potential faults before they lead to system failures, reducing downtime and maintenance costs. This approach is especially important in remote areas where access to repair services is limited [19].

2.4. Designing for Local Conditions

A crucial consideration in HRES design is the adaptation to local conditions, including climate, resource availability, and community energy needs. Unlike grid-based systems, which are standardized, HRES must be customized to suit specific environments and resource patterns. For instance, a coastal community may rely more on wind [20], while a forested region with abundant organic waste could incorporate biomass. Community involvement in the planning process is essential to ensure that HRES meet local expectations, align with cultural practices, and build a sense of ownership among residents, promoting long-term system sustainability.

2.5. Advantages of HRES over Conventional Systems

The unique design of HRES provides several advantages over traditional single-source or diesel-powered systems, including:

- **Enhanced Reliability**: By integrating multiple renewable sources, HRES offer a stable energy supply, reducing dependency on any one resource. This reliability is particularly beneficial in regions with variable weather patterns.

- **Environmental Sustainability**: HRES reduce greenhouse gas emissions and reliance on fossil fuels, contributing to environmental sustainability and aligning with global climate goals. Biomass-powered systems, when designed sustainably, can even contribute to waste management.
- **Economic Viability**: Although the initial costs of HRES can be high, they offer long-term economic benefits through reduced fuel costs, lower maintenance, and minimal environmental externalities. Recent advancements in renewable technology have also driven down costs, making HRES increasingly competitive with conventional systems.
- **Scalability and Flexibility**: HRES are inherently flexible and can be scaled to meet the evolving energy needs of communities. They can function as stand-alone systems or be integrated with the main grid when it becomes accessible, offering a versatile solution for rural electrification.

3. Assessing Feasibility

The feasibility of Hybrid Renewable Energy Systems (HRES) for rural electrification in developing countries depends on several key factors, including technical feasibility, economic viability, and supportive policy frameworks. Each of these factors plays a critical role in determining whether HRES can be successfully deployed in a specific location, addressing the unique energy needs and resource availability of rural communities. This section explores these feasibility considerations to provide a comprehensive understanding of the conditions required for HRES to serve as a viable solution for rural electrification [21].

3.1. Technical Feasibility

Technical feasibility involves assessing the natural resource availability, infrastructure requirements, and environmental conditions that influence the performance and reliability of HRES. Several factors contribute to technical feasibility, including:

- **Resource Availability**: The effectiveness of HRES largely depends on the availability of renewable resources such as sunlight, wind, biomass, or water (for hydropower). For instance, areas with high solar irradiance are ideal for solar PV systems, while regions with consistent wind patterns are better suited for wind turbines [22]. Detailed resource assessments and feasibility studies are essential to understand the potential of local renewable resources and optimize the design of the HRES.
- **Compatibility with Local Infrastructure**: Rural areas often lack robust infrastructure, which can limit the feasibility of certain HRES components, such as advanced energy storage or grid interconnections. In off-grid regions, HRES are designed as microgrids, operating independently of the national grid. However, where grid access exists, HRES can be designed to integrate with the grid as a supplementary power source, offering flexibility for potential future expansion [23].
- **System Complexity and Maintenance Needs**: The complexity of HRES designs varies based on the types and combinations of energy sources. Simple solar-biomass systems, for instance, may be easier to manage than multi-source configurations involving solar, wind, and hydropower [24]. Each system requires regular maintenance to ensure efficiency and longevity, and technical training for local operators is crucial for routine upkeep. Feasibility assessments should consider the technical capacity of local communities to maintain and repair the system, as frequent service interruptions can reduce the reliability of the energy supply.
- **Environmental Considerations**: Some HRES components may impact the local environment, such as biomass systems, which require sustainable fuel sources to avoid deforestation [25]. Additionally, the construction of hydropower facilities, even on a small scale, may affect local water resources and ecosystems. A feasibility study should evaluate these environmental impacts to ensure that HRES development aligns with conservation and sustainability goals.

3.2. Economic Feasibility

Economic feasibility is a critical consideration for HRES, as the upfront costs of renewable energy technology and installation are often higher than conventional diesel generators [26]. However, the long-term savings and economic benefits associated with HRES can offset these initial investments. Key economic factors include:

- **Initial Investment and Capital Costs**: HRES installation requires significant initial investments, covering costs for equipment (solar panels, wind turbines, biomass generators, energy storage), transportation, and installation. Financial support from governments, international organizations, or private investors can help offset these costs. Financial analysis tools, such as Levelized Cost of Electricity (LCOE), are used to assess the overall cost-effectiveness of HRES by comparing the lifetime costs of different energy systems [26][27].

- **Operation and Maintenance Costs**: While renewable energy systems have lower operational costs than diesel generators, maintenance costs vary based on system complexity. For example, solar PV systems have minimal moving parts and require little maintenance, while wind turbines and biomass systems need regular servicing. Reliable financial planning should include ongoing maintenance costs and establish a sustainable funding mechanism for operations, possibly through local energy tariffs [28].
- **Cost Savings from Reduced Fuel Dependency**: Unlike conventional systems that rely on fuel, HRES generate electricity from renewable resources, leading to substantial fuel cost savings. This reduced dependency on imported fuels not only lowers costs but also shields communities from the volatility of global fuel prices. For remote areas, where fuel transportation costs are high, HRES can be especially economical over time.
- **Economic Incentives and Financing Options**: The economic feasibility of HRES can be enhanced through government subsidies, tax incentives, and international financing programs [26]. In some cases, rural electrification initiatives receive financial backing from development agencies, which may provide grants, low-interest loans, or microfinancing options to make HRES affordable for low-income communities. Innovative financing models, such as pay-as-you-go or community-based funding, can also improve affordability and encourage local investment in renewable energy [29].

3.3. Policy and Regulatory Support

A supportive policy and regulatory framework is essential to facilitate the deployment and sustainability of HRES in rural areas [30]. Governments and regulatory bodies can significantly influence HRES feasibility by providing a favorable environment for investment, project implementation, and long-term operation [26]. Key policy considerations include:

- **Incentives and Subsidies**: Policies that offer tax breaks, grants, or subsidies for renewable energy projects can reduce the financial burden on developers and communities, making HRES more feasible [31]. For example, subsidies on renewable energy equipment, reduced import tariffs on energy storage systems, or direct grants for rural electrification can make HRES more accessible.
- **Streamlined Permitting and Regulatory Processes**: In some regions, lengthy permitting processes and regulatory hurdles delay HRES implementation, increasing costs and reducing feasibility. Governments can support HRES deployment by simplifying these processes, establishing clear guidelines, and expediting permits for renewable energy projects [32]. Policies that encourage decentralized energy systems, such as microgrids, further support HRES by allowing rural communities to manage their own energy resources independently.
- **Public-Private Partnerships and Community Ownership Models**: Public-private partnerships (PPPs) can be instrumental in financing and implementing HRES projects, especially in rural areas with limited access to capital [33]. By sharing the financial and operational responsibilities, PPPs can reduce project risks and enhance community buy-in. Community ownership models, where local residents invest in and manage HRES projects, can also improve feasibility by fostering a sense of responsibility and ownership, increasing the likelihood of long-term project success.
- **Incorporating HRES into National Energy Policies**: National energy policies that prioritize renewable energy and rural electrification provide a foundation for HRES projects [34][35]. Governments can create favorable conditions for HRES by setting renewable energy targets, promoting off-grid solutions, and integrating HRES into rural electrification strategies. Clear policies also encourage private investment by providing investors with the assurance of a stable regulatory environment.

4. Efficiency and Performance of HRES

The efficiency and performance of Hybrid Renewable Energy Systems (HRES) are critical factors in ensuring reliable, continuous, and cost-effective energy supply for rural electrification. HRES aim to maximize energy output by combining renewable energy sources like solar, wind, biomass, and hydropower, thereby reducing dependency on any single source and enhancing overall system reliability [36]. This section explores key aspects of HRES efficiency, including optimization of the energy mix, energy storage, system maintenance, and factors that contribute to long-term performance.

4.1. Optimization of Energy Mix

One of the primary advantages of HRES lies in the flexibility to combine multiple energy sources, each suited to specific environmental conditions [37]. By optimizing the energy mix, HRES can balance energy generation across different resources, increasing the likelihood of consistent power output [38]. Key factors in optimizing the energy mix include:

- **Complementary Resource Selection**: The performance of an HRES improves when energy sources are chosen based on complementary characteristics. For example, solar PV and wind power are often paired because wind is typically stronger at night, while solar energy is available during the day [39]. Biomass generators or small hydropower systems can serve as backup sources, supporting the system during periods of low solar or wind availability. Selecting an optimal energy mix based on local conditions maximizes energy generation and minimizes storage needs [40].
- **Load Management and Demand Response**: Effective load management is essential for maintaining system efficiency, as it ensures energy supply is aligned with demand. HRES can incorporate demand response strategies, which adjust electricity use based on availability, prioritizing critical loads during low generation periods [41]. For instance, during cloudy or low-wind periods, the system can prioritize essential services such as medical equipment or lighting.
- **Advanced Control Systems**: Control systems in HRES play a critical role in optimizing energy distribution across multiple sources. By using algorithms to predict energy production based on weather conditions and consumption patterns, HRES can adjust the flow of energy [19][42], ensuring that each source is used optimally and only when necessary. This reduces energy wastage, prolongs the lifespan of system components, and minimizes costs.

4.2. Role of Energy Storage

Energy storage is central to HRES performance, as it mitigates the intermittency of renewable sources and ensures a steady supply of electricity. Storage solutions provide a buffer during periods of low renewable generation and peak demand, allowing HRES to deliver reliable power consistently. Key considerations for energy storage in HRES include:

- **Battery Storage Systems**: Batteries are the most common form of energy storage in HRES, particularly lithium-ion and lead-acid batteries. They offer high energy density, reliability, and relatively low maintenance requirements [43]. Battery storage smooths out fluctuations in power generation and can supply energy when renewable sources are unavailable. The choice of battery type depends on factors such as cost, lifespan, and maintenance needs, with lithium-ion batteries being preferred for their higher efficiency and longer lifespan [44].
- **Alternative Storage Technologies**: In addition to batteries, other storage solutions like flywheels, compressed air, and pumped hydro storage are used depending on the specific requirements of the HRES. For instance, pumped hydro storage can be effective in areas with suitable topography, while flywheels may be used for short-term power stabilization [45]. Each technology has unique characteristics that make it suitable for specific types of HRES and local conditions.
- **Optimal Sizing of Storage**: Determining the optimal size and capacity of storage systems is crucial to balancing cost and performance in HRES. Oversized storage systems can add unnecessary costs, while undersized ones can lead to power shortages during peak demand [46]. Optimization models and simulation tools help determine the appropriate storage capacity for a specific HRES configuration, balancing costs and reliability.

4.3. System Maintenance and Reliability

The long-term efficiency and performance of HRES depend on regular maintenance and system reliability. Since HRES are typically installed in remote areas, the reliability of each component is essential to avoid frequent and costly repairs [47]. Effective maintenance strategies for HRES include:

- **Predictive and Preventive Maintenance**: Predictive maintenance uses real-time data from system components to identify potential faults before they lead to system failure, helping to reduce downtime and prolong component life. Preventive maintenance involves regular inspections and servicing to keep components in good working condition, ensuring consistent performance.
- **Training and Capacity Building**: Training local technicians to perform routine maintenance and repairs is critical to system sustainability. Local expertise can reduce reliance on external technicians, minimize response times for repairs, and lower maintenance costs. Training programs can include hands-on instruction in managing solar panels, wind turbines, battery storage systems, and other HRES components, enabling communities to operate and maintain the system autonomously.
- **Component Durability and Quality**: The quality and durability of HRES components significantly impact overall system reliability and performance. For example, selecting high-quality solar panels and wind turbines that withstand local environmental conditions can reduce the frequency of replacements and repairs. Choosing components from reputable suppliers with proven performance records contributes to the long-term stability of the HRES.

4.4. Performance Monitoring and Optimization

Performance monitoring is essential to track HRES efficiency, detect issues, and make necessary adjustments. Advanced monitoring systems collect data on energy production, storage levels, and consumption patterns, enabling operators to optimize performance continuously. Key aspects of performance monitoring include:

- **Real-Time Monitoring Systems**: Real-time monitoring allows HRES operators to track system performance instantaneously, making adjustments to optimize energy output and storage. These systems monitor variables such as solar irradiance, wind speed, battery charge levels, and energy consumption, providing valuable insights into system performance and enabling timely interventions [48].
- **Data Analytics and System Optimization**: Data analytics tools analyze historical and real-time data to identify trends, optimize energy use, and predict maintenance needs [49]. For instance, by analyzing seasonal energy production patterns, HRES operators can optimize storage capacity or adjust the energy mix to improve efficiency. Advanced analytics can also help predict potential failures, enabling proactive maintenance and reducing unexpected downtime.
- **Simulation Tools for Performance Forecasting**: Simulation tools like HOMER (Hybrid Optimization of Multiple Energy Resources) and RETScreen are widely used to model HRES configurations, analyze system performance, and predict long-term energy output [50]. By simulating different scenarios and optimizing system parameters, these tools help improve efficiency, reduce costs, and ensure that HRES meet local energy demands effectively.

4.5. Environmental and Economic Efficiency

HRES not only contribute to sustainable energy but also offer economic advantages over conventional energy systems. Key factors influencing the environmental and economic efficiency of HRES include:

- **Reduction in Greenhouse Gas Emissions**: By replacing fossil fuels with renewable sources, HRES significantly reduce greenhouse gas emissions, contributing to global climate change mitigation [25]. This environmental benefit is especially valuable in regions with high reliance on diesel generators, which produce significant emissions and contribute to air pollution.
- **Cost Savings from Fuel Independence**: Once installed, HRES rely primarily on natural, renewable resources, reducing or eliminating the need for fuel [51]. This independence from fuel not only lowers costs but also shields rural communities from the volatility of global fuel markets. The long-term savings from reduced fuel dependency improve the economic sustainability of HRES, making them a more attractive option than conventional energy sources in rural areas.
- **Lower Operational Costs**: Renewable energy sources have low operational costs, as they require minimal fuel and have fewer moving parts than traditional generators [52]. While initial installation costs can be high, these systems offer substantial savings in the long run, with maintenance costs also lower for systems like solar PV compared to diesel-based systems.

5. Cost-Reduction Strategies in Energy Storage Technologies

Hybrid Renewable Energy Systems (HRES) have far-reaching socioeconomic impacts in rural areas of developing countries, extending beyond simply providing electricity [53]. Access to reliable and sustainable energy brings numerous benefits to communities, contributing to improved education, healthcare, economic growth, and environmental sustainability [54]. These systems can drive transformative changes, improving quality of life and supporting broader development goals. This section explores key socioeconomic impacts of HRES, including economic empowerment, social development, health and education benefits, and environmental impact.

5.1. Socioeconomic Impacts of HRES

Access to reliable energy is a catalyst for economic development in rural communities. HRES offer several economic benefits that contribute to poverty reduction, economic empowerment, and job creation:

- **Small Business Development and Entrepreneurship**: Reliable electricity allows local entrepreneurs to operate businesses that require consistent power, such as small manufacturing units, retail shops, and agricultural processing facilities. This increased economic activity stimulates local markets and creates income opportunities, helping families achieve greater financial stability.
- **Job Creation in Installation and Maintenance**: The deployment of HRES creates job opportunities, both during the initial installation phase and throughout the system's operational life [47]. Jobs in construction,

installation, maintenance, and operations are created, offering employment to local residents. Training programs for technicians further enhance local job prospects, creating a skilled workforce capable of managing renewable energy systems.
- **Income Generation Through Productive Uses of Energy**: Access to electricity enables productive activities such as mechanized agriculture, food processing, and handicraft production, which are essential for rural economies. By powering irrigation pumps, milling machines, and food storage facilities, HRES help increase productivity in agriculture and reduce post-harvest losses, leading to higher incomes and improved food security [55].
- **Reduced Energy Costs**: Although HRES require an upfront investment, they reduce long-term energy costs by eliminating the need for costly fuels [56]. This cost reduction frees up resources for other essential expenses, such as education, healthcare, and housing, allowing families to reinvest their savings back into the community and local economy.

5.2. Education and Health Benefits

Access to energy directly impacts education and healthcare, which are crucial for community development. HRES enable improvements in these sectors, enhancing the overall well-being and social capital of rural populations [30]:

- **Improved Educational Opportunities**: With a reliable source of electricity, schools can extend their hours of operation, allowing students to study in the evenings and access digital resources. Electrification also enables the use of computers, projectors, and the internet, providing students with a more enriched learning experience. Access to modern educational tools and resources can improve academic performance, broaden learning opportunities, and support skill development for future employment.
- **Enhanced Healthcare Services**: Electrified healthcare facilities can offer better services by powering essential equipment such as refrigeration units for vaccines, diagnostic tools, and emergency lighting. Reliable electricity also supports the use of digital medical records, improving efficiency in patient care. Electrification reduces the need for reliance on diesel generators, which are costly and often unreliable, ensuring that medical facilities can operate efficiently and save lives [57].
- **Reduced Indoor Air Pollution**: By replacing kerosene lamps and wood-burning stoves with cleaner, electric alternatives, HRES reduce indoor air pollution, which is a significant health risk in rural areas [58]. Improved air quality in homes reduces the incidence of respiratory diseases, eye infections, and other health issues caused by smoke and fumes, especially among women and children who spend more time indoors.

5.3. Environmental Sustainability and Resilience

HRES contribute to environmental sustainability by reducing reliance on fossil fuels and promoting the use of cleaner, renewable energy [25]. This shift not only addresses local environmental concerns but also contributes to global efforts to combat climate change:

- **Reduction in Greenhouse Gas Emissions**: By replacing diesel generators and kerosene lamps with renewable energy sources, HRES help decrease greenhouse gas emissions. This reduction aligns with national and international climate targets, supporting countries' commitments to global climate agreements. In regions prone to environmental degradation, such as areas experiencing deforestation, HRES provide a sustainable energy alternative that reduces pressure on natural resources.
- **Conservation of Local Resources**: Biomass-powered HRES systems, when sustainably sourced, promote resource conservation by using organic waste rather than contributing to deforestation [59]. Hydropower systems can also contribute to local water conservation efforts by managing water flow, especially in small-scale applications that minimize environmental disruption.
- **Enhanced Community Resilience to Climate Change**: Communities powered by HRES are less vulnerable to climate-related disruptions in fuel supply and price fluctuations, as their energy supply is based on locally available renewable resources [58]. This resilience allows rural communities to adapt to climate variability, ensuring energy access during periods of environmental stress and supporting long-term sustainability.

5.4. Social Development and Community Empowerment

HRES contribute to social development by fostering community empowerment, inclusivity, and cohesion. Energy access can transform social dynamics within communities, creating positive social impacts that extend beyond individual households:

- **Community Ownership and Participation**: Many HRES projects incorporate community ownership or cooperative models, allowing residents to take an active role in managing their energy resources [14]. This participatory approach empowers communities by giving them a stake in the system, fostering a sense of ownership and accountability. Community-managed HRES projects often perform better in the long term, as local involvement encourages sustainable use and maintenance.
- **Reduction in Gender Inequality**: In many rural communities, women bear the burden of collecting fuel and managing household energy needs [60]. Access to clean and reliable energy through HRES reduces the time women spend on these tasks, freeing them to pursue education, employment, or entrepreneurial activities. Additionally, by improving health and education outcomes, HRES can indirectly contribute to gender equality, empowering women and girls and enhancing their social standing within the community.
- **Increased Social Cohesion and Stability**: Reliable energy access strengthens social cohesion by reducing conflicts over limited resources such as firewood or fuel. Additionally, community-managed energy projects foster collective responsibility, promoting unity and cooperation among residents. As energy access improves livelihoods, healthcare, and education, it contributes to overall social stability and reduces outmigration from rural areas.

5.5. Long-Term Socioeconomic Development

In the long term, HRES support sustainable economic growth, enhance quality of life, and contribute to broader development goals:

- **Support for Sustainable Development Goals (SDGs)**: Access to affordable, reliable, sustainable, and modern energy aligns with the United Nations Sustainable Development Goal 7 (SDG 7) and supports other SDGs, including those related to poverty eradication, health, education, and gender equality [61]. By providing energy to remote communities, HRES contribute to holistic, inclusive development.
- **Attracting Investment and Development Initiatives**: Electrified communities are more likely to attract investment from businesses and development organizations [62]. Improved infrastructure, healthcare, and education systems make these regions more appealing for development projects, which in turn generate economic growth and attract further investment.
- **Population Retention and Urbanization Reduction**: Access to electricity can reduce the rate of rural-to-urban migration by improving living conditions and economic opportunities in rural areas. This retention of population helps maintain social structures, preserves cultural practices, and reduces pressure on urban centers, contributing to balanced regional development.

While Hybrid Renewable Energy Systems (HRES) offer numerous benefits for rural electrification in developing countries, several challenges and barriers can hinder their successful implementation and sustainability. These obstacles span technical, economic, social, and policy domains, and addressing them is crucial for realizing the full potential of HRES [63]. This section explores the primary challenges and barriers to deploying HRES in rural areas and suggests potential solutions to overcome them.

6. Challenges and Barriers

6.1. High Initial Costs and Limited Financing Options

One of the most significant challenges in HRES deployment is the high initial capital required for system design, purchase, transportation, and installation [47][61][64]. These upfront costs can be prohibitive for low-income rural communities, particularly in developing countries with limited access to affordable financing options.

- **Limited Access to Capital**: Many rural communities struggle to access loans or credit to fund HRES projects [65]. Financing barriers are often exacerbated by the lack of financial institutions in remote areas, as well as limited experience with renewable energy financing in local markets.
- **High Equipment and Installation Costs**: Renewable energy technologies, while becoming more affordable, still require substantial upfront investment, especially when combined with advanced storage systems, control units, and multiple energy sources.
- **Solutions**: To address these financial barriers, governments and development agencies could provide grants, low-interest loans, and subsidies to lower initial costs. Additionally, innovative financing models like pay-as-you-go, microfinancing, and community-based funding can make HRES more accessible to rural populations [66][67]. International partnerships and investments, as well as blended finance models that combine public and private funding, can further alleviate these financial challenges.

6.2. Technical Challenges and Lack of Skilled Workforce

HRES require technical expertise for installation, operation, and maintenance. In many rural areas, a lack of trained personnel and limited access to technical support pose significant barriers to effective HRES deployment.

- **Lack of Local Technical Skills**: Operating and maintaining HRES require knowledge of renewable energy systems, energy storage, and control units. In areas without skilled technicians, system performance can decline due to inadequate maintenance, leading to frequent breakdowns and lower reliability.
- **Complexity of System Design**: Designing an optimal HRES involves selecting appropriate energy sources, storage solutions, and load management strategies, which require specialized knowledge. Customizing systems to local conditions adds to this complexity, making it challenging to implement HRES in areas with limited technical resources.
- **Solutions**: Training programs can equip local communities with the skills needed to manage HRES, creating a locally available workforce for system maintenance and repair [68][69]. Governments and development organizations can establish capacity-building initiatives that provide technical training and resources. Partnerships with technical schools, NGOs, and private sector companies can also promote knowledge transfer and ensure long-term technical support.

6.3. Policy and Regulatory Barriers

Supportive policies and regulatory frameworks are essential for the success of HRES projects. Inconsistent policies, bureaucratic hurdles, and a lack of clarity around off-grid energy systems can inhibit the growth of HRES in rural areas.

- **Inconsistent or Unclear Policies**: In many developing countries, energy policies are not tailored to support decentralized or off-grid solutions like HRES. Policy ambiguity, including unclear licensing and regulatory requirements, can deter investment and hinder project implementation.
- **Limited Incentives for Renewable Energy**: Without government incentives, HRES projects struggle to compete with subsidized fossil fuels or grid extension projects. The lack of subsidies, tax incentives, or grants specific to renewable energy projects can further discourage investment in HRES.
- **Solutions**: Governments can streamline regulatory processes, simplify licensing for small-scale HRES, and implement policies that encourage decentralized renewable energy. Providing subsidies, tax breaks, or feed-in tariffs for HRES projects can make them more financially attractive [70][71]. National and local policies that prioritize rural electrification through renewables can help create a favorable environment for HRES growth.

6.4. Cultural and Social Acceptance

In some cases, community acceptance of new energy technologies can be a barrier. Social and cultural factors, such as unfamiliarity with renewable energy, local preferences for traditional energy sources, or concerns about technology reliability, can influence the willingness to adopt HRES.

- **Resistance to Change**: Rural communities may be accustomed to traditional energy sources, like kerosene or firewood, and may be hesitant to adopt new technologies due to lack of awareness or trust in their reliability.
- **Gender and Social Dynamics**: In some communities, decision-making may be concentrated within certain groups, limiting participation from marginalized individuals or women, which can affect the acceptance and equitable distribution of benefits from HRES.
- **Solutions**: Engaging communities in the planning and decision-making processes of HRES projects can improve acceptance and foster a sense of ownership. Education and awareness programs that inform communities about the benefits of renewable energy can help build trust in HRES. Encouraging inclusive participation, especially of women and marginalized groups, can improve social acceptance and ensure that the benefits of HRES are equitably distributed.

6.5. Environmental and Resource Constraints

While HRES are more environmentally friendly than fossil fuel-based systems, they can still face environmental and resource constraints, particularly in areas with limited renewable resources.

- **Intermittent Renewable Resources**: The availability of renewable resources like solar, wind, and biomass can vary by season or time of day. Areas with limited sunlight, wind, or organic waste may face challenges in maintaining consistent energy output.

- **Environmental Impact of Certain HRES Components**: Biomass systems may require sustainable fuel sources to prevent deforestation, and hydropower systems, even on a small scale, may impact local ecosystems. Careful resource management is necessary to prevent environmental degradation.
- **Solutions**: Site assessments and resource feasibility studies should be conducted before implementing HRES to ensure sufficient renewable resources. Hybrid configurations that incorporate multiple energy sources can mitigate resource intermittency [47][72]. Sustainable sourcing practices and environmental impact assessments can minimize the environmental impact of biomass and hydropower systems, ensuring long-term resource availability.

6.6. Long-Term Sustainability and Operational Challenges

Ensuring the long-term sustainability of HRES is essential for their continued success, but operational challenges such as maintenance costs, equipment wear, and system aging can affect performance over time.

- **Maintenance and Replacement Costs**: While renewable energy sources generally require less maintenance than conventional diesel generators, certain HRES components (e.g., batteries, wind turbines) still have a limited lifespan and require periodic replacement. In remote areas, sourcing replacement parts or technicians can be challenging and costly.
- **Degradation of System Components**: Batteries and other storage solutions degrade over time, affecting storage capacity and system reliability. Regular maintenance and upgrades are needed to sustain system performance, which can be financially and logistically demanding.
- **Solutions**: Setting up dedicated maintenance funds can ensure that resources are available for repairs and component replacements. Local training programs can empower communities to handle basic maintenance tasks, reducing dependency on external technicians. Introducing predictive maintenance practices can extend component lifespans, and regular performance assessments can help plan for upgrades and replacements.

7. Conclusion and Recommendations

Hybrid Renewable Energy Systems (HRES) represent a transformative approach to rural electrification in developing countries, offering a sustainable, reliable, and clean energy solution by integrating multiple renewable sources—such as solar, wind, biomass, and small-scale hydropower. These systems capitalize on the complementary nature of each energy source to ensure a stable power supply, even when individual resources are intermittent. HRES have the potential to reduce dependence on fossil fuels, which are both costly and environmentally harmful, particularly in remote regions where fuel transportation is challenging. By providing continuous and affordable electricity, HRES empower rural communities economically by enabling small businesses, increasing agricultural productivity, and creating jobs related to system installation, operation, and maintenance. Additionally, reliable energy access improves quality of life by enhancing healthcare services—such as refrigeration for vaccines and power for essential medical equipment—and enabling educational advancements through digital resources and extended study hours.

The environmental benefits of HRES are equally significant, as they contribute to reduced greenhouse gas emissions and align with global climate goals, offering a cleaner alternative that promotes long-term sustainability. Despite these advantages, several challenges hinder the widespread deployment of HRES. High initial costs, limited financing options, and technical complexity are substantial barriers, especially in low-income, rural areas where financial resources and technical expertise are often scarce. Policy and regulatory obstacles, such as unclear policies for off-grid systems and limited incentives for renewable energy, further complicate implementation. Cultural and social acceptance can also be a hurdle, as some communities may be hesitant to adopt unfamiliar technologies. Overcoming these challenges requires a comprehensive strategy that includes government subsidies, innovative financing models (such as pay-as-you-go or community-based funding), supportive policies, and robust training programs to build local technical capacity. By engaging communities in the planning and management of these systems, HRES projects can gain local support and enhance long-term sustainability. With collaborative efforts from governments, international agencies, private sector partners, and local communities, HRES can pave the way for sustainable development in remote areas, delivering significant social, economic, and environmental benefits that contribute to a more equitable and resilient future.

Compliance with ethical standards

Disclosure of conflict of interest

No conflict of interest to be disclosed.

References

[1] Acheampong AO, Erdiaw-Kwasie MO, Abunyewah M. Does energy accessibility improve human development? Evidence from energy-poor regions. Energy Economics. 2021 Apr 1;96:105165.

[2] Bamisile O, Cai D, Adun H, Dagbasi M, Ukwuoma CC, Huang Q, Johnson N. Towards renewables development: Review of optimization techniques for energy storage and hybrid renewable energy systems. Heliyon. 2024 Sep 10.

[3] Hassan Q, Algburi S, Sameen AZ, Salman HM, Jaszczur M. A review of hybrid renewable energy systems: Solar and wind-powered solutions: Challenges, opportunities, and policy implications. Results in Engineering. 2023 Nov 23:101621.

[4] Zebra EI, van der Windt HJ, Nhumaio G, Faaij AP. A review of hybrid renewable energy systems in mini-grids for off-grid electrification in developing countries. Renewable and Sustainable Energy Reviews. 2021 Jul 1;144:111036.

[5] Kumar GA, Shivashankar. Optimal power point tracking of solar and wind energy in a hybrid wind solar energy system. International Journal of Energy and Environmental Engineering. 2022 Mar;13(1):77-103.

[6] Javed MS, Ma T, Jurasz J, Amin MY. Solar and wind power generation systems with pumped hydro storage: Review and future perspectives. Renewable Energy. 2020 Apr 1;148:176-92.

[7] Kumar R, Channi HK. A PV-Biomass off-grid hybrid renewable energy system (HRES) for rural electrification: Design, optimization and techno-economic-environmental analysis. Journal of Cleaner Production. 2022 May 15;349:131347.

[8] Javed MS, Zhong D, Ma T, Song A, Ahmed S. Hybrid pumped hydro and battery storage for renewable energy based power supply system. Applied Energy. 2020 Jan 1;257:114026.

[9] Battery storage technology, in particular, has advanced significantly, becoming more cost-effective and efficient.

[10] Szymanski JR, Zurek-Mortka M, Wojciechowski D, Poliakov N. Unidirectional DC/DC converter with voltage inverter for fast charging of electric vehicle batteries. Energies. 2020 Sep 14;13(18):4791.

[11] Al-Ammar EA, Habib HU, Kotb KM, Wang S, Ko W, Elmorshedy MF, Waqar A. Residential community load management based on optimal design of standalone HRES with model predictive control. IEEE Access. 2020 Jan 9;8:12542-72.

[12] Khare V, Nema S, Baredar P. Solar–wind hybrid renewable energy system: A review. Renewable and Sustainable Energy Reviews. 2016 May 1;58:23-33.

[13] Hossain MS, Jahid A, Islam KZ, Rahman MF. Solar PV and biomass resources-based sustainable energy supply for off-grid cellular base stations. IEEE access. 2020 Mar 3;8:53817-40.

[14] Antar M, Lyu D, Nazari M, Shah A, Zhou X, Smith DL. Biomass for a sustainable bioeconomy: An overview of world biomass production and utilization. Renewable and Sustainable Energy Reviews. 2021 Apr 1;139:110691.

[15] Jasiūnas J, Lund PD, Mikkola J. Energy system resilience–A review. Renewable and Sustainable Energy Reviews. 2021 Oct 1;150:111476.

[16] Azimov U, Avezova N. Sustainable small-scale hydropower solutions in Central Asian countries for local and cross-border energy/water supply. Renewable and Sustainable Energy Reviews. 2022 Oct 1;167:112726.

[17] Guelleh HO, Mujtaba IM, Patel R. Computational tools used in hybrid renewable energy systems optimization-an overview. Computer Aided Chemical Engineering. 2020 Jan 1;48:1477-82.

[18] Cuesta MA, Castillo-Calzadilla T, Borges CE. A critical analysis on hybrid renewable energy modeling tools: An emerging opportunity to include social indicators to optimise systems in small communities. Renewable and Sustainable Energy Reviews. 2020 Apr 1;122:109691.

[19] Bassey KE. Hybrid renewable energy systems modeling. Engineering Science and Technology Journal. 2023;4(6):571-88.

[20] Hassan Q, Al-Musawi TJ, Algburi S, Al-Razgan M, Awwad EM, Viktor P, Ahsan M, Ali BM, Jaszczur M, Kalaf GA, Al-Jiboory AK. Evaluating energy, economic, and environmental aspects of solar-wind-biomass systems to identify optimal locations in Iraq: A GIS-based case study. Energy for Sustainable Development. 2024 Apr 1;79:101386.

[21] Zebra EI, van der Windt HJ, Nhumaio G, Faaij AP. A review of hybrid renewable energy systems in mini-grids for off-grid electrification in developing countries. Renewable and Sustainable Energy Reviews. 2021 Jul 1;144:111036.

[22] Liu L, Wang Z, Wang Y, Wang J, Chang R, He G, Tang W, Gao Z, Li J, Liu C, Zhao L. Optimizing wind/solar combinations at finer scales to mitigate renewable energy variability in China. Renewable and Sustainable Energy Reviews. 2020 Oct 1;132:110151.

[23] Akorede MF. Design and performance analysis of off-grid hybrid renewable energy systems. InHybrid Technologies for Power Generation 2022 Jan 1 (pp. 35-68). Academic Press.

[24] Canale L, Di Fazio AR, Russo M, Frattolillo A, Dell'Isola M. An overview on functional integration of hybrid renewable energy systems in multi-energy buildings. Energies. 2021 Feb 18;14(4):1078.

[25] Ebhota WS, Jen TC. Fossil fuels environmental challenges and the role of solar photovoltaic technology advances in fast tracking hybrid renewable energy system. International Journal of Precision Engineering and Manufacturing-Green Technology. 2020 Jan;7:97-117.

[26] Ma W, Xue X, Liu G. Techno-economic evaluation for hybrid renewable energy system: Application and merits. Energy. 2018 Sep 15;159:385-409.

[27] Khalil H, Abd El-Hamied R. Comparative Analysis and Assessment of Economic Profitability of a Hybrid Renewable Energy Framework via HOMER Optimization in Jordan. International Journal of Heat and Technology. 2024 Jun 1;42(3).

[28] Sen S, Ganguly S. Opportunities, barriers and issues with renewable energy development–A discussion. Renewable and sustainable energy reviews. 2017 Mar 1;69:1170-81.

[29] Lam PT, Law AO. Crowdfunding for renewable and sustainable energy projects: An exploratory case study approach. Renewable and sustainable energy reviews. 2016 Jul 1;60:11-20.

[30] Natividad LE, Benalcazar P. Hybrid renewable energy systems for sustainable rural development: Perspectives and challenges in energy systems modeling. Energies. 2023 Jan 27;16(3):1328.

[31] Susskind L, Chun J, Gant A, Hodgkins C, Cohen J, Lohmar S. Sources of opposition to renewable energy projects in the United States. Energy Policy. 2022 Jun 1;165:112922.

[32] Mehos M, Price H, Cable R, Kearney D, Kelly B, Kolb G, Morse F. Concentrating solar power best practices study. National Renewable Energy Lab.(NREL), Golden, CO (United States); Solar Dynamics, LLC, Denver, CO (United States); 2020 Jun 1.

[33] Ens K. *PUBLIC-PRIVATE PARTNERSHIP FUNDING THROUGH OFFICIAL DEVELOPMENT AID* (Doctoral dissertation, University of Erfurt).

[34] Murugaperumal K, Raj PA. Feasibility design and techno-economic analysis of hybrid renewable energy system for rural electrification. Solar Energy. 2019 Aug 1;188:1068-83.

[35] Thirunavukkarasu M, Sawle Y, Lala H. A comprehensive review on optimization of hybrid renewable energy systems using various optimization techniques. Renewable and Sustainable Energy Reviews. 2023 Apr 1;176:113192.

[36] Bajpai P, Dash V. Hybrid renewable energy systems for power generation in stand-alone applications: A review. Renewable and Sustainable Energy Reviews. 2012 Jun 1;16(5):2926-39.

[37] Sharafi M, ElMekkawy TY, Bibeau EL. Optimal design of hybrid renewable energy systems in buildings with low to high renewable energy ratio. Renewable Energy. 2015 Nov 1;83:1026-42.

[38] Reikard G, Robertson B, Bidlot JR. Combining wave energy with wind and solar: Short-term forecasting. Renewable Energy. 2015 Sep 1;81:442-56.

[39] Rahman A, Farrok O, Haque MM. Environmental impact of renewable energy source based electrical power plants: Solar, wind, hydroelectric, biomass, geothermal, tidal, ocean, and osmotic. Renewable and Sustainable Energy Reviews. 2022 Jun 1;161:112279.

[40] Basnet S, Deschinkel K, Le Moyne L, Péra MC. A review on recent standalone and grid integrated hybrid renewable energy systems: System optimization and energy management strategies. Renewable Energy Focus. 2023 Sep 1;46:103-25.

[41] Rahman MM, Shakeri M, Tiong SK, Khatun F, Amin N, Pasupuleti J, Hasan MK. Prospective methodologies in hybrid renewable energy systems for energy prediction using artificial neural networks. Sustainability. 2021 Feb 23;13(4):2393.

[42] Tharani KL, Dahiya R. Choice of battery energy storage for a hybrid renewable energy system. Turkish Journal of Electrical Engineering and Computer Sciences. 2018;26(2):666-76.

[43] Lai X, Chen Q, Tang X, Zhou Y, Gao F, Guo Y, Bhagat R, Zheng Y. Critical review of life cycle assessment of lithium-ion batteries for electric vehicles: A lifespan perspective. Etransportation. 2022 May 1;12:100169.

[44] Faraji F, Majazi A, Al-Haddad K. A comprehensive review of flywheel energy storage system technology. Renewable and Sustainable Energy Reviews. 2017 Jan 1;67:477-90.

[45] Gür TM. Review of electrical energy storage technologies, materials and systems: challenges and prospects for large-scale grid storage. Energy and Environmental Science. 2018;11(10):2696-767.

[46] Babatunde OM, Munda JL, Hamam Y. A comprehensive state-of-the-art survey on hybrid renewable energy system operations and planning. IEEE Access. 2020 Apr 16;8:75313-46.

[47] Verma S, Kameswari YL, Kumar S. A Review on Environmental Parameters Monitoring Systems for Power Generation Estimation from Renewable Energy Systems. BioNanoScience. 2024 Mar 25:1-25.

[48] Wolniak R, Grebski W. THE APPLICATIONS OF USAGE OF BUSINESS ANALYTICS IN ENERGY MANAGEMENT IN INDUSTRY 4.0 CONDITIONS. Scientific Papers of Silesian University of Technology. Organization and Management/Zeszyty Naukowe Politechniki Slaskiej. Seria Organizacji i Zarzadzanie. 2023 Nov 1(180).

[49] Kavadias KA, Triantafyllou P. Hybrid renewable energy systems' optimisation. a review and extended comparison of the most-used software tools. Energies. 2021 Dec 8;14(24):8268.

[50] Eriksson EL, Gray EM. Optimization and integration of hybrid renewable energy hydrogen fuel cell energy systems–A critical review. Applied energy. 2017 Sep 15;202:348-64.

[51] Bull SR. Renewable energy today and tomorrow. Proceedings of the IEEE. 2001 Aug;89(8):1216-26.

[52] Kaur G, Kaur J, Sharma A, Jain A, Kumar R, Alsubih M, Islam S, Ammarullah MI. Techno-economic investigation and empowering rural resilience through bioengineering: a case study on self-sustainable village energy models. International Journal of Low-Carbon Technologies. 2024 Jan 18;19:1275-87.

[53] Roseland M. Sustainable community development: integrating environmental, economic, and social objectives. Progress in planning. 2000 Jan 1;54(2):73-132.

[54] Emezirinwune MU, Adejumobi IA, Adebisi OI, Akinboro FG. Synergizing hybrid renewable energy systems and sustainable agriculture for rural development in Nigeria. e-Prime-Advances in Electrical Engineering, Electronics and Energy. 2024 Mar 1;7:100492.

[55] Ismail MS, Moghavvemi M, Mahlia TM, Muttaqi KM, Moghavvemi S. Effective utilization of excess energy in standalone hybrid renewable energy systems for improving comfort ability and reducing cost of energy: A review and analysis. Renewable and Sustainable Energy Reviews. 2015 Feb 1;42:726-34.

[56] World Health Organization. Access to modern energy services for health facilities in resource-constrained settings: a review of status, significance, challenges and measurement. World health organization; 2014.

[57] Cromartie KA. *Assessing the potential for renewable energy systems in remote arctic communities as a means of reducing regional diesel fuel dependence* (Doctoral dissertation).

[58] Ceglia F, Marrasso E, Roselli C, Sasso M. Energy and environmental assessment of a biomass-based renewable energy community including photovoltaic and hydroelectric systems. Energy. 2023 Nov 1;282:128348.

[59] Laxmi V, Parikh J, Karmakar S, Dabrase P. Household energy, women's hardship and health impacts in rural Rajasthan, India: need for sustainable energy solutions. Energy for sustainable development. 2003 Mar 1;7(1):50-68.

[60] Parra C, Kirschke J, Ali SH. Ensure access to affordable, reliable, sustainable and modern energy for all. InMining, Materials, and the Sustainable Development Goals (SDGs) 2020 Oct 13 (pp. 61-68). CRC Press.

[61] Williams NJ, Jaramillo P, Taneja J, Ustun TS. Enabling private sector investment in microgrid-based rural electrification in developing countries: A review. Renewable and Sustainable Energy Reviews. 2015 Dec 1;52:1268-81.

[62] Khan T, Yu M, Waseem M. Review on recent optimization strategies for hybrid renewable energy system with hydrogen technologies: State of the art, trends and future directions. International Journal of Hydrogen Energy. 2022 Jul 15;47(60):25155-201.

[63] Wang Y, He X, Liu Q, Razmjooy S. Economic and technical analysis of an HRES (Hybrid Renewable Energy System) comprising wind, PV, and fuel cells using an improved subtraction-average-based optimizer. Heliyon. 2024 Jun 6;10(12).

[64] Page MT, Okeke C. Stolen dreams: how corruption negates government assistance to Nigeria's small businesses. Carnegie Endowment for International Peace.; 2022.

[65] Brown D, Dahlan N, Richardson-Barlow C. Evaluating microgrid business models for rural electrification: A novel framework and three cases in Southeast Asia. Energy for Sustainable Development. 2024 Jun 1;80:101443.

[66] Salseggen MY. *Innovative social practices in rural electrification: a comparative case study of Rubagabaga mini-hydropower project (Rwanda) and PECO Rwenzori Micro-hydropower project (Uganda)* (Master's thesis, NTNU).

[67] Odulaja BA, Nnabugwu OC, Abdul AA, Udeh CA, Daraojimba C. HR'S role in organizational change within Nigeria's renewable energy sector: a review. Engineering Science and Technology Journal. 2023 Nov 29;4(5):259-84.

[68] Shoemaker M, Ribeiro D. Through the local government lens: Developing the Energy Efficiency Workforce. InAmerican Council for an Energy-Efficient Economy 2018 Jun.

[69] Bello SF, Lawal RO, Ige OB, Adebayo SA. Optimizing vertical axis wind turbines for urban environments: Overcoming design challenges and maximizing efficiency in low-wind conditions. GSC Advanced Research and Reviews. 2024;21(1):246-56.

[70] Masterson CD. Wind-Energy Ventures in Indian Country: Fashioning a Functional Paradigm. Am. Indian L. Rev.. 2009;34:317.

[71] Guo S, Liu Q, Sun J, Jin H. A review on the utilization of hybrid renewable energy. Renewable and Sustainable Energy Reviews. 2018 Aug 1;91:1121-47.