Design Solar Photovoltaic Diesel Hybrid System with Battery Storage for Rural Remote Area: A Case Study of Mwala Village Mbeya District

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DOI: https://doi.org/10.62277/mjrd2024v5i20048

ARTICLE INFORMATION

Article History

Received: 15th December 2023
Revised: 12th April 2024
Accepted: 25th May 2024
Published: 10th June 2024

Keywords

Solar
Photovoltaic
Diesel
Battery
Rural

ABSTRACT

Reliable hybrid systems (solar photovoltaic and diesel generators) have been shown to produce high-quality energy that supports different social and economic activities in Mwala village and Mbeya region in the United Republic of Tanzania, which contain three hundred households for the purpose of reducing poverty. The system was designed after load demand analysis with the help of Hybrid Optimisation of Multiple Electric Renewables (HOMER) software. For simulations on a diesel generator standalone system, a generator with penetration of renewable energy resources (solar photovoltaic) system, and a solar PV standalone system. The components of the hybrid system configuration include a generator of 24 kW, a solar photovoltaic of 29.5 kW, an inverter of 10.4 kW, and a generic 1 kWh lead acid with 120 strings. The paper features a detailed analysis of fuel consumption, optimisation of the system, capital cost, operating cost, electrical energy obtained, gas emissions, and sensitivity analysis. The result obtained from the model revealed that the total energy generated was about 75366 kWh per year, with an excess of 7240 kWh per year, which increased the reliability of power and allowed the availability of energy for new buildings and electrical appliances. The gas emissions from a generator standalone system were three times higher than those of a reliable hybrid system. Based on the energy demand, the solar PV diesel hybrid system with batteries has proven to supply reliable power 24/7.

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1.0 Introduction

In many rural and remote areas worldwide, the lack of access to electricity remains a persistent challenge due to the increase in populations, which hinders the progress of social and economic activities in society. There have been a number of innovative solutions emerging in response to the pressing need for electrification of rural and remote areas, including solar photovoltaic (PV) hybrid systems with battery storage as viable alternatives to traditional grid-based electric systems. This paper explores the potential of the hybrid system in addressing the energy needs of rural and remote areas in Mwala village, in Mbeya district, with the existing 300 households. The hybrid approach not only reduces dependence on fossil fuels but also enhances energy resilience and mitigates environmental impact, aligning with global efforts to combat climate change and achieve sustainable development goals.

Within the African continent, where electrification rates remain among the lowest globally, the adoption of solar PV diesel hybrid systems holds immense potential for accelerating socio-economic development. Africa's abundant solar resources make it particularly well-suited for solar energy generation, whereas the integration of diesel generators addresses the intermittency of solar power and ensures uninterrupted electricity supply. By leveraging this technology, African countries can transition to traditional grid-based electrification models and accelerate progress towards universal energy access.

Based on Tanzania's diverse geography and vast rural areas, the installation of solar PV diesel hybrid systems presents the best solution to the nation's energy challenges and accelerates progress towards universal energy access. The design of solar photovoltaic diesel hybrid systems with battery storage offers a versatile and scalable solution to the energy needs of rural and remote areas worldwide, including Africa and Tanzania as a country. Tanzania is among the sunbelt countries with a solar radiation range of 4.1–7.5 kWh/m^2 for different regions of the country (Bernardos et al., 2015). However, prior experiences have demonstrated that issues with budgetary limitations and a lack of necessary technological capabilities might cause some initiatives to be delayed or even abandoned. In the short to medium term, focusing on demand-side management (DSM) may be essential for guaranteeing a sustainable energy system in Tanzania. This analysis examines Tanzania's energy demand, supply, cost trends, and underlying factors. Both the total primary energy and electricity consumption show an upward tendency, and issues with the supply side indicate that an energy deficit is going to be a problem in the future. Unmet energy demand might thus get worse in the future without a large increase in supply and, very likely, DSM.

Economic growth, pricing, electrification rate, population increase by 3.0% (Statistics, 2022), industrialization, shifts in the economic structure, and energy efficiency are some of the major factors. Peak demand is anticipated to average 1274.74 MW and 1490.33 MW yearly during the medium and long terms (2020–2025 and 2025–2030), respectively (Adom et al., 2023). In Tanzania, there are abundances of remote villages that are located far away from the utility grid, low population density areas with low levels of energy demand, high levels of power loss, and difficult terrain that hinder the extension of the main grid. As a result, such villages are normally powered by standalone solar photovoltaic generators to meet the demand for electricity for lighting and phone charging.

However, the current increase in global fuel prices has drawn serious attention to using renewable energy sources in these remote locations. Since these remote areas largely depend on diesel, an increase in global fuel prices will significantly impact these societies, as they rely heavily on electricity supply (Ani, 2016). Therefore, the penetration of available renewable energy resources, which include wind and hydro energy, in these locations has shown great tangible benefit, especially in reducing the dependence on diesel fuel, which is highly fluctuating in price.

Tanzania, being gifted with an abundance of solar radiation, has a wide potential for solar energy applications to meet the electricity demand of remote villages. Therefore, the combination of readily available renewable energy sources like solar PV and standalone diesel generators, commonly referred to as a reliable hybrid system, has proven to be the most effective solution for reducing energy interruptions in remote areas (Rice et al., 2023).

Depending on the design, the use of a hybrid PV/diesel system comes with various advantages. They have low maintenance costs and low pollutant emissions (Ismail et al., 2012). It was found that adding renewable energy sources to the energy system lowers the amount of fuel used and the amount of carbon monoxide, sulphur dioxide, and NOx released into the air by traditional energy generating units (Adefarati & Bansal, 2017). This means that generators run for fewer hours, cost less to maintain, and use less diesel fuel (Maleki et al., 2022). The hybrid diesel/photovoltaic system with a battery bank is a modern energy source that is sustainable for development in rural, remote areas (Peerapong & Limmeechokchai, 2017). In terms of the technical aspects of system component configuration and the availability of 24/7 access to the produced energy, a solar photovoltaic diesel hybrid with a battery storage system outperforms all other systems. The design has demonstrated the importance of including a battery storage system, which is used to store excess energy during sunny days, and reducing energy loss from solar photovoltaic modules. The benefits of renewable energy projects in rural remote areas include enhancing the growth of developments in areas of the social economy through job and income generation opportunities for rural remote residents (Thirunavukkarasu & Sawle, 2020). This paper focuses on the design of a solar photovoltaic diesel hybrid system with battery storage in rural remote areas, mainly addressing energy needs in Mwala village in Mbeya district. At the end of this paper, the appropriateness of utilizing a hybrid PV/diesel energy system over a standalone diesel system will be discussed mainly in terms of minimizing fuel consumption, optimizing the system, capital costs involved, operating costs, electrical energy generated, harmful gas emissions, and sensitivity analysis.

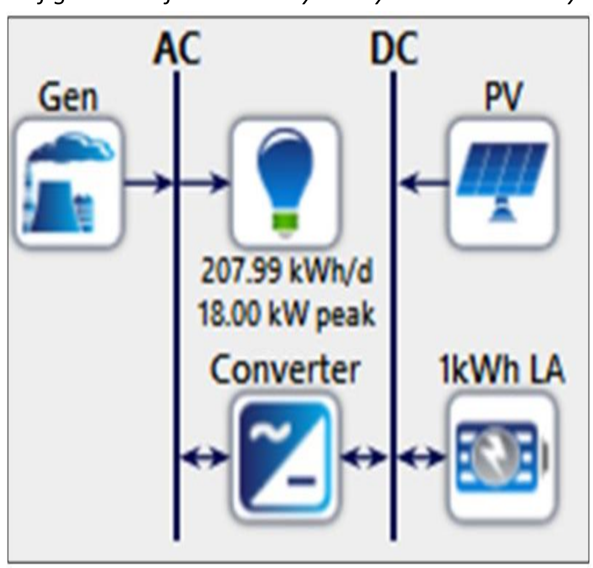
2.0 Materials and Methods

In Mwala village, in the Mbeya area of the United Republic of Tanzania, the most effective methods for designing solar photovoltaic hybrid systems were evaluated using the Hybrid Optimisation of Multiple Energy Resources (HOMER) program. The simulation was divided into three stages: defining input data, simulating, and assessing outcomes. It was used to evaluate system emissions, necessary investment, payback length, net present cost, and current value. The pre-design employed data collection techniques such as assessing the energy demand in Mwala village from available households, schools, and dispensaries through surveys and observation methods. Tools used for the analysis of data were Excel and HOMER software were used for data analysis.

2.1 HOMER Software

HOMER (Hybrid Optimisation of Multiple Electric Renewables), the micropower optimisation model, improves the task of evaluating designs of both off-grid and grid-connected power systems for a different application. When designing a power system, the best configuration of the system components is selected based on the specifications provided by the manufacturer of solar photovoltaic components. These decisions are complicated because of the large number of technologies available in the market, as well as the variation in technology costs and availability of energy resources. HOMER's optimization and sensitivity analysis aid in the assessment of many possible system configurations. System Architecture. Figure 1 shows the configuration of a PV diesel hybrid system with battery storage.

Figure 1
Configuration of PV Diesel Hybrid System with Battery



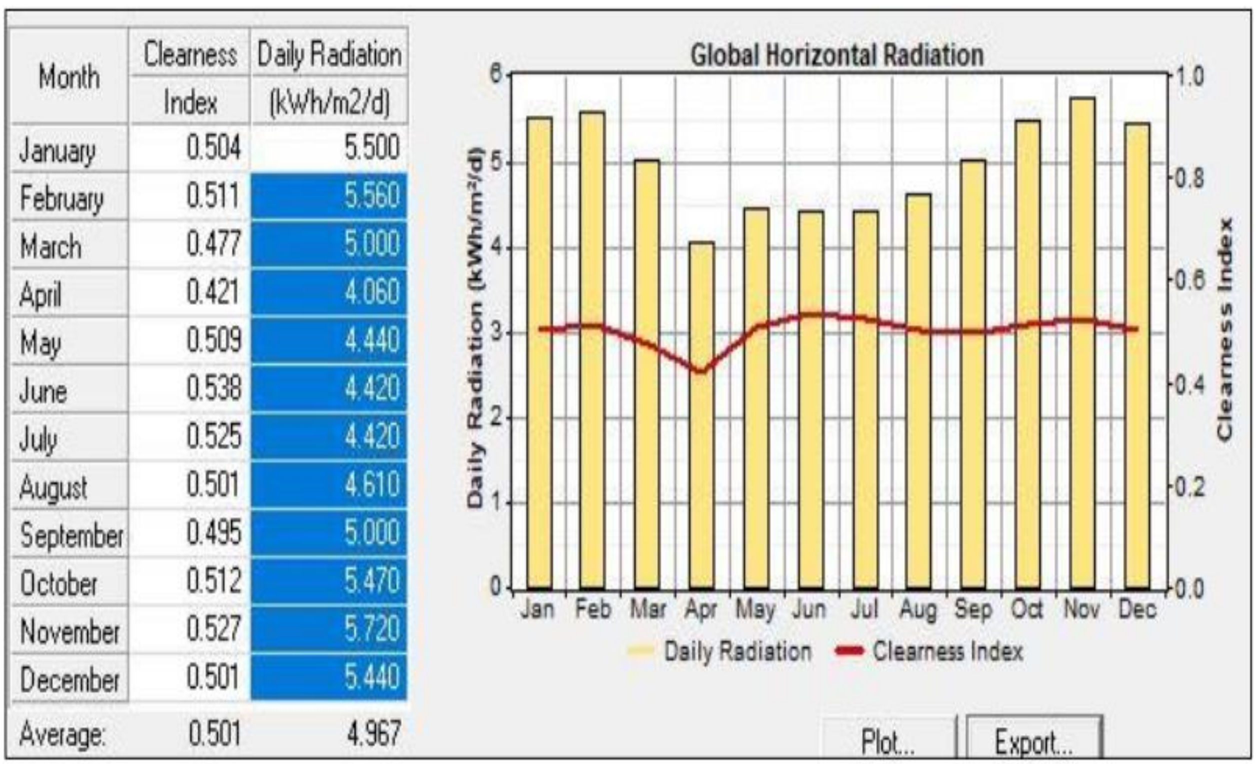
2.2 Load Assessment

Mwala village consists of 300 households, and the daily consumption of energy is 208 kWh for both domestic, commercial, and community loads. It is evident that load requirements vary throughout the day, with the highest demand occurring at night when television and lighting are fully operational. Most of the villagers went to their daily activities in the morning to earn income; also, children went to school. In the afternoon, some of the villagers went back home, so the domestic load increased. The load in the village per day shows variability from morning to night; during the summer and winter seasons, the load is the same, but the climatic conditions do not allow the use of fans for cooling purposes.

2.3 Solar Radiation (Insolation)

The solar radiation data for the selected remote area was estimated to range between 4.02 and 5.76 kWh/m^2/day and the clarity index is 0.501. It is noticed that more sunshine is expected to occur in the months of September, October, November, December, January, February, and March, which are the summer seasons, and the scaled annual average of solar radiation is 4.97 kWh/m^2/day. During the winter season, in the months of April, May, June, July, and August, the insolation availability decreased. Figure 2 shows global horizontal radiation.

Figure 2
Global Horizontal Radiation



Month	Clearness Index	Daily Radiation (kWh/m2/d)
January	0.504	5.500
February	0.511	5.560
March	0.477	5.000
April	0.421	4.060
May	0.509	4.440
June	0.538	4.420
July	0.525	4.420
August	0.501	4.610
September	0.495	5.000
October	0.512	5.470
November	0.527	5.720
December	0.501	5.440
Average:	0.501	4.967

2.4 Design Specifications

In a solar photovoltaic diesel hybrid system with a battery bank, there are four main system configuration components (see Table 1), which include the diesel generator, solar photovoltaic modules, batteries, and inverter.

Table 1
System Configuration Components

Description	Data
a) 12V Lead acid battery	
Nominal voltage (V)	12
Nominal capacity (kWh)	1
Maximum capacity (Ah)	83.4
Capacity ratio	0.403
Rate constant (1/hr)	0.827
Round trip efficiency (%)	80
Maximum charge current (A)	16.7
Minimum state of charge (%)	40
Capital cost ($)	300.0
Replacement ($)	300.0
Operating and maintenance cost ($/year)	10.00
b) Generator	
Fuel	Diesel
Fuel curve intercept (L/hour)	0.891
Fuel curve slope (L/hr/Kw)	0.251
Initial cost per kW of capacity ($)	500.00
Replacement cost per Kw of capacity ($)	500.00
Operating and maintenance per Kw of capacity ($)	0.030
Generator capacity (kW)	24
c) Inverter (Converter)	
System converter (kW)	1
Efficiency (%)	9
Lifetime (Years)	1
Capital cost ($)	3
Replacement cost ($)	3
Capacity (kW)	1
d) Photovoltaic (PV)	
Size(kW)	2

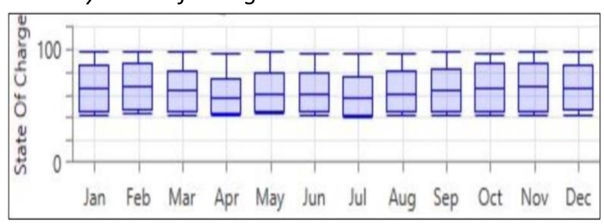
2.5 Photovoltaic Modules

Solar energy is used as the baseload power source in this hybrid system. PV modules are sold per watt power ($/Wp), Rs/Wp in India, or Tsh/Wp in Tanzania shillings, where the exchange is 1$ = 2500 Tshs and 1INR = 35 Tanzania shillings, but throughout the selection of components of the hybrid system, the US Dollar was used. The array required to meet the specific load was typically sized for worst-case solar insolation and is considered eight times the load rating. The solar photovoltaic array would only generate electricity when there is enough sunshine and a clear sky, starting from 9:00 a.m. to 4:00 p.m. The generator charges the storage battery at night or when there is no sunlight.

2.6 Storage Battery

The selected battery is a generic 1kWh lead acid battery with a bus voltage of 12V and a number of strings in parallel of 120. The battery bank has the capacity to supply electricity for 10 hours at a minimum charge level of 40%, requiring the generator to continuously charge the storage bank in order to maintain power supply to the micro-grid. In this PV hybrid system, the number of batteries used is 120, and the expected life is six years. The system discharges 14031 kWh annually, consumes 17466 kWh annually, and incurs losses of 3500 kWh annually. Figure 3 shows the monthly state of charge.

Figure3
Monthly State of Charge



2.7 Inverter/ Converter

It is the system's brain that takes in the direct current (DC) produced by modules or arrays and stores it in the battery, converting it into alternating current (AC) electricity suitable for use in homes, community centres, and commercial areas. Based on the design, several parameters from the system converter were considered, including hours of operation, energy out, energy in, and energy losses. Table 2 presents the system converter's electrical summary.

Table 2
System Converter Electrical Summary

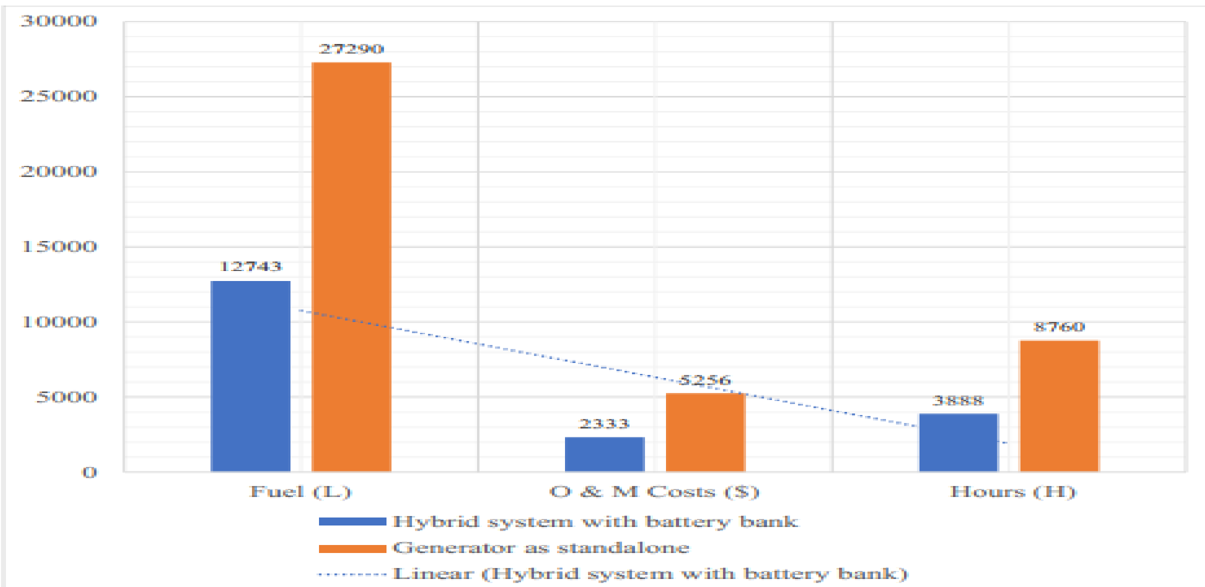
Quantity	**Value**	**Units**
Hours of operation	3864	Hrs/yr
Energy out	13330	kWh/yr
Energy in	14031	kWh/yr
Losses	702	kWh/yr

3.0 Results and Discussion

3.1 Minimize Fuel Consumption

Minimising fuel consumption is one of the most important factors to take into consideration. By adopting a PV-diesel hybrid system, we can decrease the number of hours needed forgenerator to run, that means the maintenance cost will also be reduced. In the designed hybrid system, the fuel consumption is 12743 litres, with the generator running for 3888 hours. When the generator is used as a stand-alone generator for electricity generation, the fuel consumption is high, and the running hours are 8760. Employing solar photovoltaic has reduced fuel consumption from the generator during the day, resulting in lower operation and maintenance costs. The generator's running hours have decreased compared to the original design of the system. Figure 4 illustrates the comparison of fuel, running hours, operation, and maintenance between a hybrid system and a standalone generator.

Figure 4
Comparison of Fuel, Hours, O&M for the Hybrid System and Generator Standalone



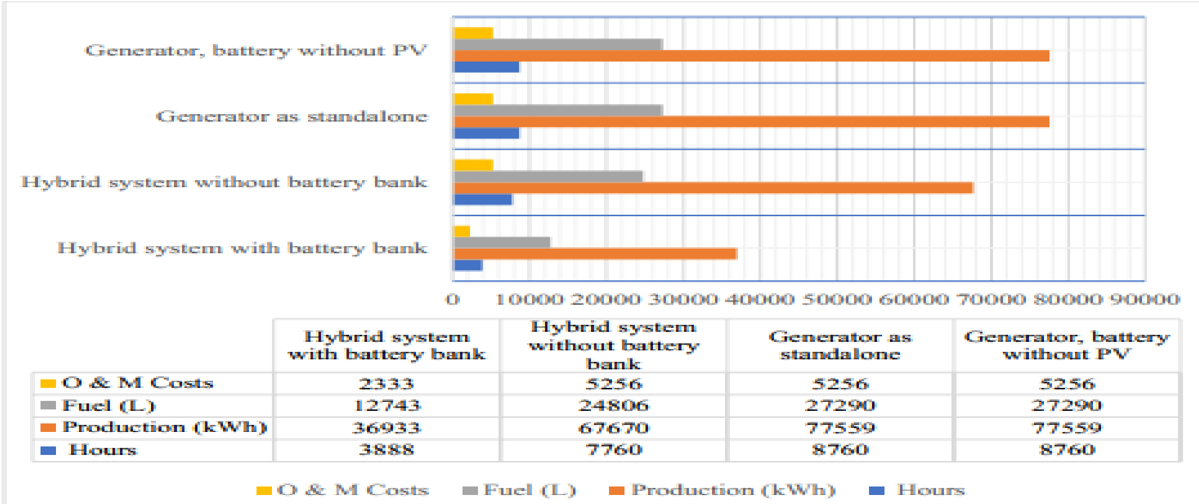
3.2 Optimization of System

Based on the design system, the selection of a system that has economic viability has been taken into consideration.

Again, parameters such as fuel, generator running hours, and system operating and maintenance costs were considered. The running costs of the system should be low, with a high output. There were four systems for comparison: a solar PV diesel hybrid system, a generator stand-alone, a generator with a battery bank, or a solar PV standalone system. The solar PV diesel hybrid with battery has lower operating and maintenance costs ($2333), fuel consumption of 12743 litres, and running hours for generator 3888 as compared to other systems. Optimising the system is crucial for making sure the designed solar PV hybrid system with battery storage works smoothly and saves money. Figure 5 shows a comparison of different-designed systems.

Figure 5

Comparison of Different Systems



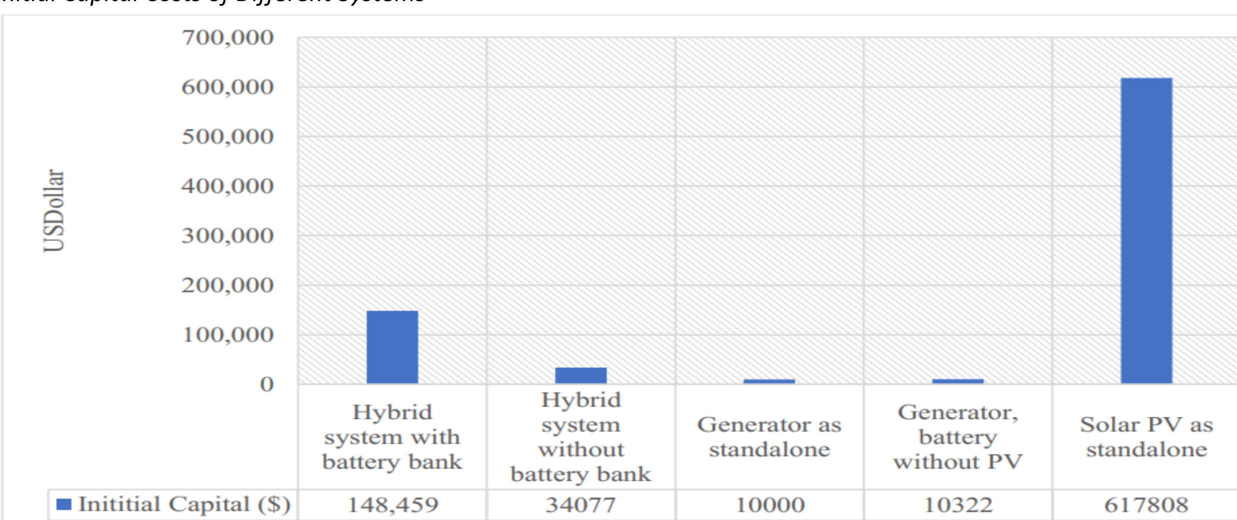
	Hybrid system with battery bank	Hybrid system without battery bank	Generator as standalone	Generator, battery without PV
O & M Costs	2333	5256	5256	5256
Fuel (L)	12743	24806	27290	27290
Production (kWh)	36933	67670	77559	77559
Hours	3888	7760	8760	8760

3.3 Capital Cost

Capital costs are fixed, one-time expenses incurred on the purchase of equipment used in the production of electricity in a hybrid system. It is the total cost that required to be paid at once for the purpose of acquiring the equipment for a project. The capital costs for a hybrid system are typically existing between the costs for a prime diesel and those of a large PV system. The capital cost for PV system found on the bi-directional inverter and solar Photovoltaic arrays. The initial cost for the Hybrid system with battery bank is higher which cost US Dollar 148,459.00 compared to Generator used as standalone costs to US Dollar 10,000.00 and the initial capital for Solar Photovoltaic standalone system costs US Dollar 379,627.00 which is more than two times of the PV diesel hybrid system with a battery bank. Though the capital cost might seem high at first, the selected system from the design has shown good system because saves money over time. (See Figure 6).

Figure 6

Initial Capital Costs of Different Systems



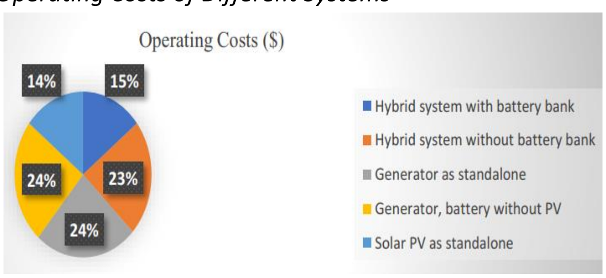
	Hybrid system with battery bank	Hybrid system without battery bank	Generator as standalone	Generator, battery without PV	Solar PV as standalone
Inititial Capital ($)	148,459	34077	10000	10322	617808

3.4 Operating Costs

Operating costs are those costs incurred every year of operation, including fuel and engine maintenance costs for a diesel generator and a solar photovoltaic system, which are determined by checking the battery bank one to four times, cleaning the contact terminal, and measuring the specific gravity of the lead acid used. The operating cost for the solar PV system is US$ 22,664.00 by 14 percent, which is significantly lower than the PV diesel hybrid system's US$ 22673.00 by 15 percent and the generator's US$ 38084.00. The designed system has demonstrated a lower operating cost compared to other systems. Figure 7 shows the operating costs of different systems.

Figure7

Operating Costs of Different Systems



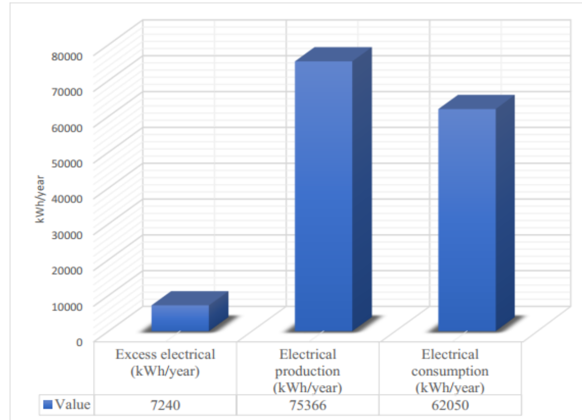
3.5 Electrical Energy Generated

According to the design, solar electricity could somewhat offset the diesel fuel used in this isolated residential residence, but it won't replace the necessity for a diesel generator. Despite the fact that residential loads best match PV output because they normally peak during the day and in the afternoon, a diesel generator backup is still required for rainy days during the rainy season.

As shown in Figure 8, the total energy generated is about 75366 kWh per year, with an excess of 7240 kWh per year. The total electrical consumption in Mwala village is 62050 kWh per year, which meets the village's energy needs. The system ensures a consistent and stable supply of electricity, reducing the risk of power outages and grid instability.

Figure 8

Summary for Electrical Generated



3.6 Harmful Gas Emissions

Given that using diesel typically results in air pollution, this section compares the harmful gas emissions of a standalone diesel system versus a hybrid PV/diesel system with batteries. Compared to a solar PV diesel hybrid system, the standalone diesel system emits more harmful gases such as carbon dioxide, carbon monoxide, unburned hydrocarbons, particulate matter, sulphur dioxide, and nitrogen. It should be noted that the analysis assumed no penalty would be imposed for the pollutant. For the diesel standalone system, total harmful gas emissions were 135,048.5 kg/year. Therefore, from the standpoint of the gas emissions effect, extending the diesel generator's operating hours results in higher fuel consumption and greenhouse gas emissions, while shortening the generator's operating hours results in lower fuel consumption and greenhouse gas emissions. (See Table 3).

Table 3

Emission Gases from Diesel Generator Standalone System

Pollutant	**Emission (Kg/year)**
Carbon dioxide	131,503
Carbon monoxide	325
Unburnt hydrocarbon	36
Particulate matter	24.5
Surfur dioxide	264
Nitrogen oxides	2,896

In a solar photovoltaic hybrid system with a battery bank, the number of harmful gases is decreased from

135,048 kg/year to 52,967 kg/year (see Tables 3 and 4), which means that due to the use of solar photovoltaic, the diesel generator's running time is reduced, resulting in fewer emission gases. Again, utilising a solar PV hybrid system with battery storage helps mitigate greenhouse gas emissions, combat climate change, and improve air quality, leading to significant environmental and public health benefits.

Table 4

Emission Gases from Solar Photovoltaic Diesel Hybrid System with Battery Storage

Pollutant	Emission (Kg/year)
Carbon dioxide	51,577
Carbon monoxide	127
Unburnt hydrocarbon	14.1
Particulate matter	9.6
Surfur dioxide	104
Nitrogen oxides	1,136

3.7 Sensitivity Analysis

Performing sensitivity analysis helps make a single analysis applicable to more than one installation. When the price of fuel increases, it affects the levelized cost, net present cost, and operating cost; when the PV price decreases, it reduces the present cost and cost of energy. The price of fuel has a significant impact on the system's operating cost, total net cost, and energy cost. When the price of fuel is $ 0.4, the cost of energy is $ 0.255/kWh, and vice versa. The hybrid PV/diesel system with battery would have the lowest total NPC of all the systems, though, if the price of diesel were to rise significantly. As a result, the price of diesel and the value of global solar irradiance have fluctuated to determine whether implementing various energy systems is appropriate. Sensitivity analysis is a crucial tool for assessing the reliability and performance of solar PV hybrid systems with battery storage under real-world conditions (see Table 5).

Table 5

Sensitivity Results for an Increase in Diesel Price

Serial No:	Diesel price ($/L)	Total NPC ($)	COE ($/kWh)
1	0.4	244,730	0.255
2	0.6	294,806	0.307
3	0.8	344,882	0.359
4	1.0	394,958	0.411

4.0 Conclusion

This study examined the design of a standalone hybrid power system, with an emphasis on a solar/diesel energy system with battery-based energy storage. If you use the HOMER software to simulate a solar photovoltaic diesel system with a battery that has an auto-size generator of 24.0 kW, a solar PV generic flat plate of 29.5 kW, a storage bank of 1 kWh, 120 strings of lead acid, and a system converter of 10.4 kW, you can use diesel resources much less. High penetration of renewable energy resources (solar photovoltaic) helps to reduce pollutants, such as carbon emissions, thus reducing the greenhouse effect. Again, it was proven that using a solar photovoltaic diesel hybrid system with a battery would be more economical when the price of diesel increased significantly. With a projection period of 25 years and a 6.5% annual real interest rate, it was found that using the solar photovoltaic hybrid system with the battery could achieve a significantly lower net present cost. Various aspects of design, including solar photovoltaic systems, have been explored in this system, taking into account factors such as sensitivity analysis, reliability, cost-effectiveness, and environmental impact. Implementing solar PV hybrid systems with battery storage has the significant impact of reducing dependence on traditional fossil fuel-based energy sources. This shift not only mitigates greenhouse gas emissions but also enhances energy security by diversifying the energy mix. In terms of potential outcomes, the widespread adoption of solar PV hybrid systems with battery storage has the potential to accelerate the transition towards a more sustainable and resilient energy future for Tanzania at large.

5.0 Recommendations

A solar PV diesel hybrid system with battery storage has high energy reliability 24/7, is used in less populated remote villages, and is uneconomical for grid connection. Therefore, based on the design, the reliable hybrid system can accelerate the growth of social and economic activities by reducing poverty and offering multiple environmental benefits in Mwala village and Mbeya district.

6.0 Funding Statement

The study was financed by the researchers.

7.0 Acknowledgement

We are so grateful to the Mbeya University of Science and Technology, where the researchers work, for giving us time and resources to undertake the research. Additionally, we would like to express our gratitude to the MRCC Principal for granting us permission to conduct the study and present the results.

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