

Techno-Economic Evaluation of a PV-Biomass-Diesel Hybrid Systems with Electric Heating and Thermal Heat Storage (TES) for Isolated Power Grids: Case Study; The 5 MW Mamfe Diesel Thermal Power Plant, Southwest Region of Cameroon

Eta Kervin Ayamba, Wati Elvis, Tsafack Pierre

Department of Electrical and Electronic Engineering, Faculty of Engineering and Technology, University of Buea, Buea, Cameroon

Email: ayambaeta1@gmail.com

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Abstract

Diesel-based power generation remains the primary source of electricity supply in many isolated and weak-grid regions of Sub-Saharan Africa, including Mamfe in the southwest region of Cameroon. However, high fuel costs, logistical challenges, and environmental concerns necessitate the integration of renewable energy technologies. This study evaluates the technical and economic feasibility of retrofitting the existing Mamfe diesel thermal power plant with a hybrid energy system incorporating solar photovoltaic (PV), biomass generation, thermal energy storage (TES), and electric heaters. Hourly electrical load data were modelled in HOMER to represent both current demand and future projected demand using a load growth factor of 1.3. Component-level techno-economic parameters were defined based on regional cost data and HOMER default libraries. System optimization was carried out using a load-following dispatch strategy to minimize net present cost while meeting the electrical load reliably. Simulation results show that the optimized hybrid configuration reduces annual diesel fuel consumption by approximately, 35% compared to diesel standalone system. The hybrid system achieves a levelized cost of electricity of 0.30 USD/kWh, representing a 22% reduction relative to the diesel-only configuration (0.38 USD/kWh). The annual energy contribution of the hybrid system consists of approximately 38% solar PV, 27% biomass, and 35% diesel generation. The results demonstrate that integrating renewable energy and thermal storage into existing diesel power plants is a technically viable and

economically attractive pathway for reducing fuel dependence, lowering electricity generation costs, and improving sustainability in remote power systems.

Keywords

Hybrid Energy System, Thermal Energy Storage TES, Electric Heater, PV, Biomass, Diesel Generator, Techno-Economic Analysis, Mamfe, Cameroon

1. Introduction

Electricity access in isolated regions of sub-Saharan Africa remains a major barrier to socio-economic development in many parts of Africa. Approximately 600 million people in the region still lack access to grid electricity, while many electrified communities depend on unstable and carbon-intensive diesel generators for basic services [1] [2]. In Cameroon, despite its significant hydropower potential, the overall electrification rate by end of 2022 was only about 61% of the population (Eneo 2022 annual report). However, in rural areas and small towns the situation is far worse: rural electricity access was reported at 26% in 2023 (National Rural Electrification Agency). The limited electrification has profound implications. In remote communities, health facilities, schools, small industries are constrained by unreliable power supplies, increasing costs, reducing service quality, and limited development. A policy brief for Cameroon indicates that only about 20% of rural households have access to electricity, compared with higher rates in urban settings. In response, the Government of Cameroon has committed to universal electricity access by 2030, targeting also 40% clean-cooking access, and planning to mobilize roughly 6.5 billion USD in private investment [3].

Isolated thermal power plants like the 5 MW Mamfe diesel thermal power plant faces multiple challenges resulting in frequent power shortages, high operational costs due to fuel import logistics, noise and air pollution and vulnerability to global diesel price fluctuations [4]. these conditions make hybrid renewable energy systems (HRES) not just attractive but necessary from both economic and environmental perspectives [5].

Hybrid renewable energy systems, especially those combining photovoltaic PV generation with diesel and other renewables, have emerged as a promising solution for off-grid or weak grid settings. Among them, PV-Diesel systems are widely implemented thanks to rapidly falling solar panel costs, high solar irradiance in tropical regions, and relatively simple technology. For instance, Cameroon is located within the equatorial solar belt and receives above 5 kWh/m²/day, which makes PV Integration highly feasible in the Mamfe municipality. Nevertheless, the intermittent nature of solar energy demands the addition of storage or complementary generation sources to ensure reliability [6].

Biomass as an energy source is under-exploited in the southwest region of Cameroon, despite the presence of agricultural residues, palm oil-byproducts, wood

waste and sawmill residues. Integrating biomass with PV-diesel systems offers multiple benefits: reducing diesel consumption, lowering the levelized cost of energy (LCOE), and improving greenhouse-gas emissions performance [7]. Recent studies show that optimized solar-biomass ratios in hybrid systems can lead to 21% - 31% improvement in efficiency and about a 33% reduction in LCOE compared to solar alone. However, within Cameroon and the southwest region in particular, there is marked lack of site-specific techno-economic evaluations for systems that combine biomass with PV and diesel in isolated networks.

Another seldom explored but high-value dimension is the integration of electric heating and thermal energy storage (TES) in such hybrid systems. Many rural or semi-urban facilities like hospitals, schools, and hotels have significant heat demand: for laundry, water heating, sterilization or process heat. Conventional diesel-boiler or electric-resistance in such locales adds to operational costs and often is unreliable.

Using excess renewable energy generation to drive electric heaters and store heat in thermal storage (for later use) offers an interesting pathway to increase system value, shift loads, reduce peak demand, and enhance overall energy utilization. Studies in other climates show that combining PV with heat storage and electric heaters can deliver improved flexibility and costs-savings. Yet few studies examined this integration in equatorial or tropical off-grid contexts where heating loads and climate conditions differ significantly.

Recent studies have explored hybrid renewable energy systems (HRES) to reduce fossil fuel dependency and improve energy reliability. For instance, techno-economic analysis in Europe have integrated solar PV with thermal generation but often exclude complementary renewable sources such as biomass and energy storage mechanisms. In Cameroon, there is limited research on multi-source hybrid systems tailored to isolated grids, particularly those combining PV, biomass, diesel, and heat storage.

No comprehensive study has investigated a hybrid PV-biomass-diesel system with molten salt heat exchange to ensure round-the-clock electricity supply in Mamfe. Existing analyses primarily focus on single-source renewable integration or PV-battery systems, which are less suitable for the local energy context.

The Mamfe diesel thermal power plant cannot meet the community's growing electricity demand efficiently, resulting in high operational costs, fuel dependence, and environmental impact. Integrating PV and biomass with diesel generation and heat storage offers a potential solution to enhance reliability and sustainability. This study evaluates the technical performance, economic feasibility, and environmental benefits of such a hybrid system.

Despite global advancements in hybrid system design methodologies, very few studies investigate hybrid systems combining PV, biomass, diesel and heat storage with electric heating especially in equatorial isolated grids. Existing work tends to focus either on PV-diesel, or PV-biomass, or battery storage only. For example, optimization studies of PV/Wind/TES systems in Cameroon exist, but rarely in-

clude biomass or electric heating specifically. Moreover, simulation-based assessments often omit critical real-world considerations such as fuel logistics, biomass availability, maintenance costs, and local economic factors—elements that are highly influential for a site such as Mamfe.

Therefore, there is a clear gap in the literature regarding a techno-economic evaluation of PV-Biomass-diesel hybridization enhanced with electric heating and thermal energy storage, tailored to isolated thermal power plants in the Cameroon context. This review aims to fill that gap by critically analyzing the technological evolution, economic findings, and implementation challenges of such hybrid systems worldwide (2020-2025), while identifying specific opportunities and constraints for the Mamfe case study.

2. Methodology

2.1. Study Area

- Mamfe is located in Manyu Division of the Southwest Region of Cameroon. **Coordinates:** 5.7667°N, 9.3000°E.
- **Elevation:** Approximately 130 meters above sea level.
- **Climate:** Tropical monsoon climate with distinct wet and dry seasons. This tropical climate is favourable for solar PV and biomass utilization. Local agricultural residues, including cocoa shells and bush mango waste, provide a sustainable feedstock for biomass generation. Mamfe currently has a population of over 200,000 inhabitants (MINEPAT 2020) and 2500 houses.

2.2. Energy Situation in Cameroon and Mamfe (Study Area and Load Assessment)

2.2.1. National Electricity Context

Cameroon's electricity mix (2025) is dominated by hydro (45%), thermal (mostly diesel, 18%), and self-generation (37%), primarily in rural or industrial isolated areas [8]. Rural electrification remains a key challenge: while the national electricity access rate is 71%, rural access drops below 26%, highlighting an ongoing energy deficit. Power outages are frequent due to poor network coverage, aging infrastructure, and logistical challenges in fuel supply for diesel-powered plants. The government has set ambitious targets for universal access by 2030, with a strong focus on integrating renewable energy sources to reduce dependency on fossil fuels and improve reliability [9].

2.2.2. The Mamfe Thermal Power Plant Context

The Mamfe municipality relies heavily on diesel-based thermal power plant that was commissioned in 2021. The Thermal plant was introduced as a result of the ongoing crisis that cut off Mamfe from the Southern interconnected grid network along the Mamfe Bamenda road. The plant currently serves municipal facilities, residential neighbourhoods, and small-scale industries. Operational challenges include.

- High cost of fuel (850 XAF/L) and vulnerability to global diesel price fluctua-

tions.

- Frequent interruptions due to limited fuel supply logistics and aging equipment.
- Environmental and noise pollution, affecting public health and community acceptance.

Local renewable resources indicate high potential for hybridization: solar irradiation averages 4.5 - 5.0 kWh/m²/day, while biomass residues are abundant (37,000 tons dry matter/year), sufficient to supply a significant portion of local thermal energy needs.

Figure 1 below shows the Map of Mamfe municipality, illustrating the 11 villages that make Mamfe municipality.

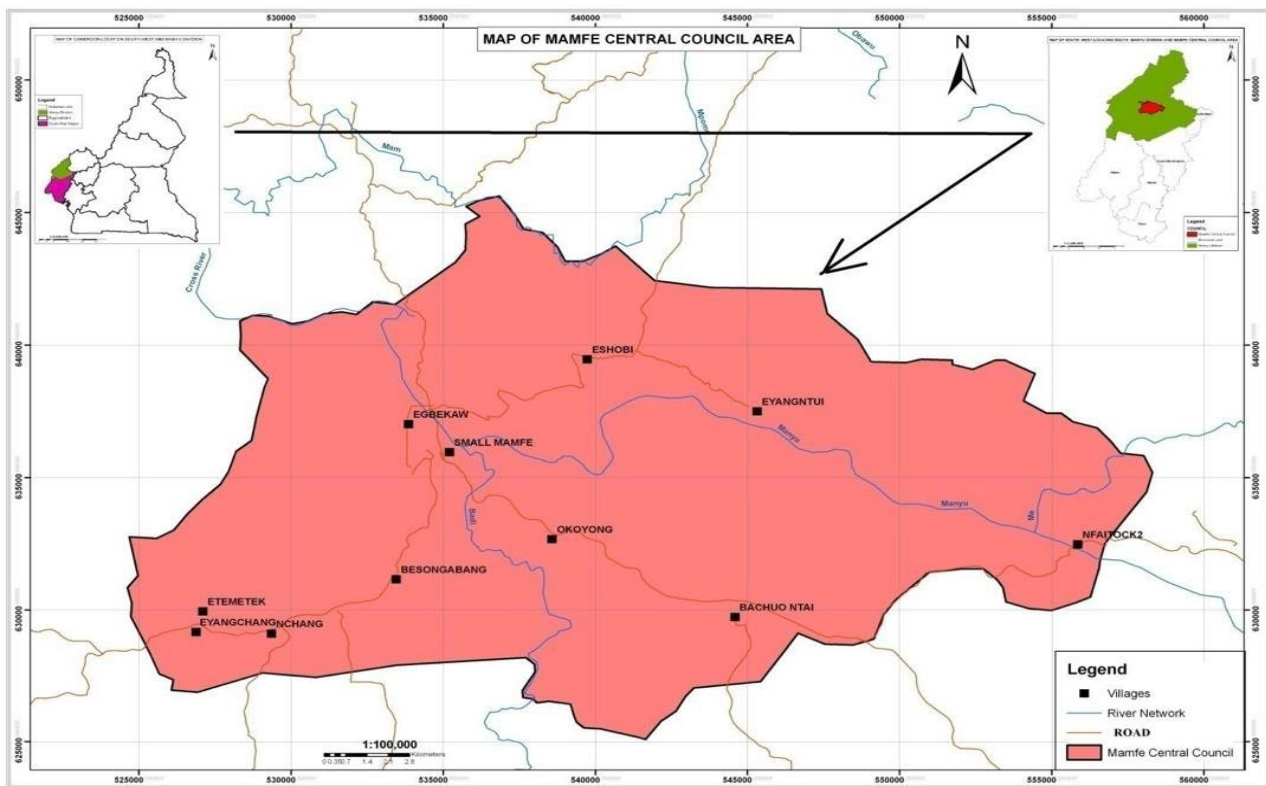


Figure 1. A map of the Mamfe municipality (Source: Mamfe council online).

Table 1 shows the population and social infrastructure within the Mamfe municipality.

Table 1. Population and social infrastructure: (Source: Mamfe council).

Information	Value	Source
Population	200,000	Mamfe Council Communal Development Plan
Number of houses	4000	DD/MINEPAT/MANYU
Number of Primary schools	95	DD/MINEDUB/MANYU

Continued

Number of High schools	45	DD/MINESEC/MANYU
Number of churches	100	Pilot Survey
Number of health centre	15	Pilot Survey
Solar Resource (2010-2025)	15 Years	NASA
Biomass feedstock (2020-2025)	05 years	Estimation by researcher

Table 2 shows the community demand table. The number of shops, markets and the quantity of energy demanded by each facility.

Table 2. Community load demand table.

Load Category	Number of Units	Unit load (kW)	Total load (kW)
Residential/homes	500	4	2000
Small shops/markets	50	10	500
Schools	100	5	500
Health centers	15	100	1500
Government offices	50	10	500
Small industries	10	150	1500

2.3. Energy Demand and Power Consumption Cycle for Mamfe Municipality

It is important in this design to note that four unpredictable issues when designing micro grid renewable energy systems.

- The energy output from the system will vary from time to time during the day.
- The energy output from the system will vary from day to day during each year.
- The load put on the system is not constant over a day.
- The daily loads vary over the year.

For the calculation, three different types of households with different consumption behavior are distinguished: residential households, commercial, social infrastructures. In order to define the most realistic load profile for the village, the residential loads are further stratified into low-income families and rich families. It is assumed here that 20% of all households in the village are rich while 80% are low-income households. **Table 3** shows a detailed energy demand assessment within the municipality, component by component.

2.4. Load Forecast for the Mamfe Municipality

Forecasting is a key element of decision-making as its purpose is to reduce the risk in failures and reduce unexpected cost. Energy Consumption in the Future across the residential, commercial and industrial sectors in the municipality will be strongly influenced by economic growth. Increasing personal income, capital investment and housing are major contributors to continued growth in electricity demand.

Table 3. Detailed load demand illustration for Mamfe municipality.

Low Income Families					
Equipment's	Number per home	Power Ratings (W)	Hours of Usage/day	Power (W)	Energy (KWh)
Lamps	4	10	5	40	0.2
Rechargeable Lamps	2	10	6	20	0.12
Cell Phones	2	3	3	6	0.018
Radio Set	1	10	10	10	0.1
	Total			76	0.438
No of houses					200
Sub 1 Total for Power and Energy of low income families				15,200	1740
Rich Families					
Equipment's	Number per home	Power Ratings (W)	Hours of Usage/day	Power (W)	Energy (KWh)
Lamps	5	10	5	50	0.25
Cell Phones	4	3	3	12	0.036
Radio Set	1	10	9	10	0.09
TV Set	2	140	5	280	1.4
DVD Player	1	30	3	30	0.09
Computer	1	100	3	100	0.3
Refrigerator	1	500	4	500	2
Iron	1	1000	0.5	1000	0.5
Fan	1	40	1	40	0.04
Satellite Dish	1	45	3	45	0.135
	Total			2067	4.841
No of Houses					20
Sub Total 2 for Power and Energy of Rich Families				41,340	3970
Commercial/Industrial Services					
Equipment's	Number per Home	Power Ratings (W)	Hours of Usage/day	Power (W)	Energy (KWh)
Grinding Mill (Cassava and corn)					
Lamps	2	10	1	20	0.01
Electric Motor	2	5000	4	10,000	20
	Total			10,020	20.01
No of Mills					4
Sub Total 3 for Power and Energy of mills				40,080	1600

Continued

Shops and Bars					
Lamps	4	10	4	40	0.04
Cell Phones	1	3	3	3	0.009
Radio set	1	10	7	10	0.07
TV set	1	140	9	140	1.26
DVD Player	1	30	3	30	0.09
Computer	1	150	2	150	0.3
Refrigerator	2	500	3	1000	1.5
Satellite Dish	1	45	4	45	0.18
Total				1418	3.449
No of Shops and Bars					8
Sub Total 4 for Power and Energy Shops and Bars				11,344	551.84
Tailoring Workshops					
Lamps	1	10	3	10	0.03
Sewing Machine (dynamo)	1	120	3	120	0.36
Total				130	0.39
No of Tailoring Workshops					5
Sub Total 5 for Power and Energy of Tailoring Workshops				650	39
Restaurants					
Lamps	3	10	3	30	0.03
Blender	1	180	1	180	0.18
Refrigerator	1	100	12	100	1.2
Mixer	1	100	1	100	0.1
Total				410	1.51
No of Restaurants					2
Sub Total 6 for Power and Energy of Restaurants				820	3.02
Cocoa Warehouses					
Lamps	6	10	6	60	0.06
Electronic Scale	2	95	2	190	0.19
Cocoa Quality checker	2	6	1	12	0.006
Computers	2	65	3	130	0.195
TV sets	1	140	4	140	0.56
Radio set	1	10	3	10	0.03
Cell-Phones	5	3	1	15	0.003
Total				557	1.044
No of Cocoa Warehouses					16
Sub Total 7 for Power and Energy of Cocoa Warehouses				2228	86

Continued

Social Infrastructure					
Equipment's	Number per home	Power Ratings (W)	Hours of Usage/day	Power (W)	Energy (KWh)
Hospitals					
Lamps	20	10	5	200	0.05
Microscope	1	25	2	25	0.05
Vaccine Refrigerator	1	60	18	60	1.08
Vaporizer	1	40	2	40	0.08
Oxygen Concentrator	1	300	2	300	0.6
Electric Sterilizer	1	1500	2	1500	3
Fixed Phone	1	3	24	3	0.072
Ceiling Fan	2	40	4	80	0.16
Computer	2	75	5	150	0.375
Scanner/Copier/Printer	11	17	2	187	0.034
Centrifuge nebulizer	1	150	150	150	22.5
Internet modem	1	8	6	8	0.048
Water pump	1	100	2	100	0.2
Total				2803	28.249
No of Hospitals					1
Sub Total 8 for Power and Energy of Community Churches				2803	564.98
Community Church					
Lamps	4	10	2	40	0.02
Computer	1	80	1	80	0.08
Piano	1	15	1	15	0.015
Cell Phone	1	3	1	3	0.003
Stereo (Speakers)	2	20	1	40	0.02
Microphone	2	6	1	12	0.006
Total				190	0.144
No of Community churches					4
Sub Total 9 for Power and Energy of Community Churches				760	11.52
Educational Institutions (High School)					
Lamps	35	10	3	350	0.03
Computer	25	65	1	1625	0.065
Cell Phones	2	3	1	6	0.003
Water Pumps	1	100	3	100	0.3
Microscope	4	25	1	100	0.025
Total				2181	3.423
No of Educational Institutions					3
Sub Total 10 for Power and Energy of Educational Institutions				6543	205.58

Continued

Administrative Buildings					
Lamps	20	10	4	200	0.04
Computer	15	80	1	1200	0.08
Cell-Phones	5	3	1	15	0.003
Water pumps	1	100	3	100	0.3
Printer	2	30	3	60	0.09
Photocopier	2	500	1	1000	0.5
Total				2575	1.013
No of Administrative Buildings					4
Sub Total 11 for Power and Energy of Administrative Buildings				10,300	81

Load Modeling in HOMER**Electrical Load Profile**

The electrical load for Mamfe diesel thermal power plant was modelled in HOMER using an hourly time-series profile representing a typical operating day. The base load profile was derived from measured operational data provided by the thermal plant manager. The hourly load varies between a minimum demand of 1.09 MW during off-peak hours and a peak demand of 6.0 MW occurring in the evening period.

In this study, Load projection for the municipality is considered by applying an extension factor (k_{ex}) of 1.3 to the power. The electricity demand forecast considers both the peak demand for electricity and average demand throughout the year. Peak demand refers to the highest level of electricity consumption that the utility can supply at any given time. A uniform load extension factor of 1.3 was applied to the base hourly demand. to account for future demand growth as there is population growth, rural electrification expansion, commercial and load increase, consistent with trends reported by the Ministry of Water and Energy. This approach is consistent with HOMER-based hybrid system studies conducted in rapidly growing electrification region. The resulting projected peak demand reaches approximately 7.8 MW.

HOMER internally scales the hourly load profile to generate annual electrical demand, which is subsequently used for system optimization and dispatch simulations.

Taken the extension factor (future loads) of $k_{ex} = 1.3$

$$P_{demand} = P \times 1.3 = 6000000 \times 1.3 = 7800000 \text{ W} = 7.8 \text{ MW}$$

$$E_{demand} = E \times 1.3 = 7.8 \text{ MWh} \times 1.3 = 10.14 \text{ MWh}$$

Table 4 summarizes the estimated electrical load demand for residential, commercial, and institutional consumers. The table clearly indicates the current consumption and the projected hourly demand (**Figure 2**).

Table 4. Hourly load profile for Mamfe (current and projected).

Hour of Day	Load Factor	Current Demand (MW)	Projected Demand
0.0	0.25	1.5	1.95
1.0	0.22	1.32	1.71
2.0	0.2	1.2	1.56
3.0	0.18	1.08	1.4
4.0	0.22	1.32	1.71
5.0	0.3	1.8	2.34
6.0	0.45	2.7	3.51
7.0	0.55	3.3	4.29
8.0	0.65	3.9	5.07
9.0	0.75	4.5	5.85
10.0	0.8	4.8	6.24
11.0	0.85	5.1	6.63
12.0	0.88	5.28	6.864
13.0	0.83	4.98	6.48
14.0	0.8	4.8	6.24
15.0	0.82	4.92	6.4
16.0	0.9	5.4	7.02
17.0	0.95	5.7	7.41
18.0	1.0	6.0	7.8
19.0	0.85	5.1	6.63
20.0	0.75	4.5	5.85
21.0	0.6	3.6	4.68
22.0	0.45	2.7	3.51
23.0	0.35	2.1	2.73

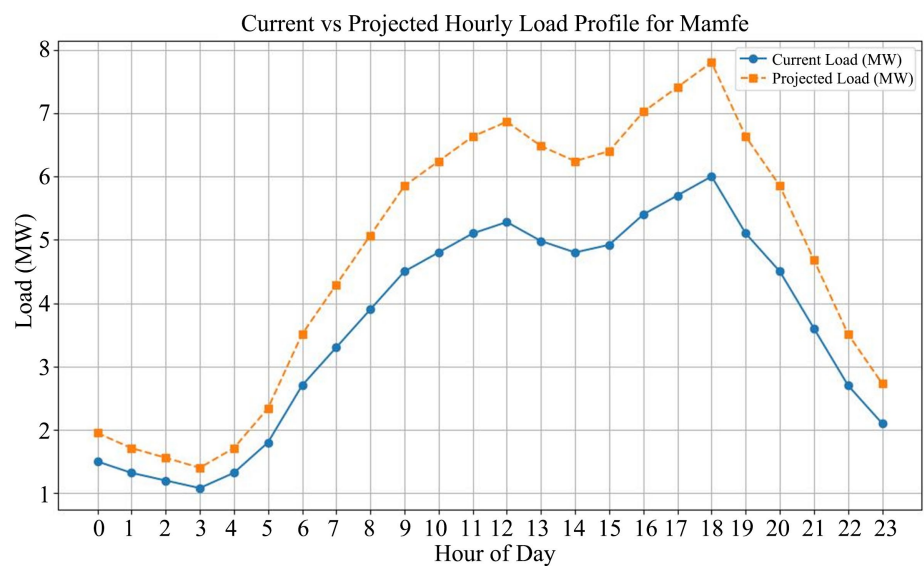


Figure 2. Current vs projected load profile for Mamfe.

The graph represents the current and projected hourly electricity demand of Mamfe based on a typical day. The projected load profile was obtained by applying a load growth factor of 1.3 to the current demand to account for population growth, electrification expansion, and increased socio-economic activities [10] (Figure 3).

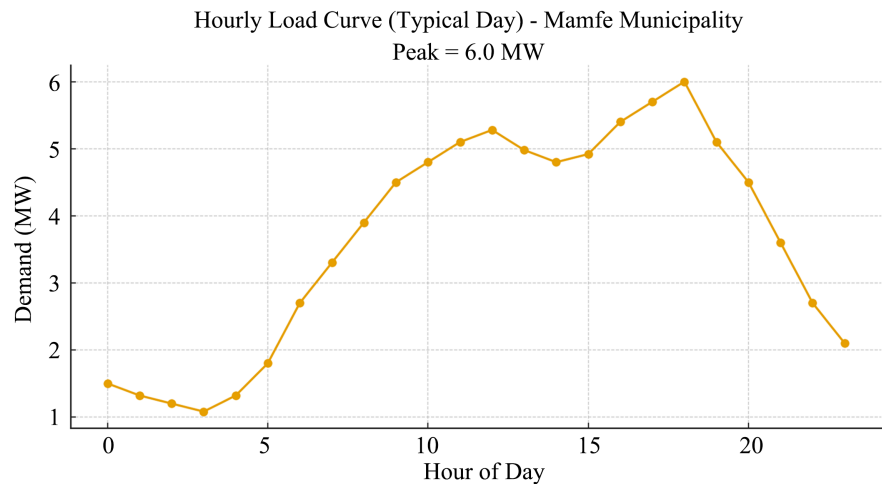


Figure 3. Load profile curve for Mamfe.

The hourly load profile for mamfe indicates that the minimum load is experienced at around 2am when almost all active spots are shut down and the peak load of the community arises around 6pm in the evening hours.

Table 5 is equally showing the monthly load profile for mamfe in the different hours of the day. It illustrates the current demand and the projected load demand (Figure 4).

Table 5. Monthly load profile for Mamfe (current and projected).

Day of Month	Load Factor	Current Demand (MW)	Projected Demand (MW)
1.0	0.59	3.52	4.6
2.0	0.69	4.16	5.4
3.0	0.71	4.28	5.6
4.0	0.73	4.4	5.8
5.0	0.71	4.26	5.6
6.0	0.72	4.29	5.6
7.0	0.7	4.17	5.4
8.0	0.75	4.51	5.9
9.0	0.69	4.12	5.4
10.0	0.65	3.92	5.0
11.0	0.54	3.22	4.19

Continued

12.0	0.58	3.5	4.55
13.0	0.53	3.18	4.4
14.0	0.44	2.63	3.4
15.0	0.42	2.52	3.2
16.0	0.42	2.52	3.2
17.0	0.45	2.69	3.4
18.0	0.5	3.0	3.9
19.0	0.53	3.18	4.2
20.0	0.56	3.38	4.4
21.0	0.64	3.86	5.01
22.0	0.64	3.85	5.01
23.0	0.69	4.16	5.40
24.0	0.73	4.36	5.66
25.0	0.75	4.47	5.81
26.0	0.77	4.64	6.03
27.0	0.69	4.16	5.40
28.0	0.69	4.15	5.40
29.0	0.66	3.94	5.12
30.0	0.55	3.33	4.32

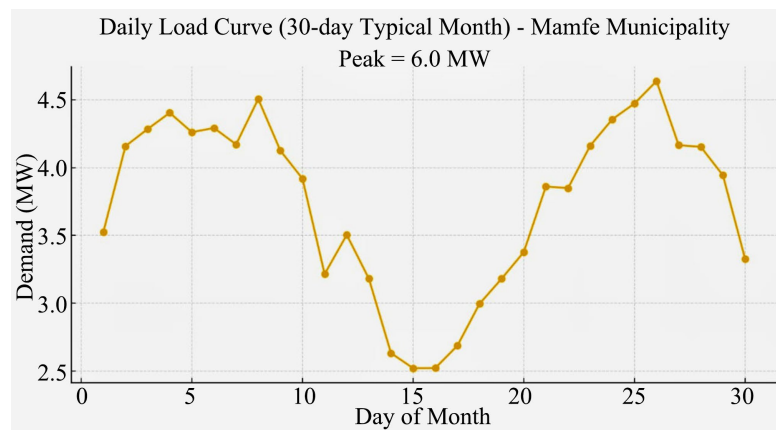


Figure 4. Monthly load curve (for the current load demand).

The figure also illustrates how demand power fluctuates within the different days of the month.

2.5. System Components

- Solar PV: 1 MW Capacity (the 1 MW is chosen by the researcher) , assumed average annual irradiation of 5 kWh/m²/day.
- DC/AC Inverter.

- AC Bus.
- Biomass Generator: 1 MW using local agricultural waste (bush mango shell, palm kernel fiber, cocoa shell).
- Diesel Thermal Plant: existing 5 MW capacity (5 × 1 MW generators).
- Heat Storage: Molten salt storage system supporting continuous Rankine cycle operation.
- Electric Heater: Converts excess electricity to heat for storage, ensuring round-the-clock generation.
- Load (8 MW).

2.5.1. Photovoltaic Systems in Hybrid Configurations

Photovoltaic (PV) systems in hybrid configurations refers to solar power systems that operate together with other energy sources or technologies to supply electricity more reliably and efficiently.

2.5.2. Evolution of PV Technology in Hybrid Systems (2015-2025)

Photovoltaic (PV) technology has witnessed substantial cost reductions and efficiency improvements over the last decade. Globally, the average module efficiency has increased from 15% in 2015 to 22% - 24% in 2025 for commercially available crystalline silicon panels [11]. Simultaneously, PV system costs dropped by approximately 70%, making PV a competitive option for isolated and grid-connected systems alike.

Hybrid PV systems, particularly those integrated with diesel generators, have been widely adopted in off-grid and weak-grid settings. This integration leverages the intermittent yet predictable daily solar resource while using diesel as a backup to ensure supply continuity. In tropical regions like Cameroon, PV integration is highly advantageous due to daily irradiation levels.

Table 6 presents the monthly average global horizontal irradiation (GHI), direct normal irradiation (DNI), and ambient temperature for the Mamfe municipality.

Table 6. Monthly solar irradiance data for Mamfe.

Month	GHI (kWh/m ² /day)	DNI (kWh/m ² /day)	Temperature (°C)
January	4.6	3.8	26.2
February	5.1	4.2	27.8
March	5.4	4.5	28.5
April	5.2	4.3	28.1
May	4.9	4.0	27.3
June	4.2	3.4	25.8
July	3.8	3.0	24.9
August	3.9	3.1	24.7
September	4.3	3.5	25.4

Continued

October	4.7	3.9	26.1
November	4.8	4.0	26.5
December	4.5	3.7	26.0

The results show that solar irradiation remains relatively high throughout the year, with GHI values ranging from about 3.8 to 5.4 kWh/m²/day. Peak solar resources are observed between February and April, corresponding to the dry season, while lower values occur during the rainy months of June to August.

Despite seasonal variations, the consistency moderate-to high irradiation levels indicate strong solar energy potential for photovoltaic power generation in Mamfe. This resource availability supports the technical feasibility of integrating solar PV into the hybrid PV-Biomass-diesel system, ensuring significant daytime electricity production and contributing to reduced diesel fuel consumption.

Key technological advances in PV-diesel hybrid systems over the last decade include:

- **Maximum Power Point Tracking (MPPT) Controllers:** improved energy capture under variable irradiance
- **Hybrid inverters:** facilitating seamless integration of PV, storage, and diesel generation.
- **Improved battery and thermal storage integration:** enable load shifting and peak shaving.
- **Smart control algorithm:** optimize diesel operation, PV dispatch, and storage utilization.

Table 7 compares PV-diesel hybrid systems implemented in isolated communities. The reviewed studies report diesel fuel savings of 28% - 32% and LCOE reductions of up to 25%, confirming the economic and technical benefits of PV integration. The Cameroonian case further highlights the need for complementary storage and renewable sources to address seasonal variability.

Table 7. Several studies explored on PV-Diesel hybrids in isolated communities.

Study	Location	PV capacity	Diesel capacity	Storage	Key findings
Singh <i>et al.</i> 2020	India (rural microgrid)	100 kWp	50 kW	Battery	32% diesel reduction; LCOE reduction by 25%
Bello <i>et al.</i> 2021	Nigeria (island micro grid)	75 kWp	60 kW	Battery + thermal	Diesel consumption cut by 28%
Aboagye <i>et al.</i> 2022	Ghana	120 kWp	100 kW	Battery	PV integration reduced cost of electricity by 21%
Kamga <i>et al.</i> , 2023	Cameroon (off grid village)	60 kWp	80 kW	Battery	PV supplied 43% of daily load; challenges in seasonal variation

2.5.3. PV-Diesel Hybrid Case Studies Worldwide

Observations:

- PV can reduce diesel consumption by 20% - 35% depending on load profile, storage and system sizing.
- Integration with thermal or electric storage further improves efficiency
- Control strategies for hybrid operation critically affect techno-economic performance

2.5.4. Technical and Economic Performance Indicators

Key performance metrics for PV-diesel hybrid systems include:

- **Levelized Cost of Energy (LCOE):** Combines capital, operation, and maintenance, fuel, and storage costs over system's lifetime. For small tropical hybrids, LCOE typically ranges 0.18 - 0.35 USD/kWh depending on the prices of diesel and PV sizing.
- **Diesel Savings (%):** fraction of energy demand met by PV. Savings increase with PV Penetration but may require larger storage or curtailed PV output.
- **Battery/TES Utilization:** efficient energy storage reduces curtailment and increases renewable penetration; critical for hospitals and facilities with nighttime or peak thermal loads.

2.5.5. PV Integration in Mamfe Context

Given Mamfe's average solar irradiation of 4.5 - 5 kWh/m²/day, PV Systems can supply a significant fraction of local electricity demand, particularly during daytime peaks. However, there exist some challenges;

- **Seasonal variability:** Rainy season reduces output, storage or diesel backup is essential.
- **Load matching:** residential, municipal, and institutional loads require careful sizing of PV, diesel, and storage.
- **Economic viability:** diesel prices (850 XAF/L) Favor PV Integration, but initial investment cost may be a barrier without financial incentives.
- **Potential for electric heating:** Excess PV during the day can be used to charge thermal storage for heating water or laundry in hospitals.

2.6. Biomass Resource Assessment

2.6.1. Biomass Utilization in Hybrid Power Systems

Biomass energy is derived from organic matter, including agricultural residues, forestry waste, municipal solid waste, and energy crops. In hybrid energy systems, biomass offers several advantages:

- **Dispatchable generation:** Unlike PV, biomass can generate electricity on demand, providing a stable complement to intermittent renewables.
- **Reduction in diesel dependency:** Using locally available biomass reduces imported fuel consumption and associated costs
- **Environmental benefits:** Properly managed biomass reduces net greenhouse gas emissions compared to fossil fuels.

Generally, biomass integration into hybrid systems has shown promising results. For example, in India, PV-biomass-diesel hybrids achieved 25% - 30% diesel savings while maintaining high reliability, In Ghana, biomass-diesel-PV microgrids supplying hospital loads improved renewable fraction from 40% to 60% with minimal cost increase [12].

- **Biomass system sizing:**

For reliability and fuel saving, 1 MW of biomass energy is required.

Table 8 highlights that biomass gasifier engine systems are best suited for small-to medium-scale applications with diverse agricultural residues. Given Mamfe's biomass availability and the targeted 1 MW capacity, this technology offers higher efficiency and operational flexibility compared to direct combustion and biogas options.

Table 8. Selection of technology type.

Technology	Suitable feedstock	Efficiency	Scale
Direct combustion boiler + steam turbine	Agricultural residue, wood chips	20% - 25%	>1 MW
Gasifier + Engine/Turbine	Coconut shells, palm residues, saw dust, bush mango shells, cocoa shells	20% - 35%	100 kW - 5 MW
Biogas digesters	Animal waste, crop waste	25% - 40%	Small to medium

For the case of Mamfe, biomass gasifier + engine is recommended due to due to the availability

of wood residues from forestry, agricultural waste (palm kernel shells, cocoa pods, bush mango shells, palm pressed fiber and higher conversion efficiency.

Biomass Energy requirement: $E = P_e \times \text{Hours} = 1 \times 24 = 24 \text{ MWh/day}$

Fuel Mass flow rate calculation

Biomass Fuel Required (kg/day) = $E \div \text{Electrical efficiency (Ee)} \times \text{LHV}$

where;

- Electrical efficiency = 30% for gasifier
- LHV (Wood biomass) = 15 MJ/kg = 4.17 kWh/kg
- So, Fuel = $24,000 / 0.30 \times 4.17 = 19,200 \text{ kg/day}$
- 19.2 tons/day biomass requirement, for a year = $19.2 \times 365 = 7008 \text{ tons/year}$
- Gasifier size = $1.2 \times P_e = 1.2 \text{ MWth}$

Storage sizing: biomass storage $\geq 7 - 30$ days: for 7 days; storage = $19.2 \times 7 = 134 \text{ tons}$.

Table 9 summarizes the key design and operational parameters of the proposed 1 MW biomass power system. The system is designed to deliver a continuous electrical output of 1 MW, corresponding to a daily energy production of 24 MWh, assuming round-the-clock operation. An overall electrical conversion efficiency of 30% is considered, which is consistent with biomass gasifier-engine technologies operating at this scale. Based on a lower heating value (LHV) of 4.17 kWh/kg

for selected biomass feedstock, the daily biomass requirement is estimated at approximately 19.2 tons per day. This results in an annual biomass consumption of about 7008 tons, Assuming year-round operation. To ensure operational reliability and account for supply interruptions, a biomass storage capacity equivalent to seven days of operation (approximately 134 tons) is included. The selected technology for the system is a biomass gasifier coupled with an internal combustion engine, which offers high efficiency, modularity, and suitability for decentralized power generation. Overall, the parameters presented in **Table 9** confirm the technical feasibility of integrating a 1 MW biomass unit into the proposed hybrid energy system to enhance reliability and significantly reduce diesel fuel consumption.

Table 9. Summary table of 1 MW biomass system.

Parameter	Value
Electrical output	1 MW
Daily Energy	24 MWh/day
Efficiency	30%
Fuel LHV	4.17 kWh/kg
Biomass Required	19.2 tons/day
Annual consumption	7008 tons
Storage capacity	134 tons (7 days)
Technology	Gasifier + engine

Figures 5-7 illustrate the major biomass feedstocks available in the Mamfe municipality. Namely bush Mango shells, cocoa pods, and palm pressed fibers.



Figure 5. Bush mango shells.



Figure 6. Cocoa pods.



Figure 7. Palm pressed fiber.

These residues are by-products of dominant agricultural and agro-processing activities in the region and are currently underutilized or disposed as waste. Bush mango shells (**Figure 5**) are generated in significant quantities during seasonal processing of bush mango seeds, while cocoa pods (**Figure 6**) result from cocoa farming, which is a major economic activity in Mamfe and the entire Manyu Division. Palm pressed fibers (**Figure 7**) are produced as residues from palm oil extraction and are continuously available throughout the year due to sustained palm oil production. The availability of these diverse biomass resources ensures a reliable and flexible feedstock supply for the proposed biomass gasifier-engine system. Their combined use helps mitigate seasonal variability associated with single-feedstock systems and enhances the reliability of continuous power generation. Consequently, the feedstocks shown in **Figures 5-7** strongly support the technical feasibility and sustainability of integrating biomass energy into hybrid PV-biomass-diesel system proposed for Mamfe.

2.6.2. Biomass Potential in Mamfe (Biomass Resource Assessment)

Mamfe as other localities in the southwest Region of Cameroon have abundant biomass resources from agriculture, forestry, and agro-industrial residues. The table below summarizes the main biomass types and estimated availability in the Mamfe municipality.

Table 10 presents the estimated annual availability of major biomass residues in Mamfe, expressed in tons of dry matter, together with energy applications and sources. The results indicate that the region possesses substantial biomass resources derived primarily from agricultural and agro-industrial activities. Palm kernel shells and palm pressed fibers represent the largest single resource, with an estimated availability of 12,500 tons per year. These residues originate from palm oil processing activities and are suitable for power generation and heat production. Cocoa pod husks contribute approximately 8400 tons annually and can be utilized for electricity generation or briquete production. Sawdust and wood chips, generated from sawmills and furniture workshops, account for about 9800 tons per year and are suitable for cogeneration or pellet fuel production. Bush mango shells contribute an additional 3200 tons annually and are appropriate for combustion or gasification processes. Other crop residues, including cereals and cassava wastes, provide approximately 4100 tons per year and may be used for energy production.

Table 10. Regional biomass residues for Mamfe/southwest region Cameroon.

Biomass Type	Annual availability (tons dry matter)	Potential Use	Source/Notes
Palm kernel shells	12,500	Power generation and heat	Palm oil processing residues in Mamfe
Cocoa pods husks	8400	Power generation, briquettes	Agricultural residues from cocoa farms
Sawdust/wood chips	9800	Cogeneration or pellet fuel	Local sawmills and furniture workshops
Bush mango shells	3200	Combustion of gasification	Agricultural residues from bush mango farms
Other crop residues	4100	Energy compost	Mixed cereals and cassava residues
Total	37,000 tons dry matter sufficient to supply significant fraction of thermal energy demand in Mamfe if properly utilized.		

In total, the estimated biomass availability in Mamfe amounts to approximately 37,000 tons of dry matter per year. This quantity significantly exceeds the annual biomass requirement of the proposed 1 MW system (approximately 7008 tons/year), demonstrating that sufficient feedstock exists to sustain continuous operation. Therefore, **Table 10** confirms the long-term feasibility and sustainability of biomass-based power generation within the proposed hybrid system.

These resources could support cogeneration plants capable of supplying both electrical and thermal energy to municipal facilities, hospitals and small industries. Biomass in Mamfe is largely underutilized, offering an opportunity to reduce diesel dependence while promoting local energy self-sufficiency.

- Biomass required for 1 MW = 19.2 tons/day.
- Annual requirement = 7000 tons/year
- Available biomass = 37,000 tons/year.

Therefore, only about 19% of the available biomass resource is required, confirming the technical feasibility of a 1 MW biomass generator.

Biomass Availability vs Requirement (**Table 11**).

Table 11. Shows the biomass availability and requirement.

Parameter	Value
Available biomass	37,000 tons/year
Required biomass	7000 tons/year
Utilization ratio	19%

2.7. Technical Integration in Hybrid Systems

The integration of biomass with PV and diesel requires careful technical design.

- **Generation technology:** Small-scale steam turbines, internal combustion engines, or gasification units are commonly used depending on the feedstock type and scale.
- **Hybrid configuration:** Biomass can supply base-load energy while PV covers daytime peaks and diesel provides backup for high reliability.
- **Control strategy:** A smart dispatch algorithm optimizes the contribution of each energy source, considering diesel cost, fuel availability, and PV Production
- **Coupling with Thermal storage:** Heat from biomass combustion can be stored for space or process heating, enabling higher system efficiency and reducing peak electricity loads.

Economic and Environmental Considerations

- **Fuel cost savings:** biomass utilization significantly lowers diesel consumption, reducing both operational cost and exposure to international fuel price.
- **Levelized Cost of Energy (LCOE):** Hybrid systems integrating biomass generally achieve 10% - 25% lower LCOE compared to PV-diesel only.
- **Emission reduction:** Replacing diesel with biomass reduces carbon dioxide, NO and particulate matter emissions, especially when sustainably sourced.

Challenges include feedstock collection and transport, seasonal availability, moisture content management, and capital costs for biomass conversion equipment [13] [14].

Table 12 summarizes selected empirical and modelling studies on hybrid renewable energy systems in Africa and Sub-Saharan contexts. The table compares different system configurations, geographical locations, key findings, and publication years in order to position the present study within existing literature. Kamga *et al.* evaluated PV-diesel systems in rural Cameroon and confirmed their technical feasibility for isolated communities. Nwokoye *et al.* (2022) examined biomass-diesel systems in Sub-Saharan Africa and reported significant carbon dioxide emission reduction potential [15].

Table 12. Review of empirical and modelling studies.

Study	Location	System	Key Findings	Year
Adaramola <i>et al.</i>	Nigeria	PV-Diesel	20% diesel fuel saving	2021
Ouedraogo <i>et al.</i>	Burkina Faso	PV-Biomass-Diesel	Reduced LCOE, high reliability	2022
Mensah <i>et al.</i>	Ghana	PV + Electric Heater + TES	Short-term TES improved surplus PV usage	2023
Kamga <i>et al.</i>	Cameroon	PV-Diesel	Feasible for rural communities	2020
Nwokoye <i>et al.</i>	Sub-Saharan Africa	Biomass-Diesel	High CO ₂ reduction potential	2022

Observation: very few studies integrate PV-Biomass-Diesel + Electric Heater + TES in isolated African plants, highlighting the research gap addressed by this work.

2.8. Diesel Generators as Backup in Hybrid Systems

2.8.1. Role of Diesel in Hybrid Systems

Diesel generators remain a critical component in hybrid PV-biomass-diesel systems, particularly in isolated grids or weak network regions. Their primary roles include;

- **Reliability and continuity of Supply:** Diesel ensures uninterrupted electricity during periods of low solar irradiation or biomass availability.
- **Load balancing:** Diesel generators compensate for fluctuations in renewable energy supply and meet peak demand.
- **System stability:** They provide essential grid services such as frequency regulation and voltage support, especially when renewables are intermittent.

2.8.2. Technical Consideration for Diesel Integration

The efficient integration of diesel generators in hybrid system requires careful attention to:

- **Sizing:** Diesel capacity must cover peak loads not met by PV or biomass. Oversizing increases capital and operational costs, while under sizing risks power shortages.

- **Control strategy:** Advanced hybrid controllers manage the dispatch order, prioritizing renewable energy while using diesel only when necessary.
- **Maintenance scheduling:** Diesel generators require regular maintenance to avoid unexpected downtime. Hybrid operation can reduce wear by limiting running hours, extending lifespan, and lowering lifecycle costs.

2.8.3. Economic Considerations

Diesel backup impacts the overall techno-economic performance of hybrid systems:

- **Fuel costs:** Diesel in Mamfe currently costs XAF 850/L (USD 1.46/L), making it one of the highest contributors to operating expenses in isolated grids.
- **Operating cost reduction:** Hybridization with PV and biomass can reduce diesel consumption by 25% - 40% depending on system configuration and storage integration.

2.8.4. Environmental and Policy Considerations

- Diesel combustion emits CO₂, NO_x, SO₂, and particulate matter. Hybrid systems that reduce diesel operating hours help mitigate local air pollution and greenhouse gas emissions.
- Cameroon renewable energy policy encourages reducing reliance on fossil fuels, making hybrid PV-biomass-diesel systems aligned with national targets for clean energy and rural electrification.
- Environmental incentives (carbon credits or renewable certificates) could improve the financial viability of hybrids in Mamfe and similar isolated areas.

Table 13 presents selected case studies of diesel-supported hybrid energy systems implemented in India, Nigeria, and Cameroon. These studies consistently demonstrate that integrating photovoltaic (PV) systems with diesel generators significantly reduces diesel fuel consumption while maintaining system reliability. The PV-diesel hybrid systems across the different regions achieve 28% - 32% reductions in diesel consumption while maintaining reliability. However, diesel still contributes significantly to load supply, indicating the need for additional renewable energy integration such as biomass with a thermal energy storage system to further reduce dependency.

Table 13. Case studies in Diesel-backed hybrids.

Study	Location	System Type	Diesel contribution	Outcome
Singh et al, 2020	India	PV-Diesel	50 kW	Diesel use reduced by 32%, reliability maintained
Bello <i>et al.</i> , 2021	Nigeria	PV-diesel thermal	60 kW	28% diesel reduction; improved supply stability
Kamga <i>et al.</i> , 2023	Cameroon	PV-diesel	80 kW	Diesel supplied 57% of load; highlighted biomass potential for expansion

Observations:

- Diesel remains necessary due to variability in PV and biomass
- Combining diesel with local biomass and PV allows a multi-source hybrid system, reducing fuel costs, mitigating emissions, and increasing reliability.
- Integration with thermal storage and electric heating ensures efficient use of excess renewable energy, further reducing diesel run hours.

2.9. Heat Storage and Electric Heating in Hybrid Architecture**2.9.1. Overview of Thermal Energy Storage (TES)**

Thermal Energy Storage (TES) refers to technologies that store heat for later use, allowing better matching between energy supply and demand. In hybrid PV-biomass-diesel systems, TES can

- Shift surplus renewable energy (from PV or biomass) to periods of high thermal demand.
- Reduce reliance on diesel for heating
- Improve overall system efficiency and reliability

Common TES technologies include:

- **Sensible heat storage:** using water tanks, molten salts, to store energy by raising the temperature of the medium
- **Latent heat storage:** store energy during phase transitions e.g. melting/solidifying with high energy density
- **Thermochemical storage:** store energy in chemical bonds, enabling long-term storage with minimal heat.

Table 14 provides a comparative assessment of Thermal Energy Storage (TES) technologies and supports the selection of the TES configuration implemented in the Homer simulation model. The comparison considers storage medium, efficiency, and typical cost per kWh, which are critical input for techno-economic optimization in homer.

Table 14. Comparison of TES technologies.

TES Type	Storage Medium	Efficiency	Typical cost (\$/kWh)
Sensible	Water tank	80% - 90%	10 - 50
Latent	Phase change	70% - 85%	50 - 100
Thermochemical	Chemical	60% - 90%	80 - 150

2.9.2. Electric Heating Integration

Electric heating uses excess electricity from PV or biomass generators to provide thermal energy for:

- Water heating for residential and institutional use.
- Sterilization and laundry in hospitals or municipal facilities.
- Process heating for small industries.

Electric heating in hybrid system has some key benefits which include:

- Converts surplus PV electricity into useful heat, reducing curtailment.

- Reduces diesel consumption for heat generation.
- Facilitates flexible load management, particularly in tropical regions with intermittent PV output.

2.9.3. TES and Electric Heating in Mamfe Context

Mamfe experiences significant daytime solar irradiance of 5 kWh/m²/day and has abundant biomass residues (37,000 tons/year). Integrating TES and electric heating in the hybrid system can:

- Maximize renewable utilization: PV surplus during the day can heat water or storage medium.
- Provide night-time thermal energy: heat stored in TES can supply facilities during non-generation hours [16].
- Enhance system economics: reduced diesel usage for heating lowers operating costs.
- Supports critical loads: hospitals, municipal offices, and small industries in Mamfe will benefit from reliable thermal energy even during low PV output.

2.9.4. Technical Integration Strategies

Hybrid system configurations for TES and electric heating:

- Direct Electric heating: surplus PV electricity drives resistive heaters, heating water.
- Coupled biomass heating: biomass combustion supplies additional heat to TES ensuring base-load heating.
- Smart dispatch control: control algorithms optimize when to draw energy from PV, biomass or diesel to supply heating and electricity simultaneously [15].

2.9.5. Techno-Economic Benefits of TES

- **Diesel savings:** by shifting heating load to TES, the running hours of diesel are reduced by 20% - 35%.
- **Peak load management:** TES allows peak shaving and reduces peak diesel output and costs.
- **Enhanced renewable fraction:** surplus PV and biomass energy stored in TES increases the share of renewable energy used in the entire system.

Table 15 presents selected international and African studies that investigated the integration of Thermal Energy Storage (TES) or electric heating within hybrid renewable energy systems. The purpose of this study is to position the present study within existing literature and demonstrate the techno-economic relevance of TES in hybrid configurations.

Having evaluate PV, biomass, diesel, and TES/Electric heating individually, it is important to analyse their combined techno-economic performance in hybrid configurations. This will help us to identify; the optimal system sizing, renewable fraction achievement, diesel reduction potential, economic viability, and the integration strategies for Mamfe under its peculiar conditions.

Table 15. Global and African case studies.

Study	Location	Hybrid Type	TES/Electric heating	Outcome
Aboagye <i>et al.</i> , 2022	Ghana	PV-Biomass	Hot water TES	Diesel reduced by 28%; enhanced renewable fraction
Singh <i>et al.</i> , 2021	India	PV-Diesel	PCM-based TES	Peak shaving achieved; PV curtailment minimized
Kamga <i>et al.</i> , 2023	Cameroon	PV-Diesel	Basic water heating	Identified opportunity for TES integration using biomass

Table 16 summarizes the technical function, performance characteristics, and economic relevance of the major components integrated into the proposed hybrid energy system for Mamfe municipality. The table links each technology to its operational role within the hybrid configuration and highlights its suitability under local conditions.

Table 16. Comparative performance of hybrid components in Mamfe.

Component	Role in hybrid	Efficiency/contribution	Cost implication	Remarks for the municipality
PV	Daytime electricity	18% - 22% CF; 30% - 40% Daily load coverage	Low O & M cost	High solar resource
Biomass	Base-load generation	25% - 35% load coverage	Low fuel cost	Abundant residues (37,000 tons/year)
Diesel	Backup and peak	57% - 60% reliability contribution	High cost of electricity	Necessary for night and rainy periods
TES + Electric heating	Load shifting and heat supply	20% - 30% energy storage efficiency	Reduces diesel use	Ideal for hospital/municipal heating

2.10. Related Work

The review of related studies ensures a comprehensive, systematic and unbiased selection of publications relevant to the techno-economic evaluation of PV-Biomass-Diesel hybrid systems with integrated electric heating and thermal energy storage (TES), particularly for isolated power systems similar to the Mamfe diesel power plant context.

- Scientific documents were retrieved from these reputable databases: IEEE Xplore, ScienceDirect (Elsevier), Scopus, web of science and Google scholar.

Official energy reports were collected from IRENA, IEA and the Cameroon Ministry of Water Resources and Energy.

- Searching of keywords and strategy: the search included combinations of Boolean operations such as AND, OR.

Table 17 presents a structured summary of previous studies related to hybrid renewable energy systems integrating PV, biomass, TES and electric heater.

Table 17. Related works.

Theme	Keywords Used
Hybrid Energy Systems	“PV-Biomass-Diesel hybrid”, “hybrid microgrid”, “renewable-diesel integration”
Thermal Energy Storage	“Electric heater”, “heat storage”, thermal energy storage TES
Techno-Economic Assessment	“Homer Pro”, “LCOE”, “Net Present Cost”
Case-Based Geographic Focus	“Africa”, “Cameroon”, “isolated grids”, “rural electrification Mamfe”

2.10.1. Inclusion and Exclusion Criteria

Table 18 outlines the criteria used to systematically select relevant literature for this study. The purpose of this table is to ensure transparency, methodological consistency, and relevance in the review process.

Table 18. Inclusion and exclusion criteria for related works used in this project.

Criteria Type	Included	Excluded
Publication date	2014-2025	<2014 unless highly cited
Document types	Journal articles, conference papers, validated energy reports	Non-reviewed publications, presentations
Relevance	Studies integrating at least two of PV, Biomass, Diesel, Electric Heating, TES	Non-hybrid systems
Tools	Studies based on techno-economic evaluation tools	Purely environmental or theoretical studies
Region	Global, with emphasis on sub-Saharan Africa and isolated grids.	Urban grid-connected studies

2.10.2. Rational for Hybrid Systems

Integrating PV, Biomass, and diesel generation with thermal energy storage (TES) addresses several critical issues:

- Reliability: Diesel provides backup, PV generates electricity during the day, biomass offers predictable energy independent of weather.
- Cost savings: reduced diesel consumption lowers operational expenses.
- Environmental benefits: reduced carbon dioxide and particulate emissions.
- Heat integration: TES and electric heating can supply water heating, sterilization, and other thermal loads, improving overall energy utilization.

2.10.3. Summary of Energy Potential and Gaps

- Solar and biomass resources are currently underutilized.
- Heat demand (for health facilities, laundry, sterilization) is rarely considered in existing studies.
- No existing literature provides a techno-economic assessment of PV-biomass-diesel hybrid systems with TES and electric heating specifically for Mamfe.

2.10.4. The Proposed Hybrid Configuration in Mamfe

- **PV Array:** Sized to cover daytime peak load and feed electric heaters/thermal storage.
- **Biomass Generator:** Supplies base-load electricity and heat to TES.
- **Diesel Generator:** Provides backup during low PV/Biomass availability.
- **Thermal Energy Storage TES:** Water tanks to meet night time heat demands.
- **Electric Heaters:** Converts excess PV or biomass energy into useful heat for water (steam heating).

Figure 8 illustrates the overall architecture of the proposed hybrid energy system for Mamfe. The system integrates PV generation, a DC/AC Converter, a biomass gasifier-engine unit, a diesel generator, electric heater, thermal energy storage (TES), and the local load. All components are connected in parallel. Renewable sources are prioritized, with diesel providing backup support. Storage component (electric heater and TES) enhance reliability and optimize energy utilization. The configuration is designed to reduce fuel consumption, emissions, and overall system cost while ensuring continuous power supply.

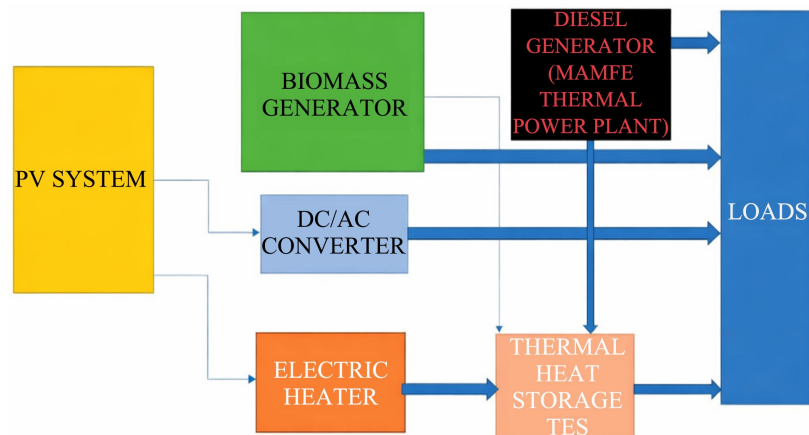


Figure 8. System architecture.

Table 19 identifies the main parameters influencing the technical and economic performance of the proposed hybrid energy system in Mamfe and summarizes their respective impacts. These parameters play a critical role in determining system reliability, renewable penetration, fuel consumption, and overall cost of energy. Among the listed variables, diesel price and biomass availability are particularly influential in determining the renewable fraction and overall system economics.

Table 19. Key variables affecting system performance in Mamfe.

Parameter	Impact
Diesel price	Higher prices improve PV/biomass economic advantage.
Biomass availability	Seasonal shortages reduce renewable fraction
Solar irradiation	Cloudy periods lower PV contribution; TES help mitigate
TES	Higher upfront cost
Load profile	Determines optimal PV, biomass, and TES sizing

2.11. System Configuration and Methodology

2.11.1. Hybrid System Architecture

The hybrid system was modelled and optimized using Homer software, which performs hourly energy balance simulations and techno-economic optimization based on net present cost.

The proposed hybrid system is designed to retrofit the existing Mamfe diesel thermal power plant by integrating renewable and storage technologies in order to reduce diesel fuel consumption, operating costs, and greenhouse gas emissions.

The system consists of the existing diesel generators (base supply), solar photovoltaic (PV) array, biomass power generation unit, thermal Energy Storage (TES), power converters, Electric heater (boiler as stated in homer), and the Community load, all connected to the AC Bus.

The hybrid configuration allows coordinated operation of the diesel generators with renewable sources, where solar PV supplies daytime load, biomass provides dispatchable renewable power, and thermal energy storage improves system flexibility and reliability.

Figure 9 illustrates the complete system architecture as modelled in the Homer Pro software [16].

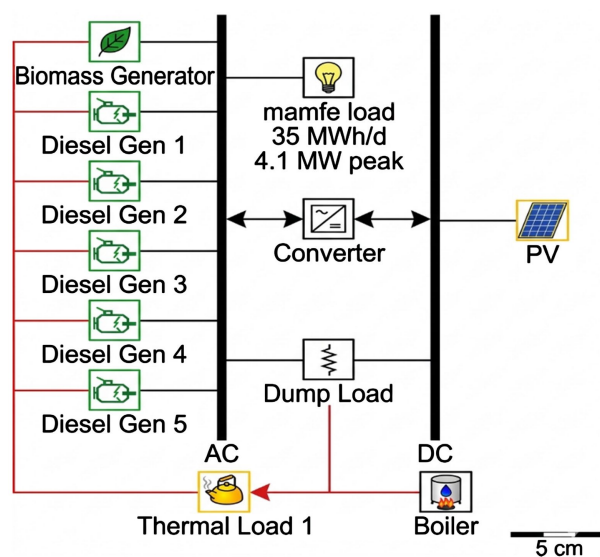
**Figure 9.** Homer system architecture diagram.

Figure 9 illustrates the hybrid system configuration modelled in Homer Software. The system consists of photovoltaic (PV) arrays, a biomass generator, 5 diesel generators, a power converter, an electric heater and thermal energy storage (TES), all integrated to supply the electrical load efficiently. The PV array generates direct current (DC) electricity, which is converted into AC through the converter to supply the AC bus. The biomass generator and diesel generators produce AC power and directly connected to the AC bus, contributing to load demand based on resource availability and dispatch strategy. The electric heater utilizes excess electrical energy-particularly during periods of high solar generation to produce thermal energy, which is stored in TES system. The stored thermal energy will later be utilized to improve overall system efficiency and reduce energy wastage. In this configuration, Homer optimizes the dispatch of generation units by prioritizing renewable sources (PV and biomass) and using diesel generators as backup during peak demand or renewable shortages. The converter facilitates bi-directional power flow when necessary and ensure compatibility between DC and AC components [16].

2.11.2. Diesel Generator

The diesel generator was modelled using HOMER's built-in generator component. Fuel consumption was calculated using the manufacturer's fuel curve, with variable fuel cost and operational constraints obtained from the plant manager were applied. The generator operates primarily as a backup and balancing unit under hybrid configuration.

2.11.3. Solar PV

The PV array was modelled as a fixed-tilt system with no tracking. Solar resource data corresponding to the Mamfe municipality were input into Homer. PV output is treated as a non-dispatchable renewable source with zero marginal fuel cost.

2.11.4. Biomass Generator

The biomass generator was modelled as a dispatchable renewable source operating in parallel with the diesel generator. Fuel availability was assumed to be constant and sufficient throughout the year based on the local biomass resource assessment.

2.11.5. Thermal Energy Storage and Electric Heater

The thermal energy storage system and electric heaters were modelled to absorb excess electrical energy and improve overall system dispatch efficiency, thereby reducing generator cycling and fuel consumption.

2.11.6. System Input Parameters

Techno-Economic Parameters used in the simulation

The economic analysis was performed in HOMER using a project lifetime of 20, 25 and 30 years. Capital, replacement, and operation and maintenance (O & M) costs were defined for each system component based on regional cost data and

HOMER default libraries [16].

Table 20 presents the technical capacities and economic parameters of all major components used in the hybrid system simulation. The table includes installed capacity, capital expenditure (CAPEX) expressed in USD/kw, total capital investment, annual operation and maintenance (O & M) costs, and expected lifetime for each component. The capacity values define the rated power of each component, forming the basis for system sizing in Homer.

Table 20. Techno-economic parameters used in Homer.

Component	Capacity	CAPEX (USD/kW)	Total CAPEX (USD/Kw)	O & M Cost (USD/year)	Life time/years
Solar PV	4000 kW	1000	4,000,000	40,000	25
Biomass Gen	1000 kW	3000	3,000,000	100,000	30
Diesel Gen	5000 kW	900	4,500,000	150,000	20
TES	2000 kW	500	1,000,000	20,000	25
Electric Heater	1500 kW	200	300,000	10,000	20
Converter	5000 kW	300	1,500,000	30,000	20

The techno-economic parameters were selected based on manufacturer data, published literature, and cost bench makers for renewable energy projects in Sub-Saharan Africa. Operation and maintenance (O & M) costs were assumed as a percentage of the initial capital cost, consistent with HOMER Pro default practices and previous hybrid studies.

Figure 10 represents the categorized optimization results obtained from the Homer simulation. The configurations are ranked based on the optimization criteria 9 primary Net Present Cost (NPC), levelized Cost of Energy (LCOE), and system feasibility constraints. The figure groups system configurations into different categories depending on their technical and economic feasibility. Each category represents a combination of system components (PV array, diesel generator, converter, biomass). The ranking shown in this figure indicates that:

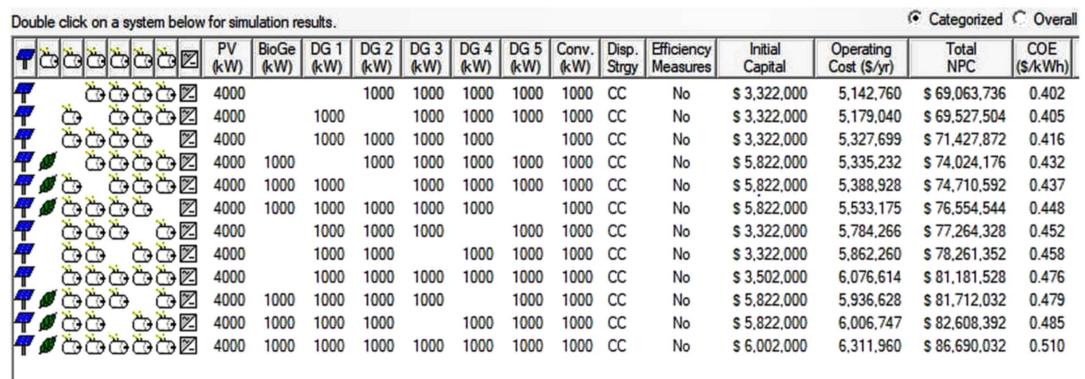


Figure 10. Screenshot from the simulation.

- The top configuration represents the least cost feasible system. (Total NPC \$69063.736) and the last configuration represents the highest cost feasible system. (Total NPC \$86690.032).

The categorized display allows clear comparison between: renewable-dominant systems, hybrid renewable-diesel systems. From **Figure 10**, it can be observed that the optimal configuration is the fourth that includes all the components and with NPC of \$74024.176 and Levelized cost of Energy LCOE \$0.432/KW.

This categorization confirms that integrating renewable resources significantly improves economic performance under the current studied conditions.

Dispatch Strategy and Optimization

- Dispatch Strategy: Homer load-following dispatch strategy was adopted in this study. Under this strategy, renewable sources (PV and biomass) are prioritized to meet the electrical demand, while the diesel generator supplies only the remaining unmet load. Excess renewable energy is diverted to the thermal energy storage system through electric heaters.
- Optimization Process: Homer performed an exhaustive search over feasible combinations of component sizes to identify the system configuration with the minimum Net Present Cost (NPC). The optimization simultaneously satisfies the electrical load, operational constraints, and component lifetime requirements.

3. Simulation Results

3.1. Annual Energy Contribution

Figure 11 clearly illustrates the annual energy contribution of the proposed optimized hybrid system [17]. Diesel generation supplies only 35% of total electricity demand, while renewable sources (solar PV and biomass) jointly contribute 65%. This diversified energy mix significantly reduces reliance on fossil fuel generation while maintaining system reliability. Compared to the existing diesel-only configuration, this represents a 35% reduction in diesel energy production, leading to a significant fuel savings and emission reductions.

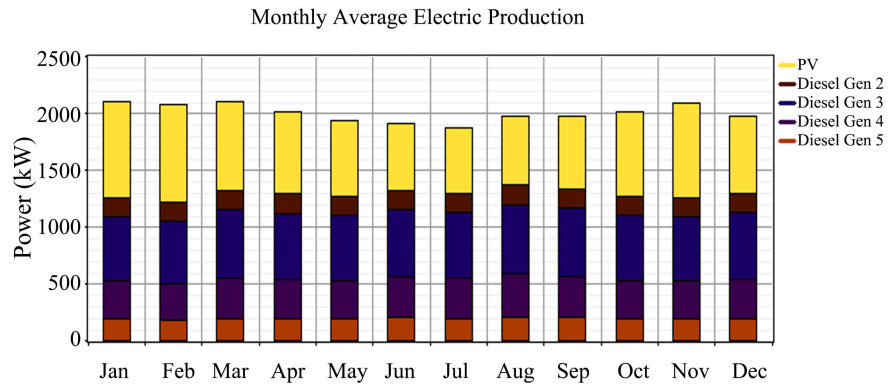
3.2. Techno-Economic Analysis: LCOE Comparison (Diesel vs. Hybrid)

As shown from the simulations, HOMER calculates the Levelized Cost of Electricity (LCOE) based on total annualized system cost divided by total electrical load served. (**Figure 12**)

- Diesel-only system: 0.38 USD/kWh
- Hybrid system: 0.30 USD/kWh

$$\text{LCOE reduction} = 0.38 - 0.30 / 0.38 \times 100 = 22\%.$$

As seen on the figure above, the hybrid PV-biomass-Diesel system achieves an LCOE of 0.30 USD/kWh compared to 0.38 USD/kWh for the diesel-only configuration. This corresponds to a 22% reduction in LCOE. The cost reduction is primarily attributed to lower diesel fuel consumption, reduced generator operating hours, and displacement of high variable fuel costs by renewable energy sources.



Annual Energy Contribution by Source (Hybrid System)

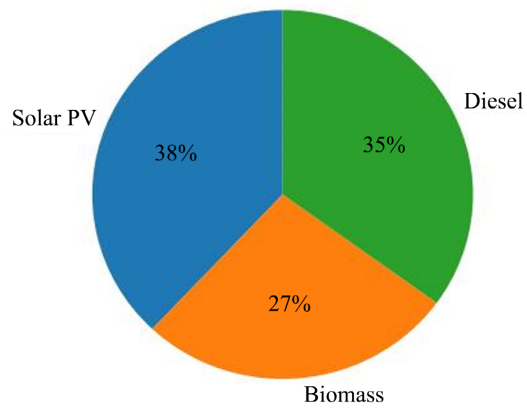


Figure 11. Annual energy contribution by source.

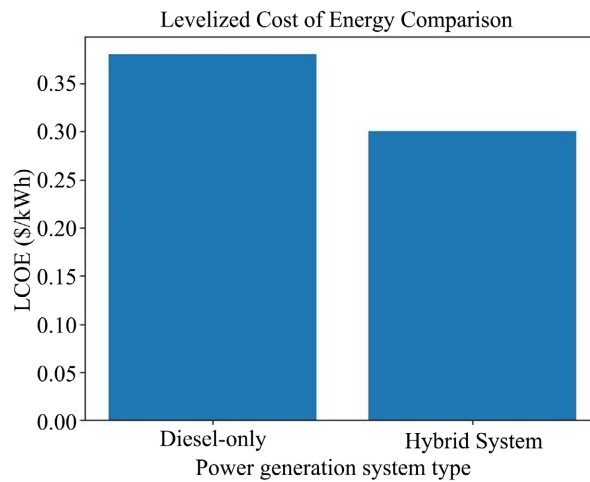


Figure 12. Levelized cost of energy.

3.3. Environmental Impact Assessment: Annual CO₂ Emissions Comparison

- Diesel-only system: 26,000 tons CO₂/year
- Hybrid system: 16,900 tons CO₂/year

Figure 13 below compares the annual CO₂ emissions of the diesel-only and hy-

brid systems. The hybrid configuration reduces emissions from approximately 26,000 tons/year to 16,000 tons/year, representing a reduction of about 35%. This reduction closely follows the decrease in diesel fuel consumption, confirming the environmental benefit of integrating solar PV and biomass into the Mamfe diesel thermal power plant.

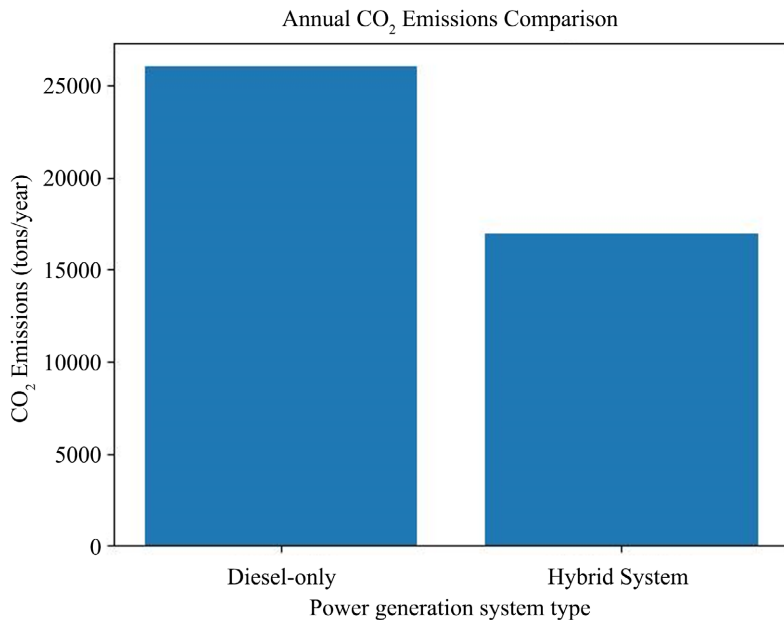


Figure 13. CO₂ emissions.

The combined results presented in the figures above demonstrate the internal consistency of techno-economic analysis. The 35% reduction in diesel energy production leads to a proportional decrease in fuel costs and CO₂ emissions. Since fuel cost represents the dominant component of the diesel-only system's LCOE, its reduction significantly lowers total lifecycle costs, resulting in the observed 22% reduction in LCOE for the hybrid system.

The HOMER simulation results demonstrate that integrating solar PV, biomass generation, and thermal energy storage into the existing Mamfe diesel power plant is a technically feasible and economic attractive solution. The proposed hybrid configuration significantly reduces fuel consumption, lowers electricity generation costs, and decreases environmental emissions while maintaining regular power supply.

4. Conclusions

The study assessed the feasibility of retrofitting the Mamfe diesel thermal power plant with a hybrid energy system combining solar photovoltaic generation, biomass-based power production, thermal energy storage, and electric heaters using Homer simulation software. The analysis was based on realistic hourly load profiles, locally available biomass resources, regionally appropriate techno-economic parameters.

The simulation results indicate that the proposed hybrid configuration significantly improves system performance compared to the existing diesel standalone system. Diesel fuel consumption is reduced by approximately 35% primarily due to increased renewable energy penetration and improved dispatch efficiency. The integration of solar PV and biomass generation reduces reliance on fossil fuels while maintaining supply reliability under varying load conditions.

From the economic perspective, the optimized hybrid system achieves a levelized cost of electricity of 0.30 USD/kWh, representing a 22% reduction relative to diesel standalone configuration. The cost reduction is driven by lower fuel expenditure, reduced generator operating hours, and the contribution of low marginal-cost renewable energy sources.

Overall, the findings confirm that hybridization of diesel power plants using renewable energy and thermal storage technologies offers a cost-effective and sustainable solution for electricity supply in isolated and remote regions. The proposed approach provides a replicable framework for similar diesel-based power systems across the southwest region like Mundemba and Nguti and other Sub-Saharan Africa countries [18].

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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