RAYA JOURNAL OF SCIENCE AND DEVELOPMENT

RJSD 1(1):2025

Designing and Modeling of Off-Grid Stand-Alone Hybrid Energy System: the Case of Kelto, Chercher, Ethiopia

Hiluf Alemu[1], Znabu Mehari[1], Abrha Ftsum[2]

[1] Department of Mechanical Engineering Raya University, Maichew, Ethiopia

[2] Department of Electrical and Computer Engineering Raya University, Maichew, Ethiopia

Article History:
Received: 2025-08-05
Accepted: 2025-09-24
Published: 2025-11-06
DOI: https://doi.org/10.82489/rjsd.2025.1.01.39

Suggested citation:
Hiluf, A., Znabu, M., & Abrha, F.(2025): Designing and Modeling of Off-Grid Stand-Alone Hybrid Energy System:The Case of Kelto, Raya Chercher in the Tigray region of Ethiopia. RJSD 1(1): 45-57; DOI: 10.82489/rjsd.2025.1.01.39

***Correspondence :**
Hiluf Alemu
hilufalemu07@gmail.com

Abstract

This study addresses the critical challenge of rural electrification in Raya Chercher of the Tigray region. Despite the area's high solar irradiance (7.27 kWh/m²/d) and moderate wind resources (4.132 m/s, it is not applied in the community. To bridge this research gap in location-specific HRES design of Tigray, the researchers develop a model integrating solar PV, wind turbine and diesel. This research work uses HOMER Pro for integrating solar photovoltaic (PV) generators, wind turbines, and a diesel generator as a backup. Having revised literatures on research potentials, it has been analyzed a year of recorded wind and solar data. Mathematical modeling of hybrid power systems was applied with optimization; cost and sensitivity analysis conducted using HOMER Pro software. This study aims to establish electricity supply for 350 households from a monthly energy demand, and a load profile was developed for daily electric demand of 277.62 kWh per day and a peak load of 20.46 kW. The optimized hybrid system achieved a renewable fraction of 65.6%. The study results in an internal rate of return (IRR) of 28% and a Levelized cost of energy of $0.198/kWh, with a nominal discount rate of 12% and fuel price of $1.41/L. This indicates hybrid systems offer a viable solution for rural electrification in Ethiopia. This could also have roles in mitigating environmental impacts, reducing greenhouse gas emissions, and decreasing reliance on fossil fuel and potential of hybrid renewable energy technologies to provide affordable electricity in off-grid communities.

Keywords: *hybrid system, HOMER Pro, peak load, levelized cost of energy.*

1. Introduction

Access to electricity remains a major challenge in rural Ethiopia, hindering economic development, education, and healthcare(Dawde, 2013). Despite government efforts like the National Electrification Program (NEP 2.0) (Ministry of Water, Irrigation, 2019), remote areas such as KELTO still lack reliable power, forcing dependence on costly and polluting diesel generators. Hybrid Renewable Energy Systems (HRES), combining renewables and energy storage, present a viable solution for rural electrification (Owoeye et al., 2022). Most rural Ethiopians rely on biomass due to the national grid's inaccessibility, limiting development opportunities. Although Ethiopia has abundant renewable energy potential, these resources remain underutilized despite rising energy demand (Girma, 2013). Implementing solar-wind-diesel hybrid systems in villages like KELTO (Chercher, Tigray) could reduce costs, lower environmental impact, and provide reliable electricity.

Figure 1

Annual wind power density at 50 m height in protected areas of Ethiopia (Hailu & Kumsa, 2020)

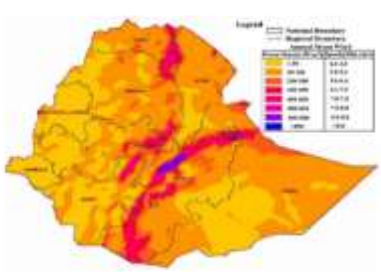


Table 1

Background community information

Particulars	Detail Information
Country	Tigray, Ethiopia
Community	Kelto, Chercher
Latitude	12.5409
Longitude	39.8027
Elevation above sea level	1050.15 m
Number of households	~ 350
Estimated population	1550
Main socio-economic activity	Farming

The lack of grid-connected electricity in KELTO results in limited access to lighting, refrigeration, education, and healthcare services. The community's traditional reliance on diesel generators incurs high operational costs and causes environmental pollution. While previous studies have explored HRES in Ethiopia broadly, there is a notable gap in location-specific, techno-economic analyses for the Tigray region, where unique socio-economic conditions and resource availability (moderate wind speeds compared to other regions) require tailored solutions. This study could fill the gap by providing a detailed model and feasibility analysis for Kelto by optimize a cost-effective, reliable, and environmentally friendly HRES that leverages locally available renewable energy resources. It also has the following specific objectives:

1. Assessing the energy demand profile of KELTO
2. Evaluating renewable energy potentials (solar and wind)
3. Simulating and optimizing system configurations using HOMER

4. Comparing economic and technical performance metrics

2. Literature Review

Several studies have explored hybrid systems for rural electrification. Solomon et al. (2013) evaluated a small Hydro/PV/Wind system for Ethiopia and found hybrids to be more economical than single-source systems. Abrham et al. (2021) discussed barriers and strategies in Ethiopia, highlighting the role of policy and community engagement, and tools like HOMER have been widely used to model such systems. However, limited studies focus specifically on Ethiopian contexts like Tigray, where resource availability and socio-economic dynamics vary.

According to Gadda et al (2016), the research work in the Tigray region of Ethiopia there are 8 selected regions from high wind energy sources to low wind sources as Mekelle (3.488m/s), Atsbi (2.589m/s), Chercher (2.557m/s), Senkata (2.184m/s), Maichew (1.1387m/s), Adigrat (1.183 m/s), Adwa (1.114 m/s), Shire (1.1044 m/s) respectively as shown figure below.

Figure 2

Map of Ethiopia showing the data collected from stations in the Tigray region of Ethiopia (Gaddada & Kodicherla, 2016)

However, a critical analysis of the literature reveals a significant gap. Many studies provide high-level national assessments but lack depth in specific regional contexts. Accordingly, the studies mapped wind resources across Tigray, identifying Chercher (where Kelto is located) having a moderate wind speed of 2.557 m/s, which is lower than in Mekelle. This suggests that effective HRES designs for this area must rely on a different resource mix, potentially with a greater emphasis on solar PV. This study directly addresses this gap by providing a nuanced, localized techno-economic analysis for a community within this moderate-resource belt, moving beyond generic models to deliver actionable blueprint. Furthermore, while prior work often summarizes existing research, this paper critically leverages these findings to justify its specific component sizing and economic assumptions, creating a more robust and defensible model.

According to Solomon (2013), Design and Analysis of an Off-Grid Hybrid Renewable Energy System to Supply Electricity for Rural Areas in the Atsbi districts of the Eastern zone of Tigray Regional State, North Ethiopia was conducted. The study was focused on the solar-wind and diesel generator hybrid system optimized for the rural community of Haressaw among the sub-districts of Atsbi district in the regional state of Tigray, Ethiopia with a Primary load demand of 1505kWh/day, the peak load of 284kW, deferrable energy with 17kWh/day, and deferrable peak load with 3.6kW was involved.

The Hybrid renewable source of energy design for the rural(Village) electrification in Ethiopia was carried out by Zelalem(2013) to examine a method for designing and simulating of stand-alone hybrid renewable energy source system in Ethiopia's SNNPR region. The system, powered by photovoltaic panel batteries and an inverter system, uses a diesel generator as a backup. The HOMER optimization program is used to optimize the component size and Levelized Cost of Energy. A novel method for calculating rural electric load in a remote Ethiopian village uses a hybrid renewable energy system of PV array, diesel generator, battery storage, and converter, for a selected hamlet of 200 households in the southern part of Ethiopia with an energy cost of $0.401/kWh is achieved by generating 95% of energy from solar arrays and 5% from diesel generators. The project required two battery changes, but the last occurred in 24 years, resulting in a salvage value of $90,000, demonstrating the system can provide uninterrupted power for a full day.

Katti et al.(2012) examined that numerous methods for producing power from renewable resources like solar, wind, biogas, etc. were studied and it costs more to generate wind and solar energy on an individual basis. They can mitigate greenhouse gas emissions, diversify energy sources, lessen their reliance on foreign fuels, enhance air quality, cut down on greenhouse gas emissions, and boost the economy by generating jobs in the wind and solar energy system manufacturing and installation industries. They can electrify rural areas utilizing solar and wind-integrated systems, and in the future, this technology can also be used in metropolises to prevent unintentional load shedding. A straightforward system sizing algorithm is created to maximize system efficiency. Utilizing the payback period and life cycle cost analysis, the total cost of the unit is determined.

A Case Study on a Micro Study with a Hybrid Power System for Rural Electrification was done by Sandip Kumar. et al.(2022), was focused on and explores the design, simulations, and analysis of hybrid renewable energy resources for a rural village in Digha, West Bengal, India. The primary load of the proposed hybrid renewable energy system for the village is 1650 kWh/day with a peak load of 385.51 kW, and the deferrable load is 24.86 kWh/day with a peak load of 4.62 kW. Also, they designed hybrid renewable energy systems, consists a PV array, diesel generator, wind turbine, battery storage, and converter, designs for an off-grid village in India, producing 86.5% of energy from solar, 11.5% from wind, and 1.96% from diesel. They use the HOMER program to determine the most cost-effective configuration for hybrid renewable energy systems, considering the optimal size and operating plan for each piece of equipment.

A study done by Hailu & Kumsa (2020), explains the nation's present reliance on a certain type of energy, while also promoting the renewable energy resources used to close the gap between supply and demand and improve the quality of life in rural regions. The nation has access to a variety of renewable energy sources, including biomass, hydropower, solar, wind, and geothermal energy. Currently, Ethiopia consumes 4.5 GW of energy capacity in total across its industrial, residential, and other sectors. This amount is divided among roughly about 3.8 GW with hydropower (not including the recently opened Genal Dawa III power plant), 324 MW of wind power, 7.5 MW of geothermal energy, 317 MW of biomass, and other sources. To help researchers and government officials determine the best renewable energy technologies to meet the energy needs of rural communities, this article addresses the exploitable and exploited potentials of Ethiopia's renewable energy resources. Additionally, the adoption of renewable energy technologies has undoubtedly increased the use and profitable distribution of energy sources among rural homes across the nation that are not connected to the grid, even in places that are particularly grid-connected.

The study used HOMER for optimization, examining hybrid system designs based on load demands, applications, locations, and climatic data. Different locations had different electricity access, and each hybrid power system required a unique design. These article papers use the same HOMMER Pro software tool to design and optimize an off-grid hybrid power system for various household uses. These research works argue that the government has not implemented hybrid power systems yet, and the article differs from related studies due to application, load demand, and geographic area.

The high cost of energy, high net present cost, designs that do not meet load demand, the exclusion of community and commercial loads from load profiling, use of the current load profile of the rural study community, the lower percentage of renewable penetration, the proposal of a single optimal system configuration, and use of load demand values unrelated to the study site are a few of the research gaps identified in these works. To broaden its scope, this article focused on economic performance elements that are relevant to investment decisions, including payback periods, internal rate of returns, present value, yearly worth, and returns on investment.

In addition to providing electricity for a large number of households, this work has also used the same software to design and optimize an off-grid hybrid power system for lighting, baking, communication, schools, health services, and small commercial businesses. The application, load demand, meteorological data, area location, and number of households included set this work apart from related studies.

2.1. Site Description and Load Assessment

This research study work was conducted in Kelto (ቆልጥቦ) village in Tigray regional state in Ethiopia. Kelto(ቆልጥቦ) is a village in the South Chercher district in southern Tigray regional state with 12.48751° latitude and 39.78736° longitude. The village has a total of 350 households with 1 health post and 1 elementary school. There was no electricity access to the village and the surrounding community. Kelto is the village in Southern Tigray with a good climate, presents a suitable location for a hybrid energy system due to its moderate wind availability and strong solar irradiance, averaging 7.27 kWh/m²/day. This community of 150 households, including essential services and small businesses, has an estimated average daily energy demand of 277.62 kWh. With an average wind speed of 4.132 m/s also recorded, the potential for utilizing solar and wind resources, in conjunction with a diesel generator and battery storage, appears promising for providing sustainable and reliable electricity to Kelto.

2.2 Load Profile

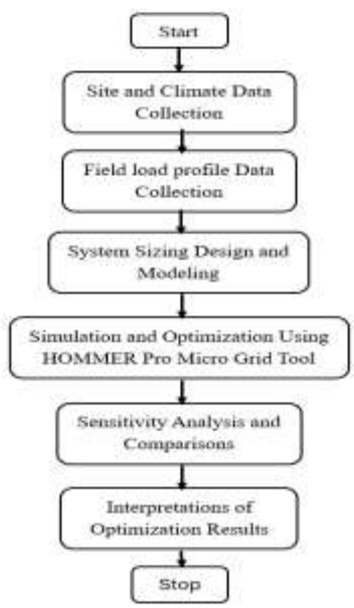
The average daily load is 277.62 kWh, Peak load: 20.71 kW, Load includes lighting (40%), refrigeration (20%), ICT (15%), water pumping (15%), and other uses (10%).

3. Methodology

This research involves modeling, design and optimization of a hybrid energy system (HRES) using multi-level methodology. Mathematical modelling method was used for modelling, design and optimal sizing of system components was achieved by using Ampere-Hour optimal design method, while Homer Pro Analysis Tool was used for simulation and optimization. The optimal system was designed for the rural electrification of an off-grid community of KELTO Village using the climatic data of the study community and the load profile of an electrified community that has the same socio-economic status with the study community of Raya Chercher. The research methodology steps adopted and used are summarized in Figure 3 below.

Figure 3

Methodology Flow Chart



3.1. Resource Assessment

The data are obtained from the total electric appliances in households and elementary schools. The daily duration of the hour use was obtained based on interviews with electricity users in Chercher(ጨርጨር) town. Wind speed and solar irradiation data were taken with daily data 4.132 m/s at 10 m height and 7.27 kWh/m^2, respectively. Elevation from sea level (MERRA-2) in 2023 year. Average for 0.5 x 0.625-degree lat/long) of the rural region is 1050.15 meters. These data were prepared in a suitable format for input to HOMER to find an optimal load share of the resources. The Solar irradiance: 5.5 kWh/m²/day average, Wind speed: 4.5 m/s annual average and Diesel price: $1.05/L

3.2. Wind Power Modeling

Wind power is defined by the wind velocity and the area of the wind flow(Girma, 2013). Theoretical power captured by the wind is calculated as:

$$P = 0.5\rho A V^3 \tag{3.1}$$

Where: P = the power in the wind (watts), ρ = Air density (1.225 kg/m^3), A $= \frac{\pi D^2}{4} =$ the cross-sectional area through which the wind passes (m^2), V = wind speed (m/s). At its theoretical best (Betz Limit), a wind generator will not be any better than 59% efficient. Typically, 35% is a more realistic energy conversion efficiency to expect. The most commonly used of Hellmann exponential law, which correlates the wind speed readings at two different heights(Dawde, 2013), and is expressed by (3.2):

$$\frac{V}{V_O} = \left(\frac{H}{H_O}\right)^{\alpha} \tag{3.2}$$

Where: v = the speed to the height H (30 m), v_0 = 3.07 m/s =the Average speed to the height H_0, H_O = wind mast height (frequently referred to as a 10 m height), and α = the friction coefficient or Hellman exponent. The coefficient is a function of topography at a specific site and is frequently assumed as a value of 1/7= 0.14 for open land.

Using the Betz limit of 16/27=0.595, induction factor a=1/3, and the 1-2-3 formula, the average power can be written in terms of the average wind speed, density of air, and rotor diameter.

$$\overline{P_w} = \rho\left(\frac{2}{3}D\right)^2)\overline{V}^3 \tag{3.3}$$

The rotor power of the wind turbine by employing the axial induction factor(a) is given by

$$P_R = \frac{1}{2} * \rho * A * V^3 * 4a(1-a)^2 \tag{3.4}$$

The non-dimensional power coefficient Cp represents the fraction of the power in the wind that is extracted by the rotor is

$$C_P = \frac{P}{\frac{1}{2} * \rho * V^3 * A} = \frac{\text{RotorPower}}{\text{Power in the wind}} \tag{3.5}$$

This capacity factor (C_F), represents the fraction of average power output (P_T) over a period to the rated electrical power (P_R) (Gaddada & Kodicherla, 2016).

$$C_F = \frac{P_T}{P_R} \tag{3.6}$$

3.4. Solar Power Modeling

The Solar resource data input to the HOMER is the average global horizontal radiation measured in the year 2023 and compared to NASA POWER. The average solar energy is 7.27 kWh/m^2 per day and the possible share of solar energy in meeting a total power demand of 53.355 kW per day, with a 10% loss considered for the system, is:

$$\% \text{ Share of Solar PV panel} = \frac{\text{Energy Generation from PV per day}}{\text{Total Power Demand per day}} * 100\% \quad (3.7)$$

The total energy load is given by:

$$E_{\text{Load Total}} = \frac{E_{\text{load}}}{\eta_{\text{BOS}}} \quad (3.8)$$

3.5. Diesel generator

A 25 kW, 100 kVA diesel-generator model with four-stroke was used with a unit capital of $12500 and replacement cost of $11879, an operations and maintenance cost of $0.140/hour, and 14,000 operating hours in a lifetime of 25 years. The following tables show the design and HOMER simulation generated by the Diesel generator.

3.6. Battery Model

The selected battery model is an Iron Edison LFP 5600 Ah solar battery with a rated capacity of 200 Ah, 48V, 85% charge efficiency, 80% depth of discharge (DOD), 100 A maximum charge current, 100 A maximum discharge current, a lifespan of 16 years, and installation cost of $ 3250 / Unit (Rack et al., n.d.). Considering three (3) days of autonomy will not affect the system simulated with HOMER, the size of the batteries is calculated using the equation.

$$E_{\text{battery}} = \frac{E_{\text{load}} * n}{\text{DOD} * \eta_{\text{BBOS}}} \quad (3.9)W$$

The results of calculations indicate that the battery has a 200 Ah capacity.

3.7. Power Converter

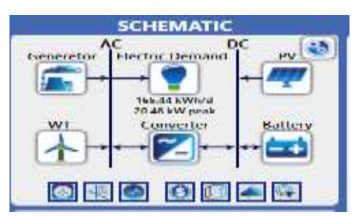
A converter is used to maintain the flow of energy between AC and DC components. In this research, the generic converter power models, with an average installation unit cost of about $349.38/kW and a lifetime of 5 years.

3.8. System Configuration and Simulation

This analysis results in economic and technical system performance for 25-years of lifetime. The simulation tool HOMER is aimed at finding the optimal system based on the cost and size of existing components. The most practical and feasible HRES configurations that meet the system's input limitations as set by the design system and workable arrangements are below in ascending order of cost of energy (COE) and Net Present Values (NPV). Therefore, the most economical configurations in this work are solar and wind. diesel, battery, and converter.

Figure 4

Hybrid System Configuration



3.9. Simulation Parameters

Project lifespan is 25 years, discount rate:12% and Renewable fraction target is >60%

3.10. Optimization and Sensitivity Analysis

Multiple configurations were analyzed. Sensitivity analysis included: Fuel price variations from \$0.8 to \$1.2/L and Solar and wind resource fluctuations (±10%)

In this configuration system, the sensitivity variables considered are the diesel fuel price (0.75,1,1.41 \$/1.41\$/L) and nominal discount rates (12%). The total number of 9 system optimizations due to three sensitivity cases.

3.11. Optimal Configuration

The process you've described outlines a standard approach to designing and optimizing hybrid energy systems using tools like HOMER. It's crucial to identify the combination of components and operational strategies that result in the most cost-effective solution (lowest NPC) while meeting the energy demands of the community. The decision variables you mentioned, such as the size of the renewable energy generators, energy storage, and the dispatch strategy, are indeed central to achieving this optimal balance.

According to the modeling software it suggests that PV 45 kW, Wind is 30 kW, Diesel of 40 kW, and Batteries with 187.2 kWh and The LCOE of \$0.198/kWh, Net Present Cost with \$249,724. Annual operating cost was \$8,875 with renewable energy contribution 68%.

3.12. Estimation of Primary Load

Primary load refers to the immediate energy needs of households, including lighting, baking, and laboratory equipment. The load determination was performed for 350 households with an average of five family members, representing a rural population of 1750.

3.13. Domestic Load

The electricity demands in Ethiopia's households are primarily used for low-energy appliances like compact fluorescent lamps, radios, and TVs. The highest electricity-intensive activity is Injera baking, which has a 52% efficiency. Each household uses 2 units of 13W compact fluorescent lamps and a 2.85kW Injera baking machine for one hour per day.

Table 2

Domestic Load

Appliances	Qua	Cap.	Time (h/day)	Peak Load	KWh/day
Low energy lights	2	13	6	0.026	0.156
Television	1	50	6	0.050	0.3
Radio	1	5	3	0.005	0.015
Baking	1	2850	1	2.85	0.40714
Total		2918		0.4885	0.87814

Note. Qua= Quantity, Cap.= Capacity (Watts), Time = Time(h/day)

3.14. School Load

The school's peak workload is expected to occur during evening hours, with classrooms equipped with two CFLs. The desktop computer will be used eight hours a day, while the printer will be used for an average of one hour.

Table 3

School Electricity Demand

Appliances	Quantity	Watts	Run time	Peak load (KW)	Daily load (KWh/day)
CFL Lamp	15	15	4	0.225	0.9
Outdooramp	3	15	4	0.045	0.18
Toilet room	2	15	4	0.03	0.12
computer	1	50	6	0.05	0.3
Printer	1	50	1	0.05	0.05
Total		145		0.4	1.55

3.15. Health Clinic Load

The health facility has fluorescent bulbs for eight rooms, microscope, radio communication apparatus, 21inch television, vaccine freezer, and desktop computer for various operations.

Table 4

Health Center Energy Load

Appliances	Quantity	Watts	Run time(hr/day)	Peak load (KW)	Daily load (KWh/day)
Microscope	1	25	4	0.025	0.1
CFL Lamp	5	15	10	0.075	0.75
Television	1	50	12	0.05	0.6
freezer	1	20	4	0.02	0.08
Computer	1	50	6	0.05	0.3
Printer	1	50	1	0.05	0.05
Total		210		0.27	1.88

3.16. Church Load

The religious church has four lamps for light and speaker for sound magnifying purposes.

Table 5

Church Energy Load

Appliances	Quantity	Watts	Run time (hr/day)	Peak load (KW)	Daily load (KWh/day)
CFL Lamp	4	20	10	0.080	0.8
Megaphone	1	50	15	0.05	0.75
Total		70		0.13	1.55

3.17. AC Primary Load Inputs for Optimizing of Hybrid System

The proposed system is based on wind, solar, and diesel generators as backup during a shortage of renewable resources of solar and wind. The axillary components like battery storage and converter to change from direct current (DC) to alternative current (AC) load in-house applications are the main considerable components. The data map of the AC primary load profile shows its maximum from 18 hours of the day to 23 hours which ranges from 15-25KW as shown in the figure below.

Figure 5

Comparison of current system with the proposed System

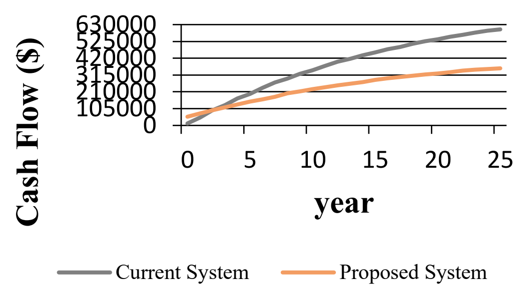
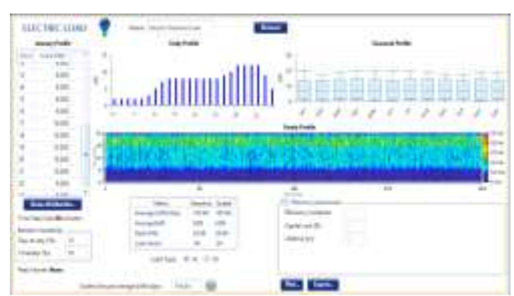


Figure 6

Electrical Load Profile



3.18. Cash Flow, Constraints, and Economic Analysis Proposed system

The lifetime of the system design is 25 years, with an annual real interest rate of 8% and 12% was used to calculate the Net Present cost (NPC) of the project. According to the design and modeling of the hybrid system, the HOMER software, the NPC is $600084, the Initial Capital is $12500, the O&M cost is $45452/yr, and the levelized cost of energy is 0.769/KW.

HOMER propose to adding a 0.37 kW of PV, 269 kWh of battery capacity, and 25 kW of wind generation capacity up to 8 in quantity. This would reduce your operating costs to $23,388/yr. Your investment has a payback of 1.88 years and an IRR of 51.2%.

The wind turbine represents the highest capital share with $114000(85.5%), second Generator with $12500(9.5%), third battery with $4133.64(3.1%), fourth is converter with 1963.13(1.9%) out of total cost $132596.77.

3.19. Environmental Impact Assessment

Carbon dioxide emissions have been reduced by an estimated 42 tons annually. The hybrid approach aligns with Ethiopia's climate goals and SDG 7 targets. The government has planned to increase the share of renewable energy by 2030. This plan is taken into consideration by using the PV-diesel hybrid system to reduce the pollution and the greenhouse gases emitted from electricity generation.

Sensitivity analysis optimizes each sensitivity variable while analyzing the impact of external elements. After entering the sensitive parametric variables into the software, the optimization procedure is repeated. Variations in the climate, the cost of parts and fuel, interest rates, capacity constraints, operational reserves, and other factors can all be considered sensitivity variables. HOMER performs numerous optimizations with a range of sensitive inputs to determine the power system's sensitivity. There are tabular and graphical displays for the HOMER sensitivity results.

In this configuration system the sensitivity variables considered are the diesel fuel price (0.75,1,1.41 $/L) and nominal discount rates (8 and 12%) with detailed cash flow statement. the total we have 9 system optimizations due to three sensitivity cases.

These calculations are performed by HOMER. The advantages of this eco-friendly system are healthier environment, lower electricity and reduction of medical bills, under 25 years project lifecycle.

4. Result and Discussion

4.1. Community Energy Usage and Load Profile

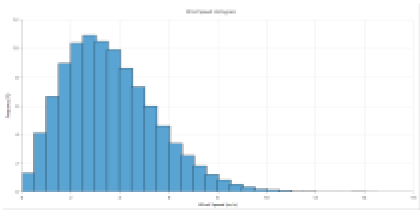
The whole 350 household communities need an average daily load demand of 277.62 including lower, medium and high-level energy demand for their daily life cycle.

4.2. Weibull distribution

Weibull distribution is a measure of the annual distribution of wind speeds. Weibull distribution parameters help to attribute wind regimes of two wind turbines installed at two different sites but having the same wind speed may result in different power outputs as wind speed distribution varies. The Weibull distribution for the given site of KELTO village was calculated in the following graphs.

Figure 7

HOMER Generated Probability Distribution Function of Chercher Wind Speed



4.3 Solar power Modeling

From table 6 above, the maximum and minimum solar radiation occurs on April and December respectively. The average solar radiation becomes 7.105 KWh/d/m^2 which is good enough for solar electricity. Clearness index shows clearness of sky or clouds covering the sky during different seasons. More clear means more solar energy generation and becomes an appropriate.

The clearness index is the clearness of the sky from cloudiness (transmission of the radiation directly from the sky to the earth's surface). The clearness index value is dimensionless and varies from 0 to 1 representing the cloudiest and sunniest months from 0.536 in August to 0.728 in February.

Figure 8

Monthly Solar Radiation Sources and Clearness Index

4.4. Battery

In this research three days of autonomous was considered. The last row shows the first days of battery capacity of 200 Ah with 5117.083 Ah battery capacity and second day of 10234.17 Ah which is twice or double of the first day and continue for the next days.

Table 6

Inverter specifications

Inverter type	Leonics MTP-413 F 25 kW
Efficiency	94%
Max Voltage	120-480 V
String inverter size	25 KW
Lifetime	10 years

In this research, the efficiency of the inverter is 94 % converting capacity for the 10-years life span of the project.

5. Conclusion and Future Work

This study presents a design and modeling of a stand-alone hybrid energy system for Kelto village, demonstrating its technical feasibility and economic viability. This optimized system, with a Levelized Cost of Energy (LOCE) of $0.3594/kWh, promises to significantly improve living standards and boost socioeconomic development in rural communities. This approach is more affordable and environmentally sound, achieving a 65.6% renewable fraction and a 28% internal rate of return (IRR). By decreasing the need for costly fuel ($1.41/L) and minimizing greenhouse gas emissions, hybrid systems are a preferable choice for sustainable electrification in Ethiopia, with the KELTO system designed for a daily electric demand of 165.44 kWh and a peak load of 20.46kW. This paper could contribute to the existing body of knowledge by providing a detailed, location-specific techno-economic model for a region in Tigray with moderate wind resources. The findings have practical implications for policymakers and developers, showcasing a replicable model for rural electrification that reduces fossil fuel dependence and promotes sustainable development.

The analysis assumes a fixed load profile; a dynamic load growth scenario could be incorporated in future studies. We recommend that future research to explore innovative financing mechanisms to overcome the high initial capital cost of renewable components.

References

Dawde, O. Y. (2013). *Wind Resource Data Analysis : The case of MYDERHU project site , Tigray regional state , Ethiopia*.

Gaddada, S., & Kodicherla, S. P. K. (2016). Wind energy potential and cost estimation of wind energy conversion systems (WECSs) for electricity generation in the eight selected locations of Tigray region (Ethiopia). *Renewables: Wind, Water, and Solar*, *3*(1). https://doi.org/10.1186/s40807-016-0030-8

Girma, Z. (2013). Hybrid renewable energy design for rural electrification in Ethiopia. *Journal of Energy Technologies and Policy*, *3*(13),38–53. http://www.iiste.org/Journals/index.php/JETP/article/viewFile/9765/9972

Hailu, A. D., & Kumsa, D. K. (2020). Ethiopia renewable energy potentials and current state. *AIMS Energy*, *9*(1), 1–14. https://doi.org/10.3934/ENERGY.2021001

Katti, P. K. (2012). *Energy Procedia Rural Electrification Through Solar and Wind Hybrid System : A Self Sustained Grid Free Electric Power Source*. *14*, 2081–2087. https://doi.org/10.1016/j.egypro.2011.12.1211

Kumar, S., Paswan, M. K., & Behera, S. (2022). *Micro Study of Hybrid Power System for Rural Electrification- A Case Study*. *13*(7), 4888–4896.

Ministry of Water, Irrigation, and E. (2019). Lighting to All : National Electrification Program 2.0: Integrated Planning for Universal Access. *Thematic Program Document*, *October*,49.https://www.east-africasummit.com/sites/default/files/clarion_www_poweringafricatanzania_com/pdfs/nep_2.0_ethiopia.pdf%0Awww.ens.dk/en

Nebey, A. H. (2021). Design of optimal hybrid power system to provide reliable supply to rural areas of Ethiopia using MATLAB and Homer. *Renewables: Wind, Water, and Solar*. https://doi.org/10.1186/s40807-021-00067w

Owoeye, K. S., Udofia, K. M., & Okpura, N. I. (2022). *DESIGN AND OPTIMIZATION OF HYBRID RENEWABLE ENERGY SYSTEM FOR RURAL ELECTRIFICATION OF AN OFF-GRID*. *10*(1), 2842.

Rack, A., Lifepo, M., Greenfaith, C., Energy, N., Co, T., About, H., Cases, P., Support, N., Home, C., Rack, A., & Lifepo, M. (n.d.). *ℬ ≚*. *15*, 4–6.

Study, C., District, A., & Bahta, S. T. (2013). *Design and Analyzing of an Off-Grid Hybrid Renewable Energy System to Supply Electricity for Rural*