

Original Research Paper

## Analyzing the Design and Implementation of Sustainable Energy Systems in Island Communities

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**Abstract:** This review critically analyzes the design of sustainable energy systems implemented on islands and beyond. It emphasizes the importance of integrating renewable and non-renewable energy sources to enhance energy output in hybrid systems. Due to the Island's unique geographical and environmental characteristics, islands face distinct energy supply and sustainability challenges. The review examines different aspects of sustainable energy system design, such as renewable energy sources, energy storage solutions, grid integration, and policy frameworks. Hence, by synthesizing current research and case studies, this review aims to provide insights into effective strategies for designing sustainable energy systems that are specifically tailored to the needs and constraints of islands. This paper detailed the critical role of renewable energy sources such as solar, wind, hydro, and biomass in driving sustainability in island communities and urges energy stakeholders and policymakers to embrace their potential to effectively energize rural and underprivileged areas.

**Keywords:** Microgrid, Renewable Energy, Sustainable Energy.



## 1. Introduction

The escalating global population growth and energy demands underscore the urgent need for sustainable energy solutions. This increase in energy demand calls for so many researchers to tailor their research to energy disparity affecting 1.3 billion people, predominantly in Africa [1]. Despite the ongoing research to meet the energy demand, researchers are tailoring their research toward renewable sources that are clean, harmless and environmentally friendly. Non-renewable energy sources have historically dominated power generation, the shift towards renewables like wind, solar, hydro, and biomass is imperative to mitigate environmental degradation and climate change [2]. The high demand and low generation of energy led to the innovative combination of two energy sources to generate a reasonable amount of energy [3]. The process of technologically combining two sources of energy is known as energy hybridization. Hybrid systems involve the integration of multiple renewable or non-renewable energy sources to offer a promising avenue for reliable and continuous power production, especially in regions with unreliable infrastructure.

Renewable energy sources reduce environmental impact and foster socioeconomic development, particularly in remote and isolated communities that have the challenges of grid connection due to their geographical location [4]. The challenges lie in optimizing these hybrid systems to ensure cost-effectiveness and minimal environmental footprint. Identifying the most economically viable hybrid system highlights the significance of customized solutions for specific energy source combinations. Ultimately, tackling global energy challenges requires a comprehensive approach that includes research, innovation, and a dedication to sustainable practices. By harnessing renewable energy sources and advancing hybrid systems, a more equitable, environmentally sustainable, and economically feasible energy future can be achieved.

## 2. Literature Review

Renewable energy refers to the generation of energy from natural resources, such as sunlight, wind, rain, tides, waves, and geothermal [5]. These resources are naturally replenished and provide a sustainable and environmentally friendly alternative to finite fossil fuels, which contribute to environmental degradation. The global shift towards renewable energy is driven by concerns over climate change, energy security, and the depletion of finite resources. The innovative technologies involved in renewable energy include solar photovoltaics (PV), wind turbines, hydroelectric power, biomass, and geothermal energy [6]. These sources have witnessed significant advancements in efficiency and cost-effectiveness in recent years, thereby increasing their competitiveness with traditional energy sources. Governments, businesses, and individuals are making investments in renewable energy infrastructure to reduce greenhouse gas emissions, combat climate change, and establish a more resilient energy system for future usage.

### 2.1. Microgrid Design and Analysis

A microgrid is an interconnected network of loads and distributed energy resources (DERs) that can function as a unified entity alongside the main grid. It has the flexibility to connect to or disconnect from the grid, operating seamlessly in both grid-connected and standalone modes.

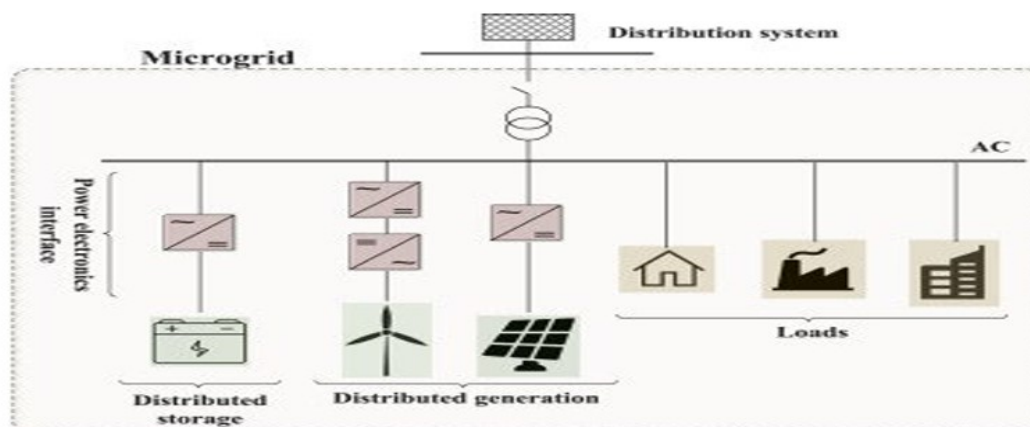


Figure 1. a Simple Microgrid Connected to The Distribution Network [8]

Microgrids offer numerous advantages, including improved customer reliability and resilience against grid disturbances, integration of renewable energy sources (RES), enhanced energy efficiency, and the ability to sustain autonomous operations during grid downtimes for grid-connected systems. Furthermore, microgrids enable cost savings, extended energy provision, and participation in energy markets [7]. Figure 1 is the simple microgrid connected to the distributed networks.

Distributed generation (DG) represents the decentralized production of energy from various small-scale sources, particularly Renewable Energy Sources (RES) [9][10][11]. DG systems are essential components of microgrids, providing localized power generation and reducing dependence on centralized power plants [12]. Microgrid design and analysis encompasses the refinement of power flow and control mechanisms to ensure optimized and reliable operations of the system.

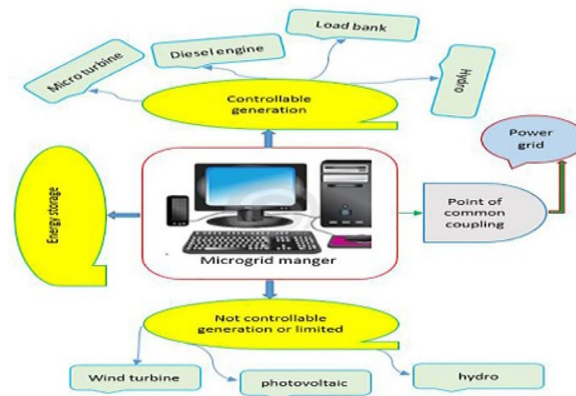


Figure 2. Schematic of a Microgrid with Different Connected Energy Sources [12]

The current research is on developing algorithms for optimal power dispatch, efficient energy management, voltage regulation, frequency control, and coordinated integration of DERs within the microgrid for efficient and effective power delivery [13]. The architecture of microgrids is shaped by the evolution of energy storage systems, renewable energy technologies, smart grid infrastructure, and communication networks. The integration of these technological advancements enhances the control, monitoring, and management of microgrids, leading to improved performance and stability [14]. The architecture of a microgrid model captures both the dynamic and steady-state characteristics of microgrids, addressing the drawbacks aspects such as power flow dynamics, voltage stability, energy management, and response to grid disturbances [15]. Figure 2 is the schematic of microgrid with different connected energy sources. These challenges of microgrids are more experienced in Africa, especially in Uganda.

## 2.2. Renewable Energy Integrated Microgrids in Uganda

The exploration of microgrid behavior and performance in Ugandan reveals a dynamic landscape of research and innovation aimed at addressing energy challenges and fostering sustainable development. According to Kumar and Majid [16] undertook a comprehensive study focusing on the enhancement of irrigation practices for a banana plantation through wind energy power generation. The researcher discovered the efficacy of wind turbines, particularly at wind speeds of 20 m/s, alongside a thorough cost analysis encompassing investment, maintenance, and operational considerations. The calculated net present value and net real rate of return elucidate the economic viability of such ventures, providing tangible insights for future endeavors. Similarly, Elegeonye et al. [17] researched on an integrated approach to electrifying remote areas in Uganda, leveraging on a combination of energy technologies and storage solutions alongside traditional diesel generation. Employing sophisticated modeling through HOMER software, their grid design aims to mitigate the challenges posed by renewable resource variability, offering a pragmatic solution for community electrification. Figure 3 is the designed Hydro-PV-Battery-Diesel Hybrid system that was efficiently used by the researcher. Despite its good efficiency, this design lacks clean and friendly energy generation because of the carbon footprint of the diesel generator.

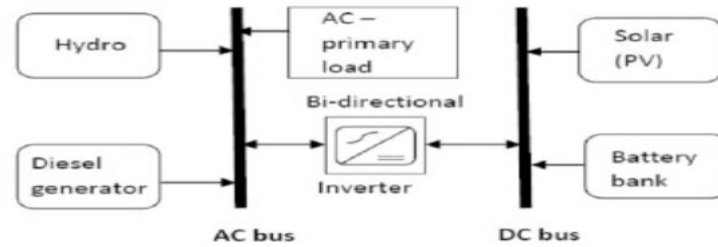


Figure 3. Parallel Hydro-PV-Battery-Diesel Hybrid system [17]

The power sector in Uganda has experienced consistent growth, with a primary focus on rural electrification to improve electricity access for rural communities. This is achieved through both grid extension and isolated mini-grid approaches. However, the implementation of hydropower mini-grids in rural areas has faced challenges, particularly related to system failures resulting in shutdowns and load shedding. To investigate the root causes of these issues, a comprehensive study was conducted on an existing isolated hydropower mini-grid. The study involved a thorough review of published articles and reports, as well as an analysis of enrollment patterns, energy sales, and load demand. In addition, a field survey was conducted using a structured questionnaire to gather real energy demand data. The performance of the system was further evaluated through simulation using HOMER pro × 64 software. The findings of the study revealed a decline in customer enrollment, reduced energy sales, and a significant number of system shutdowns. To address these challenges, various hybridization options for the existing hydropower system were modeled. The proposed hybrid system demonstrates the potential to substantially reduce fuel consumption from 222 to 23.2 L/day and emissions from 82.5 to 8.3 kg/year on average, while also improving system reliability. Simulated values of key metrics such as Net Present Cost (NPC), Levelized Cost of Electricity (LCOE), and operating costs indicate favorable outcomes. Despite the observed shortcomings in mini-grid performance, there is a noticeable improvement in livelihoods due to enhanced access to social and economic services [18].



Figure 4. HOMER System Architecture [18]

Over 1.3 billion people lack access to grid electricity, and Uganda serves as an example, with less than 12% of the population having access. Existing analyses on grid-connected distributed generation often fail to consider the unreliability of grid power, which is frequently affected by outages. This paper aims to address this oversight by proposing new analytical methods using HOMER to tackle the issue of unreliable grid electricity. We have developed a model that determines optimal configurations and provides cost predictions for reliable power generation. We have demonstrated the effectiveness of this model in a Ugandan village, but its applicability extends universally. Our results indicate that diesel power generation is the most cost-effective option, although slight shifts in pricing can make solar/diesel hybrids competitive. While enhancing reliability increases costs, it is a justifiable expense for users who prioritize reliability [19].

Uganda possesses abundant natural energy resources, primarily renewables, that have the potential to meet its growing energy needs. However, despite this potential, only 9–12% of the population, mainly in rural areas, has access to electricity. The energy sector faces numerous challenges, resulting in ongoing imbalances between supply and demand. Historically, Uganda has relied on hydropower,

supplemented by biomass, diesel-based thermal, and solar electricity. However, the country is now exploring distributed generation based on renewable energy sources. This paper assesses Uganda's potential for renewable energy, current progress in distributed generation, government policies, challenges within the sector, and proposed solutions. It argues for the integration of various distributed generation systems to optimize the use of renewable energy, thereby addressing the country's electricity needs and promoting economic growth. By harnessing abundant renewable resources through distributed energy generation, Uganda can improve energy access and enhance socioeconomic well-being in the region [20].

This article presents a renewable energy mini-grid model specifically designed for remote areas in Uganda, providing a sustainable alternative to expensive and polluting thermal generators. The focus of this model is Kalangala Island, Uganda, which experiences an average daily solar flux of  $300\text{W/m}^2$  and has an estimated wind speed potential of  $6\text{m/s}$  at a height of  $10\text{m}$ . To accurately assess the available resources, Artificial Neural Networks (ANN) are used. The model is validated by comparing it with meteorological and ANN forecasts to ensure its accuracy. By forecasting short-term solar and wind energy, the model enables effective planning and financial viability analysis, comparing the costs with thermal generators. The technical feasibility of the model is confirmed by utilizing a DIGSILENT power factory, which highlights the potential for solar integration and cost savings [21].

### 2.3. Hybridizations and Optimization of Renewable Energy Sources in Uganda

Hybridizations and Optimization of Renewable Energy Sources involve combining different types of renewable energy technologies, such as solar, wind, hydro, and geothermal, to maximize energy production and efficiency [22]. Optimization techniques utilize advanced algorithms and models to determine the most efficient combination of energy sources, considering factors like location, weather patterns, and energy demand. This approach aims to enhance reliability, sustainability, and cost-effectiveness in the generation of renewable energy [23]. Research conducted by Eze et al. [23] aimed to devise a sustainable hybrid solar PV-biogas microgrid tailored for off-grid rural communities in Uganda. The researcher employed a comprehensive mixed-design approach for data collection which comprised a literature survey and mathematical design analyses. The microgrid entails a  $5\text{KWp}$  solar PV system complemented by a biogas generator for continuous electricity supply during daytime, as well as backup provision during periods of low sunlight and at night. The investigation unveiled notable environmental benefits, including a reduction in greenhouse gas emissions and enhancement of air quality.

This design showed high efficiency with an excellent environmentally friendly due to its pure renewable hybridization. Similarly, Toolit [24] present a methodology for optimizing microgrid systems from a techno-economic standpoint, demonstrated through a case study of St. Mary Lacor Hospital in Gulu, Uganda. Due to the unreliable Ugandan national grid, the hospital faces operational challenges and incurs additional expenses for backup solutions [25]. The authors conducted a two-month data collection campaign, using 200 realistic load profiles derived from a Monte Carlo procedure based on on-site surveys. This data was utilized to design an ideal microgrid capable of efficiently powering loads in both grid-tied and stand-alone configurations, with a primary focus on maximizing energy supply reliability. The optimization approach leverages the Poli.NRG tool from Politecnico di Milano, which determines optimal component sizes and dispatch strategies. The numerical outcomes of this simulation offer valuable insights for hospital management, aiding in the evaluation of new generators and the formulation of effective energy policies.

Furthermore, Hidayat et al. [27] examined a hybrid power system in Uganda comprising a photovoltaic power plant, electrical storage, and diesel generator backup. The research underscored the critical role of battery storage in mitigating low daily electrical consumption and managing peak loads during periods of reduced solar radiation. Despite the initial high investment costs, the optimal configuration of PV-storage-diesel generators demonstrated economic benefits, including significant reductions in fuel consumption. The disadvantage of this research is the carbon emission from the diesel generator which leads to environmental degradation.

Uganda's aspirations for substantial power generation, falling short of targets, necessitate a heightened focus on renewable energy, particularly solar photovoltaic (PV). Eastern Uganda, characterized by low global solar irradiance, presents an opportune environment for PV deployment. Katongole et al. [28] endeavored to optimize sizing and conduct techno-economic analyses of a solar PV-diesel hybrid system tailored for Busitema Health Centre III. The research achieved a commendable  $85.5\%$  renewable energy fraction and a substantial total electrical energy output. The promising production of the design gives it an edge but still has drawbacks such as MPP tracking

which enhances power output. The integration of a solar tracking system enhances solar energy consumption efficiency by maximizing sunlight collection throughout the day [29]. More detailed research on the integration of solar tracking is imperative to consolidate information from diverse studies and methodologies, with a focus on optimizing system components, sizing, and operational strategies. The HOMER approach emerges as a valuable tool for simulating different hybrid systems, facilitating insights from investigations conducted across various periods, locations, and nations.

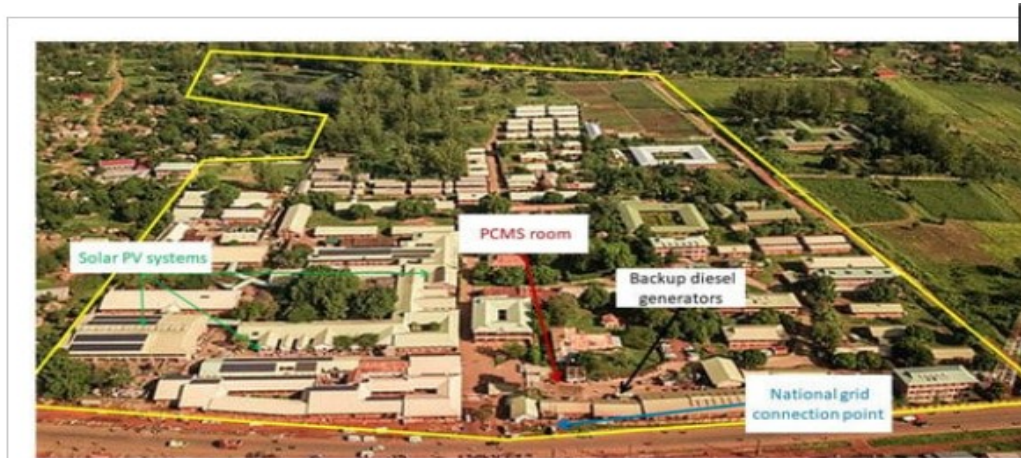


Figure 5. Overview of the Lacor Hospital's Energy Community

In Algeria, a novel energy management technology integrating pumped hydro storage and batteries was developed to orchestrate a hybrid energy storage system [30]. This was designed to use hourly time series data and a grey wolf optimizer in MATLAB software to estimate the appropriate system size. Hybrid storage systems emerge as superior in terms of reliability and cost, with an ideal energy supply system. However, these hybrid systems are susceptible to changes in irradiation, temperature, and load, necessitating additional measures such as power upgrades to ensure optimal performance.

The research on the potential of wind and solar energy viability and sensitivity in Bangladesh using off-grid and grid-connected scenarios was conducted by Hasan et al. [31]. The researcher employed the neural network method to measure wind speed and sun irradiance, the study evaluates promising findings for predicting dependability. PV-Grid, Wind-Grid, Wind-PV-Grid, and off-grid hybrid renewables were developed in Homer-pro environment taking into account various parameters such as NPC, COE, RF, load demand, RES supply availability, system economics, and greenhouse gas emissions. From the findings, sensitivity analyses revealed that optimal system configurations are notably influenced by variations in wind speed, solar radiation, nominal discount rate, and wind turbine lifetime, emphasizing the importance of thorough feasibility assessments before renewable energy installation. Das and Kundu [32] conducted similar research in Bangladesh mountain regions titled Feasibility Analysis of Self-sustainable Hybrid Systems. Similar findings were obtained agreeing with the research conducted Hasan et al. [31].

The paper presents a comprehensive feasibility study on the integration of renewable energy generation systems into the energy infrastructure of Popova Island [33]. This study acknowledges the significant potential of these systems in meeting the island's power requirements. To evaluate the financial viability of this integration, an analytical framework is employed, utilizing the Monte Carlo method and an energy systems model. The framework takes into account uncertainties and risks associated with input variables. Multiple scenarios are generated through Monte Carlo-based parameterizations and are then inputted into the Hybrid Optimization of Multiple Energy Resources (HOMER) model. The wide range of outcomes derived from these scenarios serves as a valuable resource for stakeholders, providing valuable insights into the potential benefits of increased utilization of renewable energy, resulting system configurations, and reduced electricity costs [33]

The research article discusses the electrification of three villages in the Kollegal block, India, using off-grid hybrid renewable energy systems [34]. The aim is to provide reliable energy while reducing

costs and CO<sub>2</sub> emissions. To achieve this, system control, component sizing, and selection are optimized through the use of Genetic Algorithm (GA) and HOMER Pro Software. Four combinations of hybrid systems are compared, and a sensitivity analysis is conducted on the best solution, considering changes in wind speed and biomass fuel prices. The study concludes that the GA-based HRES (biogas+biomass+solar+wind+fuel cell with battery) is the optimal solution, providing energy at \$0.163 per KWH with 0% unmet load, surpassing the cost-effectiveness of HOMER [34].

#### **2.4. Teno-Economic Feasibility of Renewable Energy Designs**

This study aimed to assess the feasibility of nine renewable hybrid systems for providing electricity to remote areas in Southern Cameroons, using climate data from Wum. The analysis, conducted with HOMER Pro version 9.9.2, focused on metrics such as NPC, COE, and CO<sub>2</sub> emissions. Among the systems studied, scenario G, a combination of PV, diesel, small hydro, and batteries, emerged as the most economically viable, with a COE of \$0.443/kWh. This was compared to \$0.674/kWh for scenario E, a pure renewable system. Despite emitting CO<sub>2</sub> due to its diesel component, scenario G was deemed economically superior due to its lower COE and related costs. However, from an environmental standpoint, scenario E was optimal due to its zero emissions. The study also found that the optimal systems were robust to uncertainties in input variables. Overall, off-grid systems were found to be more attractive for rural electrification in Southern Cameroons due to their reliability, ease of implementation, and environmental friendliness compared to grid connections. The findings are crucial for informing policymakers and investors in renewable energy in Cameroon, with future studies recommended to utilize ground resource data for a more accurate assessment. Additionally, government support through policies, regulations, incentives, and funding is essential for the growth of the renewable energy sector [35].

The study further suggested a short-term optimization technique for hybrid hydro-solar power producers, employing fuzzy theory to address seasonal and daily uncertainties. By considering nine common scheduling situations, the optimization approach proves feasible and efficient, with solar power production accounting for a significant percentage of total output. This highlights the importance of incorporating natural constraints and regulatory consequences into scheduling decisions for hybrid power systems [36]. This paper also focuses on a compensatory large-scale hydro-photovoltaic generation system in which reliable power supply and beneficial power generation equilibrium are simultaneously considered based on natural limitations and policy impacts.

This article evaluates the feasibility of a Hybrid Renewable Energy System (HRES) in meeting the energy requirements of thirty residences in Al-Qurayyat city, KSA, in line with the country's sustainability objectives. Initial simulations identify the most optimal configuration: PV/WT/DG/Converter/BSS, which achieves a reliability factor (RF) of 92.8% with a Net Present Cost (NPC) of \$358,616 and a Cost of Energy (COE) of \$0.166/kWh. An alternative configuration, PV/WT/Converter/BSS, offers a 100% RF but at higher costs. The proposed HRES, in comparison with a CPV-HRES, demonstrates the economic superiority of PV technology despite lower energy yields. This study pioneers the integration of concentrated photovoltaics (CPV) into HRES, highlighting the economic and environmental benefits of hybrid systems for rural electrification and emissions reduction [37].

Khan et al. [38] identified a hybrid energy solution that is both technically feasible and economically sustainable for off-grid electrification in the village of Korkadu, located in the Puducherry region. This solution aims to establish an optimal configuration comprising solar PV, wind turbine, bio generator, and battery bank backup, effectively meeting the anticipated energy demand reliably for Rs. 10.18/KWh. At the core of this endeavor lies the design and analysis of a hybrid renewable system, emphasizing efficient utilization of solar energy resources. The research focuses on low-cost solutions for long-term rural development which underscores the potential of hybrid systems in providing sustainable energy access to remote areas [38].

This study investigates the feasibility of meeting the energy demands of a town by utilizing both on-grid and off-grid renewable energy systems, with a specific focus on the technological and economic aspects. The results suggest that, in terms of Net Present Cost (NPC), Operation & Maintenance (O&M) expenses, Cost of Energy (COE), and Renewable Fraction (RF), on-grid systems generally yield better performance compared to off-grid systems. Among the eight different hybrid system configurations analyzed, the PV-WT-MH-GRID-CT system proves to have the lowest COE of \$0.034/kWh in the on-grid scenario, contributing to a reduction in CO<sub>2</sub> emissions when compared to off-grid setups. In off-grid scenarios, the PV-WT-MH-BT-CT-DG configuration emerges as the most viable option, with an NPC of \$612,748, COE of \$0.145/kWh, O&M costs of \$20,334, and an RF of

95.5%. Variations in solar radiation and wind speed have an impact on system performance, leading to changes in NPC, COE, O&M, and RF. For example, decreased solar radiation and increased wind speed result in decreased NPC and COE, while O&M costs increase, affecting the overall feasibility and efficiency of the system [39].

Afolabi and Farzaneh [40], demonstrates the environmental advantages of hybrid micro hydro/PV/DG/wind power systems in Nigeria, which contribute to reducing pollutant emissions and advancing Sustainable Development Goal 7. Similarly, Hossen et al. [41], highlights the effectiveness of off-grid PV-wind-biomass hybrid energy systems in Bangladesh, showcasing considerable reductions in costs and emissions compared to conventional power sources.

In recent years, there has been a global surge in interest in environmental concerns and renewable energy. This has resulted in significant projected growth in the microgrid market, with expectations of reaching a market size of USD 400 billion by 2020 [42]. South Korea, specifically, is actively involved in fostering industries related to microgrids. However, there has been little discussion on the deployment of nanogrids in the country, and there are few real-life examples. Research indicates that nanogrids could be more cost-effective than microgrids in scenarios where power loads are spread out over long distances, such as islands or sparsely populated areas. As the costs of nanogrid components decrease, their market is expected to expand further. This study, which focuses on comparing microgrids and nanogrids on Jeju Island in Korea, suggests that for clustered loads, nanogrids should be considered a priority. However, for widely dispersed loads, governments should assess which grid type is more economical. The study acknowledges its limitations, such as solely considering costs calculated through HOMER and neglecting factors like labor and property prices. Future research should include these factors. External factors, such as economies of scale and governmental policies supporting renewable energies, were also not taken into account, which could affect project costs [42]. Despite these limitations, the study is significant in shedding light on the economic feasibility of nanogrids versus microgrids, filling a gap in existing literature. Similarly, Ayan and Turkay [43], evaluated the optimal design and techno-economic of hybrid HRES for rural electrification in India. Their study emphasizes the cost-effectiveness and long-term sustainability of HRES in meeting varied energy needs which is in line with the research conducted by Assis et al. [42].

This study aimed to investigate how renewable energy sources can effectively meet the energy demands of nearby electricity consumers. The findings revealed that the success of variable-renewable-energy-based hybrid systems heavily relies on statistical energy-demand parameters. By analyzing data from existing consumers, valuable insights were obtained for optimizing the sizing of these systems. While standalone hybrids offer exceptional reliability, their energy costs remain high due to storage limitations, particularly pumped storage. The study suggests that load aggregation could enhance the performance of hybrid systems and that these systems can withstand various weather conditions. However, in the case of Algeria, despite the environmental superiority of renewable energy generation, it currently struggles to compete with the national power system in terms of cost-efficiency [44].

This paper examines the energy requirements of a cluster of 10 traditional houses in a rural area of Morocco. It evaluates various scenarios for an off-grid Hybrid Renewable Energy System (HRES) and utilizes the HOMER software to assess combinations of solar, wind, and biomass energy sources. The objective is to determine the most efficient and cost-effective configuration. Scenario A, which includes biomass, wind, photovoltaic (PV), and battery storage, is identified as the optimal choice. It can meet a daily energy demand of 91.38 kWh and handle a peak load of 6.44 kW, at a cost of 0.2 \$/kWh. This configuration demonstrates competitive initial investment and maintenance costs, Net Present Cost (NPC), and electricity cost when compared to other options considered. Furthermore, it is estimated to reduce CO<sub>2</sub> emissions by 26.48 tons per year, underscoring its environmental benefits. By substituting conventional fossil fuel-dependent power plants with renewable energy alternatives, these systems can offer economic viability and long-term sustainability for rural regions in Morocco. The paper suggests that as unit prices decline, these solutions could become feasible alternatives to grid connections. This presents significant opportunities for off-grid electricity generation in African rural areas abundant in renewable resources [45].

The study was focused on the development of an off-grid hybrid renewable energy system (HRES) for a remote island in South Korea that lacks traditional power sources. Wind and solar energy were considered, resulting in two recommended systems: System A, which had the lowest Net Present Cost (NPC), and System B, which had the lowest Levelized Cost of Energy (LCOE). The estimated daily energy demand for the island was 24,720 kWh, with a peak of 2292 kW in winter. The average wind speed was 3.6 m/s, and the daily solar radiation was 4.13 kWh/m<sup>2</sup>. System A had an NPC of \$11.3

million, slightly lower than System B's \$17.6 million. However, System B offered cheaper electricity at \$0.122/kWh compared to System A's \$0.159/kWh. Both systems included a STX 93/2000 wind turbine and varying PV panel capacities. System A could generate 9,016,674 kWh/year, while System B could produce 9,812,942 kWh/year. To manage energy surplus and deficit, pumped hydro storage (PHS) was designed, which proved to be more economical than batteries. The construction costs for PHS were \$1.34 million for System A and \$1.45 million for System B, compared to \$1.80 million and \$1.58 million for batteries, respectively. Additionally, the study explored the variations in NPC and LCOE of different systems by adjusting input variables such as the discount rate, project lifetime, and daily load [46]. Figure 6 is the Conceptual design of a typical hybrid renewable energy system.

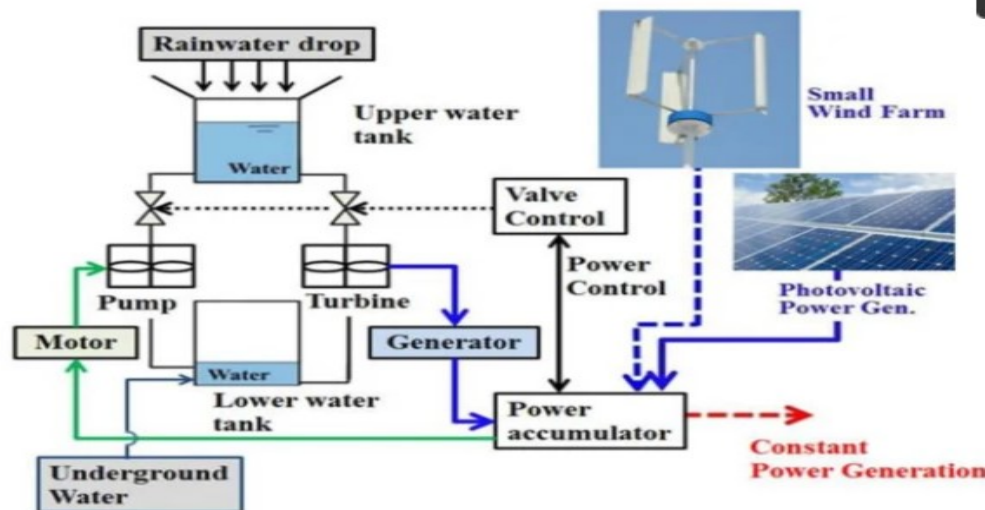


Figure 6. Conceptual Design of a Typical Hybrid Renewable Energy System [46]

## 2.5. Design of Sustainable Energy System in an Island

Islands serve as a microcosm of the broader energy challenges faced by the world [47]. Their isolation and vulnerability to climate change impacts exacerbate these challenges. Therefore, developing sustainable energy systems for islands necessitates a thorough understanding of their unique energy requirements, resource availability, and environmental considerations [48]. This review evaluates the key components and considerations involved in designing sustainable energy systems for islands. It primarily focuses on maximizing the penetration of renewable energy, enhancing energy resilience, and mitigating carbon emissions.

## 2.6. Factors to be Considered Before Designing Sustainable Energy Systems on an Island

**Renewable Energy Sources:** The integration of renewable energy sources is a fundamental aspect of sustainable energy systems on islands. Solar, wind, hydro, and geothermal energy offer vast and often untapped potential for islands to decrease their reliance on imported fossil fuels and transition towards a cleaner energy mix [49][50]. However, the intermittent nature of renewable energy sources presents challenges in ensuring a reliable and resilient energy supply. This review assesses the optimal combination of renewable energy technologies based on factors such as resource availability, variability, and cost-effectiveness [51]. It emphasizes the importance of a diversified portfolio to address intermittency and enhance energy security.

**Energy Storage Solutions:** Effective energy storage is crucial for balancing supply and demand in island energy systems, especially considering the variable nature of renewable energy generation [52]. Battery storage, pumped hydro storage, and emerging technologies like hydrogen storage play essential roles in stabilizing grids, reducing curtailment, and facilitating the integration of renewables [53]. This review evaluates the suitability of various energy storage solutions for island settings, taking into account scalability, efficiency, and environmental impact. It also explores innovative approaches to maximize the value of stored energy assets [54].

**Grid Integration:** The integration of renewable energy into existing grids poses technical, regulatory, and institutional challenges, particularly in island settings with limited grid infrastructure

and capacity [55]. Grid modernization, demand-side management, and smart grid technologies are necessary for enhancing grid flexibility, resilience, and efficiency [56]. This review examines best practices for grid integration, including grid-forming inverters, microgrid systems, and peer-to-peer energy trading platforms. The focus is on optimizing energy flows, minimizing losses, and maximizing self-consumption of locally generated renewable energy.

**Policy Frameworks:** Effective policy frameworks are crucial for incentivizing investment in sustainable energy infrastructure, promoting energy efficiency, and fostering market competition in island economies [57]. This review analyzes the role of policy instruments such as feed-in tariffs, renewable energy targets, carbon pricing mechanisms, and energy subsidies in driving the transition to sustainable energy systems [58][59]. It also provides case studies of successful policy interventions in various island contexts, offering valuable insights into the design and implementation of effective policy frameworks tailored to local conditions and priorities.

Table 1. Selected Review Papers on HRES

S/N	Reference	Hybrid system & location	System Type		Feasibility Study					Performance Matric
			Grid-Connected	Standalone	Software	Economics	Technical	Environmental	Reliability	
1	Guezgouz et al. [44]	PV+Wind+PHS+BESS (Algeria)		✓	MATLAB	✓			✓	COE and LPSP
2	Nurunnabi et al. [31]	PV+Wind+BESS Bangladesh	✓		HOMER Pro	✓	✓	✓	✓	NPC, COE, RF & GHG emissions reduction
3	Muh & Tabet [35]	PV+Hydro+Diesel+BESS (Cameroon)		✓	HOMER Pro	✓				COE
4	Wang et al. [36]	PV+Hydro (China)		✓	LINGO	✓				COE
5	Murugaperumal & Raj [38]	PV+Wind+Biomass+BESS (India)		✓	ANN-BP HOMER Pro	✓	✓			NPC and INR
6	Ali & Jang [46]	PV+Wind+BESS (South Korea)		✓	HOMER Pro	✓	✓			NPC and LCOE
7	El-Houari et al. [45]	PV+Wind+Biomass+BESS (Morroco)		✓	HOMER Pro	✓				COE
8	Krishnamoorthy Murugaperumal, Srinivasan, & Prasad [43]	PV+Wind+Biogenerators+BESS (India)		✓	HOMER Pro	✓				COE
9	Oladigbolu et al. [40]	PV+Wind+Hydro+diesel+BESS (Nigeria)		✓	HOMER Pro	✓	✓	✓		NPC, COE, and RF
10	Jain, S., & Sawle, Y. [39]	PV+Wind+Biomass+Hydro+BESS (India)	✓		HOMER Pro	✓	✓			NPC and COE
11	Hossen et al. [41]	PV+Wind+Biomass+BESS (Bangladesh)		✓	HOMER Pro DigSILE NT	✓	✓	✓	✓	NPC, COE

Table 1 shows the summary of the selected related review paper on the hybrid Renewable Energy systems. This analytical review paper provided an overview of research on Renewable Energy

Systems (RES) conducted in Uganda and other regions, with a focus on microgrids and hybrid systems. These studies explore various methodologies to address energy challenges in rural and off-grid areas. They utilize a combination of solar, wind, hydro, biomass, and diesel generation technologies to develop viable solutions. Researchers in this review used tools like the HOMER software and MATLAB to design and optimize systems, considering factors such as cost, reliability, environmental impact, and energy storage capacity. However, despite the extensive research in this field, a notable gap exists such as the incorporation of Solar Maximum Power Point Tracking (MPPT) in HRES for effective energy optimization. This gap highlights the need for further investigation into the role and significance of solar MPPT in optimizing hybrid renewable energy systems. Hence, addressing these drawbacks of hybrid systems has the potential to enhance the accuracy and efficiency of HRES designs and optimization leading to more reliable and sustainable energy solutions in the world, especially in Africa and Uganda.

### 3. Methodology

This article presents a comprehensive analysis of fifty-nine published sources, encompassing books and journal articles that pertain closely to renewable energy hybridization, microgrid and island energy integrations. Among these sources, thirty-nine were indexed in Scopus, while the remaining twenty originated from esteemed textbooks, conference proceedings, and journals indexed in the Web of Science.

### 4. Finding and Discussion

This review research collectively contributes to the understanding and advancement of hybrid renewable energy systems, showcasing their viability, economic benefits, and environmental advantages across diverse geographical regions. However, it is crucial to address research gaps, such as the absence of Solar Maximum Power Point Tracking (MPPT) in HRES optimization studies, as identified by Mensah et al. [29]. Further research on the function and importance of solar MPPT within the framework of HRES optimization, as well as comparisons of various MPPT techniques, would enhance the robustness and effectiveness of hybrid renewable energy systems. The implementation of a sustainable hybrid RES on the Island promises multiple benefits such as reducing greenhouse gas emissions, decreasing energy costs, creating local job opportunities, and serving as a model for similar communities.

### 5. Conclusion

In conclusion, this paper presents a comprehensive review of renewable energy prospects, focusing on Africa with a special emphasis on Uganda. It emphasizes the importance of integrating renewable and non-renewable energy sources to enhance energy output in hybrid systems. It also highlights their associated drawbacks. Specifically, it explores the potential benefits of deploying hybrid systems in island microgrids, including reduced greenhouse gas emissions, lower energy costs, job creation, and serving as a blueprint for similar regions. This paper emphasizes the critical role of renewable energy sources such as solar, wind, hydro, and biomass in driving sustainability in island communities and urges energy stakeholders and policymakers to embrace their potential to effectively energize rural and underprivileged areas.

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