OPTIMIZATION OF HYBRID RENEWABLE ENERGY BASED MICROGRID SYSTEMS FOR SUSTAINABLE RURAL COMMUNITIES USING HOMER PRO

Gurugubelli.Saikiran[1], K. Vaisakh[2]

M. Tech Scholar[1], Professor[2]

Department of Electrical Engineering, Andhra University, Visakhapatnam, AP

Abstract: *Access to reliable and sustainable energy is crucial for rural communities, particularly those without grid connections. Energy scarcity affects economic growth, education, and healthcare, necessitating innovative solutions. This study explores the potential of hybrid renewable energy systems mini-hydro, wind power, and battery storage to address these challenges in the Muyuka Rural Community. Hybrid systems provide reliable energy where grid infrastructure is lacking, with mini-hydro offering stable generation, wind power providing variable generation and battery storage ensuring consistent supply during low-generation periods. The study uses HOMER Pro software to optimize system configurations and assess key indicators such as Net Present Cost (NPC), Levelized Cost of Energy (LCOE), and system reliability. The aim is to determine the most cost-effective and sustainable energy mix for the community. Additionally, an alternative scenario integrating grid power, photovoltaic (PV) energy, and battery storage for a microgrid is examined. This analysis focuses on optimizing the economic efficiency of the system, reducing grid dependence, mitigating peak load demand, and enhancing energy resilience. The findings will contribute to the development of viable, sustainable, and reliable energy solutions for rural areas.*

Keywords- Off-grid; Wind/mini-hydropower systems; mini-grid; cost optimization Grid-Connected Mode, Microgrid, Net present cost, cost of energy (COE), SOC, Homer Pro.

I. INTRODUCTION

The world is increasingly focusing on the transition to renewable energy sources, driven by the need to reduce dependency on fossil fuels and combat climate change. In particular, rural and off-grid communities, which often lack reliable access to electricity, represent a significant challenge and opportunity for the adoption of renewable energy technologies. These communities, often isolated from the central grid, face difficulties such as power outages, high energy costs, and limited infrastructure, leading to lower economic growth and quality of life. As a result, the implementation of sustainable energy solutions that can provide clean, reliable, and affordable electricity is essential.

Among the various renewable energy technologies, wind power and mini-hydro systems have gained attention due to their scalability, environmental benefits, and ability to meet local energy needs in remote areas. wind energy, abundant in most parts of the world, offers an ideal solution for off-grid systems, while mini-hydro power, utilizing the potential of local water resources, provides a stable and consistent energy supply. The combination of and mini-hydro in a hybrid energy system can significantly enhance the energy reliability and sustainability of rural communities, reducing dependence on diesel generators and minimizing environmental impacts.

In this context, HOMER Pro (Hybrid Optimization of Multiple Energy Resources) software plays a crucial role in the design, simulation, and optimization of hybrid renewable energy systems. HOMER Pro enables users to model different energy resources, loads, and storage solutions, facilitating the identification of optimal system configurations based on technical, economic, and environmental factors. The software is particularly valuable for off-grid and microgrid applications, as it allows for the evaluation of multiple system combinations to ensure that energy needs are met in the most cost-effective and efficient manner.

This study focuses on the design and simulation of an off-grid wind/mini-hydro renewable energy system for the Muyuka Rural Community in Cameroon, using HOMER Pro [1] Muyuka, like many rural areas, suffers from unreliable and expensive electricity supply, with many households relying on costly and polluting diesel generators. This research aims to explore the potential of renewable energy systems to provide a reliable, affordable, and environmentally friendly electricity supply for the community. By utilizing local wind and mini-hydro resources, the study seeks to design an energy system that can meet the community's electricity demand in a sustainable manner.

Furthermore, another the study includes an economic optimization of the system through HOMER Pro, considering the specific load profile of the community. optimization of a community load-based microgrid system using HOMER Pro, connected to the grid, focuses on creating a cost-effective and sustainable energy solution for local communities. A microgrid is a localized energy system that integrates various energy sources, including renewable options like solar and wind, alongside conventional generation methods and energy storage systems. HOMER Pro is a powerful tool used to model and optimize these microgrid configurations, evaluating factors like energy demand, system reliability, and economic feasibility. By connecting the microgrid to the main grid, it can operate in parallel, providing backup power and enabling energy exchange, which further enhances its economic viability. The goal is to optimize the system’s design to minimize costs, improve energy security, and reduce reliance on fossil fuels, making it a crucial component in advancing sustainable and resilient community energy systems.

A. Study Location

Scenario1: Muyuka is a town located in the Fako Division of the Southwest Region of Cameroon, as shown in Figure 1a. It serves as the headquarters of the Muyuka subdivision. The town is situated at coordinates 4°17.4′ N and 9°24.9′ E. The subdivision consists mainly of rural communities with smaller villages, including Owe, Ekata, Bafia, Muyenge, Yoke, Malende, Meanja, and Mpundo. Muyuka has a population of 86,268 people, with 67.5% of the population living in rural areas [8]. In 1947, a hydropower plant was built on the Yoke River, known as the Yoke Hydropower Plant.

Fig.1. Study location in Muyuka Rural Community

Scenario2: In this study, the micro-grid system for a small community in a city is designed using HOMER Pro, considering an annual increase in energy demand. The micro-grid components include an AC load (community), solar panels (PV modules), a Grid connected, and a battery energy storage system. The chosen location for the project is Bhubaneswar, Odisha, India, at coordinates 20.2961° N, 85.8245° E. [11] The load profile for the community is based on synthetic data available in the software. The total peak load for this area is 21 .37 kW, and the daily energy consumption is 165.59 kWh.

Fig.2: Study Location Bhubaneswar, Odisha, India

B. Collecting the resources

Solar resources data: used in HOMER Pro comes from the National Renewable Energy Laboratory's (NREL) database, which provides detailed information about solar energy resources. Specifically, the data consists of monthly average values for global horizontal irradiance (GHI). GHI refers to the total solar radiation received on a horizontal surface, including both direct sunlight and diffuse radiation from the sky.

Fig.3: Daily Radiation

Wind and Hydro resources: the project are sourced from reliable databases. Wind resource data is obtained from the National Renewable Energy Laboratory (NREL) database, as shown in Figure 4. The temperature profile for the site is taken from the NASA Surface Meteorology and Solar Energy Database. Figure 3 displays the average solar radiation at 4.49 kW/m²/day, with a clearness index of 0.51. The site's temperature profile is illustrated. For the hydropower system design, existing data from [9] is used. The scaled annual average flow rate for the hydro resource is 22.17 m³/s, with a minimum residual flow of 1 m³/s, as shown in Figure 5.

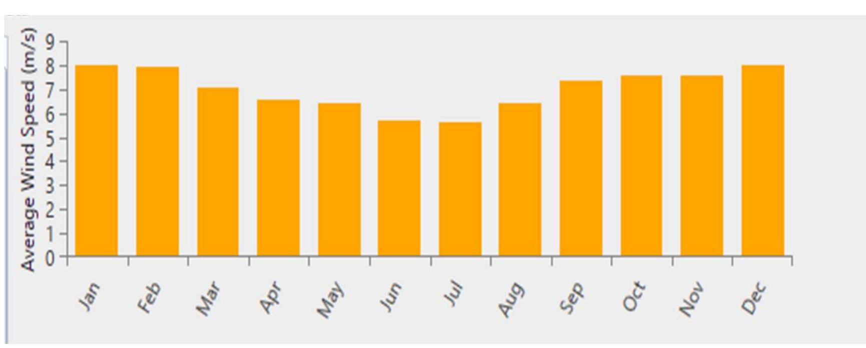


Fig.4: Wind Speed Profile

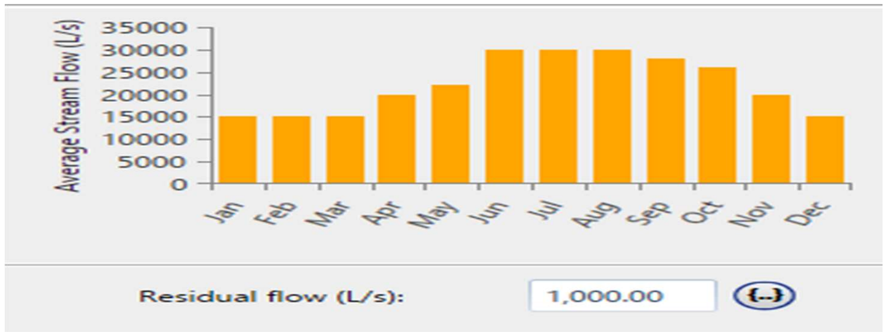


Fig .5: Hydro Resources

2. SYSTEM DESCRIPTION

A. Load Profile

The rural population of Muyuka subdivision is around 60,000 people. [8] The average energy demand for the community is less than 5 kWh per month, with the peak demand reaching about 3 MW. The daily, seasonal, and yearly load profiles of the community are shown in Figure 5. For this project, the community's load profile has a peak demand of 3 MW, with daily variations of 10% and 20% changes at different time intervals.

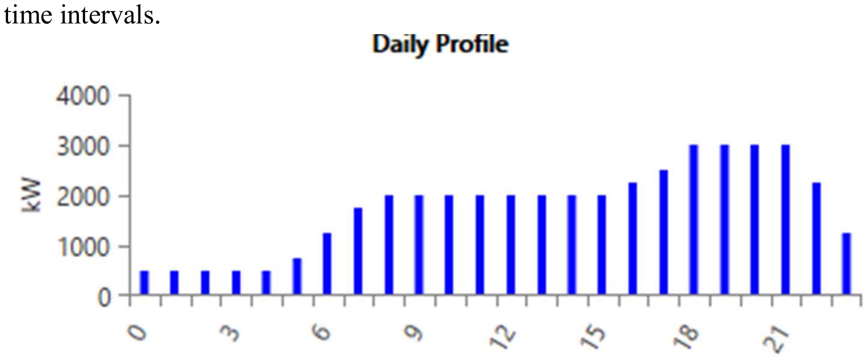


Fig.6: Data Collection

The load profile data for the proposed location is generated using HOMER Pro software. It assumes a daily energy demand of 165.59 kWh and a peak load of 21.37 kW.[11] The data is structured as a community load profile, with June being identified as the month with the highest demand in the seasonal profile

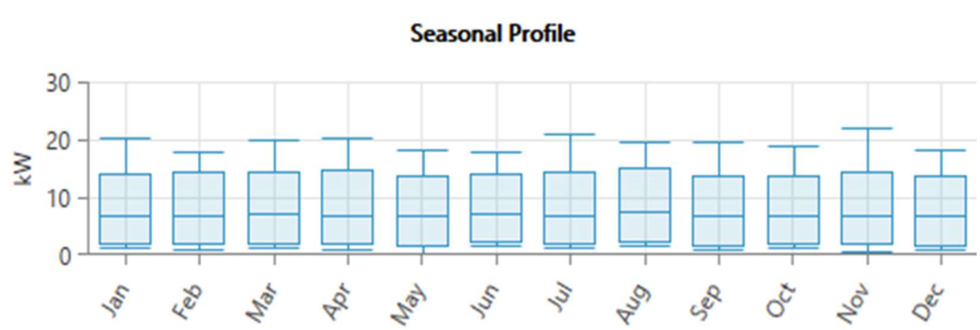


Fig.7: Seasonal Profile

B. Equipment Selection and project optimisation

WIND TURBINE: The wind turbine modules selected are of a generic type. The size of the wind turbine array is determined based on the load demand. A wind turbine system with a rating of 1.5 MW, specifically the Generic 1.5 MW model, is considered for the project, with a simulation size of 1500 kW. The initial cost, replacement cost, and operation and maintenance costs have been adjusted to account for the balance of system costs and other expenses. The parameters for the wind module are shown in Table 1

Table.1: Wind Turbine Generic 1.5MW

Quantity	1
Capital ($)	$3,000,000.00
Replacement (&)	$3,000,000.00
O&M($/year)	$30,000.00

Advanced Grid: The primary purpose of the grid connection is to ensure reliability and provide backup power when renewable energy generation (such as solar or wind) is insufficient to meet the community's load demand. This is particularly important during periods of low renewable generation (e.g., cloudy or calm days) or when energy storage (like batteries) is depleted. The grid provides an additional source of electricity to ensure that the community always has power. Reaming Each Parameter Values In Reference's [1] [11]

Table.2: Grid Parameters

Grid Power Price($/kWh)	0.650
Grid sellback Price($/kWh)	0.050

3. METHODOLOGY

The methodology begins with estimating the electric load requirements for the region, followed by collecting data on available resources such as solar and wind energy. These resources are then used to optimize and analyze the microgrid system. The cost of each component is input into HOMER software, which uses a grid search algorithm and a proprietary derivative-free algorithm to find the least-cost system configuration. The goal is to minimize electricity production costs while maximizing the use of available resources. The most cost-effective system design is selected as the optimized result. Additionally, the costs associated with each component are analyzed, and time-series data for the entire year is considered to understand the energy balance and performance of each system component.

3.1 Problem Formulation

Mini-Hydro System Design:

The mini-hydro power generation is typically modelled based on the available water head (height of water) and flow rate.

A) Mini-hydro energy output (daily):

$$E_{hydro} = \rho * g * Q * H * \eta_{hydro} * t \qquad (1)$$

B) Battery Storage System:

To ensure a reliable off-grid system, energy storage in batteries is essential. The capacity and behaviour of the battery storage system can be modelled by the following equation:

Battery charge/discharge:

$$E_{battery} = C_{battery} * V_{battery} * \eta_{battery} \tag{2}$$

C) Load and Generation Balance:

The load demand must be met by the generation from renewable resources, the grid, and storage. The basic energy balance equation can be expressed as:

$$L(t) = P_{renewable}(t) + P_{grid}(t) + \frac{dE_{storage}(t)}{dt} \tag{3}$$

D) Net Present Cost (NPC):

$$NPC = \sum_{t=1}^{T} \frac{C_{initial}(t)}{(1+i)^t} + \sum_{t=1}^{T} \frac{C_{operational}(t)}{(1+i)^t} \tag{4}$$

C) Levelized Cost of Energy (LCOE):

$$LCOE = \frac{NPC}{\sum_{t=1}^{T} E_{generation}(t)} \tag{5}$$

3.2 Proposed Model in HOMER

Grid-Connected Mode: In grid-connected mode, the microgrid is synchronized with the grid and can import or export power. In this mode, the microgrid relies on the grid connection to ensure reliability, and HOMER Pro optimizes the use of renewable energy, storage, and grid import/export strategies to minimize costs and enhance system performance.

Dispatch Strategy: In the load following (LF) dispatch approach, renewable energy sources charge the battery, while the generators produce just enough power to meet the current demand. On the other hand, the cycle charging (CC) dispatch approach involves the generators producing more power than needed to meet the load, with the excess energy directed to charging the battery bank. [11]A target state of charge is set, typically around 80%, and the generators charge the batteries to this level. Once this target is reached, the load following dispatch strategy is used to gradually top off the battery charge.

4. SIMULATION AND OPTIMISATION WITH HOMER-PRO

Microgrids are complex systems where many factors change at the same time. The solar power they rely on is unpredictable and depends on the weather, while energy use (load) can change quickly, causing peaks and spikes. Batteries and other devices in the system have their own ways of reacting to these changes. All these factors make it difficult to analyze microgrids.

To help manage this complexity, we use model and simulation to optimize both performance and costs. Simulation helps us check if the system can provide enough energy to meet demand and estimates the total cost of the system over its lifetime. This total cost includes all expenses and revenues, adjusted for the time value of money.

HOMER-Pro software, which works in one-hour steps, is useful for simulating microgrids because it captures important details about energy demand and renewable resources while still being able to handle complex calculations. In the system, hydropower runs at full capacity to ensure stable voltage and frequency, making the system more efficient. Solar energy helps balance the power supply, and batteries store excess energy when demand is low. During high demand periods, stored energy from the batteries is used to meet the need.

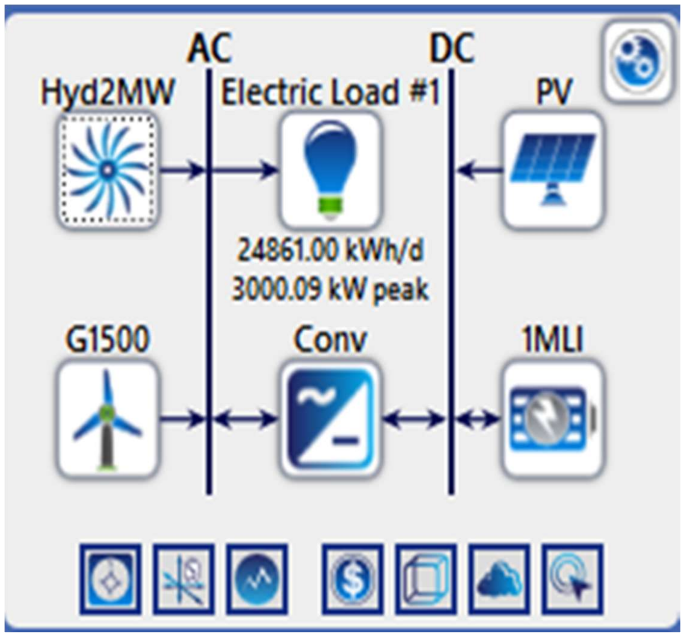


Fig .8: Simulation Diagram

scenario :2 HOMER software simulates how a power system works by calculating the energy balance every hour for a whole year. It takes into account factors like solar energy, temperature, component costs, and diesel prices. The system uses a "load-following" method, meaning the generator only produces enough power to meet the current demand. Renewable energy, like solar, is used to recharge the storage and cover any extra energy needs. If it's profitable, the generator can also sell excess power to the grid. HOMER ranks systems by the lowest energy cost, and the best system is chosen. In this case, the converter size ranges from 0 to 24 kW because the maximum power needed is 21.37 kW. The optimal system costs more upfront because it includes solar panels, which are expensive, but it has a lower energy cost in the long run.

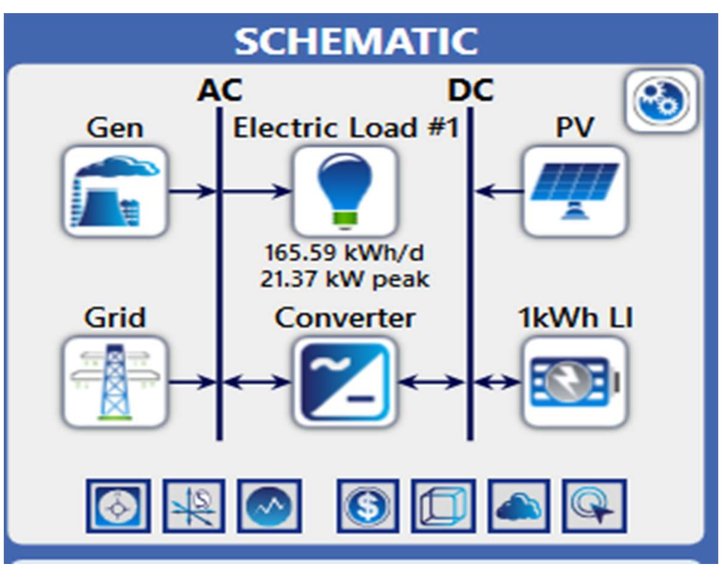


Fig.9: Proposed model of microgrid in HOMER Pro

5. RESULTS AND DISCUSSION

The proposed system includes hydro, wind turbines, batteries, and a converter. The main energy sources are hydroelectric power and wind, while the battery bank helps to improve the system's stability and reliability. An inverter is used to condition the power. The mini-hydropower system works together with the wind power system

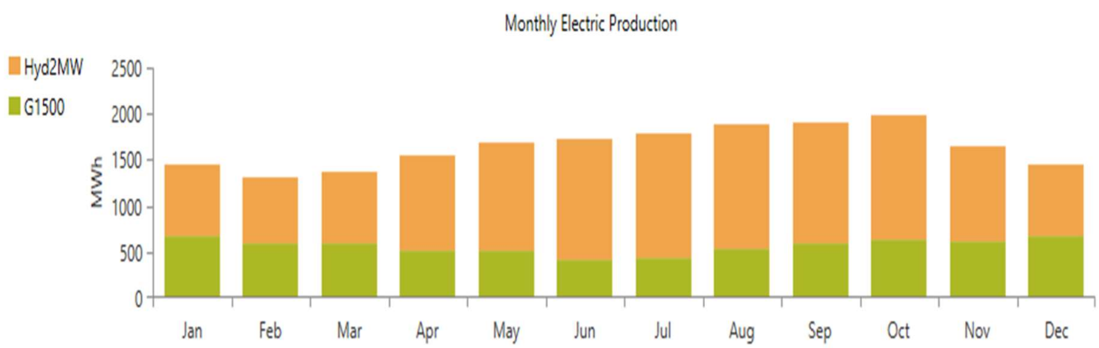
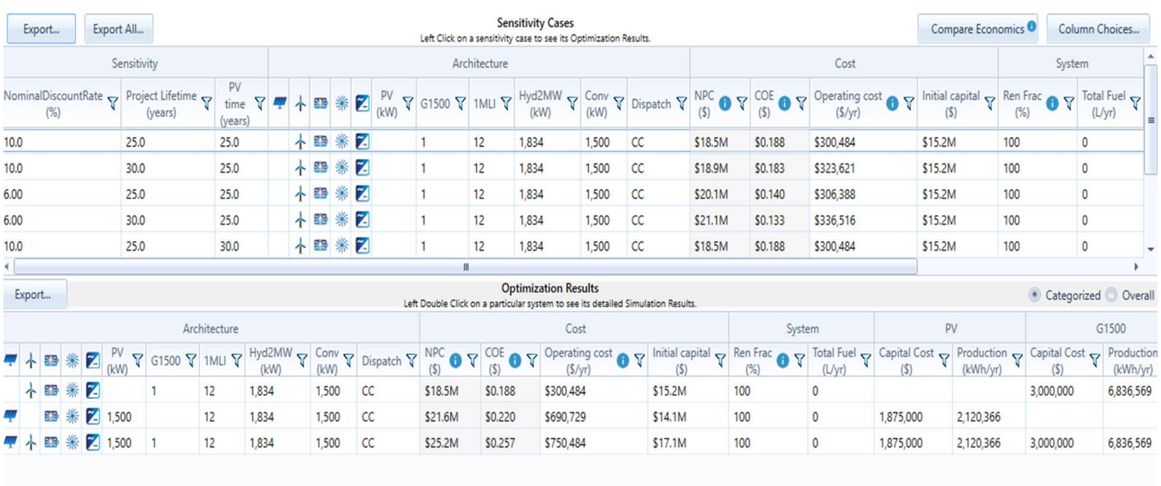


Fig.10: Monthly electric production

The best combination for the system includes one 1.5 MW Generic wind turbine, 16 units of 1 MW batteries, a 2 MW hydro generator producing 1,834 kW peak, and a converter working at 1,711 kW. The system uses a cycle-following dispatch strategy, meaning that when the generators operate, they produce excess energy to charge the batteries.



Sensitivity Cases

Left Click on a sensitivity case to see its Optimization Results.

NominalDiscountRate (%)	Project Lifetime (years)	PV time (years)	PV (kW)	G1500	1MLI	Hyd2MW (kW)	Conv (kW)	Dispatch	NPC ($)	COE ($)	Operating cost ($/yr)	Initial capital ($)	Ren Frac (%)	Total Fuel (L/yr)
10.0	25.0	25.0		1	12	1,834	1,500	CC	$18.5M	$0.188	$300,484	$15.2M	100	0
10.0	30.0	25.0		1	12	1,834	1,500	CC	$18.9M	$0.183	$323,621	$15.2M	100	0
6.00	25.0	25.0		1	12	1,834	1,500	CC	$20.1M	$0.140	$306,388	$15.2M	100	0
6.00	30.0	25.0		1	12	1,834	1,500	CC	$21.1M	$0.133	$336,516	$15.2M	100	0
10.0	25.0	30.0		1	12	1,834	1,500	CC	$18.5M	$0.188	$300,484	$15.2M	100	0

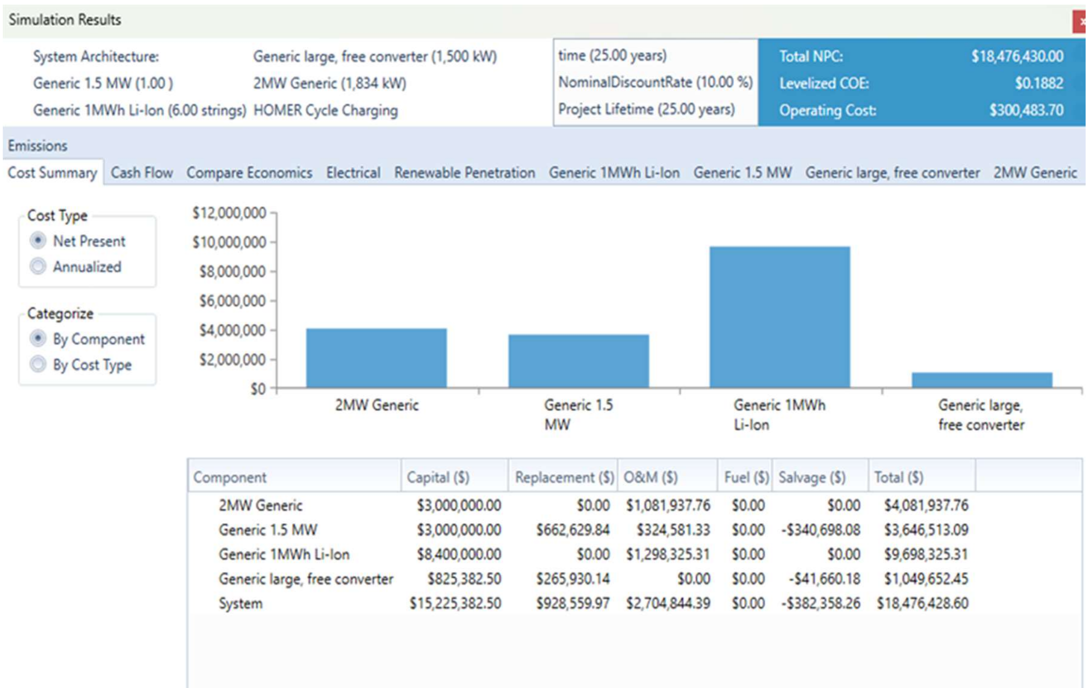
Optimization Results

Left Double Click on a particular system to see its detailed Simulation Results.

PV (kW)	G1500	1MLI	Hyd2MW (kW)	Conv (kW)	Dispatch	NPC ($)	COE ($)	Operating cost ($/yr)	Initial capital ($)	Ren Frac (%)	Total Fuel (L/yr)	PV Capital Cost ($)	PV Production (kWh/yr)	G1500 Capital Cost ($)	G1500 Production (kWh/yr)
	1	12	1,834	1,500	CC	$18.5M	$0.188	$300,484	$15.2M	100	0			3,000,000	6,836,569
1,500		12	1,834	1,500	CC	$21.6M	$0.220	$690,729	$14.1M	100	0	1,875,000	2,120,366		
1,500	1	12	1,834	1,500	CC	$25.2M	$0.257	$750,484	$17.1M	100	0	1,875,000	2,120,366	3,000,000	6,836,569

Fig.11: sensitivity cases& optimal results Off-Grid wind/Mini Hydro Renewable Energy System

The total cost for the system is $18.4 million, with an initial capital requirement of $14.1 million. The annual operation and maintenance cost is $300,484. The optimized system's energy cost is $0.188 per kWh. This result shows the most cost-effective way to generate energy with the lowest cost of energy (COE).



Component	Capital ($)	Replacement ($)	O&M ($)	Fuel ($)	Salvage ($)	Total ($)
2MW Generic	$3,000,000.00	$0.00	$1,081,937.76	$0.00	$0.00	$4,081,937.76
Generic 1.5 MW	$3,000,000.00	$662,629.84	$324,581.33	$0.00	-$340,698.08	$3,646,513.09
Generic 1MWh Li-Ion	$8,400,000.00	$0.00	$1,298,325.31	$0.00	$0.00	$9,698,325.31
Generic large, free converter	$825,382.50	$265,930.14	$0.00	$0.00	-$41,660.18	$1,049,652.45
System	$15,225,382.50	$928,559.97	$2,704,844.39	$0.00	-$382,358.26	$18,476,428.60

Fig.12: Cost summary

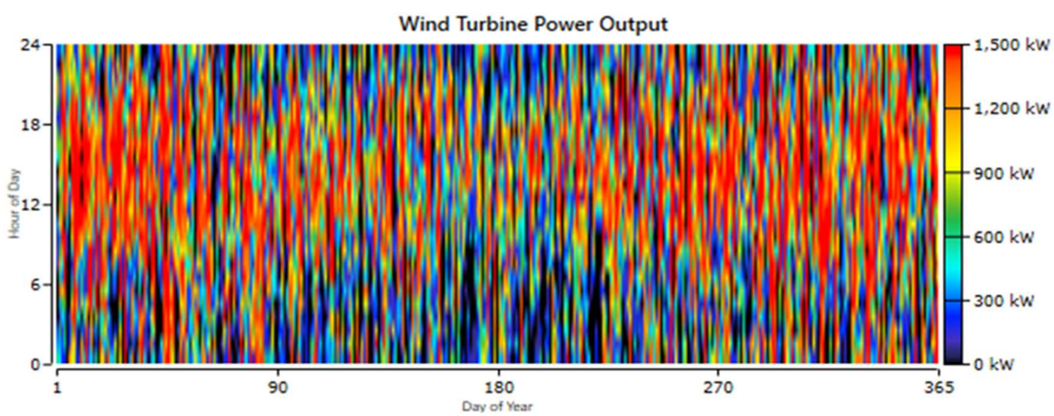


Fig .13: wind turine output day of year

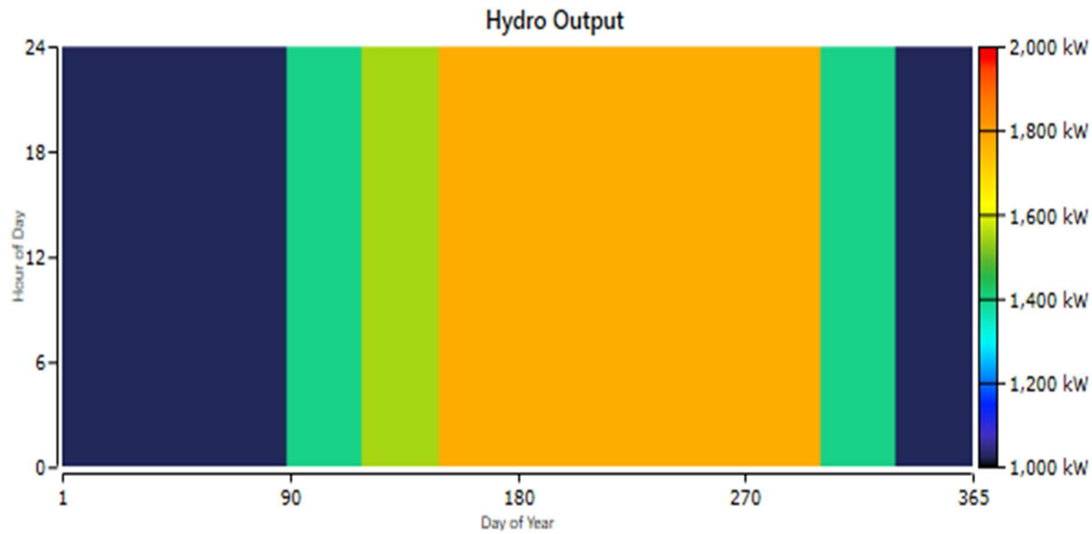


Fig.14: Hydro output day of year

HOMER Pro runs simulations considering all possible combinations of components for the system. It calculates the power coming in and going out from each component on an hourly basis throughout the system's lifespan, taking into account all costs and charges. After running the simulation for all possible configurations, it ranks the results based on the Net Present Cost (NPC), Cost of Energy (COE), and electrical performance. The most cost-effective system is shown in Figure 7 In this case, the best system configuration includes lithium-ion batteries, solar panels (PV), Grid, and converters. The system has a renewable energy share of 92.3%, meaning most of the power comes from solar energy. The Grid run energy share 7.74%. The total power generated by the microgrid is 87,135 kWh, with 80,395kWh (92%) coming from solar, and 6,730 kWh (7.74%) for grid. The monthly electricity generation from the hybrid system is shown in Figure 8, where you can see that solar panels produce most of the power, but during peak months, when demand is higher, the diesel generators help meet the load. The cost of each system component is detailed in Table 6, and this configuration is the most cost-effective in terms of NPC. During the day, from 11 AM to 6 PM, solar panels produce energy, which charges the batteries, keeping their state of charge (SOC) high. After sunset, the batteries begin to supply power to meet the demand, causing their SOC to drop overnight until they are nearly drained by morning. The next day, the solar panels start recharging the batteries. In the peak demand months, the batteries' SOC tends to stay low throughout most of the day because they are frequently used to supply power. If the batteries are fully discharged, the grid provides backup power during the night.

Production	kWh/yr	%
Generic flat plate PV	80,395	92.3
Grid Purchases	6,740	7.74
Total	87,135	100

Consumption	kWh/yr	%
AC Primary Load	60,440	81.2
DC Primary Load	0	0
Deferrable Load	0	0
Grid Sales	13,955	18.8
Total	74,396	100

Quantity	kWh/yr	%
Excess Electricity	6,397	7.34
Unmet Electric Load	0	0
Capacity Shortage	0	0

Quantity	Value	Units
Renewable Fraction	90.9	%
Max. Renew. Penetration	1,230	%

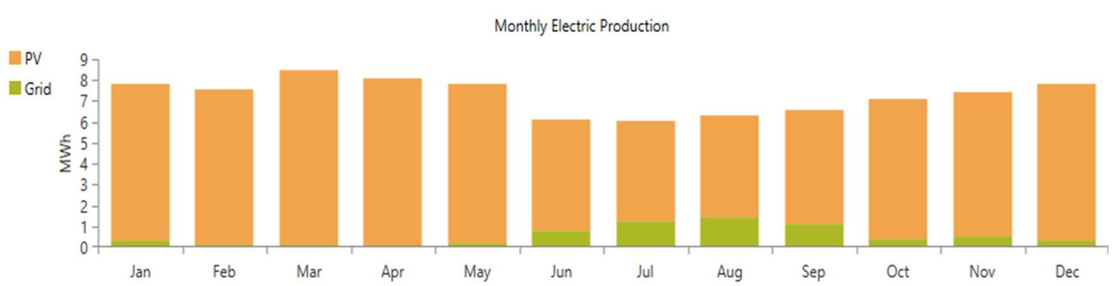


Fig.15: Monthly electric production

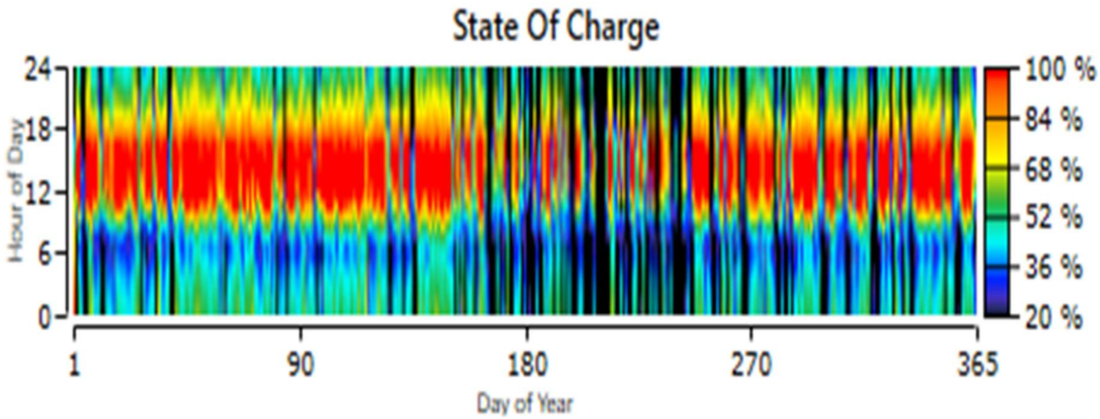


Fig.16: Sate of charge day of year

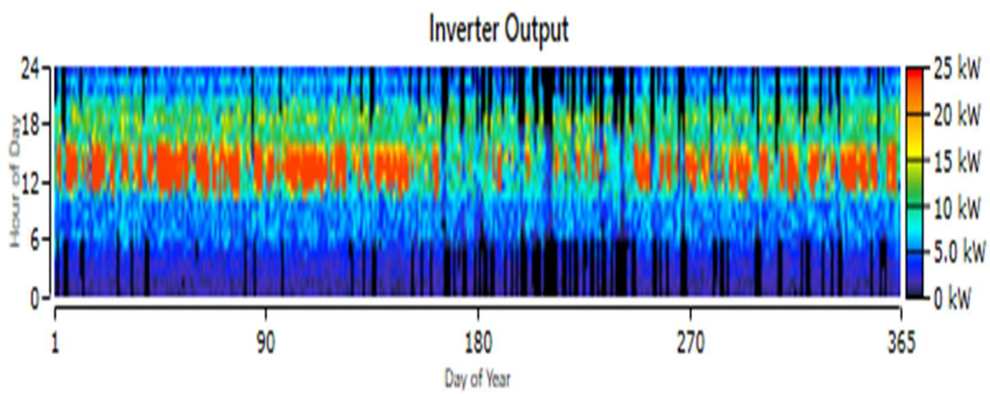


Fig .17: Inverter output day of year

6. CONCLUSION

This study looked at designing, simulating, and optimizing off-grid and microgrid renewable energy systems for rural communities, focusing on two main areas: wind and mini-hydro energy systems in Muyuka and designing solar and grid community-based microgrid using HOMER Pro software. The goal was to assess the technical, economic, and environmental feasibility of these systems and identify the best options for long-term sustainability. The simulation for Muyuka showed that combining wind and mini-hydro power can reliably meet the energy needs of rural areas. And sometimes seasonal variations Low water resources occurred when wind energy can be meat the load demand for rural community and another area scenario solar energy during the day, steady power supply at night or during cloudy weather. When load demand energy can provide a grid This hybrid system is ideal for off-grid areas with no access to the national grid. The community-based microgrid, which combines solar, hydro, and storage, was also found to be technically feasible and efficient in meeting energy demands. Economically, the study showed that renewable energy reduces the cost of energy over time compared to using diesel generators. Although the initial investment for renewable systems is higher, the long-term costs are much lower because there's no need for fuel and maintenance is reduced. HOMER Pro helped identify the most cost-effective configurations, proving that renewable energy is a smart long-term investment. Environmentally, both systems reduce carbon emissions, air pollution, and reliance on fossil fuels, contributing to the fight against climate change and improving local air quality. Socially, these systems can enhance the quality of life in rural communities by providing reliable electricity for education, healthcare, and local businesses, which can boost economic development. Key recommendations for success include conducting detailed resource assessments for local solar and mini-hydro potential, involving the community in planning, designing scalable systems for future growth, and regularly monitoring the systems for optimization. In conclusion, off-grid hybrid renewable energy systems, like the wind/mini-hydro and solar, grid connected setup and community-based microgrids, are cost-effective, environmentally friendly, and provide long-term benefits for rural electrification. With careful planning, optimization, and community involvement, these systems can improve quality of life, promote sustainable development, and help reduce global carbon emissions.

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