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Review Article

A Systematic review of the design and optimization of a Hybrid Solar-PV, battery storage, and diesel generator system for sustainable electrification of Kalangala Island, Uganda

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Abstract

Access to reliable, affordable, and sustainable electricity is fundamental to socio-economic development, particularly in remote and underserved regions. In response to escalating concerns over climate change, energy insecurity, and the limitations of centralized grid systems, hybrid renewable energy systems integrating solar photovoltaic (PV), hydropower, diesel generators, and battery storage have emerged as robust alternatives to conventional energy models. This study presents a systematic review of 44 peer-reviewed articles focused on the design, performance, and optimization of hybrid energy systems in off-grid and weak-grid contexts. The review identifies infrastructure aging, load variability, inadequate storage capacity, and persistent reliance on fossil fuels as key challenges undermining energy reliability, even in grid-connected scenarios. A detailed technical synthesis is conducted, evaluating critical factors influencing hybrid system performance, including solar irradiance variability, PV cell and module efficiency, thermal and angular effects on PV output, and hydropower classification based on head height, capacity range, and operational mode (e.g., run-of-river vs. reservoir-based systems). Solar PV is emphasized for its high resource potential and modular scalability, while hydropower, particularly low-head and run-of-river schemes, is examined as a geographically suitable complement for island settings such as Kalangala District, Uganda. The analysis also highlights the pivotal role of microgrid architectures and energy management systems in enabling real-time optimization, resilience, and cost-effectiveness. Aligning with national and continental development frameworks, including Uganda Vision 2040 and the African Union's Agenda 2063, the study concludes that a well-optimized solar–hydro–diesel–battery hybrid microgrid, leveraging existing infrastructure and modern control strategies, can serve as a replicable model for the sustainable electrification of remote island communities.

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1.0 Introduction

Access to reliable, affordable, and sustainable electricity remains a central pillar for socio-economic development and industrial growth across the globe (Asghar, et al., 2022; Eze, et al., 2024). As the world grapples with the dual challenges of climate change and energy insecurity, there is an increasing shift toward the deployment of hybrid renewable energy systems. These systems combine two or more sources of energy typically integrating renewable and conventional sources to optimize reliability, efficiency, and environmental performance. Hybrid systems are particularly gaining traction in remote and islanded communities where traditional grid expansion is economically or geographically unfeasible (Dutt, 2014; Eze, et al, 2025). Across Africa, the energy landscape continues to be defined by low electrification rates, especially in rural and off-grid areas. Despite the continent's vast renewable energy potential, including abundant solar, wind, hydro, and biomass resources, millions of people still lack access to electricity. Consequently, governments, development partners, and private sector players are increasingly investing in decentralized and hybrid energy systems as practical alternatives for expanding electricity access. These efforts are also aligned with the African Union’s Agenda 2063 and the UN Sustainable Development Goal 7, which calls for universal access to affordable, reliable, sustainable, and modern energy (Sparks, 2016,)

In East Africa, energy demand is growing steadily due to population growth, urbanization, and economic development. However, supply gaps, over-reliance on hydropower, and transmission infrastructure challenges persist (Soriano, 2022). As a response, regional strategies have promoted the integration of renewable energy sources with existing grid systems and off-grid solutions. Hybrid power systems, particularly those integrating solar photovoltaic (PV), diesel generation, and battery storage, have shown significant promise in enhancing energy security, reducing dependency on fossil fuels, and minimizing greenhouse gas emissions (Nwaigwe, et al., 2019). In Uganda, the government has implemented several policies and initiatives aimed at improving energy access, especially in remote and island regions. The Electricity Connection Policy (ECP), the Rural Electrification Strategy and Plan, and the Uganda Vision 2040 collectively emphasize sustainable and inclusive energy development. Nonetheless, many islands and isolated communities, such as those in Lake Victoria, still face acute energy deficits due to high costs and logistical constraints associated with grid extension (Boateng, 2016, eze etal., 2025).

Kalangala District, located in the Ssese Islands on Lake Victoria, exemplifies these challenges. Despite its potential for tourism, agriculture, and fisheries, the district has historically suffered from unreliable power supply, which has impeded economic growth and social development. In recent years, efforts to bridge this energy gap have included the deployment of a 33kV submarine cable linking the island to the mainland grid, complemented by localized diesel generators and solar PV installations. However, the system remains suboptimal due to load fluctuations, limited storage, and overdependence on fossil fuels. This review focuses on the design and potential optimization of a Hybrid Power System for Kalangala Island, leveraging the existing 33kV submarine cable infrastructure. It evaluates the technical, environmental, and economic feasibility of integrating renewable energy sources particularly solar PV with energy storage and backup systems to create a resilient and sustainable energy solution for the island’s growing needs.

2.0 Methodology

2. 1. Literature search strategies

A comprehensive search strategy was implemented across multiple databases, including ScienceDirect, IEEE Xplore, Google Scholar, Scopus, Web of Science, and SpringerLink. The search focused on various combinations of key terms such as "Hybrid renewable energy systems," "Solar PV and battery storage," "Diesel backup for renewable energy systems," "Kalangala Island energy," "Off-grid renewable energy solutions," "Energy systems design optimization," and "Island electrification." To ensure the capture of the most recent advancements in the field, the search was limited to studies published in English between 2013 and 2023. This approach provided a comprehensive overview of current trends and developments in hybrid renewable energy systems, particularly in the context of island electrification.

2.2 Search Criteria

To ensure transparency, rigor, and reproducibility, the review adhered to a predefined protocol that outlined clear objectives, inclusion and exclusion criteria, and a detailed methodology. This protocol was registered with a systematic review database such as PROSPERO or a similar platform to enhance the credibility of the review process.

2.3 Inclusion criteria

The inclusion criteria comprised studies that evaluated hybrid renewable energy systems involving components such as solar PV, wind, hydro, battery storage, and diesel backup systems. Research that focused on rural or island electrification, particularly within Sub-Saharan Africa or similar regions was also included. Additionally, studies assessing the integration of renewable and conventional energy sources in hybrid systems, as well as those published in peer-reviewed journals, conference proceedings, or technical reports from recognized institutions, were considered. Only studies conducted within the past ten years (2013–2025) were included to ensure relevance to current technological developments.

2.4 Exclusion criteria

The exclusion criteria ruled out studies that focused solely on conventional or non-hybrid power generation systems. Articles not published in English were excluded, along with research that did not report on the technical or operational aspects of hybrid systems such as studies centered exclusively on economic impacts or policy analysis without a technical focus.

*2.5 **Data Extraction***

Data were extracted from the selected studies using a standardized form to ensure consistency and accuracy. The key data points collected included study characteristics such as author(s), year of publication, study type, and geographical region. Information on hybrid system configurations was gathered, focusing on the integration of components like solar PV, wind, battery storage, and diesel backup systems. Technical design considerations including system capacity, performance metrics, optimization methods, and overall efficiency were also documented. Furthermore, the extraction process captured the challenges reported in each study, such as integration issues, technical barriers, and economic constraints. The environmental, social, and economic impacts of the hybrid systems were noted, alongside the methods employed for energy optimization, including control algorithms and load management strategies. Finally, the results and conclusions of each study were reviewed, particularly those related to system reliability, sustainability, and improvements in energy access.

3. Literature Review

The integration of microgrids with the main grid is increasingly recognized as a strategic approach to improving energy reliability, lowering operational costs, and facilitating the incorporation of renewable energy sources (Hirsch, et al., 2018). This literature review explores the key design considerations and technical challenges associated with the interconnection of a microgrid to the main utility grid on Kalangala Island, Uganda. Particular emphasis is placed on the utilization of a 33kV medium-voltage submarine cable as the primary transmission link (Basak, et al, 2012). The review aims to provide insights into optimal system configuration, grid stability, load management, and the role of hybrid energy solutions in ensuring sustainable and resilient electricity supply for island communities.

3.1 Solar Photovoltaic Power Potential

Almost all life and power on Earth derive their energy mostly from the Sun. Energy resources are now classified into two primary categories: conventional (non-renewable) and non-conventional (renewable) due to a variety of physical, chemical, and nuclear processes (Glaser, 1968). Coal, oil, and natural gas are examples of conventional energy sources that are limited and gradually run out. Renewable (non-conventional) energy sources, on the other hand, like sun, wind, and hydropower, are more sustainable over the long run because they are organically restored during or after energy conversion operations. Solar energy is the most plentiful and widely accessible renewable resource. Solar thermal or photovoltaic (PV) systems can directly capture it, whereas wind and hydropower systems, which rely on solar-induced atmospheric and hydrological cycles, can do so indirectly. In contrast to solar energy's enormous potential, other renewable energy sources like geothermal energy and tidal power which is controlled by planetary gravitational forces contribute just slightly. Using semiconducting materials that exhibit the photovoltaic effect, sunlight is converted into electrical power as part of the direct use of solar energy using photovoltaic (PV) technology (Rothwarf & Böer, 1975; Eze et al, 2021). PV systems' scalability, modular design, minimal environmental impact, and continually falling levelized cost of power have made them a key component of decentralised and sustainable energy solutions. Because of these characteristics, PV systems are especially well-suited for off-grid and grid-tied applications, particularly in isolated and underserved areas (Quaschning, 2014).

3.2 Solar Energy and Radiation

The Sun is a massive source of radiant energy, generated through continuous nuclear fusion reactions at its core. Each square meter of the Sun's surface emits approximately 63.11 megawatts (MW) of radiant power, and with a total surface area of about 6.0874×10^{18} m², the Sun produces an immense and virtually inexhaustible energy output. At the Earth's mean distance from the Sun approximately one Astronomical Unit (AU), or 1.496×10^8 km the solar irradiance, commonly referred to as the solar constant, is approximately 1360 W/m². However, this value is not truly constant; it fluctuates slightly over the year due to the elliptical nature of Earth's orbit, peaking around perihelion in early January when Earth is closest to the Sun (Da Rosa & Ordóñez, 2021; Quaschning, 2014; Weir, 2005; Eze, et al., 2017).

Power density, or energy flux, represents the radiant power received per unit area and is typically measured in watts per square meter (W/m²). The solar radiation incident at the outer edge of Earth's atmosphere, known as extraterrestrial solar radiation, undergoes attenuation before reaching the Earth's surface due to various geometric and atmospheric factors (Miller, 2016; Eze, et al., 2022). Geometric factors include the latitude of the location, solar zenith angle, and the tilt and orientation of the photovoltaic (PV) module, all of which influence the angle and intensity of sunlight received. Atmospheric factors, on the other hand, significantly reduce the intensity of solar radiation through mechanisms such as reflection by atmospheric particles, absorption by gases including ozone (O_3), water vapor (H_2O), oxygen (O_2), and carbon dioxide (CO_2), and scattering phenomena. Rayleigh scattering occurs due to air molecules smaller than the wavelength of light, while Mie scattering is caused by larger particles like dust, aerosols, and pollutants (Pettongkam, 2018; Weir, 2005). A comprehensive understanding of these variables is essential for accurate solar resource assessment, optimal PV system design, and the planning of efficient hybrid renewable energy systems, especially in geographically and climatically diverse regions.

3.3. Solar PV Cell Technology

Through the photovoltaic effect, solar energy can be directly converted into electrical power using solar photovoltaic (PV) cells, or indirectly by first transforming it into heat or chemical energy. The direct conversion of solar energy through the photovoltaic effect is the main topic of this study. A PV cell operates on a principle that is very similar to that of a traditional p-n junction diode. A potential difference is created across the junction when photons, or light particles, stimulate electrons at the junction of two different semiconductor layers. Current can be driven through an external circuit by this voltage. The product of the square of the circuit's resistance and current yields the electrical power output. When photons' excess energy is not transformed into electrical energy, it usually causes heat accumulation inside the cell and is released into the surrounding air (A. Kumar & Verma, 2021; Pettongkam, 2018). It was in 1839 that French physicist Alexandre-Edmond Becquerel made the initial discovery of the photovoltaic phenomenon. However, the semiconductor period marked the beginning of substantial scientific improvements, and Bell Laboratories developed the first silicon solar cell in 1954 with an efficiency of about 5%. This pioneering PV cell was swiftly used in space applications, especially to power American satellites. From space exploration to terrestrial uses, PV technology has evolved throughout time, from large-scale utility grid integration to wristwatches (R. Kumar & Jagadeesh, 2014; Quaschning, 2014).

The fundamental design of a solar cell is depicted in Figure 1, where the generated electric current is collected by metallic contacts positioned on both surfaces of the semiconductor junction. A fine silver mesh on the top (illuminated) surface effectively conducts the induced current while permitting light to flow through. This mesh's design strikes a balance between reducing shading losses and increasing electrical conductivity. The design of PV modules has a number of extra elements to improve performance. To improve light absorption and decrease reflection, an anti-reflective coating—typically composed of titanium dioxide (TiO_2)—is placed to the cell's surface. Although current technology allow for a choice of colours to better fit building aesthetics, this coating gives the solar cell its distinctive blue tint. A cover glass attached with transparent adhesive ensures durability and weather resistance while providing mechanical protection (R. Kumar & Jagadeesh, 2014; Quaschning, 2014).

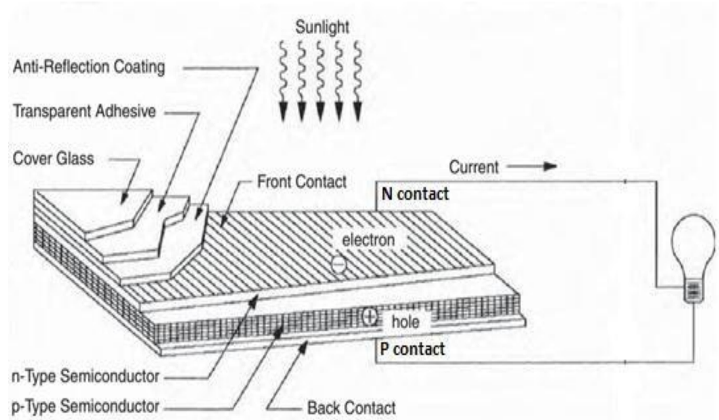

Figure 1: Basic Construction of PV Cell with Performance-Enhancing Features (Kumar and Jagadeesh, 2014)

It is crucial to take into account both the inherent qualities of the semiconductor material and the features of sunlight in order to completely comprehend how a PV cell operates. The material's kind and surface area, the amount of sunlight (solar insolation), and the incident light's wavelength dispersion are the main determinants of a photovoltaic device's power production. One important performance parameter is a solar cell's efficiency, which is the ratio of electrical energy output to incident solar irradiation. This metric, called photovoltaic cell efficiency, measures how well the gadget transforms solar radiation into electrical energy that may be used (Pettongkam, 2018).

3.4 PV Module and Array

A photovoltaic (PV) cell, as previously described, serves as the fundamental building block of a PV power generation system. However, the power output of a single cell is limited, typically producing a voltage of around 0.5–0.6 V and current in the range of milliamps to a few amps, depending on its size and the incident irradiance. To achieve practical levels of electrical power suitable for real-world applications, multiple cells must be electrically interconnected. These interconnections are arranged in series to increase the voltage and in parallel to increase the current, thereby forming a PV module. When several modules are combined, the assembly is referred to as a PV array, covering several square meters of surface area (A. Kumar & Verma, 2021; Quaschning, 2014). One of the distinguishing features of PV systems is their modularity and scalability, offering unparalleled flexibility among renewable energy technologies. This modular nature enables PV systems to be tailored for a broad range of power demands—from micro-power applications such as wristwatches and pocket calculators to large-scale, grid-connected installations generating several megawatts for public electricity supply. Additionally, PV systems allow for incremental capacity expansion, making them particularly attractive for applications where phased deployment is advantageous.

3.4.1 Electrical Characteristics

The electrical behavior of a PV cell can be effectively described using an equivalent circuit model, as shown in Figure 2. This model is based on the single-diode representation of a PV cell and includes key parameters that govern its performance. The output current I from the cell is expressed as shown in equation (1).

$$I = I_L - (I_d - I_{sh}) = I_L - I_d - I_{sh} \quad (1)$$

Where: I is the output (load) current (A), IL is the light-generated current (A), ID is the diode (dark) current (A) and Ish is the shunt leakage current (A).

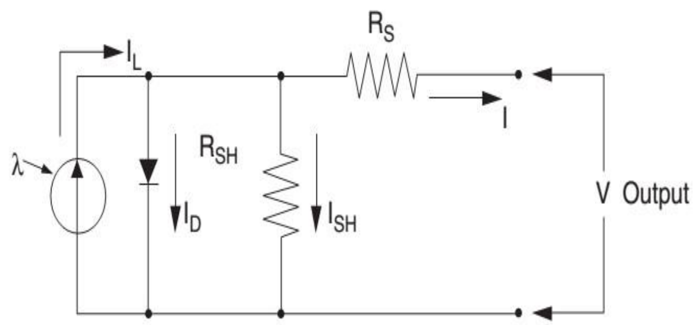

Figure 2: Equivalent Circuit Diagram of a PV Module (Pettongkam, 2018)

The resistance in series Contact resistances, junction depth, and the semiconductor's bulk resistance all contribute to resistive losses inside the cell, which are taken into consideration by Rs. Leakage routes across the p-n junction are modelled by the shunt resistance Rsh, which is inversely proportional to leakage currents. Internal losses are implied by Rs=0 and Rsh=∞ in ideal PV cells. But in real silicon cells, which are usually one square inch in size, Rs falls between 0.05 and 0.1 Ω, and Rsh falls between 200 and 300 Ω. Remarkably, while changes in Rsh have a negligible impact, tiny increases in Rs can drastically reduce the output power (R. Kumar & Jagadeesh, 2014; Quaschning, 2014). The current supplied to the external load in the equivalent circuit is equal to the total of the diode current Id and the shunt-leakage current Ish, as well as the difference of IL produced by the illumination (Eze et al., 2024; Eze et al., 2024). Equations (2) - (4) provide the cell's open-circuit voltage Voc, which is determined when the load current is zero, or when I=0.

$$V_{oc} = V + IR_{sh} \quad (2)$$

The diode current is governed by the characteristic equation(Tesema and Bekele, 2014)

$$I_d = I_D[\frac{QV_{OC}}{e^{AKT}} - 1] \quad (3)$$

Thus, by combining equations (1) and (3), the load current becomes

$$I = I_L - I_D\left[\frac{QV_{OC}}{e^{AKT}} - 1\right] - \frac{V_{OC}}{R_{sh}} \approx I_L - I_D[\frac{QV_{OC}}{e^{AKT}} - 1] \quad (4)$$

Where, I stands for the load current (A), I_D for the diode's reverse saturation current (A), I_L for the cell's current (A), I_{sh} for the current flowing through the shunt resistance (A), VOC for the open circuit voltage (V), Q for the charge on an electron (C) (1.6 X 10-19C), K for Boltzmann's constant (1.38 X 10-23 J/°K), T for the cell's operating temperature (K), and A for the diode quality (curve fitting constant).

Leakage current to the earth is the final term in the equation. It is usually disregarded in practical cells and is insignificant in comparison to IL and ID. By applying a voltage Voc to the cell in the dark and measuring the current entering the cell, one can experimentally determine the diode-saturation current. This current is frequently referred to as the reverse diode-saturation current or the dark current (R. Kumar and Jagadeesh, 2014). Short-circuit current (Ish) and open-circuit voltage (Voc) are the two most crucial and frequently used metrics for characterising the electrical performance of PV cells. By shorting the output terminals and monitoring the terminal current in full light, the short-circuit current can be determined. Under zero terminal voltage, the short-circuit current is as indicated by equation (5), ignoring the tiny diode and the ground-leakage currents (Goswami et al., 2020; R. Kumar and Jagadeesh, 2014).

$$I_{SC} = I_L \quad (5)$$

Again, ignoring the ground-leakage current, which makes I=0 at Equation (4), gives the open-circuit voltage shown in Equation (6)

$$V_{OC} = \frac{AKT}{Q}\ln(\frac{I_L}{I_D} + 1) \approx \frac{AKT}{Q}\ln(\frac{I_L}{I_D}) \quad (6)$$

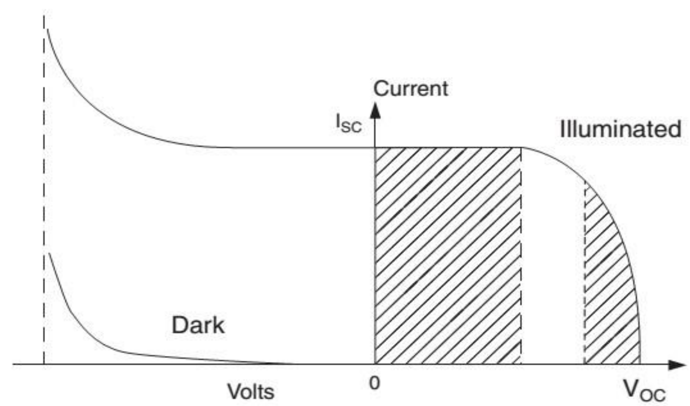

Figure 3: Current vs. Voltage characteristic of the PV module in dark and sunlight (Pettongkam, 2018)

The electrical behavior of a photovoltaic (PV) cell is typically illustrated by its current-voltage (I-V) characteristic curve, as shown in Figure 4. At the top-left corner of the curve, where the voltage is zero, lies the **short-circuit current (ISC)**, which is the current measured when the output terminals are shorted, as defined in Equation (5). Conversely, at the bottom-right corner, where the current is zero, is the **open-circuit voltage (VOC)**, representing the voltage measured when the output terminals are open, as expressed in Equation (6). In the left shaded region of the curve, the PV cell behaves as a near-constant current source, generating a voltage in response to the connected load. In the right shaded region, the current decreases sharply with a slight increase in voltage, and the cell operates more like a constant voltage source with internal resistance. The transition between these two operating modes is marked by a distinct **knee point** on the curve.

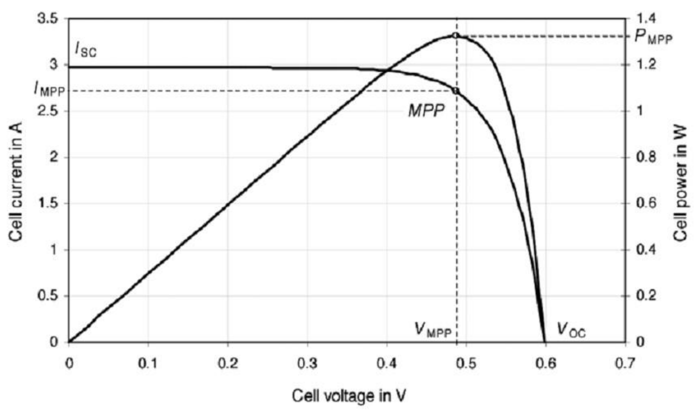

Figure 3: I-V and P-V Characteristics of the PV module In Sunlight (Quaschning, 2014)

In Figure 3, the power-voltage (P-V) curve is plotted alongside the current-voltage (I-V) characteristic. The graph illustrates that the PV cell delivers no power at either zero voltage or zero current. Maximum power is generated at the voltage corresponding to the **knee point** of the I-V curve. For this reason, PV power systems are typically designed to operate near this knee point, slightly biased toward the left, where the cell exhibits constant current source behavior. In electrical system analysis, the PV cell is often approximated as a constant current source (Quaschning, 2014). The overall power output of a PV system depends on the type and surface area of the PV material, as well as the intensity of incident solar radiation (Albadi & El-Saadany, 2010; Tesema & Bekele, 2014). Mathematically, this relationship is represented in Equation (7).

$$P_{PV} = \eta_{mp} x \eta_{PC} x A_{PV} x G_T \qquad (7)$$

Where: P_{pv} is the power output of the PV array (W), A_{pv} is the surface area of the PV module (m²), η_{mp} is the maximum power point efficiency of the PV module (typically between 14% and 20%), η_{PC} is the efficiency of the power conditioning equipment (approximately 90%), and G_T is the incident solar radiation on the array surface (W/m²).

3.5. Factors Influencing the Electrical Design of a Solar Array

The electrical performance and design of a solar photovoltaic (PV) array are significantly influenced by three key environmental parameters: solar irradiance (sun intensity), angle of solar incidence (sun angle), and cell operating temperature. Optimal power generation occurs under conditions of high irradiance, low ambient temperatures, and perpendicular sunlight incidence typically observed on cold, clear, sunny days (R. Kumar & Jagadeesh, 2014; Pettongkam, 2018). The magnitude of the photocurrent generated by a PV cell is directly proportional to the intensity of the incident sunlight. On overcast or partially cloudy days, the reduction in solar irradiance leads to a proportional decline in photocurrent generation. Consequently, the photovoltaic conversion efficiency—defined as the ratio of electrical output to the solar energy input is strongly influenced by the solar radiation intensity (A. Kumar & Verma, 2021). However, beyond a certain threshold of irradiance, the photo-conversion efficiency of the PV cell exhibits diminishing sensitivity to further increases in sunlight intensity. This nonlinear behavior reflects the inherent limitations in charge carrier collection and recombination dynamics at higher photon flux levels. Figure 3 illustrates the relationship between irradiance and PV efficiency, emphasizing the importance of optimizing system design within practical operational ranges to ensure reliable and efficient performance.

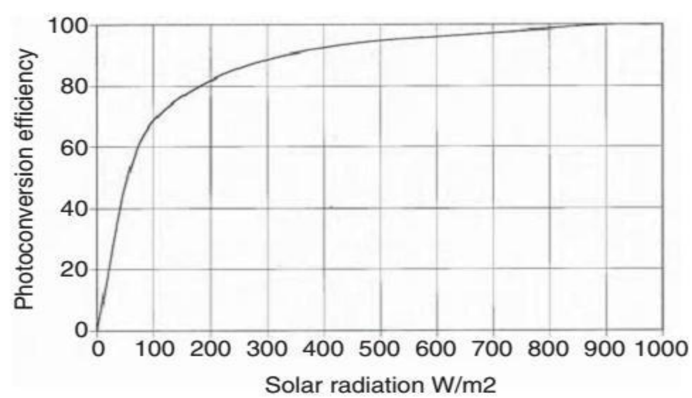

Figure 3: Photo-Conversion Efficiency vs. Solar Radiation (A. Kumar and Verma, 2021)

The output current of a photovoltaic (PV) cell is strongly dependent on the angle of solar incidence. This relationship is commonly described by the cosine law, expressed as shown in equation (8)

$$I = I_o \cos\theta \qquad (8)$$

Where; I =output current, I_o = current from the sun (reference), and θ = angle of the sun line measured from the normal to the PV surface.

This approximation holds accurately for sun angles ranging from 0° to approximately 50°, beyond which the deviation between theoretical and actual current output increases substantially. When the angle of incidence exceeds 85°, the effective component of irradiance on the PV surface becomes negligible, and the cell generates little to no electrical output. In practical applications, the current-angle behavior deviates from the ideal cosine response due to optical and surface reflection losses. This real-world response is described by the **Kelly Cosine Curve**, which provides a more accurate characterization of PV performance at higher angles of incidence. The Kelly curve accounts for factors such as refractive index variations, cell encapsulation, and surface scattering, and is illustrated in Fig. 4.

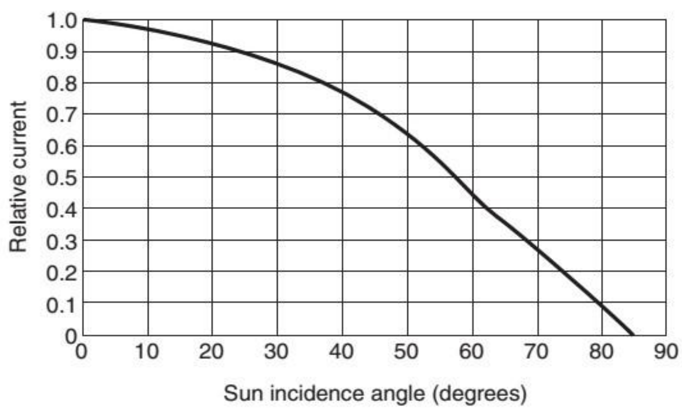

Figure 4: Kelly Cosine Curve for PV Cell (Kumar, *et al.*, 2021)

3.6. Photovoltaic System Components

A photovoltaic panel or array alone is insufficient to constitute a complete PV power system. Rather, an effective and functional PV system is an integrated assembly of several interdependent components that work collectively to ensure consistent energy generation, optimal power conversion, efficient storage, and safe delivery to the load. The mounting structure serves as the mechanical foundation, offering physical stability and proper orientation for the PV panels; it may be fixed or adjustable, particularly in systems utilizing sun-tracking mechanisms. An optional sun tracker significantly enhances energy yield by continuously adjusting the tilt and azimuth angles of the PV array to align with the sun's path, a feature especially advantageous in large-scale or high-efficiency installations. Power electronics comprising charge controllers, maximum power point tracking (MPPT) units, and DC-DC converters play a vital role in regulating the electrical output from the PV modules, ensuring efficient charging of the storage system while protecting the batteries from overcharging or deep discharging. In applications requiring alternating current (AC), such as grid-connected or hybrid systems, an inverter is employed to convert the direct current (DC) from the PV array into AC at standard frequencies (typically 50 or 60 Hz), making the energy usable by conventional household or industrial appliances. Figure 5 is a typical standalone solar PV system. Energy storage, commonly in the form of battery banks, is essential in scenarios where uninterrupted power supply is critical, such as off-grid systems or during periods of low solar irradiance. This storage component ensures power availability during nighttime or cloudy conditions. The effective integration of these system components enables the PV system to function with high reliability, safety, and performance under diverse environmental and operational conditions (Quaschning, 2014; Weir, 2005).

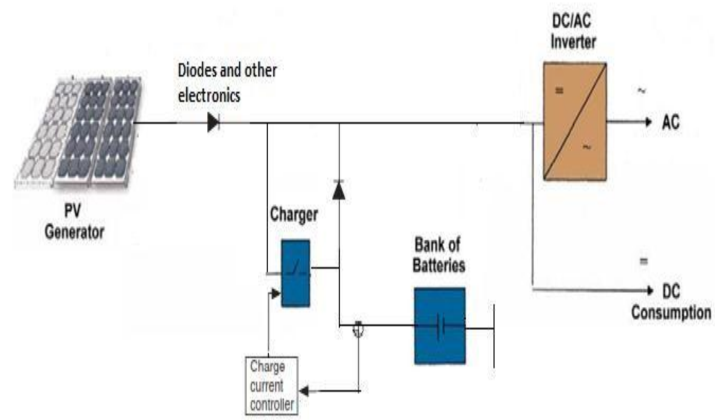

Figure 2.1: Non-Tracking PV Power System for Standalone (Quaschning, 2014)

Economic feasibility remains a pivotal determinant in the successful deployment of any energy system, including photovoltaic (PV) converters. Presently, the technological development of PV converters is advancing rapidly, accompanied by a continual decrease in associated costs. These advancements aim to enhance conversion efficiency while simultaneously reducing the cost per watt of PV modules. Historically, improvements in conventional single-crystal silicon solar cells have been gradual, progressing from approximately 10% efficiency in the 1950s to about 34% by 2016. More substantial gains have emerged through the development of multi-junction solar cells. Triple-junction cells saw an increase from 34% in the early 2000s to 44% by 2016. Current advancements in quadruple-junction cells have achieved efficiencies of up to 46%. Although these high-efficiency cells offer performance that is competitive with conventional energy conversion technologies, they are not yet widely commercialized due to the high costs associated with materials and manufacturing. As a result, their use is currently limited to specialized applications, such as in aerospace and space-based technologies. However, ongoing research and economies of scale are expected to reduce these costs, making high-efficiency PV technologies more accessible to general consumers in the near future (R. Kumar & Jagadeesh, 2014; Quaschning, 2014; Zaman et al., 2014).

3.7 Hydropower Systems

Hydropower is one of the most well-established and widely utilized forms of renewable energy, converting the kinetic and potential energy of falling or flowing water into electricity. Historically, it has also been employed for various mechanical applications, including irrigation, as well as powering watermills, sawmills, textile mills, and other machinery (Punys et al., 2011). Modern hydropower generation involves a combination of civil infrastructure and electromechanical components. Water is stored in a reservoir formed by a dam and is directed through an intake structure into a penstock, which may also consist of tunnels. The pressurized water is then channeled to a hydraulic turbine, where its energy is converted into mechanical power. This mechanical energy is subsequently transformed into electricity via a generator. Figure 6 is the schematic representation of a typical hydropower system that includes components such as the dam, intake structure, penstock, turbine, generator, and outflow channel, all of which work in coordination to ensure efficient energy conversion (Pettongkam, 2018).

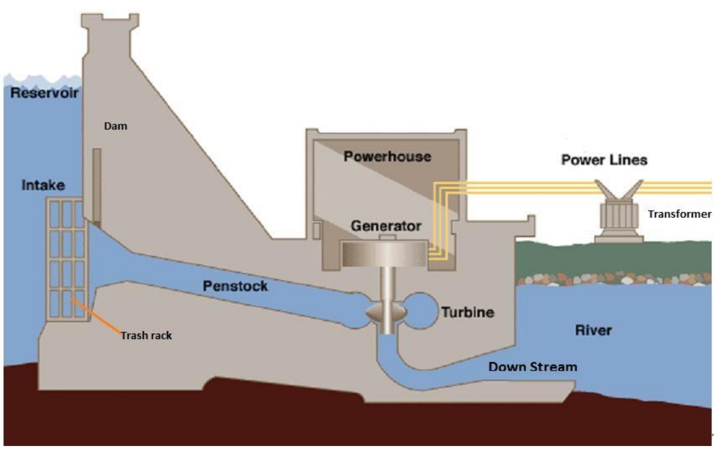

Figure 6: Generalized Hydropower Schematic Diagram (Ackermann, 2012)

3.7.1 Hydropower Components

The core components used for electricity generation in hydropower systems are largely similar across various plant sizes and types. However, certain infrastructure elements such as dams, surge tanks, and tunnels are typically necessary only in larger installations and may be absent in smaller systems (Pettongkam, 2018; Punys et al., 2011; Wu et al., 2018). One of the fundamental components is the **dam**, which diverts river flow towards the powerhouse for energy conversion, while also providing water storage and hydraulic head. The type of dam employed depends heavily on the local topography and geotechnical conditions. Nonetheless, dams may be unnecessary if the plant draws water from pre-existing natural reservoirs, such as lakes with river inflows (e.g., the Tana Beles Hydropower Plant in Ethiopia), or if it operates as a run-of-river system, especially in smaller or ecologically-sensitive designs. **Spillways** are crucial for directing excess water from the reservoir to downstream channels safely. These may include overflow, side channel, or shaft types, depending on the dam structure and site characteristics. The **intake** serves as the entry point for water flowing toward the turbines and must be engineered to reduce head losses, prevent vortex formation, and minimize sediment and debris ingress into the **penstock**, the pressurized conduit delivering water to the turbine. To further prevent the entry of debris, a trash rack is installed at the intake, safeguarding the turbine runner from potential damage (Tamrat, 2007). Gates and valves are essential for flow regulation and maintenance operations. These include devices such as stop logs, sliding gates, flap gates, butterfly, sleeve, rotary, and spherical valves, all of which must be selected with consideration for system head losses and operational effectiveness under full-flow conditions. In larger systems, a **surge tank** (or pressure relief tank) is integrated to mitigate water hammer effects caused by sudden valve closures or openings. Tunnels, including headrace, tailrace, surge shaft, and bypass types, provide enclosed passageways through natural terrain, typically hilly regions. The **penstock**, whose layout and structural integrity depend on site topography and plant configuration, must be carefully designed to minimize hydraulic losses and ensure cost-effective construction. The **powerhouse** is the central facility where hydraulic energy is transformed into electrical energy through electromechanical equipment such as turbines, generators, and transformers. Depending on the site's terrain, the powerhouse may be constructed either underground or on the surface. Finally, the **tailrace** (or afterbay) conveys water back to the river after it exits the turbine. Its design varies depending on the type of turbine employed, ensuring smooth water discharge and minimizing flow disturbances (Punys et al., 2011; Wu et al., 2018).

3.7.2 Principles of Hydropower Plants

The fundamental principle underlying all hydropower plants, irrespective of their scale, is the conversion of the potential energy of stored water into electrical energy. Water accumulated at a higher elevation possesses potential energy due to gravitational force. When this water is released, it flows downward through a specific vertical distance known as the *head*, converting its potential energy into kinetic and pressure energy. This energy is harnessed by hydraulic turbines, which transform it into mechanical energy through rotational motion. The turbine shaft, coupled to an electrical generator, then converts this mechanical energy into electrical power. The theoretical power output of such a system is governed by several physical parameters and is mathematically expressed as in equation (9)

$$P_h = \eta_{TG} \times \rho \times Q \times H_{net} \quad (9)$$

Where: P_h is the power output from the hydropower unit (W), η_{TG} is the overall efficiency of the turbine and generator ($0 < \eta \leq 1$), ρ is the density of water (typically 1000 kg/m³), Q is the volumetric flow rate of water (m³/s), g is the acceleration due to gravity (approximately 9.78 m/s²), H_{net} is the net head available for power generation (m).

Accurate estimation of flow rate and net head is essential for hydropower design and operation. The net head is determined by subtracting hydraulic losses arising from friction, turbulence, and structural transitions such as penstocks, valves, and trash racks from the gross head, which is the vertical distance between the upstream and downstream water levels. Measurement techniques for head include pressure sensors, altimeters, and differential level gauges, while flow rate assessments may utilize current meters, area-velocity methods, or gauging stations (Pettongkam, 2018; Punys et al., 2011).

3.7.3 Classification of Hydropower Plants

Hydropower plants are systematically classified based on three primary criteria: the head availability, operational scheme, and installed capacity. These classifications inform the selection of appropriate technologies and design strategies for specific site conditions and energy needs.

A. Classification by Head

Hydropower plants are primarily classified based on the available head, which refers to the vertical elevation difference between the headwater and the tailwater. This parameter plays a crucial role in determining the appropriate turbine type and overall plant design. High-head hydropower plants, characterized by heads exceeding 100 meters, commonly use Pelton turbines due to their efficiency in harnessing energy from high-pressure water flows. Medium-head plants operate within a head range of 30 to 100 meters and typically employ Francis turbines, which are well-suited to a broad range of flow conditions. In contrast, low-head plants, where the head is less than 30 meters, often utilize Kaplan or bulb turbines. These turbine types are designed to perform effectively under high flow rates and low-pressure differentials, making them ideal for such settings (Pettongkam, 2018; Wu et al., 2018).

B. Classification by Operational Scheme

Hydropower plants can be categorized based on their operational schemes, particularly in how they manage water flow. **Run-of-River (RoR)** systems utilize the natural flow of rivers with minimal or no water storage, making them environmentally friendly. However, their output is highly dependent on seasonal river discharge fluctuations. In contrast, **storage hydropower** plants employ dams to create reservoirs, enabling controlled and reliable electricity generation year-round, even during dry periods. Another key type is the **pumped storage system**, which consists of two reservoirs at different elevations. These systems function in a reversible manner: surplus energy during low demand periods is used to pump water to the upper reservoir, while during peak demand, the stored water is released to generate electricity. Pumped storage is vital for energy balancing, grid reliability, and large-scale renewable energy integration.

C. Classification by Installed Capacity

Hydropower facilities can also be classified according to their installed or rated power output, with specific capacity ranges used to distinguish between different plant scales. While these classifications may slightly vary by country or organization, a widely accepted categorization includes the following: Large Hydropower Plants (HPPs), with capacities greater than 100 MW, are typically integrated into national grids and are capable of supplying both base and peak loads. Medium HPPs range from 15 to 100 MW and are commonly used for regional electricity supply and grid support. Small HPPs, which generate between 1 and 15 MW, are often deployed to power small industries or communities, with the option of grid connectivity. Mini HPPs, producing between 100 kW and 1 MW, are well-suited for village-scale or off-grid electrification. Micro HPPs, with capacities between 5 and 100 kW, cater to the energy needs of small rural communities or institutions. Lastly, Pico HPPs, which generate less than 5 kW, are ideal for individual households or low-power uses in isolated areas (Punys et al., 2011; Tamrat, 2007). For the purpose of this study, all hydropower systems with installed capacities below 15 MW are collectively classified as Small Hydropower Plants (SHPs).

3.7.4 Small Hydropower Plants

Small hydropower plants (SHPS) refer to hydroelectric systems designed to operate on a scale appropriate for supplying electricity to small communities, rural areas, or industrial facilities. Although the precise definition varies across countries and organizations, a generating capacity of up to 15 megawatts (MW) is commonly recognized as the upper threshold for classifying a hydropower system (Pettongkam, 2018; Punys et al., 2011; Tamrat, 2007). Compared to large hydropower projects, SHPs require significantly lower investment and involve minimal civil construction, making them more environmentally friendly. Large-scale hydropower developments often result in the displacement of communities, notable alterations to the biosphere, and substantial environmental impacts, necessitating comprehensive environmental impact assessments. In contrast, SHPs typically operate with minimal or no reservoirs and are regarded as low-impact energy solutions. They can be connected to existing grid networks to supply affordable renewable energy or be deployed in remote or isolated locations where grid extension is uneconomical. Furthermore, SHPs can be integrated as components of hybrid power systems, working in conjunction with solar (photovoltaic or thermal), wind, or both, to enhance energy reliability and sustainability (Punys et al., 2011).

3.8 Hydraulic Turbines

Hydraulic turbines are rotary machines that transform the potential energy of water into mechanical energy. Central to their operation is the runner an assembly of blades, vanes, or buckets that rotates as water acts upon it. Based on their operating principles, turbines are broadly categorized into two types: impulse and reaction turbines. Impulse turbines convert water's potential energy into kinetic energy via a high-speed jet directed tangentially at the runner buckets, causing rotation in open air. Examples of impulse turbines include Pelton, Crossflow, and Turgo types. In contrast, reaction turbines operate with the runner submerged in water and utilize both pressure and velocity changes across the turbine to generate power. Common examples include Francis, Propeller, and Kaplan turbines. The choice of turbine depends on factors such as head, flow rate, and site conditions (Pettongkam, 2018; Tesema and Bekele, 2014).

3.9 Hybrid Power Systems

A **hybrid power system** combines multiple sources of energy generation typically renewable technologies such as solar and wind, with conventional generators and energy storage units. These systems are designed to enhance energy reliability and efficiency while minimizing dependence on fossil fuels. A central element in hybrid system design is the integration of renewable energy sources, which contributes to lower greenhouse gas emissions and reduced operational costs. However, the intermittent and variable nature of renewables presents significant operational challenges, as highlighted by Zakeri and Syri (2015). **Energy storage solutions**, particularly battery systems, play a pivotal role in mitigating these issues by stabilizing the power supply and ensuring demand is met during periods of fluctuating renewable output. According to IRENA (2019), storage is fundamental to the effective operation and scalability of hybrid power systems.

Hybrid power systems can consist of various combinations, such as solar PV, wind turbines, diesel generators, and hydropower. These systems may operate independently or with backup sources, and their design often accounts for the intermittent nature of renewables like solar and hydro, which are dependent on climatic conditions. In contrast, sources such as biogas and biomass offer more consistent energy output. By strategically combining different technologies, hybrid systems can deliver cost-effective and resilient energy solutions. For instance, a PV-hydro hybrid system can be tailored to meet variable power demands without relying on expensive diesel fuel. Such systems are especially advantageous for regions with similar climatic profiles to the Kalangala Islands in Lake Victoria, Uganda, where the proposed hybrid model could enhance energy access while minimizing environmental and economic costs (Bhandari and Ahn, 2021).

Figure 7: Bukuzindu Hybrid Power Station on Kalangala Island

3.9.1 PV-Hydro Hybrid System

A PV-hydro hybrid system integrates PV and hydropower technologies at a single location to enhance the reliability and sustainability of power generation. This configuration becomes particularly beneficial during the dry season when river flow rates decline, reducing the water volume available for hydropower generation and subsequently diminishing the plant's output. To compensate for this seasonal shortfall, a PV plant can be installed alongside the hydropower facility. Typically, solar irradiance is higher during dry periods than in the rainy season, which increases the energy yield from the PV system. Consequently, the photovoltaic component supplements the reduced hydropower output, ensuring a more stable energy supply. The inverter output from the PV system is synchronized with the hydropower generator to achieve seamless integration and continuous power delivery (Bhandari and Ahn, 2021).

Hybrid systems that combine renewable energy sources offer numerous advantages over standalone systems. One key benefit is enhanced reliability and continuity of power supply, as hybrid configurations can provide backup during periods when one source is underperforming. They also promote improved energy services while reducing greenhouse gas emissions and environmental noise, thanks to their reliance on clean and sustainable technologies (Lau et al., 2010). Economically, hybrid systems are advantageous due to their lower operational and maintenance costs and their ability to generate electricity cost-effectively. Moreover, they offer flexible energy solutions capable of meeting baseload demands by intelligently combining variable and dispatchable renewable energy sources (Rezaei et al., 2021). These attributes make hybrid systems a practical and sustainable solution for modern energy needs.

Table 1: Summary of Related Research

Authors	Topic	Contributions	Research Gap
Bekele and Tadesse (2012)	Hybrid system with small hydropower, PV, Wind, and Diesel for Dejen District, Ethiopia	Used HOMER to analyze hybrid energy mix for rural electrification	Relied heavily on diesel generators; did not explore alternative renewable combinations
Tamrat (2007)	Independent rural electrification with small hydropower, PV, and Wind in Ethiopia	Conducted comparative analysis without integrating hybrid systems	Lacked optimization of hybrid system components
Tesema and Bekele (2014)	Techno-economic analysis of hybrid renewable energy for Werder District, Ethiopia	Identified Wind/PV/Diesel as the most feasible, with Wind as the dominant source	No integration of other renewable sources like biogas
Batnaineh et al. (2014)	Pre-feasibility of floating hydro-PV hybrid in Brazil	Studied PV on floating structures, highlighting benefits and cost trade-offs	Increased PV costs due to water evaporation effects
Lotfi et al. (2013)	Hybrid PV/Wind/Micro-Hydro/Diesel for rural electrification in India	Investigated hybridization with multiple renewables	Did not optimize system for cost and efficiency
Lal et al. (2011)	Standalone PV and fuel cell system	Applied Fuzzy Particle Swarm Optimization for system design	Lacked hybridization with wind or hydro sources
Rashidi et al. (2012)	Standalone hybrid Wind/PV/battery system	Assessed life cycle cost, embodied energy, and loss of power supply probability	Did not compare with other hybrid configurations
Shafiullah and Carter (2015)	PV/Diesel/Battery hybrid system analysis	Found PV/Diesel/Battery to be more cost-effective than standalone diesel	High upfront costs still a challenge
Girma (2013)	PV/Battery/Diesel vs. standalone diesel in Ethiopian schools	Showed cost-effectiveness and environmental benefits of hybrid systems	Did not explore hybridization with biomass or other renewables
Odoi-Yorke and Woenagnon (2021)	PV/Fuel cell hybrid for telecom in Ghana	Demonstrated lower LCOE than grid tariffs	Limited focus on other renewable combinations
Goswami and Sadhu (2021)	Floating PV on wastewater treatment systems	Showed increased efficiency and economic benefits	Lacked analysis of hybridization with other renewables
A. Kumar and Verma (2021)	PV/Biomass/Battery microgrid in India	Showed economic and reliability benefits	Did not explore grid integration scenarios
Delano et al. (2020)	PV/Battery/Diesel hybrid for rural electrification in Benin	Demonstrated lower battery usage and CO2 emissions	Limited scalability assessment
Olatomiwa et al. (2015)	PV/Diesel/Battery system for Nigerian locations	Found optimal system configurations	Lacked analysis of alternative renewable sources
Li et al. (2020)	Multiple hybrid configurations for rural China	Found PV/Wind/Biomass to be the most viable	Did not focus on site-specific adaptability
Goswami et al. (2020)	PV/Wind grid-connected hybrid for Indian island	Showed lower LCOE and CO2 reduction	Lacked analysis of off-grid potential
Adaramola et al. (2014)	PV/Wind/Diesel hybrid for rural Ghana	Found cost-effectiveness in rural electrification	Did not include battery storage optimization
Adaramola et al. (2017)	PV/Battery/Biodiesel generator system	Found high LCOE even with subsidies	Need for alternative cost reduction strategies
Agyekum and Nutakor (2020)	PV/Wind/Diesel/Battery for Mankwadze township, Ghana	Found sensitivity to diesel prices and inflation	Indicated need for biogas hybridization for sustainability

The summary of the reviewed literature illustrated in Table 1 provides comprehensive insights into various hybrid renewable energy configurations for rural electrification. A majority of studies have focused on the integration of solar PV, wind, and diesel generators, often supported by battery storage. While these combinations have demonstrated technical and economic feasibility, several critical limitations remain. Notably, there is a persistent reliance on diesel, which undermines sustainability goals due to its environmental and economic implications. Additionally, many studies lack thorough system optimization or comparative analysis across a broader range of renewable sources. Despite growing interest in solar-wind hybrids, very few efforts have explored the integration of biogas a renewable resource with high potential in agricultural and rural contexts into hybrid systems. This gap is particularly evident in the African context, where biogas from organic waste could offer a sustainable, locally available energy source. Therefore, this review critically examines existing research in related fields, identifies significant gaps, and proposes appropriate recommendations to address these shortcomings

4.0 Review Findings

The classification of hydropower systems significantly influences key design decisions, turbine selection, and feasibility assessments, especially in regions with varied topographical and hydrological conditions. A thorough review of the literature reveals that hydropower technologies exhibit remarkable versatility, adapting effectively to a broad range of site-specific parameters, including head height, flow rate, and energy demand. Notably, low-head hydropower systems, operating under heads of less than 30 meters, are identified as a critical solution in regions with limited elevation differentials. These systems typically utilize Kaplan and cross-flow turbines, which are particularly suited for high-flow, low-pressure scenarios, ensuring reliable energy production in geographically constrained environments. The study also classifies hydropower plants into three primary types based on operational characteristics: (1) **Run-of-river systems**, which utilize natural river flows with minimal storage, offering a low environmental impact; (2) **Reservoir-based systems**, which incorporate dams for water storage, enabling controlled generation to meet peak demand; and (3) **Pumped storage systems**, which function as grid-scale energy storage solutions, enhancing load balancing and improving system stability, particularly in grids integrating variable renewable energy sources such as solar and wind. In addition, hydropower systems are classified according to their installed capacity, with distinct categories emerging: large-scale (>30 MW), medium-scale, small-scale, micro-hydro, and pico-hydro (<5 kW). Each category serves specific applications, ranging from supporting national power grids to providing electrification solutions for individual households (Pettongkam, 2018). These classification frameworks are critical for the development of context-specific hydropower solutions that contribute to enhancing energy accessibility, ensuring environmental sustainability, and building resilience within both centralized and decentralized energy systems.

5.0 Conclusion

This study underscores the significant potential of hybrid renewable energy systems to address the persistent energy challenges faced by remote island communities, particularly in Uganda's Kalangala District. By optimizing the integration of solar photovoltaic (PV) power, battery storage, and backup diesel generation, this research demonstrates the feasibility of a more reliable, efficient, and sustainable energy solution that reduces dependence on fossil fuels and minimizes environmental impact. The findings highlight key factors influencing system performance, including solar irradiance patterns, PV cell efficiency, and the use of low-head hydropower systems, all of which contribute to the overall resilience of the hybrid energy system. The application of advanced energy management strategies and the leveraging of existing infrastructure, such as the 33kV submarine cable, offers a scalable model for decentralized electrification, particularly in regions where grid expansion is economically unfeasible. The incorporation of hydropower, with its diverse operational schemes ranging from run-of-river to pumped storage further complements the system, enhancing grid stability and ensuring continuous power supply, especially during periods of fluctuating demand. This study supports Uganda's energy policy objectives, including the Electricity Connection Policy (ECP), the Rural Electrification Strategy, and Uganda Vision 2040, by providing a concrete pathway for achieving universal access to sustainable energy. The proposed hybrid system not only aligns with national energy goals but also contributes to broader regional aspirations outlined in the African Union's Agenda 2063. As such, this research offers valuable insights for future hybrid system deployments in East Africa and beyond, providing a scalable, context-specific solution for energy security in remote and off-grid communities. Finally, the hybrid power system proposed for Kalangala Island exemplifies the transformative potential of integrated renewable energy solutions. With continued technological advancements, strategic policy support, and effective system design, hybrid systems can serve as a cornerstone in the transition to sustainable and resilient energy futures for island communities and other energy-deficient regions worldwide.

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Conflict of interest
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