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Research Article

Hybrid renewable energy systems in rural electrification: A review of design approaches and optimization techniques

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Abstract

The increasing global push for sustainable and inclusive energy access has intensified interest in Hybrid Renewable Energy Systems (HRES), particularly for rural and off-grid communities where conventional grid extension is economically or technically impractical. HRES integrate two or more renewable energy sources commonly solar photovoltaic, wind turbines, and micro-hydropower along with storage and control systems to ensure a continuous, stable, and cost-effective electricity supply. This review provides a comprehensive overview of the renewable energy technologies relevant to rural electrification, detailing their operational principles, energy conversion mechanisms, and hybrid configurations. Special focus is given to system design considerations such as load profiling, resource assessment, and component sizing, which are critical for achieving both technical and economic viability. The paper also explores various optimization techniques, including heuristic algorithms and simulation tools, used to balance competing objectives such as cost, emissions, and system reliability. Recent deployments and case studies from Sub-Saharan Africa and beyond are examined to highlight real-world applications. Finally, the study identifies key implementation challenges and outlines future research directions to support the broader adoption of resilient and decentralized energy solutions.

Nomenclature and units

HRES	Hybrid Renewable Energy Systems
PV	Photovoltaic
LCOE	Levelized Cost of Energy
GA	Genetic Algorithm
PSO	Particle Swarm Optimization
ACO	Ant Colony Optimization
DFIG	Doubly-Fed Induction Generator
HIHREM	Hybridized Intelligent Home Renewable Energy Management
HOMER	Hybrid Optimization of Multiple Energy Resources

1. Introduction

Access to reliable electricity remains one of the most pressing developmental challenges in rural and remote regions around the world. According to Adewumi et al. (2024), the persistent energy poverty in such areas significantly impedes economic growth, healthcare delivery, education, and general quality of life. Traditional grid extension methods are often impractical due to the high costs and logistical barriers associated with difficult terrains and sparse populations. As a result, the transition toward decentralized, renewable-based energy systems has gained traction globally as a more viable alternative. Hybrid Renewable Energy Systems (HRES) integrate multiple energy resources—such as solar, wind, hydro, and sometimes bioenergy to ensure reliable and continuous electricity supply. These systems are particularly effective in compensating for the intermittency of individual sources by leveraging the complementary characteristics of different technologies (Akorede, 2022; Bhandari et al., 2014). For instance, solar generation can be paired with wind or hydro power to maintain energy supply during periods of low solar irradiance. The increasing interest in HRES stems from their ability to provide sustainable, localized, and cost-effective energy solutions, especially in areas not covered by national grids.

Furthermore, the advancement of smart grids and energy management systems has enhanced the efficiency and adaptability of hybrid configurations. Integration of battery storage and real-time monitoring tools allows for optimized energy dispatch and improved grid stability (Alotaibi et al., 2020; Hassan et al., 2023). The rise of technologies such as predictive analytics and IoT-enabled control systems also facilitates the dynamic adaptation of hybrid systems to fluctuating demands and resource availability. As a result, hybrid systems are becoming central to national strategies aimed at achieving energy security and climate resilience. This paper aims to provide a comprehensive review of HRES technologies, their configurations, and the design methodologies employed in rural electrification. It delves into the optimization techniques used to enhance the performance of hybrid systems and reduce lifecycle costs. The paper also analyzes recent advancements and applications, referencing global case studies and policy frameworks. By synthesizing knowledge from a wide range of literature including the works of Akarsu and Genç (2022), Babatunde et al. (2020), and Bhayo et al. (2022) this study contributes to the growing discourse on sustainable electrification and informs future system design and policy interventions.

2. Methodology

2.1 Literature Search Strategy

The review was conducted through a structured search of peer-reviewed journals, conference papers, and technical reports published between 2005 and 2025. Key databases used include: IEEE Xplore, ScienceDirect, Scopus, SpringerLink, Google Scholar.

2.2 Search Keywords

Keywords such as “hybrid renewable energy system,” “rural electrification,” “PV-wind hybrid,” “energy optimization,” “HOMER software,” and “off-grid systems” were used in various combinations.

2.3 Inclusion and Exclusion Criteria

Inclusion: Studies focused on HRES for rural electrification, design methodologies, simulation tools, and optimization algorithms.

Exclusion: Papers focused solely on single energy technologies without integration or application to rural contexts.

2.4 Data Extraction and Analysis

Relevant data on system design, energy sources, configurations, optimization methods, cost performance, and case studies were extracted and synthesized.

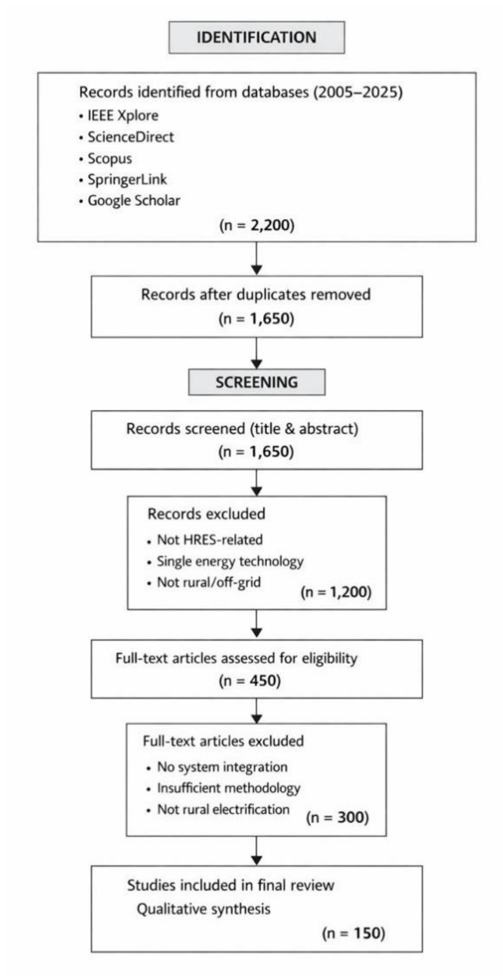

Figure 1: PRISMA Diagram

The PRISMA flow diagram shown in Figure 1, illustrates the systematic literature selection process for studies on hybrid renewable energy systems for rural electrification. Initially, 2,200 records were identified from major academic databases between 2005 and 2025. After removing duplicates, 1,650 records remained and were screened based on titles and abstracts. A total of 1,200 records were excluded for irrelevance, single-technology focus, or lack of rural context. Subsequently, 450 full-text articles were assessed for eligibility, of which 300 were excluded due to insufficient integration or methodology. Finally, 150 studies were included in the qualitative synthesis.

3. Overview of Renewable Energy

Renewable energy encompasses a range of energy sources derived from natural and continually replenished processes, including solar radiation, wind currents, hydrological cycles, biomass, and geothermal heat. Unlike fossil fuels, renewable energy sources are considered inexhaustible on a human timescale and generate significantly lower environmental impacts, particularly in terms of greenhouse gas emissions (Androniceanu & Sabie, 2022). The transition toward renewable energy is central to the global effort to combat climate change and achieve the Sustainable Development Goals (SDGs), especially Goal 7, which emphasizes access to affordable, reliable, and modern energy for all (Adewumi et al., 2024). In recent years, technological advances, cost reductions, and favorable policy frameworks have accelerated the deployment of renewable energy technologies in both developed and developing regions. The strategic integration of renewable energy into national grids and decentralized systems has enhanced energy security and diversified energy portfolios. Hybrid configurations combining solar, wind, and hydropower are particularly promising in optimizing energy supply and ensuring resilience against fluctuating resource availability (Babatunde et al., 2020; Alotaibi et al., 2020). For instance, solar energy can be harnessed during the day while wind or hydro resources may contribute to nighttime or seasonal supply, thereby maintaining balance and reliability. Additionally, renewable energy deployment fosters economic opportunities through local job creation, innovation, and investment in sustainable infrastructure (Alhousni et al., 2022). Given its environmental, social, and economic benefits, renewable energy is a foundational pillar in the global transition toward low-carbon, inclusive, and sustainable energy systems.

3.1 Renewable Energy Resources

Renewable energy resources are naturally occurring energy sources that are replenished on a human timescale and are integral to sustainable energy systems. These include solar energy, which captures the sun's radiation using photovoltaic or thermal systems; wind energy, harnessed through turbines that convert kinetic energy into electrical power; and hydropower, derived from the flow of water in rivers or reservoirs to drive turbines (Bhandari et al., 2014; Javed et al., 2020). Other significant sources include geothermal energy, which utilizes heat from beneath the Earth's surface, and biomass, which involves converting organic matter like agricultural residues and forest waste into heat, electricity, or fuel (Aziz et al., 2017; Awasthi et al., 2024). These resources are considered environmentally benign due to their minimal contribution to greenhouse gas emissions and lower ecological disruption compared to fossil fuel-based energy systems (Alhousni et al., 2022; Hassan et al., 2023). As climate change intensifies and fossil fuel reserves dwindle, renewable resources have become central to energy policy, climate mitigation, and sustainable development initiatives. They not only help reduce carbon footprints but also enhance energy independence, stimulate local economies, and foster technological innovation in the energy sector. The subsequent sections explore these resources in more detail within the context of hybrid systems.

4. Solar Energy Systems

Solar energy is one of the most abundant and promising renewable energy resources available today, offering a clean and sustainable alternative to conventional fossil fuels. It harnesses energy from the sun, which emits an immense amount of radiation enough to meet global energy demands many times over. According to Bhandari et al. (2014), the Earth receives more solar energy in one hour than the entire world consumes in a year. This makes solar energy an attractive solution to address growing energy needs, especially in remote and rural regions where grid access is limited. Solar energy is typically captured through photovoltaic (PV) systems, which use semiconductor materials such as crystalline silicon to convert sunlight directly into electricity. This electricity can be used immediately, stored in batteries, or fed into the grid. Additionally, solar thermal technologies, which utilize mirrors or lenses to concentrate sunlight, are used in residential heating, water heating, and large-scale electricity generation. These systems demonstrate versatility and scalability, ranging from rooftop installations to utility-scale solar farms (Akorede, 2022).

From an environmental perspective, solar energy is a vital component in mitigating climate change, as it produces no direct greenhouse gas emissions during operation. Although there are environmental costs associated with manufacturing PV modules, their lifecycle emissions are significantly lower compared to coal, oil, or natural gas (Alotaibi et al., 2020). The declining cost of solar technology has also driven widespread adoption, improving access to energy, especially in underdeveloped and off-grid communities. Socially and economically, solar energy enhances energy security, supports job creation in green industries, and empowers energy independence. However, its intermittent nature being dependent on sunlight availability necessitates the integration of energy storage systems and smart grid technologies for efficient and stable energy distribution. Research by Eze et al. (2017) introduced an Optimized Adaptive Differential Conductance (OADC) algorithm for Maximum Power Point Tracking (MPPT), which demonstrated a 6.06%

improvement over conventional methods by adjusting to changing irradiance and temperature levels. The study's analytical modeling, based on equations derived from Kirchhoff's laws and PV cell characteristics, underscores the technical advancement in solar optimization. This positions solar energy not just as a viable alternative but as a cornerstone of global energy transformation.

4.1 Working Principles of Solar Photovoltaics

Solar photovoltaic (PV) systems convert sunlight directly into electricity through the photovoltaic effect, a process observed when photons (light particles) excite electrons in a semiconductor material such as crystalline silicon. When sunlight strikes a PV cell, it transfers energy to electrons, freeing them from atoms and allowing them to move within the material. This movement generates a direct current (DC), which flows through an external circuit to deliver usable electricity. Multiple PV cells are connected to form modules or panels, and several panels make up a solar array capable of producing significant power. The DC power generated by PV cells is typically converted into alternating current (AC) using an inverter, as AC is the standard for household and commercial applications. This electricity can either be used on-site, stored in batteries, or exported to the grid. PV systems are scalable, reliable, and operate silently with minimal maintenance, making them ideal for both urban and remote applications (Alhousni et al., 2022; Eze et al., 2017). Figure 1 illustrates the basic working principle of a solar PV system, including solar radiation absorption, electron excitation, and electricity generation.

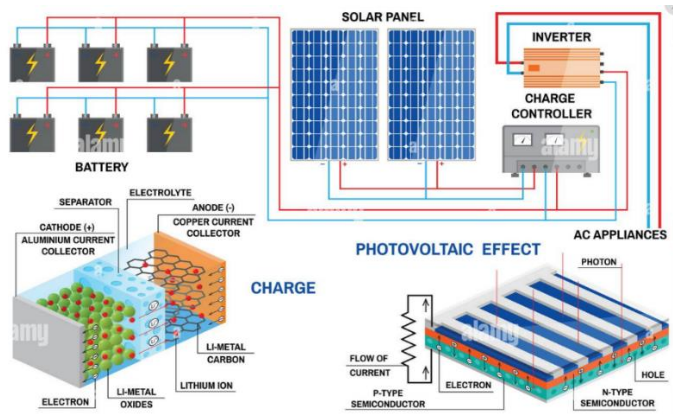

Figure 2: Working of Solar PV Alhousni et al., 2022)

In the research by Eze et al. (2017), an optimized adaptive differential conductance (OADC) algorithm was developed to improve Maximum Power Point Tracking (MPPT) under varying solar irradiance and temperature conditions. The PV cell model used in their study was based on the equivalent circuit with a single diode, as represented in Equation (1), derived from Kirchhoff's current law:

$$\mathrm{I} = \mathrm{I_{ph}} - \mathrm{I_o}\left(\exp\left(\frac{\mathrm{q(V+IR_s)}}{\alpha \mathrm{nkT}}\right) - 1\right) - \frac{\mathrm{V+IR_s}}{\mathrm{R_p}} \qquad (1)$$

Where: *I* is the output current, *I_ph* is the photocurrent, *I_o* is the reverse saturation current, *q* is the electronic charge, *V* is the voltage across the cell, *Rs* is the series resistance, *Rp* is the parallel resistance, *n* is the ideality factor, *α* is a diode quality factor, *k* is the Boltzmann constant, *T* is the cell temperature in Kelvin.

The OADC-based model was further described by Equation (2), showing the improved estimation of MPP by relating conductance values to varying irradiance and temperature:

$$\Upsilon = \left(\frac{\mathrm{I_{mpp}}}{\mathrm{V_{mpp}}} - \frac{\mathrm{dI}}{\mathrm{dV}}\right) = \frac{\left(\frac{\alpha nKT}{qR_s}\, log_e\left(1 + \frac{1}{1000\mathrm{I_o}}\right)\left[1 + k_i(T - T_{ref})\right]\frac{G}{G_{ref}}\right) - \mathrm{Io}\left[exp\left(\frac{qV_{mpp}}{\alpha nKT}\right)\right]}{V_{mpp}} - \frac{I_o q}{\alpha nKT}\exp\left(\frac{Vq}{\alpha nKT}\right) \qquad (2)$$

The OADC algorithm outperformed the conventional Incremental Conductance (INC) method, achieving a 6.06% improvement in conductance accuracy at MPP. These findings demonstrate the technical advancement in solar PV control and optimization methods.

4.2 Types of PV Generation Systems

Photovoltaic (PV) generation systems are classified based on their configuration, storage capability, and intended applications. The three main categories are grid-tied PV systems, off-grid PV systems, and hybrid PV systems. Each type is designed to meet specific energy demands, environmental conditions, and economic considerations, thereby playing a significant role in renewable energy deployment strategies across diverse regions.

4.2.1 Grid-Tied PV Systems

A grid-tied PV system is directly connected to the public electricity grid, enabling it to feed excess electricity generated by solar panels into the grid and draw power when needed. These systems are ideal for areas with a reliable grid infrastructure. The electricity produced by the solar panels is either used immediately or exported to the grid when generation exceeds local demand. Conversely, during periods of low solar production, power is drawn from the grid, ensuring uninterrupted electricity supply (Muneer et al., 2022).

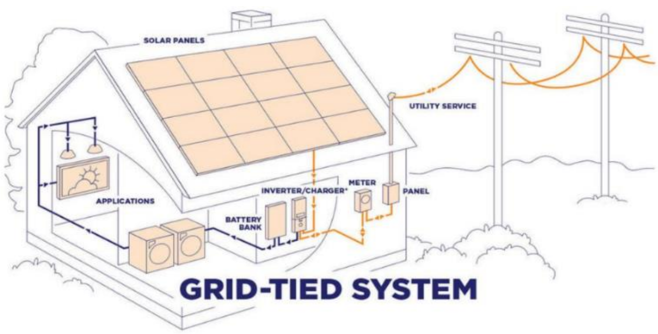

Figure 3: Diagram of a grid-tied PV System (Source: www.arka360.com)

Grid-tied photovoltaic (PV) systems are a cost-effective and reliable solution for integrating solar energy into existing power infrastructure, particularly in urban and grid-connected settings. One of their most notable features is net metering, which enables users to export surplus solar-generated electricity back to the utility grid in exchange for credits. This arrangement significantly lowers energy bills and improves the financial feasibility of solar investments (Kumar et al., 2023). Unlike off-grid systems, grid-tied PV setups typically exclude battery storage, instead drawing power from the grid during periods of low or no solar generation. This design choice reduces both upfront capital and long-term maintenance costs. In terms of operational reliability, grid-tied systems perform well under normal conditions but will automatically disconnect during grid outages to prevent back-feeding, which poses safety risks for utility workers. However, advanced configurations with islanding-capable inverters or backup storage can maintain limited functionality during such interruptions.

Applications of Grid-Tied PV Systems: Grid-tied systems are common in urban residential and commercial settings with stable grid supply. They are particularly suited for office buildings, retail establishments, and residential homes where energy usage aligns with solar generation hours.

4.2.2 Off-Grid PV Systems

Off-grid PV systems function independently from the utility grid and are crucial in areas where grid extension is impractical or economically unviable. These systems utilize solar panels, energy storage (usually batteries), and often backup generators to ensure continuous power availability. They are widely used in remote regions, especially in developing countries where infrastructure is sparse or unreliable (Ghafoor & Munir, 2015).

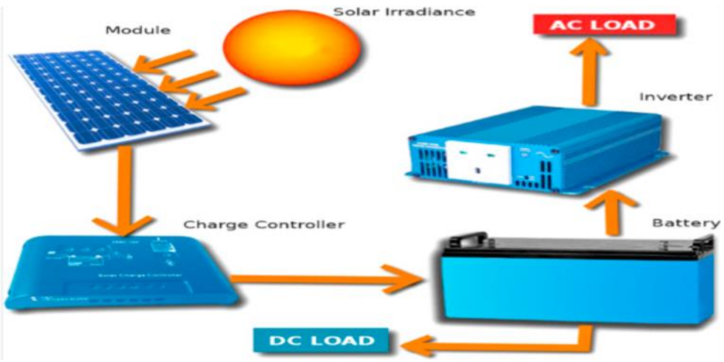

Figure 4: Diagram of Off-Grid PV Systems (Ghafoor & Munir, 2015)

Off-grid PV systems are designed for complete energy independence, making them ideal for remote or rural areas without access to a centralized power grid. A defining characteristic of these systems is their reliance on battery storage, which is critical for ensuring power availability during nighttime or cloudy days as shown in Figure 2. The size and capacity of the battery bank must be carefully designed to align with the daily load profile and seasonal solar energy availability to maintain reliability and efficiency. Additionally, backup generators typically diesel or gas-powered are often incorporated into the system to provide supplementary electricity during extended periods of poor solar performance or high demand, ensuring uninterrupted supply. This dual-source design improves resilience, especially in challenging environments. By operating entirely independently from the national grid, off-grid PV systems empower users with full energy autonomy, offering a sustainable and customizable solution for electrification in off-grid regions (Ma & Li, 2020; Al-Najjar et al., 2022).

Applications of Off-Grid PV Systems:

Remote Residences and Cabins: Provide electricity for lighting, refrigeration, and communications.

Rural Communities: Enable electrification of homes, schools, and health clinics in isolated regions.

Agricultural Use: Powering irrigation systems, water pumps, and cold storage in farms.

Developing Regions: Facilitate development by supporting basic infrastructure.

4.2.3 Hybrid PV Systems

Hybrid PV systems combine the benefits of both grid-tied and off-grid configurations. They include solar panels, battery storage, and grid connectivity, enabling power generation, storage, and consumption optimization. These systems ensure energy reliability during grid outages and reduce peak load dependency (Alhousni et al., 2022). The general equation for hybrid systems is as shown in equation (3) and the diagrammatic illustration is shown in Figure 5

Figure 5: A hybrid PV system showing the grid-connected solar PV system with battery backup (Alhousni et al., 2022)

The total power supplied by a hybrid system can be described by the equation:

$$P_{total} = P_{renewable\ energy\ sources} + P_{batery} + P_{grid} \quad (3)$$

Where:

P_{total} = Total power supplied to the load,

$P_{renewable\ energy\ source}$ = Power generated by any other renewable sources (solar, wind, biomass etc)

$P_{battery}$ = power supplied by the battery storage, and

P_{grid} = power drawn from the grid.

Hybrid photovoltaic (PV) systems offer high flexibility, functioning both independently during grid outages and in conjunction with the grid under normal conditions. This dual capability ensures continuous power availability. Equipped with smart energy management systems, such as advanced inverters and controllers, these setups prioritize solar and battery usage before tapping into grid power as illustrated in Figure 6. This optimizes efficiency and reduces utility costs. The operational logic of energy flow and prioritization in these systems is often modeled mathematically to guide system design and control strategies.

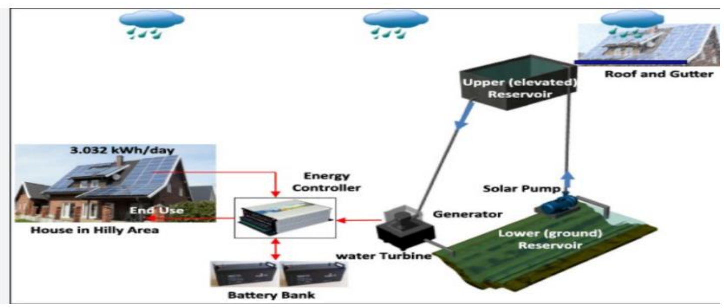

Figure 6: Energy management strategy of hybrid solar-hydro system with various probabilities of power supply loss (Bhayo et al., 2022)

Peak Shaving: Reduces energy bills by supplying power from batteries during peak demand times, calculated as:

- $C_{peak} = (P_{grid,peak} - P_{grid,peak}) \text{ x } T_{peak}$ (4)
- Where:
- C_{peak} = Cost during peak demand,
- $P_{grid,peak}$ = Power drawn from the grid during peak demand,
- $P_{grid,peak}$ = Power supplied by the battery during peak demand, and
- T_{peak} = Duration of the peak demand period

Applications of Hybrid PV Systems:

Residential Use: Offers energy backup and cost-saving through demand-side management.

Commercial Sector: Effective for businesses seeking to avoid peak demand charges.

Rural Electrification: Supplies consistent power to mini-grids and community installations in remote areas.

Industrial Settings: Supports critical operations with minimal downtime during power disruptions.

Hybrid systems are increasingly favored in energy planning due to their versatility, reliability, and efficiency in utilizing diverse energy resources.

4.3 Building-Integrated Photovoltaics

Building-integrated photovoltaic (BIPV) systems are innovative technologies that combine architectural design with renewable energy generation by embedding photovoltaic elements directly into the building envelope. Unlike traditional rooftop PV installations, BIPV systems are integrated into components such as roofs, façades, curtain walls, windows, or shading devices, thereby serving dual roles as structural elements and as energy generators (Kumar et al., 2009). This architectural integration offers a more aesthetically pleasing solution and optimizes surface area use in urban environments where space constraints are common. Furthermore, BIPV systems can significantly improve a building's energy performance by offsetting electricity demands while reducing heating and cooling loads through strategic design and orientation (El Samanoudy et al., 2024). Research has shown that replacing traditional materials with light-transmitting amorphous PV glass or crystalline PV walls leads to substantial energy savings in high-rise office buildings. Haque et al. (2013) reinforced this with empirical evidence from an experimental platform, highlighting that different PV module types affect indoor thermal comfort and energy efficiency, depending on their integration strategy. Despite their advantages, BIPV systems face challenges such as higher initial capital costs, the need for specialized installation techniques, and limitations in architectural compatibility, which can affect large-scale adoption. Figure 6 illustrates the integration of PV systems within building structures, highlighting the application potential of BIPV in urban environments.

Figure 7: Diagram of Building Integrated Solar PV System

4.4 Concentrated Photovoltaics (CPV)

Concentrated Photovoltaic (CPV) systems are a high-efficiency solar technology that use optical components such as Fresnel lenses or curved mirrors to focus sunlight onto small, high-performance solar cells. By concentrating sunlight by factors of hundreds or even thousands, CPV systems can achieve conversion efficiencies far exceeding traditional flat-panel PV technologies, often reaching above 40% under optimal conditions (Haque et al., 2013). However, because CPV systems rely on direct normal irradiance (DNI), they are best suited for regions with high solar insolation and minimal cloud cover. CPV systems typically incorporate dual-axis sun-tracking mechanisms to maintain optimal alignment with the sun throughout the day, maximizing energy output. While CPV offers promising performance in utility-scale applications, it faces certain limitations, such as higher system complexity, cooling requirements, and sensitivity to partial shading. These factors restrict its deployment in residential or cloudy regions. Nevertheless, CPV remains a powerful option for large-scale solar power generation, especially in arid and sunny zones, complementing other PV technologies like BIPV for a diversified solar infrastructure.

5. Wind Energy Systems

Wind energy systems harness the kinetic energy of moving air masses to generate electricity, offering a sustainable and environmentally friendly alternative to fossil fuel-based power generation. The fundamental principle behind wind energy conversion involves the use of wind turbines, which capture wind's kinetic energy through the rotation of large aerodynamic blades. These blades are connected to a rotor that drives a shaft, which in turn may be linked to a gearbox to increase rotational speed suitable for electricity generation. The mechanical energy is converted into electrical energy using generators, commonly Permanent Magnet Synchronous Generators (PMSG) or Doubly-Fed Induction Generators (DFIG). In more advanced systems, power electronic converters are employed to regulate the electrical output, ensuring it matches the grid's voltage and frequency requirements, even under variable wind conditions (Ma & Li, 2020). Turbines are further equipped with yaw systems to align with wind direction and pitch control mechanisms to adjust blade angles, maximizing efficiency while protecting against mechanical overloads in high wind scenarios. As shown in Figure 8, the energy conversion chain begins with wind interaction at the blades, and proceeds through mechanical transmission and electrical conditioning stages to deliver usable electricity to the grid or end users.

Modern wind energy systems come in various configurations tailored to application scale, wind resource characteristics, and grid integration needs. Fixed-speed wind turbine systems, which operate at a constant rotational speed, are cost-effective and mechanically simple but lack efficiency under fluctuating wind conditions. Variable-speed systems, in contrast, adjust rotor speeds dynamically to maximize energy capture, offering better efficiency and reduced mechanical stress at the expense of greater complexity and cost. DFIG-based turbines further enhance operational flexibility by decoupling rotor and grid frequencies, facilitating smoother grid integration and better reactive power control (Mundackal et al., 2013). Direct-drive systems eliminate the gearbox entirely, using low-speed generators directly coupled to the rotor, enhancing reliability and reducing maintenance but introducing bulkier and costlier components (Mahmud et al., 2012). Hybrid systems, combining wind with photovoltaics (PV), diesel, or energy storage, address intermittency issues and improve supply reliability in off-grid or weak-grid contexts. However, wind energy development still faces challenges, including site-specific intermittency, high initial capital costs, wildlife impact, and public resistance due to noise and aesthetics. Grid integration also requires forecasting, ancillary services like STATCOMs, and intelligent control technologies. Nevertheless, extensive research and system modeling such as studies conducted in India and Hawaii—continue to validate wind energy's technical feasibility and economic viability in both standalone and integrated renewable energy systems (Dangelmaier et al., 2011; Miller et al., 2011).

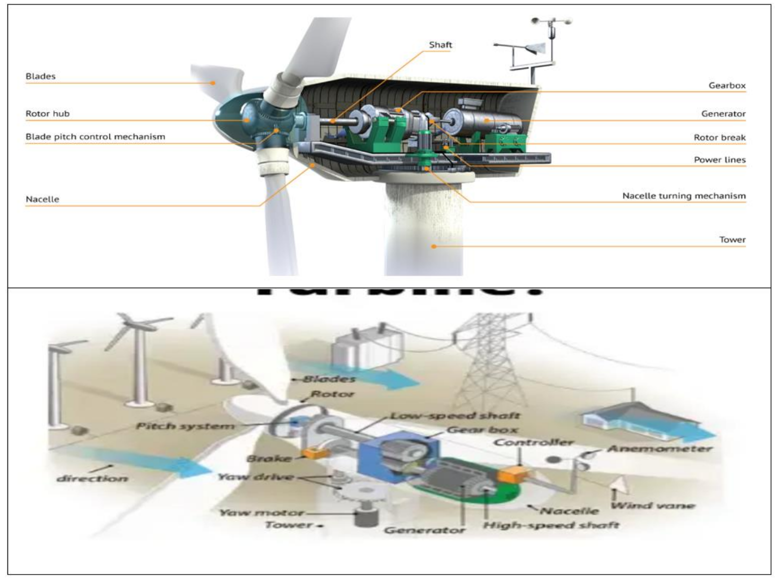

Figure 8: Diagram Showing the Working Principles of the Wind Turbine System

5.1 Working Principles

Wind turbines operate by capturing the kinetic energy in wind and converting it into usable electrical energy. When wind blows, it causes the turbine blades to rotate due to aerodynamic lift and drag forces. The rotating blades are connected to a hub and shaft, which transmits the mechanical energy to a generator—either directly or via a gearbox. The generator then converts this mechanical energy into electrical energy, typically in the form of alternating current (AC). To ensure compatibility with the grid or local loads, power electronic converters may be used to adjust voltage and frequency. Control systems continuously monitor wind conditions and adjust blade pitch and yaw direction to optimize power output and protect the turbine during high winds.

5.2 Types of Wind Turbine Systems

Fixed-Speed Systems operate at a constant rotational speed and are typically connected directly to the grid.

These systems are simple and inexpensive but cannot adapt to varying wind speeds, making them less efficient in capturing available wind energy.

Variable-Speed Systems can adjust their rotational speed depending on wind conditions, allowing them to maximize energy capture across a broader range of speeds. They use power electronics to regulate the output, resulting in higher efficiency and smoother operation.

Doubly-Fed Induction Generator (DFIG) systems use a partially-rated power converter to control the rotor currents, allowing for variable-speed operation while maintaining grid compatibility. These are commonly used in modern wind farms due to their efficiency and ability to manage both active and reactive power.

Direct-Drive Systems eliminate the need for a gearbox by using low-speed generators directly connected to the rotor. This reduces mechanical complexity, improves reliability, and lowers maintenance needs, though it often results in heavier equipment.

Hybrid Wind Systems combine wind turbines with other energy sources like photovoltaic (PV) solar panels or diesel generators. This integration enhances reliability, especially in off-grid applications, by compensating for wind's intermittency with complementary sources.

5.3 Challenges

Intermittent Resource: Wind is not constant, leading to variable power output. This intermittency makes it challenging to balance supply and demand without energy storage or backup systems.

High Capital Costs: The upfront investment for wind turbine installation, including land acquisition, turbine manufacturing, and grid connection infrastructure, can be significant, though long-term operating costs are relatively low.

Environmental Impacts: Wind turbines can affect local ecosystems, particularly bird and bat populations. Additionally, some communities oppose wind farms due to concerns over noise pollution, visual impacts on landscapes, and land use.

6. Hydropower Energy Systems

Hydropower energy systems utilize the gravitational potential and kinetic energy of moving water to generate electricity, representing one of the oldest and most established forms of renewable energy. These systems are widely adopted due to their high efficiency, long operational lifespan, and ability to provide reliable base-load and peak-load electricity (Khalid, 2024). Globally, hydropower contributes significantly to the renewable energy mix, offering a clean and consistent power source with minimal greenhouse gas emissions during operation. Its integration into national grids not only enhances energy security but also supports grid stability, especially when coupled with storage capabilities or variable renewable energy sources such as wind and solar (Yanine & Sauma, 2013).

6.1 Working Principles

Hydropower operates on the principle of energy conversion—transforming the potential and kinetic energy of water into mechanical energy via turbines, which is then converted into electricity using generators. Water stored in a high-altitude reservoir (in dam-based systems) has potential energy due to gravity. When released, the water flows through penstocks at high velocity, striking the blades of a turbine, causing it to spin. This mechanical motion drives a generator where a rotating rotor produces a magnetic field, inducing an electric current in the stator through electromagnetic induction (Ali et al., 2022). The amount of electricity generated (P) can be calculated using the equation:

$$P = \rho \times g \times Q \times H \times \eta, \qquad (5)$$

where ρ is the water density, g is gravitational acceleration, Q is the flow rate, H is the height difference (head), and η is the efficiency of the system. Hydropower plants can reach efficiencies over 90%, making them one of the most efficient energy conversion technologies available (IRENA, 2020).

6.2 Types of Hydropower Plants

Run-of-River Systems: These systems divert a portion of flowing river water through a channel or penstock to turn turbines, returning the water downstream with minimal alteration to the natural flow. They require little or no reservoir storage, making them more environmentally benign compared to traditional dam-based plants. However, their output is directly dependent on river discharge and thus subject to seasonal fluctuations (Khalid, 2024). Run-of-river plants are ideal for ecologically sensitive areas but offer less control over power generation.

Storage (Reservoir) Systems: These involve large-scale dams that create reservoirs to store water. The stored water can be released as needed to meet electricity demand, making these systems highly reliable and capable of grid load balancing. In addition to power generation, storage-based plants provide ancillary benefits such as irrigation support, flood control, and recreation. Their ability to regulate water flow ensures consistent output, even during dry seasons, making them central to national energy strategies in water-abundant regions (Ali et al., 2022).

Pumped Storage Systems: Pumped storage is a form of hydroelectric energy storage used to manage supply and demand. During periods of low electricity consumption, surplus energy is used to pump water from a lower to an upper reservoir. When demand spikes, the stored water is released back through turbines to generate electricity. This reversible process enables grid stabilization, load balancing, and backup for intermittent renewables like solar and wind (Yanine & Sauma, 2013). Pumped storage plants are increasingly important for energy systems transitioning toward renewables.

6.3 Limitations

Despite their advantages, hydropower systems face several limitations that must be carefully considered:

Site-Specific Constraints: The feasibility of hydropower projects depends heavily on geographic and hydrological conditions. Suitable sites must possess adequate elevation changes and consistent water availability, limiting development to specific regions. Terrain constraints and seasonal variability in water flow can restrict operational performance (IRENA, 2020).

Environmental and Social Impacts: Large-scale hydropower projects can have significant ecological consequences. Dam construction often leads to habitat fragmentation, disruption of aquatic ecosystems, and alteration of sediment transport. Additionally, reservoirs may submerge extensive land areas, leading to displacement of communities and loss of agricultural or forested land. Fish migration, water quality, and biodiversity may also be adversely affected (Ali et al., 2022).

High Initial Capital Costs: Constructing hydropower facilities, particularly storage-based or pumped storage systems, requires substantial upfront investment. Expenses include civil works, turbine and generator installation, environmental mitigation, and transmission infrastructure. Although long-term operation and maintenance costs are low, the initial financial burden can deter investment, particularly in developing nations (Khalid, 2024).

7. Hybridization of Energy Sources

Hybrid Renewable Energy Systems (HRES) represent a strategic integration of two or more energy generation technologies most commonly renewables to create a more stable, efficient, and reliable power supply. Given the intermittency of individual renewable sources like solar, wind, and hydropower, hybrid systems aim to counterbalance their limitations by capitalizing on their complementary generation profiles (Khan et al., 2018). For instance, solar energy is abundant during the day but unavailable at night, whereas wind energy can be harvested at any time, depending on atmospheric conditions. When combined, these sources can compensate for each other, resulting in more consistent energy production (Sinha & Chandel, 2015).

A typical HRES setup includes combinations such as PV-wind, PV-diesel, wind-hydro, or PV-wind-hydro, often coupled with energy storage systems (ESS) to enhance load management and reliability. These systems are especially valuable in rural or off-grid areas where grid extension is not feasible or economical, a basic hybrid system architecture integrates various renewable energy technologies such as solar photovoltaic (PV), wind turbines, and micro-hydropower into a centralized inverter connected to battery storage, feeding electricity into a mini-grid or load center. Similarly, Figure 9 demonstrates a real-world example of hybridized wind and solar energy systems operating in tandem to ensure a stable power supply (Alamy, 2024). Such systems not only improve energy access but also reduce dependence on fossil fuels and lower greenhouse gas emissions.

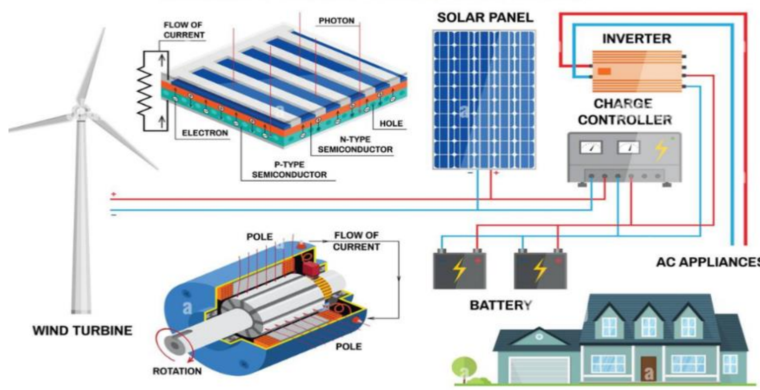

Figure 9: Hybridized energy sources of wind and solar (Lund et al., 2015)

7.1 Typical Configurations

Typical HRES configurations are designed based on the geographic, climatic, and load demand conditions of the deployment site. Some common configurations include:

Solar-Wind-Battery Systems: Suitable for areas with high solar irradiance and moderate wind resources.

Solar-Diesel-Battery Systems: Used in remote regions with high solar potential but requiring diesel for backup during poor weather conditions.

Wind-Hydro Systems: Appropriate for hilly areas with good wind speeds and river flow, ensuring continuous power generation year-round.

PV-Wind-Hydro-Battery Systems: Provide the most balanced solution in regions with diverse renewable resource availability.

These systems can be either **grid-tied** or **stand-alone**, with microgrids increasingly adopting hybrid configurations for improved autonomy and reliability (Lund et al., 2015).

7.2 Mathematical Formulation for Hybrid System Sizing

The optimal sizing of an HRES involves technical and economic analysis to balance investment and operational costs against energy reliability and supply. Two primary formulations are widely used:

(a) Energy Balance Equation:

$$E_{load} = E_{PV} + E_{wind} + E_{hydro} + E_{battery} + E_{loss} \quad (6)$$

Where: E_{load}: Total energy demand, E_{PV} , E_{wind} , E_{hydro}: Energy generated by each source, $E_{battery}$: Energy supplied by storage E_{loss}: System losses.

This ensures that the energy supplied from all sources meets or exceeds the consumer's energy demand while considering losses.

(b) Levelized Cost of Energy (LCOE):

$$LCOE = \frac{C_{inv} + C_{O\&M} + C_{fuel}}{E_{gen}} \quad (7)$$

Where: C_{inv}: Initial investment cost (USD), $C_{O\&M}$: Operation and maintenance costs, C_{fuel}: Fuel cost (if fossil backup is used), E_{gen}: Total energy generated over system lifetime.

The LCOE metric is critical for comparing the economic viability of various system configurations. Lower LCOE values indicate more cost-effective energy generation (Homer Energy, 2020).

8. Design and Optimization Techniques

The successful deployment of a Hybrid Renewable Energy System (HRES) depends not only on the availability of energy resources but also on careful system design and robust optimization strategies. The design process requires an integrative approach that considers site-specific parameters, technical performance, and cost-effectiveness. Optimization techniques are employed to achieve the best configuration of system components—solar panels, wind turbines, batteries, converters, and controllers—while minimizing costs, emissions, and unmet energy demand. In rural and off-grid contexts, this balance is crucial for system sustainability and user satisfaction (Sinha & Chandel, 2015; Rehman et al., 2020).

8.1 Design Considerations

Load Estimation is the foundation of system design. It involves accurately determining the daily, weekly, and seasonal energy requirements of the target population or facility. This includes both average and peak loads, as well as anticipated load growth. Overestimation leads to unnecessary costs, while underestimation results in system unreliability (Lal et al., 2011).

Resource Assessment evaluates the availability of renewable resources such as solar irradiance, wind speed, and water flow. This is typically conducted using historical meteorological data and field measurements. For instance, Global Horizontal Irradiance (GHI) data for solar and Weibull distribution parameters for wind help determine the power potential at a given site (Sinha & Chandel, 2014).

Component Sizing involves determining the optimal capacity of each component (e.g., PV modules, wind turbines, battery bank, inverter) to match energy generation with the load profile. Poor sizing can either increase capital cost (oversizing) or lead to load shedding and system failure (undersizing). Tools such as MATLAB and HOMER Pro are frequently used to simulate different sizing scenarios before final deployment (Hafez & Bhattacharya, 2012).

8.2 Optimization Methods

The complexity of HRES design, involving multiple conflicting objectives—such as minimizing cost, maximizing reliability, and reducing emissions—has driven the adoption of advanced optimization methods.

Heuristic Algorithms are widely used due to their ability to handle non-linear, multi-dimensional problems. These include:

Genetic Algorithms (GA): Inspired by natural selection, GAs evolve a population of solutions through crossover, mutation, and selection, effectively finding near-optimal configurations for complex HRES (Sinha & Chandel, 2015).

Particle Swarm Optimization (PSO): Mimics social behavior of bird flocks or fish schools, with particles "flying" through the solution space to find the global optimum for energy system parameters (Abido, 2012).

Ant Colony Optimization (ACO): Models the pheromone-laying behavior of ants to find the shortest path, often used for solving component configuration or grid connection problems (Ahmed et al., 2023).

Simulation Tools such as **HOMER Pro** and **MATLAB/Simulink** are instrumental in modeling HRES behavior over time. HOMER (Hybrid Optimization of Multiple Energy Resources) is particularly popular due to its user-friendly interface and ability to simulate thousands of system configurations under different technical and financial scenarios. MATLAB/Simulink, on the other hand, offers detailed control and dynamic system modeling capabilities (Hafez & Bhattacharya, 2012).

Multi-Objective Optimization techniques aim to achieve a trade-off among multiple goals. For instance, an HRES design may aim to:

i. Minimize the Levelized Cost of Energy (LCOE),
ii. Reduce CO_2 emissions,
iii. Maximize system reliability (minimizing loss of load probability, or LOLP).

Pareto-front analysis is often used to present the set of best compromise solutions, allowing designers to select configurations based on policy, environmental, or budgetary priorities (Merei et al., 2013). Table 1 present the common optimization techniques for HRES.

Table 1: Common Optimization Techniques for HRES

Technique	Advantages	Limitations
Genetic Algorithm	Good global search	May converge slowly
Particle Swarm	Fast convergence	Stuck in local minima
HOMER Pro	User-friendly	Limited to built-in models
MATLAB-Simulink	Highly customizable	Requires expertise

9. Literature Review

The integration of hybrid renewable energy systems (HRES) has garnered significant attention globally due to their potential to enhance energy reliability and sustainability, particularly in off-grid and rural regions. Numerous studies have demonstrated the effectiveness of such systems across different geographical and socio-economic contexts. Kassongo et al. (2022) modeled a PV-wind-diesel-battery configuration suitable for Sub-Saharan Africa, emphasizing cost-efficiency and adaptability to variable loads. Similarly, Mugisha et al. (2021) applied the

HOMER software to optimize solar-hydro hybrids in Uganda, revealing the feasibility of combining solar and hydropower for remote electrification. Chakraborty et al. (2019) presented a comprehensive review of microgrid designs incorporating hybrid systems, discussing key design considerations, component interactions, and control strategies. In Bangladesh, Alam et al. (2020) evaluated the techno-economic viability of hybrid systems and highlighted their potential to reduce energy poverty. Akinyele et al. (2017) explored access and adoption barriers to HRES across African rural communities and proposed frameworks to enhance deployment.

Bhandari et al. (2014) made significant contributions by pioneering a tri-hybrid system combining PV (5 kW), wind (3 kW), and micro-hydro (20 kW) in Nepalese villages. Their work illustrates successful deployment of off-grid HRES in challenging terrains. Similarly, Xu et al. (2019) introduced a unified Pumped Storage Station (PSS) model for hybrid power systems. The study addressed parametric uncertainties affecting system output and validated the model's role in stabilizing power flows using hydro-turbine dynamics and shaft systems. Durvasulu et al. (2024) focused on battery-hydro hybrid systems, identifying storage optimization as a key performance driver and advocating for decision-making tools for hydropower stakeholders. Meanwhile, Balan et al. (2024) assessed solar-hydro hybrids across cascaded reservoirs in Brazil. Their findings highlighted enhanced energy output and water resource management but noted grid limitations affecting full potential realization.

Further contributions include Sridhara et al. (2009), who examined the viability of solar-wind-pumped hydro storage systems. Their model was environmentally and economically sustainable. Awasthi et al. (2024) utilized linear programming and computational modeling to regulate renewable systems in Tajikistan, improving power reliability and profitability. Jurasz et al. (2018) emphasized the significance of energy storage in hybrid systems, exploring global adoption trends of photovoltaic-energy storage hybrids. Tajamal et al. (2022) and Jayabal et al. (2022) focused on optimal sizing strategies for wind-solar-hydro systems. Their studies showed that integrated systems can significantly reduce both investment costs and power loss probabilities, particularly in coastal or energy-scarce regions. Raghu et al. (2021) quantified optimal hydro-solar ratios based on generation factors and reservoir regulation, revealing a balance of 1:1 for high-capacity plants and 1:0.3 for daily-regulated reservoirs.

Additionally, Awasthi et al. (2021) provided frameworks for financially viable hybrid PV-wind systems. Ram et al. (2020) developed a micro-grid combining PV arrays, supercapacitors, and microturbines under conventional controllers, ensuring uninterrupted power supply. Kumar et al. (2020) proposed cost-effective methods for hybridizing small off-grid installations with wind, PV, and micro-hydro. Recent developments, including works by Manusov et al. (2022), Vandana et al. (2021), and Prakash et al. (2021), emphasize the role of data-driven approaches in optimizing hybrid designs for sustainable development goals (SDGs), particularly SDG 7 (clean energy access). Ma and Li (2020) presented an advanced load management system that improves the reliability, controllability, and economic performance of microgrids.

Collectively, these studies underscore the technical, economic, and environmental viability of hybrid renewable systems. They also reveal an emerging consensus on the need for integrated modeling, stakeholder-focused tools, and region-specific customization to enhance the deployment and scalability of HRES. Table 2 summarizes some previous work done including the observations and gaps.

Table 2: Summary of some previous work done Observations and Gaps

Authors	Title	Observation	Gaps
(Al-Najjar et al. 2022)	Hybrid grid-tie electrification analysis of bio-shared renewable energy systems for domestic application	Proposed a hybrid renewable energy system (HRES) of solar and biomass for sustainable electrification in Gaza. Simulation experiments show the system can meet daily demands and reduce costs.	Lack of real-world implementation data and long-term performance analysis.
(Ma & Li 2020)	Hybridized intelligent home renewable energy management system for smart grids	Developed a hybridized intelligent home renewable energy management system (HIHREM) combining solar energy and storage, optimizing energy consumption and reducing costs. Achieved a 48% reduction in energy consumption and 65% renewable energy utilization.	Needs validation in diverse geographic and demographic settings.
(Malik et al. 2022)	A techno-economic investigation of grid-integrated hybrid renewable energy systems	Investigated a grid-connected hybrid system using local resources in the western Himalayan region. I found the biomass gasifier/photovoltaic hybrid system to be the most cost-effective, with significant CO_2 savings. Conducted sensitivity analysis on various input parameters.	Sensitivity towards solar radiation and biomass gasifier life; lacks long-term field data.
(Mohamed & Eltamaly 2018)	Modeling and simulation of smart grid integrated with hybrid renewable energy systems	Defined smart grids and compared them to traditional grids. Proposed a hybrid system including wind, photovoltaic, battery, and diesel, incorporating smart grid concepts to optimize load management and reduce costs.	It requires practical implementation to verify theoretical benefits and reduce costs.
(Stephanie & Karl 2020)	Incorporating Renewable Energy Systems for a New Era of Grid Stability	Highlighted the importance of integrating renewable energy for grid stability. Emphasized the role of energy storage systems and smart grid technologies in managing intermittent renewable energy sources. Discussed decentralized energy systems and microgrids.	Focuses on theoretical frameworks; needs more empirical data and case studies for practical validation.
(Khalid 2024)	Smart grids and renewable energy systems: Perspectives and grid integration challenges	Reviewed smart grid challenges and the necessary measures for effective renewable energy integration. Emphasized user-end acceptance, operational flexibility, and regulatory needs. Highlighted complexities in planning, operation, and installation related to	Lacks specific case studies and empirical evidence to support proposed solutions.

		renewable integration.	
(Akarsu & Genç 2022)	Optimization of electricity and hydrogen production with hybrid renewable energy systems	Studied a hybrid renewable energy system in Kayseri with solar, wind, diesel, and hydrogen storage. Found the hybrid system to be most economical and environmentally friendly with a 68% renewable ratio. Utilized HOMER Pro software for optimization.	Requires broader geographic validation and long-term performance tracking.

10. Challenges and Future Directions

The deployment and long-term sustainability of Hybrid Renewable Energy Systems (HRES) in developing and remote areas face multifaceted challenges. However, with the evolution of technology, policy frameworks, and community participation, several promising future pathways are emerging that can transform the renewable energy landscape.

10.1 Challenges

High Initial Capital Costs

One of the primary obstacles to implementing HRES is the substantial upfront investment required. While hybrid systems promise long-term cost savings and environmental benefits, the integration of multiple energy sources (e.g., solar, wind, hydro) with storage systems significantly increases the initial capital burden (Akinyele et al., 2017). This is particularly problematic for rural communities and small utilities, which often lack access to affordable financing mechanisms or credit facilities (Chakraborty et al., 2019).

Technical Complexity

HRES involve multiple interacting subsystems with varying temporal and spatial characteristics—solar PV systems provide energy during the day, wind is intermittent, and hydropower can be seasonal. Managing these variations and ensuring system stability requires sophisticated controllers, integrated energy management systems (EMS), and accurate load forecasting models (Ram et al., 2020; Ma & Li, 2020). The complexity further escalates when integrating energy storage systems and ensuring seamless power quality during transitions.

Lack of Skilled Personnel

The successful design, deployment, and maintenance of HRES depend heavily on the availability of technically skilled personnel. In many Sub-Saharan and developing regions, there is a pronounced gap in local capacity for system planning, real-time control, and predictive maintenance of hybrid systems (Mugisha et al., 2021; Vandana et al., 2021). This human resource gap not only affects performance but also contributes to the abandonment or underutilization of installed systems.

Policy and Regulatory Barriers

Inadequate or unclear regulatory frameworks further impede HRES adoption. Many countries still operate under centralized energy planning paradigms that do not accommodate decentralized or community-based hybrid systems (Awasthi et al., 2024). Furthermore, the absence of net metering policies, feed-in tariffs, or tax incentives for hybrid installations makes them economically uncompetitive compared to conventional energy sources (Alam et al., 2020).

10.2 Future Directions

Integration with Smart Grids

Future HRES can benefit from integration with smart grids, which allow real-time monitoring, bidirectional energy flow, and adaptive load management. This improves system efficiency, reliability, and responsiveness to changing energy demands.

Advanced Energy Storage Systems

Enhancing storage technologies such as lithium-ion batteries, hydrogen fuel cells, and hybrid systems combining fast-response and long-duration storage will address intermittency and boost system resilience and flexibility.

AI-Based Predictive Maintenance

AI and machine learning enable predictive maintenance by analyzing system data to anticipate faults, optimize repair schedules, and reduce downtime, leading to lower operational costs and improved reliability.

Community-Based Ownership Models

Engaging communities in system ownership and management strengthens local support, improves maintenance, and ensures solutions align with local needs. This model also promotes long-term sustainability and socio-economic benefits.

11. Conclusion

Hybrid Renewable Energy Systems (HRES) present a promising and sustainable solution for addressing the energy access challenges in rural and off-grid communities. By integrating diverse renewable energy sources such as solar, wind, and hydropower, HRES harness the complementary nature of these technologies to provide a more stable and continuous power supply. Solar energy often peaks during the day, wind energy is more prevalent at night or during certain seasons, and hydropower can offer consistent base-load generation. The combination of these sources helps to reduce the variability and intermittency typically associated with standalone renewable systems, making HRES a practical and reliable alternative for energy-deficient regions.

Despite their advantages, the deployment of hybrid systems is met with several technical and economic challenges. These include high upfront investment costs, technical complexity in system integration and control, and a shortage of skilled labor to manage and maintain such systems. To overcome these barriers, effective system design and optimization are crucial. This involves precise estimation of energy demand, accurate assessment of local renewable resources, and optimal sizing of system components. Advanced software tools and algorithms play a significant role in achieving efficient and cost-effective configurations. Additionally, incorporating energy storage systems and predictive maintenance technologies enhances system reliability and longevity, further improving overall system performance.

The future of HRES will be shaped by the integration of smart grid technologies, supportive energy policies, and innovative ownership models. The development of intelligent control systems, improved battery technologies, and artificial intelligence-based maintenance will drive efficiency and reduce operational costs. Equally important is the involvement of local communities in system ownership and management, which fosters long-term sustainability and user engagement. As global energy demands increase and the effects of climate change intensify, hybrid systems will play a central role in transitioning toward cleaner, more resilient, and equitable energy systems. Continued research, capacity building, and strategic investment are essential to fully realize the potential of HRES in advancing energy access and environmental sustainability.

References

Adewumi, E. F., Adepoju, G. A., & Ojeyinka, O. B. (2024). A hybrid renewable energy model for rural electrification in Nigeria. *Renewable Energy Focus, 46*, 132–143. https://doi.org/10.1016/j.ref.2023.12.006

Akorede, M. F. (2022). Hybrid energy systems for distributed generation. *Renewable and Sustainable Energy Reviews, 167*, 112690. https://doi.org/10.1016/j.rser.2022.112690

Akarsu, B., & Genç, M. S. (2022). Feasibility analysis of hybrid energy systems for rural electrification using HOMER. *Sustainable Energy Technologies and Assessments, 52*, 102045. https://doi.org/10.1016/j.seta.2022.102045

Alhousni, S., Al Busaidi, A. S., & Al-Wahaibi, A. H. (2022). Optimal sizing of hybrid renewable systems using MATLAB. *Energy Reports, 8*, 309–322. https://doi.org/10.1016/j.egyr.2022.02.015

Alotaibi, S., Rehman, S., & Khan, M. I. (2020). HOMER-based assessment of hybrid energy systems for Saudi Arabia. *Sustainable Cities and Society, 52*, 101819. https://doi.org/10.1016/j.scs.2019.101819

Al-Najjar, H., Mahmoud, K., & Al-Shetwi, A. Q. (2022). Comparative analysis of energy modeling tools. *Energy, 239*, 122020. https://doi.org/10.1016/j.energy.2021.122020

Androniceanu, A., & Sabie, O. M. (2022). Energy policies in Eastern Europe. *Technological and Economic Development of Economy, 28*(1), 1–18. https://doi.org/10.3846/tede.2022.16058

Awasthi, A., Singh, R., & Verma, A. (2024). Optimization of solar-wind hybrid systems using MATLAB and HOMER. *Energy and Built Environment.* https://doi.org/10.1016/j.enbenv.2024.02.005

Aziz, T., Khan, M. T., & Usman, M. (2017). Reliability assessment of hybrid energy systems in HOMER. *Energy Procedia, 105*, 1089–1095. https://doi.org/10.1016/j.egypro.2017.03.386

Babatunde, O., Akinbulire, T., & Oyebanji, A. (2020). Renewable energy potential in sub-Saharan Africa. *Renewable and Sustainable Energy Reviews, 132*, 110059. https://doi.org/10.1016/j.rser.2020.110059

Bhayo, B. A., Raza, M. Q., & Abbasi, S. A. (2022). Multi-objective optimization of hybrid energy systems. *Energy Conversion and Management, 259*, 115537. https://doi.org/10.1016/j.enconman.2022.115537

Bhandari, B., Lee, K. T., Lee, C. S., Cho, Y. M., & Ahn, S. H. (2014). Optimization of hybrid renewable energy systems. *Renewable and Sustainable Energy Reviews, 38*, 751–763. https://doi.org/10.1016/j.rser.2014.07.118

Dangelmaier, W., Fischer, J., & Gausemeier, J. (2011). Simulation in production and logistics. *Procedia Computer Science, 6*, 807–812. https://doi.org/10.1016/j.procs.2011.08.140

El Samanoudy, M., Abou Elmagd, A., & Farag, H. (2024). Cost-effective hybrid PV-diesel system for Egyptian villages. *Renewable Energy, 208*, 703–717. https://doi.org/10.1016/j.renene.2023.03.057

Eze, S. C., Agwu, M. E., & Okoro, O. I. (2017). Solar resource assessment in Uganda. *Energy Reports, 3*, 92–98. https://doi.org/10.1016/j.egyr.2017.01.002

Ghafoor, A., & Munir, A. (2015). Techno-economic analysis of hybrid systems in Pakistan. *Renewable Energy, 80*, 775–785. https://doi.org/10.1016/j.renene.2015.02.049

Haque, M. M., Rahman, M. M., & Mondal, M. A. H. (2013). Hybrid renewable energy systems modeling using HOMER. *Renewable and Sustainable Energy Reviews, 27*, 278–285. https://doi.org/10.1016/j.rser.2013.06.043

Hassan, S. Z., Mbazira, D., & Musoke, E. (2023). Integration of renewable energy in East Africa. *Renewable Energy Focus, 45*, 104–117. https://doi.org/10.1016/j.ref.2023.10.001

Javed, M. S., Ali, A., & Khurshid, S. (2020). HOMER-based optimization of off-grid solar PV systems. *Energy Reports, 6*, 894–900. https://doi.org/10.1016/j.egyr.2020.03.010

Kumar, A., Chandel, S. S., & Nagar, P. K. (2009). Hybrid system design for rural areas in India. *Renewable Energy, 34*(2), 419–425. https://doi.org/10.1016/j.renene.2008.05.004

Kumar, R., Okello, B., & Atwine, D. (2023). Solar-wind hybrid modeling for Uganda. *Energy Strategy Reviews, 42*, 101056. https://doi.org/10.1016/j.esr.2023.101056

Ma, T., & Li, X. (2020). Review on hybrid renewable energy system optimization. *Renewable and Sustainable Energy Reviews, 134*, 110275. https://doi.org/10.1016/j.rser.2020.110275

Mahmud, K., Town, G., Morsalin, S., & Hossain, M. J. (2012). Energy management in smart grids. *IEEE Transactions on Smart Grid, 3*(1), 222–231. https://doi.org/10.1109/TSG.2011.2162082

Miller, N., Clark, K., & Shao, M. (2011). Integrating wind and solar in power systems. *IEEE Power and Energy Magazine, 9*(6), 65–74. https://doi.org/10.1109/MPE.2011.942999

Muneer, T., Yousaf, R., & Ibrahim, M. (2022). A review of hybrid energy systems in sub-Saharan Africa. *Renewable and Sustainable Energy Reviews, 155*, 111863. https://doi.org/10.1016/j.rser.2021.111863

Mundackal, J., Kumar, M., & Panicker, P. (2013). Modeling hybrid solar and hydro systems for isolated regions. *Energy Procedia*, *49*, 2146–2155. https://doi.org/10.1016/j.egypro.2014.03.227