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Original Research Paper

Performance Optimisation of Hybrid Renewable Systems for Remote Off-Grid Electrification

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Abstract: This research focuses on modelling, simulation and optimization of a HRES for off grid electrification in remote areas of Uganda using solar and wind as the renewable sources, targeting a community of 100 households and 10 medical centers in Rigbo Sub-County, Arua District. Using HOMER Pro software, five configurations were evaluated: solar only, solar and wind, solar with generator, wind with generator, and a combination of solar and wind with generator. Costs, electrical performance and environmental impact of the configurations were compared. Load profiles were developed by estimating a daily consumption of households and medical centers, scaled to total annual load of 189,500-189,581kWh. Results indicate that hybrid systems incorporating a generator, particularly the configuration of solar, wind and generator, outperforms others with the lowest total NPC and the lowest LCOE and no unmet load, while maintaining high renewable fraction and manageable CO_2 emission. Future studies should focus on validating these simulation results with empirical data from actual pilot deployments in remote Ugandan villages to account for real-world weather unpredictability. Investigating more dynamic and diverse energy demand models would also provide a deeper understanding of consumption patterns beyond uniform assumptions. Exploring the integration of advanced energy storage technologies and smart grid management could offer ways to further reduce reliance on diesel generators while maintaining system reliability.

Keywords: HOMER Pro, HRES, Off-Grid Electrification, Rural Uganda, Solar-Wind Hybrid.

1. Introduction

Access to reliable and affordable electricity is a cornerstone of socioeconomic development, playing a vital role in driving healthcare delivery, education quality, and overall standards of living. Despite Uganda’s commitment to rural electrification, over 80% of rural Ugandans still lack access to the national grid, necessitating alternative energy solutions due to the impracticality and high costs associated with grid extensions in remote areas. A great proportion of these rural communities remain without sustainable energy solutions, relying instead on expensive and unsustainable sources such as diesel and kerosene generators [1] [2]. This energy deficit severely impacts critical sectors, perpetuating economic disparity and limiting development. Fortunately, Uganda is blessed with abundant renewable energy resources, including high solar irradiance, consistent wind patterns, and hydro streams, which remain largely untapped. While existing studies have explored solar PV-based mini-grids, these systems often fail to address seasonal and diurnal variations in solar energy availability, and there remains a significant lack of practical research on the integration of diverse renewable resources within the country.

Hybrid Renewable Energy Systems (HRES) offer a strategic solution to these challenges by integrating resources such as solar PV, wind, and micro-hydro with energy storage technologies to ensure a consistent and reliable power supply even under varying environmental conditions. This research proposes the modelling, simulation, and optimisation of an HRES configuration specifically tailored to Uganda’s rural energy needs. By leveraging locally available renewable resources, this study aims to bridge existing research gaps and develop a cost-effective, sustainable solution for off-grid electrification [3]. The primary objective of this research is to model, simulate, and optimise the performance of a hybrid renewable energy system for remote areas of Uganda. Specifically, the research focuses on integrating solar PV and wind resources with energy storage technologies, analysing power generation and consumption patterns through climatic and demand data, and determining the most reliable, cost-effective, and sustainable energy configuration to meet local demand.

2. Literature Review

2.1. Renewable Energy Resources

Renewable energy consists of naturally abundant resources that can be utilised without depleting future supplies. In contrast to fossil fuels, which are finite and diminish over time, sources such as wind, solar, biomass, and tidal energy are inherently sustainable [4]. According to [5], these energies are driven by the sun, gravitational forces, and the earth’s rotation. This makes them cleaner alternatives to carbon-based fuels. Current data shows a positive trend in renewable energy adoption across Africa, with 2030 forecasts reflecting a strong regional ambition to transition toward sustainable power generation [6].

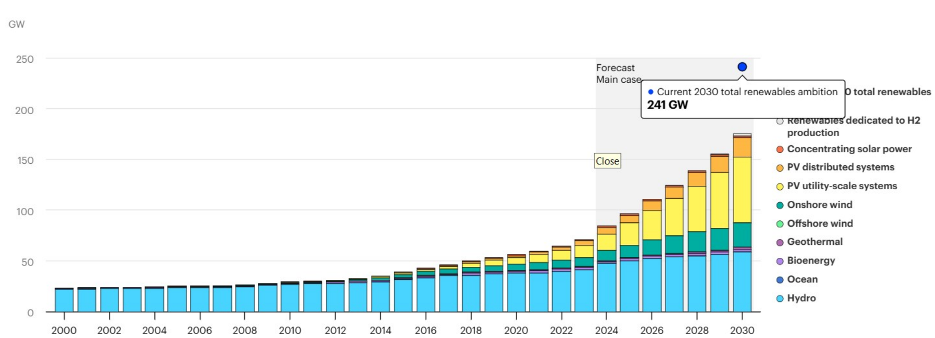

Figure 1. Historical data and forecast of Africa's renewable energies

2.2. Hybrid Renewable Energy Systems

Although renewable technologies are vital for modern power, they face challenges due to the unpredictable and stochastic nature of weather. Energy availability depends heavily on location and time, often leading to fluctuations in yield and higher costs when relying on a single source. To address this intermittency, two or more renewable resources are combined with storage units, such as batteries, to form a Hybrid Renewable Energy System (HRES). The primary goal of an HRES is to increase power production, lower costs, and reduce the environmental impact of burning fossil fuels while improving overall system efficiency [4].

Optimization is the methodology used to improve system performance by maximizing benefits while minimizing drawbacks [7]. This process generally involves metaheuristics or simulation-based techniques to determine the correct size of components like solar panels, wind turbines, and micro-hydro units. Through effective configuration, the reliability of the power supply is increased, which reduces the "loss of power supply probability" [8] [9]. This approach ensures the system remains both technically stable and economically viable.

2.3. Energy Storage Systems

Energy Storage Systems (ESS) are essential for managing the variable nature of renewables. They store extra energy during peak production and release it when natural resources are low, acting as a critical backup to maintain reliability [10].

1) Flywheel Energy Storage
   This technology stores mechanical energy as rotational kinetic energy. Flywheels are known for a long lifespan of about 20 years and high durability. Their performance does not drop with repeated use, but since they are purely mechanical, they require regular servicing to function correctly [11].
2) Battery Energy Storage
   This is the most common storage method where energy is stored chemically. While Lead Acid (PbA) batteries are affordable, they have lower efficiency (72% to 78%) compared to Lithium-Ion or Sodium-Sulphur (NaS) options. Choosing the right battery requires a detailed analysis to balance cost, power density, and lifetime cycles [12].

Table 1. Comparison of battery energy storage

Type	Efficiency (%)	Cost	Power Density (W/kg)	Lifetime (cycles)
PbA	72-78	Low	25-100	1000-2000
NiCd	89	High	140-180	3000
NaS	85	High	120-220	3000-9000
Li Ion	70-95	High	360	3000

2.4. Renewable Energy Potential in Uganda

Uganda has significant untapped potential for renewable energy development.

1) Solar Energy

Existing solar data indicates that Uganda possesses a high solar energy resource throughout the year. The mean solar radiation is approximately 5.1 kWh/m² per day on a horizontal surface. This level of insolation is favourable for several solar technologies, including solar water heating and solar photovoltaic (PV) systems. These systems are essential for providing basic electricity to rural institutions and households that lack a connection to the national grid. Currently, the total new installed photovoltaic capacity is estimated at 200 kWp annually for residential, institutional, and commercial use. While solar technology is effective for power generation, high initial costs can sometimes make it less competitive than other energy sources [13].

A solar photovoltaic system, also known as a solar power (Solar PV) system, utilizes PV modules to convert sunlight directly into electricity. According to [14], the primary components of a standard solar PV system include:

- Solar charge controller
- Inverter
- Battery bank
- Auxiliary energy sources
- Electrical loads (appliances)

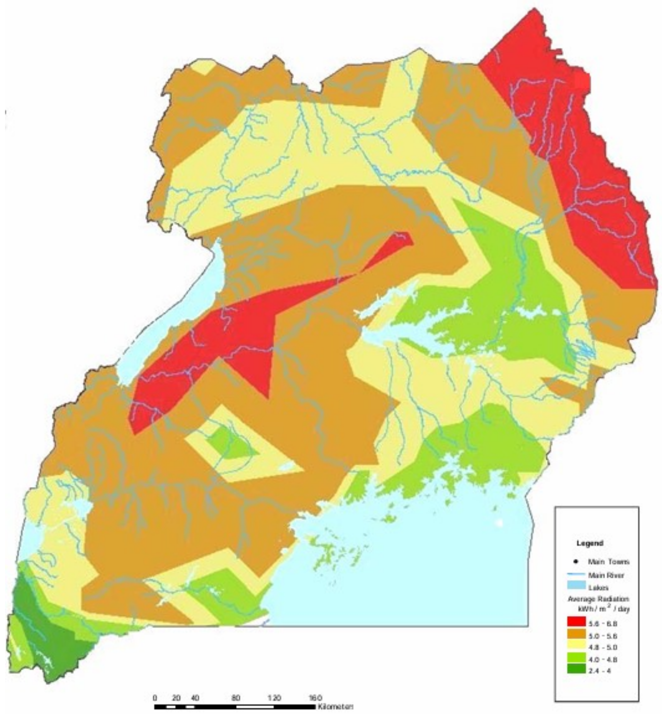

Figure 2. Solar Irradiation in Uganda

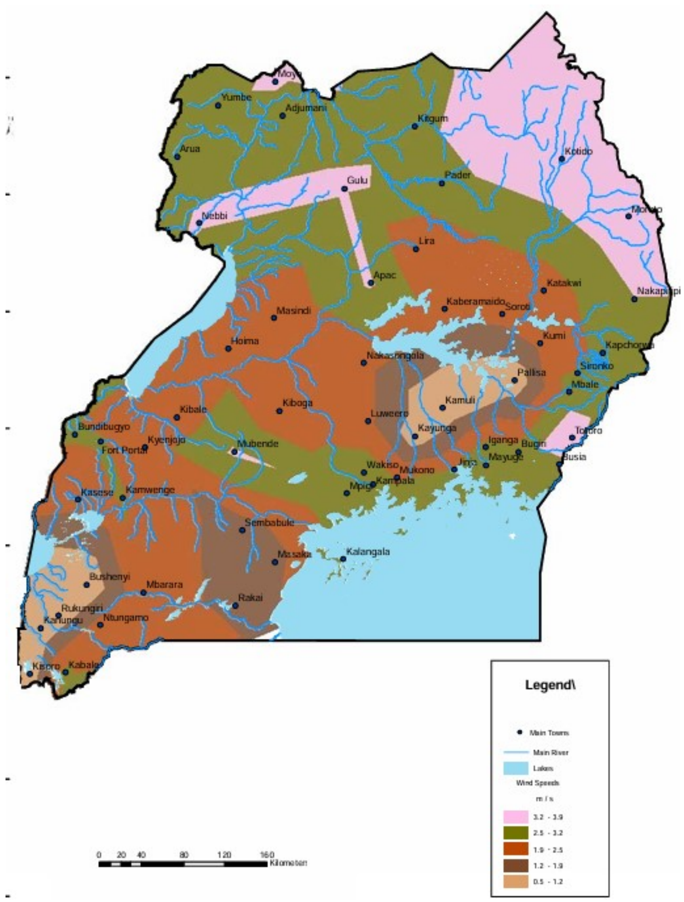

Figure 3. Wind Availability in Uganda

2) Wind Energy
Wind speeds are generally moderate across most regions of Uganda. Average speeds at low heights (below 10 m) typically range from 2 m/s to 4 m/s. In areas with complex terrain, such as hill slopes and escarpments, wind speeds may increase due to tunnelling effects. Data from the Meteorology Department suggests that Uganda's wind resource is sufficient for small-scale electricity generation and specialized applications like water pumping, particularly in the Karamoja region. Recent developments in low-speed turbines have improved the efficiency of power generation in these conditions. Studies confirm that wind-based electricity generation is feasible for small industries or rural settings, where target outputs for a mill range from 2.5 kV to 10 kV [13].

2.5. Review of Previous Studies

1) Case Studies in Uganda
Recent research has established a foundation for HRES in Uganda showed that a solar PV-diesel hybrid in Ntoroko could reduce fuel consumption by 74.7%. [15] Still, the reliance on diesel generators remains a sustainability challenge. In a separate study, reserchers designed a solar-wind hybrid for irrigation in Kalangala [16]. This proved the economic viability for farmers, but the lack of energy storage limits its use for broader community needs like healthcare and household lighting.

2) International Benchmarks
Studies outside Uganda provide further insight into optimal configurations. In Tanzania, research on hospital loads in Upanga and Ngamiani found that combining solar PV with diesel generators and battery storage was the most reliable and cost-effective solution [9]. Similarly, a study of Golbo II village in Ethiopia found that an integrated solar, wind, and diesel system provided a stable energy source with a low Cost of Energy (COE) of \$0.207 [17]. ini These findings highlight that the right energy mix is essential for the long-term success of off-grid electrification.

2.6. Previous Studies on Hybrid Renewable Energy Systems for Off-Grid Electrification

2.6.1. Case Studies in Uganda

1) Study 1: Puglia et al. [15]
The study proposes a design methodology for an off-grid hybrid electric microgrid customized for Ntoroko village, where the lack of power grid results in heavy reliance on costly and high emission diesel generators. The hybrid system combines a PV powerplant, battery storage and diesel generators as backup to ensure consistent power supply during low renewable output. The study highlights the economic benefits, emphasizing battery storage's role in managing low daily consumption with peak demands in early mornings and evenings when solar production is limited.

Key Findings:
- The hybrid system likely reduced fuel consumption by approximately 74.7% compared to diesel only system.
- Battery storage played a critical role in handling peak loads, ensuring a stable power supply during high demand periods like mornings and evenings.

Identified Gaps:
- Reliance on diesel generators for backup raises sustainability concerns due to carbon emissions and operational costs.
- The system excludes wind, limiting the diversity of renewable sources and adaptability to varied local conditions.

Relevance to Research:
This study supports the research goal of modelling, simulating and optimizing a HRES, providing a relevant Ugandan case study. Still, its dependence on diesel and lack of wind integration highlight opportunities for this research to improve sustainability and resource diversity.

2) Study 2: Ssenyimba et al. [16]
The study outlines the design of a hybrid renewable energy system integrating solar PV and wind turbines to power small scale irrigation for a banana plantation in Kalangala district. The system aims to meet irrigation pump energy demand sustainably and cost effectively, capitalizing on Kalangala's consistent solar irradiance and lake enhanced wind patterns. No energy storage is explicitly mentioned, suggesting the system aligns generation with irrigation schedules.

Key Findings:
- The hybrid system effectively combined solar and wind to address daily variations.
- It demonstrated economic viability for small scale farmers.
- The system reduced carbon emissions by replacing fossil fuel-based irrigation with renewable energy.

Identified Gaps:
- The absence of energy storage could lead to power shortages during periods of low wind or solar availability.
- The system focus on irrigation limits its applicability to wider community energy needs like households and healthcare facility electrification.

Relevance to Research:
This study supports the research objective of integrating solar and wind resources, offering a Ugandan case study. Its lack of energy storage and narrow irrigation focus present gaps that this research can address to enhance reliability and applicability.

Table 2. Summary of the previous research in Uganda

Study	Key Findings	Identified Gaps	Proposed Solution
Puglia et al. (2017)	74.7% fuel reduction with solar PV, battery, and diesel backup	Limited to solar and diesel; no wind Relies too much on diesel	Integrate solar and wind with storage, limit diesel
Ssenyimba et al (2020)	Solar-wind hybrid effective for irrigation	No energy storage and irrigation-focused	Include storage for reliability; target general electrification

2.6.2. Case Studies Outside of Uganda

1) Tanzania Case Study [17]
This study was conducted in two locations: the Upanga settlement in Dar es Salaam and the Ngamiani settlement in Tanga, Tanzania. The available renewable resources in these regions included abundant solar energy with Upanga receiving an annual global horizontal irradiance of about 1900 kWh/m² and Ngamiani approximately 2000 kWh/m² and moderate wind resources, notably with Upanga experiencing average wind speeds around 5.74 m/s. The primary load demands were defined by the local hospital facilities, with Upanga's hospitals averaging 20.26 kWh per day (peak load of 2.96 kW) and Ngamiani's hospital averaging 16.22 kWh per day (peak load of 2.37 kW).

A total of seven different HRES configurations were analyzed:
- Standalone diesel generator + storage
- Solar PV + storage
- Wind turbine + storage
- Solar PV + diesel generator + storage
- Wind turbine + diesel generator + storage
- Solar PV + wind turbine + storage
- Solar PV + wind turbine + diesel generator + storage

For Uganga, the optimal configuration was determined to be the combination of a 6.34 kW solar PV array, a 10-kW diesel generator, and an 8-string battery storage system with a 2.77 kW converter yielding a Net Present Cost (NPC) of approximately $63,136.93 and a Cost of Energy (COE) of

\$0.66. For Ngamiani, the most feasible solution was a scaled system featuring a 3.46 kW solar PV array, a 10-kW diesel generator, and a 6-string battery storage system with a 2.53 kW converter, resulting in an NPC of around \$51,544.75 and a COE of \$0.673. Both configurations proved to be technically reliable, cost-effective, and sustainable solutions for powering the critical hospital loads in these off-grid communities [18] [19].

2) Ethiopia Case Study [20]
This study was conducted in the Golbo II village, which was located in the Adaa district of Ethiopia. The available renewable resources for generating power in this region were solar and wind resources. The yearly average wind speed at Golbo was found to be at 3.901 m/s and having an annual daily solar irradiance of around 6.06 kWh/m²/day with the primary load demand of 108 kWh per day and a fixed diesel price of \$0.70 per litre.

A total of four different HRES configurations as shown below were analysed:
- Diesel generator + storage
- Solar PV + diesel generator + storage
- Wind turbine + diesel generator + storage
- Solar PV + wind turbine + diesel generator + storage

The optimal HRES configuration from the above list was found out to be the combination of 20kW solar PV, three 3kW wind turbines, a 5kW diesel generator and 24 strings battery storage option having a total NPC of \$82,734.00 with a COE of \$0.207 [21]. This configuration turned out to be a feasible solution for the residents of Golbo II village as it provided a technical, reliable and sustainable source of energy [22], [23].

3. Methodology
3.1. Steps Taken for the Methodology
The following are the proposed steps taken to facilitate the process of the methodology:
- Site selection in Uganda with enough of the proposed renewable resources
- Gather data on the renewable energy resources in the area
- Software selection for the research to model, simulate and optimize the HRES
- Collect data on the energy needs of the area for the proposed model
- Model the proposed HRES in the selected software
- Simulation and optimizing the proposed HRES system

3.2. Selection of the Area
The site selected in Arua District is Fundu Village with coordinates 3.0853 Latitude and 31.4161 Longitude. Fundu is a village in Rigbo, Madi-Okollo, Northern Uganda. It is situated nearby to the village Imvenga and roughly 330km from Kampala [18]. Figures 4 show the top view from Google Earth map of Fundu and its town council locations and the 3D view of the distance from Kampala.

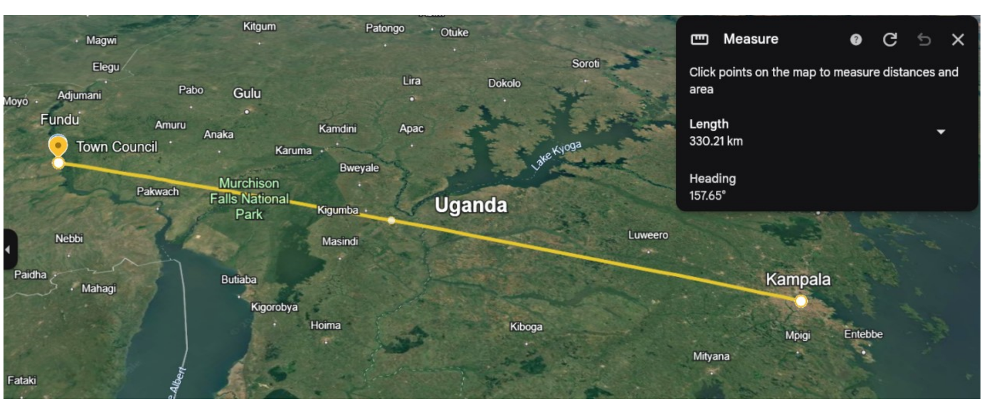

Figure 4. Distance from Kampala [Google Earth]

Fundu was selected because of its abundant solar energy resource which makes it perfect for a solar PV system [19] [20], its wind resource is moderate which is suitable for small turbines which diversify and support the system [21], and its limited access to the main grid [20]. More details on the renewable resources are provided in the Resource Assessment.

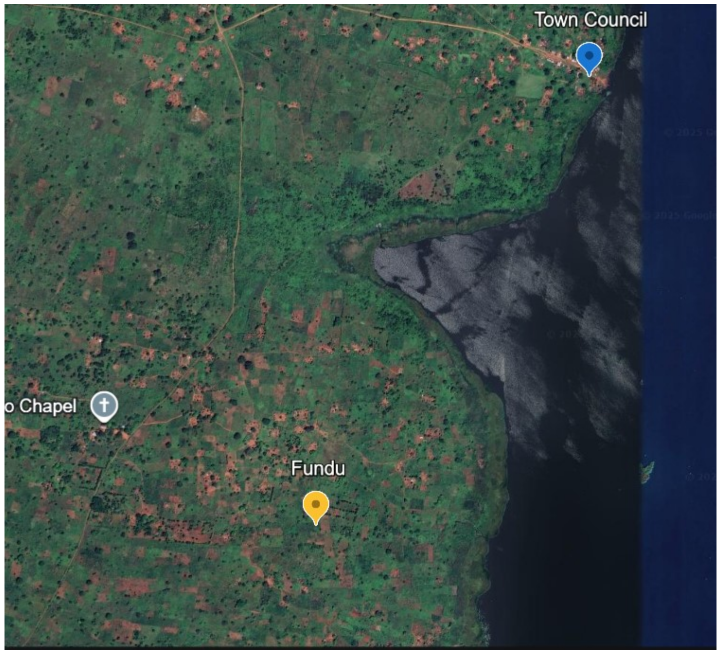

Figure 5. Top view of the village and town Council (Google Earth)

3.3. Renewable Energy Resource Assessment on Selected Site

Obtaining data for renewable energy resources is important for accurate and efficient output. The solar and wind resources were obtained from the NASA POWER DAV [24] database, alongside the temperature and the clearness index. This data is what is fed into the software selected (HOMER) to work on the simulation and the optimization, along with the load data of the area.

1) Solar Assessment

Fundu village has an annual average solar global horizontal irradiance (GHI) of 5.85 kWh/m²/day and an annual temperature of 25.76°C [25] [26]. Below, Figure 6 and Figure 7 show the information in the table in a graphical perspective of solar GHI and clearness index and temperature respectively.

Figure 6. Graphical Perspective of Solar GHI and Clearness Index

Figure 7. Graphical Perspective Temperature

2) Wind Assessment
Fundu Village receives an annual wind speed of 2.42 m/s at a height of 10 meters above the ground which is sufficient for small scale electricity generation [27]. Figure 8 is a graphical representation, Figure 8, of the wind speed at 10 meters above the ground. For this research, only the wind speed of 10 meters above the ground is used in the simulation.

Figure 8. Wind Speed at 10 meters

3.4. Data Collection on Electricity Needs
Obtaining the data on electricity needs for the village is important in the calculations of approximating the power generation needed by the HRES. The proposed HRES considered a 24-hour load demand of 100 homes and 10 small medical centers in the area. Since it is difficult to obtain actual load data for every house and medical center in the village, the energy consumption patterns of the households and medical centers in the village were analyzed to create hourly load profiles.

These profiles represented the typical energy usage of homes and medical centers in villages in Uganda in general taking into account appliances like those in the tables below (Table 3 and 4), showing the commonly used appliances in rural homes and medical centers with their typical usage time, starting and stopping.

1) Assessment of Household Load
When doing the household assessment for the load profile it was found the most active time for a household is from 7pm to 10pm of the evening with lighting, television, fan, charging and refrigerator running and the least active time is from midnight to around noon with only night lights and refrigerator running in the night and the night light replaced by charging in the morning hours.

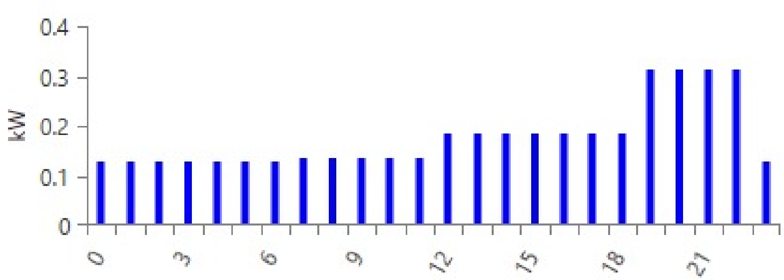

Figure 9. Graphical Representation of The Hourly Data for Household [HOMER]

In order to process the data and give the average consumptions for the households, the software needed hourly data such as the one given below in Figure 9 showing the graphical representation of the hourly data.

When feeding the data into HOMER, a peak month of July was chosen as the month in which most electricity consumption occurs. After feeding the data, HOMER calculated the following:

- The average (kWh/d): Total daily energy consumption averaged annually.
- The average load (kW): Average power demand over a day.
- Peak load (kW): Maximum hourly power demand.
- Load Factor (LF): Ratio of average load to peak load.

Table 3. Results from HOMER (Household)

Metrics	Baseline	Scaled
Average(kWh/d)	4.27	427
Average load(kW)	0.18	17.79
Peak load(kW)	0.54	53.81
Load Factor	0.33	0.33

The scaled factor used in the simulation is 100 to consider the proposed load profile in the simulation, while the baseline results represent a single household. To account for variations such as temperature changes or load shifts, day-to-day and timestep (1-hour) random variables of 10% and 20% respectively were added to the simulation.

2) Assessment of Medical Center Load

When doing the medical center assessment for the load profile it was found the most active time is from 7am to 9pm with computers, microscopy source, fan, charging, refrigerator running and lights. The least active time is from 11pm to 6am with only night lights and refrigerators running.

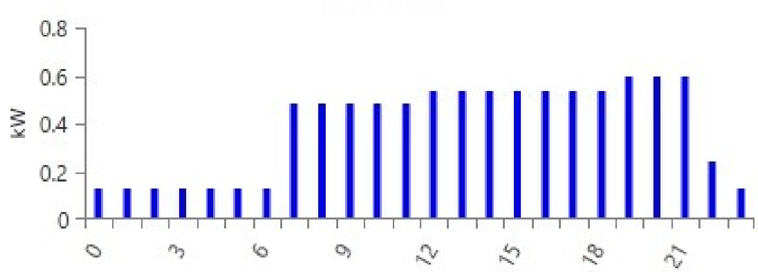

Figure 10. Graphical Representation of The Hourly Data for Medical Center [HOMER]

When feeding the data into HOMER, no peak month was chosen as there is no specific time when a community does not need medical care. After feeding the data, HOMER calculated the following from the data, as shown in Table 4.

Table 4. Results from HOMER (Medical Center)

Metrics	Baseline	Scaled
Average(kWh/d)	9.24	92.4
Average load(kW)	0.39	3.85
Peak load(kW)	1.02	10.18
Load Factor	0.38	0.38

The scaled factor used in the simulation is 10 to consider the proposed load profile, with baseline results representing a single medical center [25].

$$\textit{Scaled Annual Average} = \textit{Baseline Annual Average} * 10 \tag{1}$$

Similarly, to account for variation, day-to-day and timestep random variables of 10% and 20% were added to the simulation.

3.5. Model the Proposed HRES
After gathering the above data on the load profiles and renewable energy resources, next up is to model the proposed system and run simulations to optimize the configuration [28], [29]. The components were selected based on their functionalities, characteristics, and potential to contribute [30]. Figure 11 shows the schematic from HOMER of the system model.

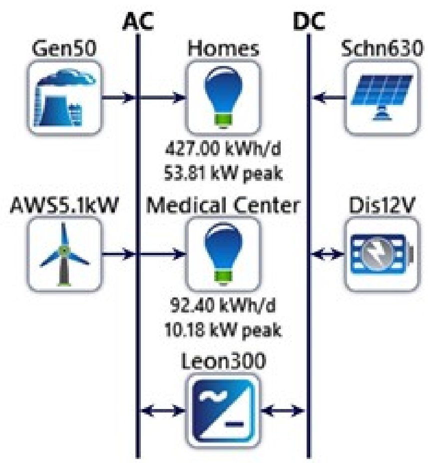

Figure 11. Schematic of the model

4. Findings and Discussion
4.1. System Configurations
After simulation and optimisation, and going through the different configurations of the schematic diagram in Figure 13, is five prominent configurations emerged from the process. These configurations and their respective schematics are:
- Solar PV + Energy Storage, as shown in Figure 12 (a)
- Solar PV + Wind Turbine + Energy Storage, as shown in Figure 12 (b)
- Solar PV + Generator + Energy Storage, as shown in Figure 12 (c)
- Wind Turbine + Generator + Energy Storage, as shown in Figure 12 (d)
- Solar PV + Wind Turbine + Generator + Energy Storage, as shown in Figure 12 (e)

4.2. Comparison of the Results
4.2.1. Cost Comparison
Drawing from the information in the configuration results, costs range depending on the components included. The total Net Present Cost (NPC) and Levelized Cost of Energy (LCOE) varied significantly across the simulated systems. Configurations that included a generator alongside solar PV or wind generally appeared towards the lower end of the total NPC and LCOE spectrum. In contrast, systems relying purely on renewables or heavily on numerous wind turbines and generators tended to have higher overall costs and LCOEs. The highest reported total NPC and LCOE were associated with Configuration 4, while the lowest was found in Configuration 5.

The cost breakdown also included replacement and salvage cost variations between the configurations. Replacement costs, representing the expense of replacing components during the research's lifespan, varied across the designs. Particularly, the configuration with a very large number of wind turbines (Configuration 4) showed considerably higher replacement costs compared to the other configurations. Salvage costs, which represent the estimated value of components at the end of the research's life and appear as negative costs, also differed between configurations, contributing a varying amount as a cost credit to the total net present value.

Operating cost and resource cost components provide further insight into these financial differences. Operating costs, separate from fuel costs, represent ongoing non-fuel expenditure and vary across the different system designs. The resource cost category is particularly significant as it directly reflects the cost of fuel consumed by the generator present in the system. Configurations that incorporated a diesel generator incurred positive resource costs due to fuel usage. In contrast, the renewable-only configurations which did not include a generator had no resource cost. Configuration 4 exhibited the highest reported resource cost, indicating significant fuel expenditure for that specific configuration.

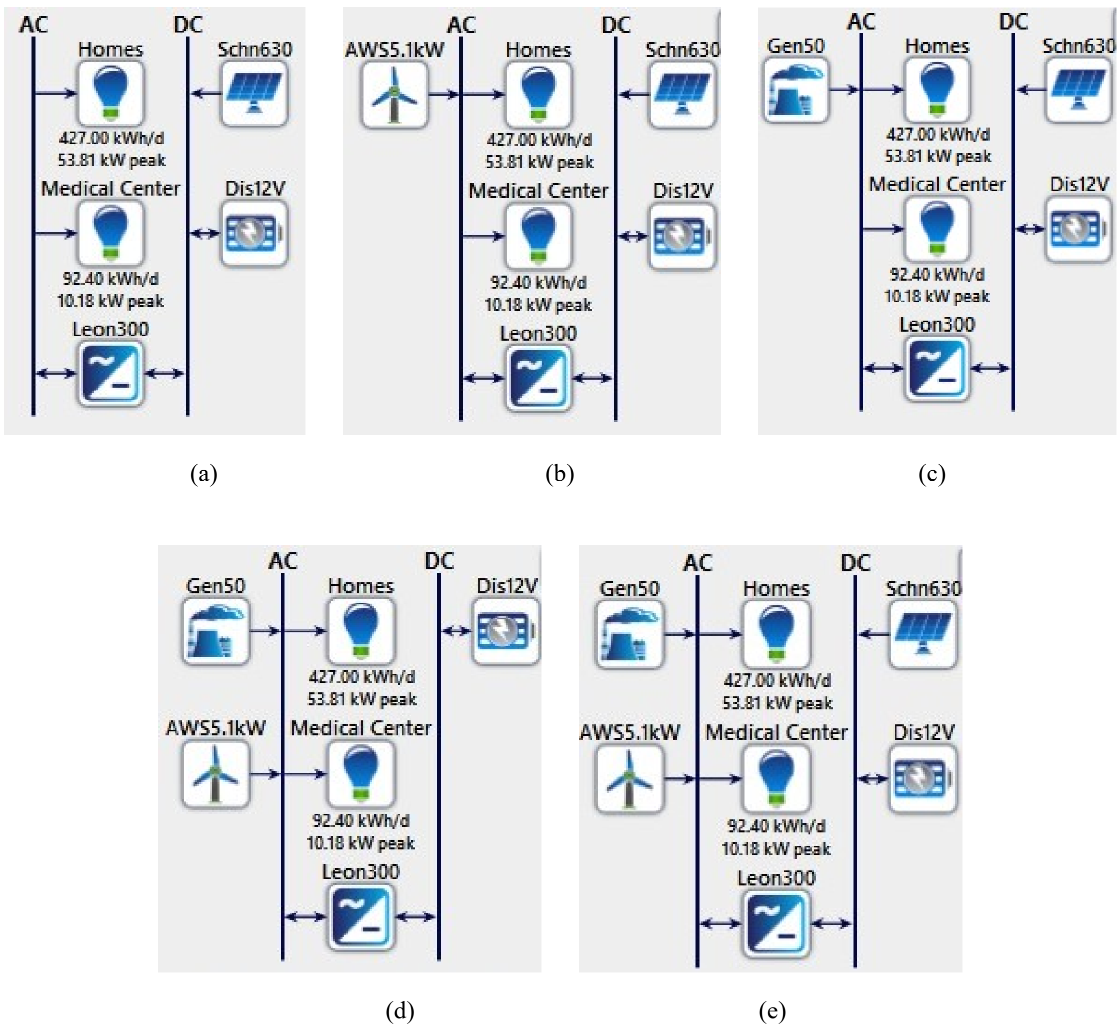

Figure 12. Schematics of the Five Prominent Configurations
(a) Configurations 1
(b) Configurations 2
(c) Configurations 3
(d) Configurations 4
(e) Configurations 5

Architecture					
SM500 (kW)	AWS5.1kW	Gen50 (kW)	Dis12V	Leon300 (kW)	Dispatch
107	18	50.0	325	51.9	LF
119		50.0	397	53.6	LF
122	26		573	63.3	CC
173			608	64.1	CC
	253	50.0	544	94.7	LF

Figure 13. Architecture of the Different Configurations

Cost			
COE ($)	NPC ($)	Operating cost ($/yr)	Initial capital ($)
$0.305	$747,201	$14,463	$560,230
$0.308	$755,614	$13,904	$575,866
$0.329	$806,643	$7,653	$707,713
$0.372	$911,078	$7,993	$807,755
$0.533	$1.30M	$24,502	$987,986

Figure 14. Costs of the Different Configurations

System					
Ren Frac (%)	Total Fuel (L/yr)	Elec Prod (kWh/yr)	Elec Cons (kWh/yr)	Excess Elec (kWh/yr)	Unmet load (kWh/yr)
95.3	3,445	242,008	189,581	23,354	0
95.1	3,526	234,418	189,581	12,149	0
100	0	272,781	189,506	53,491	75.2
100	0	328,883	189,500	104,976	81.0
92.7	4,998	424,405	189,508	206,011	73.2

Figure 15. System Outputs of the Configurations

Figures 16 and 17 show the comparisons of the total NPC and LCOE across the five configurations.

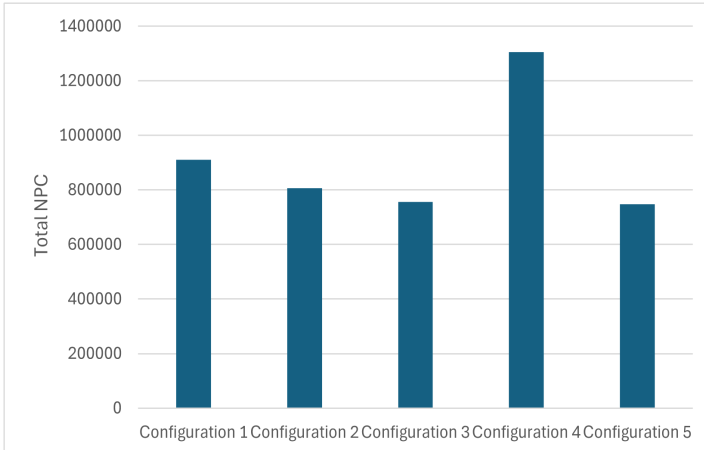

Figure 16. Comparison of Total NPC ($)

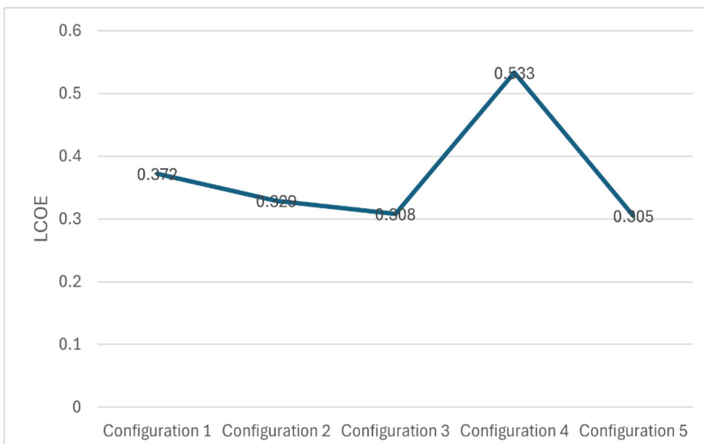

Figure 17. Comparison of LCOE($/kWh)

4.2.2. Electrical Parameter Comparison

From the above results and data from the configurations the electrical comparison of the five HRES configurations reveals differing performance characteristics. The primary energy consumption represented by the AC primary Load is around 189,500 to 189,581 kWh/yr across all configurations. The annual energy production varies significantly as shown in the configurations in chapter 4.2. the primary source of production shifts between configurations with PV dominating in configurations 1(100%), 2(84.5%), 3(96.0%) and 5(84.2%) and wind in configuration 5(96.7%).

Regarding reliability and load fulfilment, configurations incorporating a diesel generator and using the HOMER load following dispatch strategy demonstrated superior performance. Configurations 3 and 5 successfully met the entire electrical demand resulting in no unmet electric load and minimal capacity shortage of 1.41kWh/yr and 3.56kWh/yr respectively. In contrast, the purely renewable configurations employing the HOMER Cycle Charging strategy, configurations 1 and 2 as well as configuration 4 showed small amounts of unmet load and higher Capacity shortage. This indicates that while renewable only systems meet the bulk of the demand, they may not always cover instantaneous load peaks without supplemental generation [24] [25].

The environmental impact varies significantly based on the system components. The purely renewable configurations achieve 100% renewable production relative to total generation and no direct emissions from fuel combustion. Configurations including the diesel generator incur emissions configuration 3 shows 9, 231kg/yr of carbon dioxide (CO2) emission, configuration 5 shows 9, 018kg/yr of CO2, and configuration 4 despite its total production dominated by wind has the highest emission among the generator inclusive systems at 13, 084kg/yr of CO2. These configurations also report emissions for other pollutants such as carbon monoxide, unburned hydrocarbons, particulate matter, sulfur dioxide and nitrogen oxides. These energy-based renewables percentage relative to total generation in these configurations is still high ranging from 96.0 to 96.7%

Each configuration provides a breakdown of the total annual electrical production and percentage contribution by each component. All configurations include battery storage and a converter, which are considered essential for providing a reliable backup system for prioritized loads.

Figure 18 shows the comparison of electricity production among the configurations.

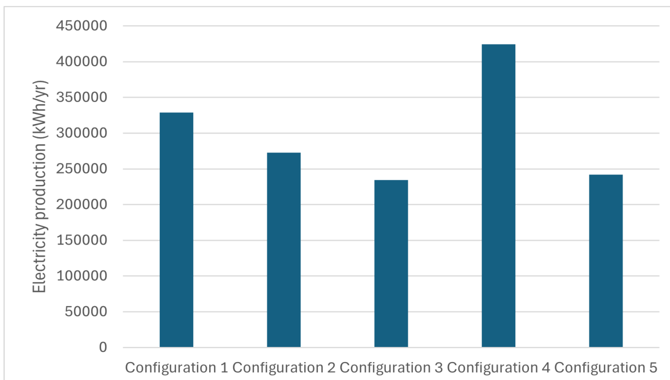

Figure 18. Comparison of Electricity Production

Based on the comparison of the five configurations for electrifying 100 houses and 10 medical centers in Fundu village, configuration 5 is the optimal choice. It delivers the lowest total NPC and LCOE, fully meets the AC load with no unmet demand and minimal capacity shortage and balances a high renewable fraction with manageable CO2 emissions. In contrast, renewable only configurations 1 and 2 struggle with unmet loads while configuration 4 incurs the highest costs and emissions making configuration 5 the best solution for reliable and cost-effective off grid electrification.

5. Conclusion

The core objective of this study was to model, simulate, and optimise a Hybrid Renewable Energy System (HRES) for a remote village in Uganda, specifically targeting a community of 100 households and 10 medical centres in Fundu Village. By evaluating multiple configurations, the research sought to determine the most effective blend of renewable technologies based on cost, performance, and environmental impact.

Analysis conducted via HOMER Pro revealed striking differences across the five configurations examined. Systems that incorporated diesel generators alongside renewable sources outperformed fully renewable setups in both cost and reliability metrics. These hybrid configurations achieved a total Net Present Cost (NPC) and Levelized Cost of Energy (LCOE) significantly lower than their renewable-only counterparts. An exception was noted in the wind-dominated hybrid system, which suffered from elevated maintenance and replacement expenses.

On the performance front, generator-supported systems met the annual energy demand flawlessly, showing minimal capacity shortages and no unmet load. In contrast, solar-only and solar-wind systems fell short during peak demand, resulting in minor unmet loads despite their environmental advantage of zero emissions. Environmentally, hybrid systems produced CO_2 emissions, with the wind-heavy hybrid configuration surprisingly yielding the highest emissions among them despite having a high renewable fraction.

These results highlight a critical insight into off-grid electrification: pure sustainability must sometimes be balanced with practical reliability. The superior performance of hybrid systems suggests they are better suited to meet the uninterrupted power needs of remote Ugandan communities, particularly for essential services like medical centres. The environmental trade-offs remain important, pointing to the need for strategies that maximise renewable contributions while minimising fossil fuel reliance. Furthermore, the poor cost-effectiveness of wind-heavy systems emphasises the value of aligning HRES designs with local resource availability to inform policy and investment decisions.

While insightful, this research has constraints. The simulations rely on idealised assumptions that may not fully reflect on-the-ground realities such as unpredictable weather patterns. The uniform energy demand model might also overlook variations in consumption across different users. Additionally, the environmental assessment focused narrowly on operational emissions, omitting the upstream impacts of producing and disposing of system components. These gaps underscore the importance of complementing simulation-based research with empirical data from future deployed systems.

This research underscores the transformative potential of hybrid renewable energy systems to bridge the energy gap in Uganda’s remote regions. By harmonising affordability, reliability, and sustainability, HRES can empower communities, enhance healthcare delivery, and drive economic growth.

Author's Declaration

The authors hereby declare significant contributions to the research process, manuscript preparation, and publication stages.

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