Techno-economic analysis of solar energy system for electrification of rural school in Southern Ethiopia

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Abstract: To provide rural communities with low-cost electricity, innovative off-grid renewable energy producing techniques have emerged. The International Energy Agency estimates that around 45% of Ethiopia’s total population have access to electricity. Nearly 85% of Ethiopia’s urban population has access to public electricity, but this figure is only 29% for the rural population. This study examines the feasibility of using combined photovoltaic (PV)/diesel/battery systems to power a remote rural school in southern Ethiopia. The performance of various hybrid systems was assessed using techno-economic and environmental analyses, and the optimal solution was chosen using the Hybrid Optimization Model for Electric Renewable (HOMER) analytic tool. The evaluation criteria include net present cost (NPC), cost of energy (COE) and emissions. The results indicate that PV/DG/battery hybrid energy system (HES) with a 7.5 kW PV, 7.3 kW DG, 6.60 kW converter, and 11 units of batteries (case I) is the most feasible, optimized, cost-effective and environmentally friendly system among the systems considered. This system has a Net Present Cost (NPC) of $32,019 and a Cost of Energy (COE) of $0.254/kWh, as computed using current equipment values. The optimized system is also environmentally benign, emitting 793 kg of carbon dioxide per year, about 91% less than the PV/diesel combination (worst case IV). Furthermore, sensitivity analysis was performed to examine the impacts of altering factors such as solar radiation, fuel price, and battery minimum state of charge (SOCmin) on system cost and performance. We believe that the information given in this paper will shed light on the current state and future prospects for renewable energy systems in rural Ethiopia.
energy deployment in Ethiopia, and also show that, if policymakers create the necessary investment environment, such projects can be a viable alternative to rural electrification.

**Subjects:** Physics; Technology; Electrical & Electronic Engineering

**Keywords:** cost of energy; Ethiopia; HOMER; off-grid renewable power; PV/diesel/battery systems; rural community

1. Introduction

While most urban inhabitants are transitioning to a more technologically advanced, globally connected, and environmentally responsible style of life, this cannot be true for the vast majority of rural communities in developing nations. As a result of the absence of access to electricity in most rural villages, the economic and infrastructural development gap has grown, poverty has exacerbated, and it has become more difficult to enhance their quality of life (Jamia O. Oladigbou et al., 2021; Sampson et al., 2021). Around 17% of the world’s population lacks access to grid electricity, with 85% residing in rural communities (Olatomiwa et al., 2018). Even though Ethiopia’s economy is growing, it has one of the world’s poorest access to modern energy supplies. The Government of Ethiopia (GoE) has been undertaking renewable energy initiatives and efforts to satisfy the country’s growing power demand while also combating climate change.

Ethiopia is endowed with renewable and sustainable energy sources. These include hydropower and, to a lesser extent, wind, geothermal and solar as well as biomass. The approximate potential for hydropower is around 45 gigawatts (GW), for wind is 10 GW and for geothermal is 5 GW, and solar irradiation ranges from 4.5 kilowatt-hours (kWh)/m²/day to 7.5 kWh/m²/day (Benti et al., 2021; Biadgo et al., 2013; Tiruye et al., 2021). Only a small amount of the renewable energy potential is harnessed today. Grid electricity is the main source of modern energy in Ethiopia. Today electricity in the country is produced from hydro, geothermal, wind, biomass (Reppie Waste-to-Energy) and diesel. The total installed electric power generation capacity as of October 2018 was 4324.3 MW, comprising of a mix of hydropower, wind generation, diesel, geothermal and Waste-to-energy from municipal solid wastes (Benti et al., 2021; Tiruye et al., 2021). Looking at the share of total installed capacity of the country’s power plants, only 3.51% of the total generated electricity comes from Diesel; the rest is from clean renewable energy resources with 88.25% from hydropower plant, 7.49% from wind power, 0.58% from biomass and 0.17% from a geothermal plant, which makes Ethiopia’s electricity among the most sustainable in the world (Benti et al., 2021).

Rural populations are scattered and geographically isolated, with high rates of illiteracy and limited access to health care, safe drinking water, and electricity. As a consequence, rural living conditions are lower than in metropolitan regions where electricity is extensively utilized (IEA, 2017), and many rural areas depend on DG systems to augment unreliable grid supplies or on kerosene-powered lighting. According to the International Energy Agency, in 2016 approximately 45% of Ethiopia’s total population had access to electricity. Nearly 85% of Ethiopia’s urban population has access to public electricity, while only 29% corresponds for the rural population (IEA, 2017). Even urban areas supplied by the national electricity grid are facing power shortages, frequent power outages, and extremely limited capacity to run appliances as a result of the country’s recurrent drought. This is due to a number of factors, including growing demand for electricity, decreased reservoir capacity, and the country’s frequent dry seasons.

The situation is deteriorating as a consequence of the slow pace of rural electrification and the expensive cost of grid extension. On the other hand, small-scale off-grid energy production is one of the most viable solutions to this issue. Providing reliable electricity to rural areas is critical
because it: (1) improves rural residents’ living standards, (2) improves educational quality, and (3) fosters infrastructure development and industrialization. Remote areas, on the other hand, have an inadequate supply of power owing to the unreliability and lack of connection to the national grid, as well as the high cost of grid extension to reach rural towns (Bekele & Palm, 2010; Bekele & Tadesse, 2012; Benti, 2017).

Furthermore, various renewable energy technologies (RET) are becoming more appealing for rural electricity generation due to their lower environmental impact and abundance of natural energy. Numerous studies have been carried out all over the world to estimate and establish the feasibility of HES generating electricity to be used in various applications and human settlements (Farahi & Fazelpour, 2018; Gaslak et al., 2018; Hossain et al., 2016). Despite their high initial capital cost, they contribute significantly to reducing GHG emissions, increase sustainability and cost-effectiveness throughout operation, and meeting rapidly increasing energy demand (Aziz et al., 2019; El-Houari et al., 2019; Imam et al., 2020). Recent cost reductions in RET, on the other hand, have demonstrated their cost competitiveness in meeting power demand (Hassan et al., 2020; IRENA, 2019). Between 2010 and 2019, the cost of solar PV dropped by 82%, followed by onshore and offshore wind, which fell by 40 and 29%, respectively (Qerimi et al., 2020; REN21, 2017). In 2019, the cost of electricity from utility-scale solar PV was approximately $0.07/kWh, down 13% annum, while the cost of energy from offshore and onshore wind both fell by about 9% annum, to $0.115/kWh and $0.053/kWh, respectively (Renewable & Agency, 2019).

According to a study on the electrification of African schools, more than half of public primary schools in at least twenty countries, including Ethiopia, lacked electricity in 2013 (World Bank and International Energy Agency, 2014). In Sub-Saharan Africa, approximately 90% of primary school students (90 million) do not have regular access to electricity; in South Asia and Latin America, this figure is 94 million and 4 million students, respectively (Action, 2013; Goodwin, 2013). It is unfortunate that schools do not have electrification because of the numerous benefits it can provide in the classroom. Lighting is critical for nighttime courses and the use of ICTs like computers and TVs in the classroom. Electrified schools may attract and retain better-qualified instructors, which has been linked to improved test results, accomplishment, and commitment to quality education.

Techno-economic assessments of integrated RESs and conventional energy sources have been performed in many studies, seeking to increase system reliability and address the unpredictable aspect off-grid-independent RE systems. Off-grid hybrid renewable electricity systems have been developed and proposed for a wide range of uses all throughout the globe. This was proved using several techniques, such as analytical models comprising life cycle cost (LCC) and loss of power supply probability (LPSP). Additionally, researchers used several software’s like MATLAB and HOMER to get the best-optimized result for the specific location in which the research work has been conducted. Yeshalem et al. (Yeshalem & Khan, 2017) developed a stand-alone hybrid PV-wind energy system for a remote Ethiopian mobile base station. Jariso et al. (Jariso et al., 2017) created an off-grid PV energy system to power a remote health clinic in south-western Ethiopia. Additionally, Kiros et al. (Kiros et al., 2020) compared the economic performance of various scenarios for electrifying Kultur village in Awilo kebele of the Axum district, Ethiopia, which is 30 km away from the nearest national grid. However, majority of the studies (Jariso et al., 2017; Kiros et al., 2020; Yeshalem & Khan, 2017) focused on the usage of hybrid RESs to boost efficiency while balancing the effect of RES variation. This study focuses on the solar PV energy system in rural Ethiopia in conjunction with a battery and a DG for energy storage and backup power supply, respectively and also examines how the sensitivity parameters affect the COE of the system. Combining solar PV with a diesel generator and battery provides various benefits, including reduced diesel generator operating time, lower operating costs, and reduced fuel usage. Additionally, the combined system minimises environmental contamination and enhances system
reliability (Gebrehiwot et al., 2019). The objective is to determine the techno-economic and environmental viability of using these energy sources to power Gara Godo village.

Gara Godo village is located in Ethiopia’s southern region, near Areka city in the Wolaita zone, and is a place with decentralized communities that are disconnected from Ethiopia’s power grid. Those areas are still without electricity. These villages are unlikely to be electrified in the near future owing to their remoteness, uncertain geographical position, poor community, low energy usage, fixed load, and scattered character. Thus, this study seeks to develop and implement a standalone PV energy system with non-stop power production for Newase primary and secondary school located in Gara Godo village. In order to provide a constant supply of electricity, a diesel plant and battery storage are incorporated in the simulation. A sensitivity study of factors such as solar irradiance, fuel price, and battery minimum state of charge (SOCmin) parameters was performed to assess the HES economic and operational performance. Improved electricity conditions may enhance quality education, economic and social activities. This will serve as a case study for rural electrification in several regions of Ethiopia utilising accessible renewable energy sources.

2. Methodology

2.1. Description of the research site
The Newase Primary and Secondary School investigated in this study is located in the Wolaita Zone of Southern Ethiopia, near Areka city. It is about 330 kilometers south of Addis Ababa, at latitude 7.091352°N and longitude 37.709235°E. The zone is classified into three agro-ecological zones, among them large proportion is Woina-Dega (middle altitude) which is about 56% of the area; the rest 35% and 9% is described as Kola (low altitude), and Dega (high altitude), respectively. The estimated average annual rainfall is 801 to 1600 mm. The rainfall in the Zone is characterized by bimodal distribution pattern and the main rainy season (Meher) is between June and end of September and (Belg) is from late February to late March/early April. The annual average temperature of the zone is 21.86°C. The altitude of the zone ranges from 501 to 2738 meter above sea level. Figure 1 depicts the site's google map view. Because the school is 11 kilometers from the nearest electrified community, obtaining electricity from the grid is prohibitively expensive, which is why this study was conducted.

2.2. School electric load demand
The appliances’ estimated total power demand is dependent on the PV system supplying the required load. The appliance’s peak operation hours were proposed. The electric appliances to be used by the school were used to estimate the load. The first step in calculating the load is

![Figure 1. Google map view of newase primary and secondary school.](image-url)
determining which appliance the school will use, taking into account the current and future state of the local community as well as the country’s energy system framework. The three-year load projection was done by considering in the village’s population growth. The following expressions were used to calculate the school’s energy demand per day:

\[ E_d (\text{kWh/day}) = \frac{N_a \cdot P_r \cdot H}{1000} \]

Where \( E_d \) is Energy demand (kWh/day), \( N_a \) is number of appliance used, \( P_r \) is power rating of each appliance (W) and \( H \) is hours of operations.

The school with ten classrooms, one office, one toilet and one laboratory is suggested. It was supplied with twenty-one desktop computers, one printer, one copier machine, two televisions, and one UPS (Uninterruptible Power Supply). Electric lighting for the school in the evenings (18:00–21:00) is recommended for people wishing to pursue basic education; therefore, lighting bulbs consume more energy at night. During the day, there is no need for power in classrooms because sunshine can brighten the rooms through the windows; consequently, the most energy-consuming appliances during the day are computers, printers, photocopy machine, televisions, and UPS. Table 1 shows a list of the electrical equipment in the school, as well as their power.

The primary load demand is shown in Figure 2 on a daily and hourly basis; the electricity load profile varies throughout the day. The load is nearly zero between midnight and morning, whereas demand rises during the day. Classes are also held in the evenings, from 18:00 to 21:00, while other equipment operates best between the hours of 8:00 to 9:00 and from 15:00 to 6:00 during day times. As a result, the daily total energy demand of Newase School is approximately 26.7kWh/day, with a peak load of 6.56 kW.

2.3. Solar resource assessment

The meteorological data for this study was obtained by entering the area’s coordinates (7.091352°N latitude and 37.709235°E longitude) on the NASA Langley research center website (NASA, 2020). Changes in mean solar radiation and related clearness index are shown in Figure 3. The amount of net irradiance reaching the earth’s surface is largely reliant on cloud cover and sky clarity (Shukla et al., 2015). Maximum monthly average daily total solar radiation occurred in November, February, and March, with lowest radiation occurring from June to August owing to peak cloud cover and rainy

| Table 1. School electric load demand |
|-------------------------------|----------|----------|----------|----------|
| Energy Demand | Appliances | Power(W) | No. of Appliances | Daily use (hrs) | Daily Energy (Wh/day) |
| School | Bulb class | 25 | 10^4 | 4 | 4000 |
| | Lab | 25 | 1 | 4 | 100 |
| | Library | 25 | 6 | 4 | 528 |
| | Television (32 LED) | 55 | 2 | 4 | 440 |
| | Desktop Computers | 150 | 21 | 4 | 16,800 |
| | Printer | 120 | 1 | 4 | 480 |
| | Photocopying | 180 | 1 | 4 | 720 |
| | UPS | 900 | 1 | 4 | 3600 |
| Total | | | | | **26,668** |
Figure 2. Village energy demand profile.

Table 2. Specifications and costs of various components

| Components  | Initial Cost | Replacement Cost | Maintenance Cost |
|-------------|--------------|------------------|------------------|
| PV system   | $1500/kW     | $1000/kW         | $10/kW/year      |
| Diesel generator | $2000/kW   | $2000/kW         | $0.03/op.hour    |
| Converter   | $6500/kW     | $400/kW          | -                |
| Battery     | $230/kW      | $230/kW          | -                |

Figure 3. Monthly average solar radiations of the study site (NASA, 2020).
season. In general, the dry season has more solar radiation than the rainy season. The other months have moderate radiations. Additionally, the findings indicate that the monthly average daily global solar radiation on a horizontal surface ranged from 4.61 kWh/m²/day (July) to 6.27 kWh/m²/day (February). The value of yearly average daily global solar radiation on a horizontal surface for study area during the time of investigation is determined to be 5.71 kWh/m²/day.

2.4. Proposed HES components’ and mathematical expressions
The proposed HES consists of four main parts: PV panels, batteries, a DG, and a converter. Using HOMER, the optimal HES combination for the school was chosen based on its techno-economic viability. Cost variables for the various simulation elements are shown in Table 2.

2.4.1. Solar PV energy system
To power the school’s loads, solar panels are utilized to produce electricity. The amount of solar radiation, cell temperature, and geographical characteristics all affect how much electricity a PV system produces (Maleki & Askarzadeh, 2014). PV module selection is influenced by the performance characteristics provided by manufacturers. The selection is actually based on the module’s efficiency and maximum power output. We selected a 12 kW Generic flat plate PV panel with a 13% efficiency for this study based on technical performance and cost (Table 2). The PV panel’s power output is calculated as follows (Nacer et al., 2016):

\[ P_{PV} = Y_{PV} f_{PV} \left( \frac{G_T}{G_{T,STC}} \right) \left[ 1 + \alpha_p (T_C - T_{C,STC}) \right] \]  

In this equation, \( Y_{PV} \) represents the output power of the PV under standard test conditions (STC) (kW), \( \alpha_p \) is the power temperature coefficient (°C\%), and \( f_{PV} \) is the PV de-rating factor (%), \( G_{T,STC} \) is incoming radiation under STC (kW/m²), \( G_T \) indicates the solar radiation striking the PV panel (kW/m²), \( T_C \) denotes the temperature of the PV cells (°C), whereas \( T_{C,STC} \) is \( T_C \) under STC (25 °C).

2.4.2. Converter system
The power converter is intended to function in both directions, either as an inverter (DC-AC) or as a rectifier (AC-DC). It maintains the electrical flow between the components of the AC bus and the DC bus. The cost factors for the converter are shown in Table 2. For the inverter input 15 years lifetime and 95% efficiency was taken, whereas 100% relative capacity and an efficiency of 95% was considered for the rectifier input [40]. The following formula may be used to determine the converter capacity:

\[ C = (3 \times L_i) + L_r \]  

In this equation, \( L_i \) and \( L_r \) represent inductive and resistive loads, respectively.

2.4.3. Battery storage
In order to operate a renewable energy-based system reliably and efficiently, a battery is needed. In case of capacity deficit, a battery is used to store excess power and provide it to the load. Battery with nominal voltage and capacity of 2 V and 2.67kWh, respectively, is used in this study, and the battery has a 20% minimum state of charge and a 95% roundtrip efficiency. The selected battery type had an 8-year life span. Table 2 shows the cost parameters for this component. The battery storage capacity is estimated by taking into account autonomous days and demand as follows (Jamiu O. Jamiu O. Oladigbolu et al., 2021; Jamiu Omotayo Jamiu Omotayo Oladigbolu et al., 2019):
Table 3. Summary of the sensitivity parameter

| Parameters                          | Sensitivity Values |
|-------------------------------------|--------------------|
| Solar Radiation (kWh/m²/day)        | 5.71  5.84  5.98  6.12  6.26  6.4 |
| Diesel Price ($/L)                  | 0.43  0.56  0.68  0.81  0.93  1.06 |
| Minimum battery SOC                 | 20  25  30  35  40  45 |

Figure 4. Standalone system design topology for the Newase School.

Figure 5. Flowchart for evaluating the economics of hybrid systems.
\[ C_{\text{bat}} = \frac{E_L \times AD}{\eta_{\text{inv}} \times \text{DOD} \times \eta_{\text{bat}}} \]  

where \( E_L \) stands for average daily load electricity (kWh/day), \( AD \) stands for autonomous days, and \( \eta_{\text{inv}} \) indicates inverter efficiency (90%), \( \text{DOD} \) stands for depth of discharge (80%), while \( \eta_{\text{bat}} \) stands for battery efficiency.

### 2.4.4. Diesel generator (DG)

Due to its low fuel consumption and efficiency, DG is used in many HESs [51]. Because RESs are largely reliant on weather conditions, which have a substantial impact on power generation levels, DGs are commonly utilized as a backup. Diesel fuel in Ethiopia is currently about $0.43/L. The price of diesel per litre varies according to global oil market conditions and diesel fuel availability. DC with a life span of 133,400 hours and a load ratio with no less than 25% was specified. Table 2 shows the DG cost parameters. The quantity of fuel needed to generate electricity is determined using Equation (4; Jamiu O. Jamiu O. Oladigbolu et al., 2021; Jamiu Omotayo Jamiu Omotayo Oladigbolu et al., 2019):

\[ F_{\text{DG}} = (a \times T_{\text{DG}} + b \times P_{\text{DG}}) \]  

### Table 4. Categorized simulation result, from HOMER

| Parameter | Case I | Case II | Case III | Case IV |
|-----------|--------|---------|----------|---------|
| PV (kW)   | 7.5    | 16.9    | -        | 4.22    |
| DG (kW)   | 7.3    | -       | 7.3      | 7.3     |
| Battery   | 11     | 22      | 13       | -       |
| Conv. (kW)| 6.6    | 6.82    | 1.93     | 1.56    |
| Disp. Strgy | LF | CC      | CC       | CC      |
| Initial Capital | $28,947 | $26,475 | $18,856 | $19,842 |
| Operating Cost ($/yr) | $237.60 | $505.86 | $1,669.00 | $2,029.00 |
| Total NPC  | $32,019 | $33,014 | $40,428 | $46,074 |
| COE ($/kWh) | $0.25 | $0.26 | $0.32 | $0.37 |
| Ren. Frac. | 92.9   | 100     | 0        | 7.8     |
| Fuel (L)  | 0      | 303     | 2,967    | 3,374   |

Figure 6. NPC and COE for different system cases.
where $F_{DG}$ denotes the DG fuel intake rate (L/h), $a$ refers to the coefficient of fuel intercept (L/kWh) (0.408 L/kWh rated), $T_{DG}$ denotes the DG capacity (kW), $b$ is the fuel slope (L/kWh) (taken as 0.236 L/kWh output) and $P_{DG}$ refers to the generator output (kW).

2.5. Economic model
The economic evaluation is an essential part of the HOMER software because of its primary goal (cost minimization). The best solution for various system models is evaluated using NPC and COE. In addition, the best system component combination is ranked based on the lowest lifespan price. Equation (5) is used to determine the NPC (Aderemi et al., 2018):

$$C_{NPC} = \frac{G_{AC}}{C_{BF}(i, N)}$$  \tag{5}
where \( G_{AC} \) donates the gross annualized cost ($/yr), \( N \) indicates the number of years, and \( i \) denotes the annual real discount rate (%). The capital recovery factor (\( C_{RF} \)) is a ratio used to determine an annuity’s present value (a series of equal annual cash flows). The following formula is used to determine the \( C_{RF} \) (Salisu et al., 2019):

\[
C_{RF}(i, N) = \frac{i(1 + i)^N}{(1 + i)^N - 1}
\]  

(6)

The average cost per kWh of useful energy generated by the system is referred to as the electricity cost (COE). The following equation computes it (Aderemi et al., 2018; Salisu et al., 2019):

\[
COE = \frac{G_{AC}}{E_G}
\]

(7)
The gross annual load (kWh) provided by the system is denoted by $E_{GYS}$. The real rate of interest is 12.5% (Economics, 2020; Jamiu O. Jamiu O. Oladigbolu et al., 2021; Jamiu Omotayo Jamiu Omotayo Oladigbolu et al., 2019).

### 2.6. Sensitivity variables
The optimal design was subjected to sensitivity analysis by varying certain variables that have a direct effect on the cost and overall performance (Escalante Soberanis et al., 2018). In this

| Authors | Key objective | Country | Hybrid system | COE/kWh |
|---------|---------------|---------|---------------|---------|
| (Bekele & Palm, 2010) | Investigate the possibility of supplying electricity from a solar–wind hybrid system to a remotely located model community detached from the main electricity grid in Ethiopia | Ethiopia | Diesel/battery/converter | 0.322 |
| (Benti, 2017) | Assess suitability of stand-alone wind-solar PV hybrid power for Debmel village which is detached off the main grid line | Ethiopia | PV/diesel/battery/converter | 0.415 |
| (Kiros et al., 2020) | Modeling of a stand-alone hybrid system for the remote area of Ethiopia | Ethiopia | PV/wind/diesel/battery/converter | 0.402 |
| (Gebrehiwot et al., 2019) | Assesses the potential of a hybrid system to electrify a remote rural village in Ethiopia | Ethiopia | PV/wind/battery/diesel | 0.207 |
| (Albert K. Awopone, 2021) | Examines the feasibility of a stand-alone photovoltaic, diesel generator and battery storage hybrid power system for the electrification of off-grid rural areas in northern Ghana | Ghana | PV/diesel/battery | 0.399 |
| (J. J. Oladigbolu et al., 2020) | Examines the potential application of hybrid solar PV/hydro/diesel/battery systems to provide off-grid electrification to a typical Nigerian rural village | Nigeria | PV/hydro/diesel/battery | 0.112 |
investigation, the chosen sensitivity factors are solar radiation, fuel price, and battery SOC_{min}. Global solar radiation, fuel price, and battery SOC_{min} base case (actual) values were 5.71 kWh/m²/day (yearly average daily radiation of the study site), $0.43/L (Current fuel price in the country), and 20% (SOC_{min} of Lead acid battery), respectively. Table 3 summarizes the sensitivity parameter analyses performed in this study.

Table 6. Emissions of pollutants generated by the optimum hybrid system and the PV/diesel system (worst case)

|                        | Proposed PV/Diesel/Battery System (kg/year) | PV/Diesel System (kg/year) |
|------------------------|---------------------------------------------|-----------------------------|
| Carbon dioxide         | 793                                         | 8,831                       |
| Carbon monoxide        | 5.00                                        | 55.7                        |
| Unburned hydrocarbons  | 0.218                                       | 2.43                        |
| Particulate matter     | 0.0303                                      | 0.337                       |
| Sulfur dioxide         | 1.94                                        | 21.6                        |
| Nitrogen oxides        | 4.69                                        | 52.3                        |

Figure 11. The influence of GSR on the NPC and COE of the optimum system.

Figure 12. Effect of GSR on the renewable fraction and annual fuel consumption.
3. Results and discussion
The HOMER simulation programme was used to identify the optimum system design depending on the economic and technical assessment of the selected distant site in Ethiopia. To analyze the system, HOMER requires data such as energy resources, economic constraints, control methods, school load demand, component technical details, costs, and the type of dispatch strategy. As shown in Figure 4, the suggested hybrid system is made up of three main components: a PV, batteries, and a DG.
To determine system performance, a sensitivity analysis was performed whereas changing variables that have a direct effect on how systems operate. The procedure shown in Figure 5 is for doing an economic analysis to identify the optimal design.

3.1. Optimization results

After carefully entering all of the considered input variables into the software, the optimization analysis is performed; it is run repeatedly to obtain feasible results. The optimization results are presented in the form of an overall and categorized representation of the most feasible power system architecture that meets the load and input constraints set by the modeler. The viable options are given in ascending order of NPC. The categorized table showed the least cost effective combination of all component configurations, while the overall optimization results displayed all economically feasible system configurations based on their NPC. Following simulation, power systems are selected to achieve the lowest possible NPC. Additionally to these criteria, a lower cost of energy (COE), a greater renewable energy share, a lower surplus electricity production, and a lower diesel fuel consumption may be used to evaluate power generating schemes to ascertain their technical viability. The hybrid system configuration derived from the simulation study is shown in Table 4. There are combinations available for PV/diesel/battery (case I), PV/battery (case II), diesel/battery (case III), and PV/diesel without battery (case IV). The PV/diesel/battery (case I) combination is the most cost-effective, while the PV/diesel configuration has the least favorable economics (Table 4).

A comparison of the technical, economic, and environmental aspects of all the case designs in Table 4 reveals that the system in Case III and IV has the lowest initial capital cost but the highest NPC. This is primarily due to the DG’s high operational and fuel costs. While Case II is the most environmentally friendly (with 100% renewable fraction), it demands a large initial capital investment. The best hybrid system was determined to be the Case I system. This system is the most economically viable option while maintaining adequate technical performance. It has the potential to significantly help Ethiopia’s government in meeting its commitments under the Paris Climate Agreement and the Kyoto Protocol.

The optimum system (case I) consists of a 7.50 kW PV array with 11 unit batteries, a 7.30 kW DG, and a 6.60 kW converter. The yearly operating cost of this optimal design is $237.60, the COE is $0.254/kWh, the NPC is $32,019, and the initial capital cost is $28,947 (Figure 6). Additionally, as compared to the PV/diesel system (case IV), the optimum configuration lowers operating expenses, COE, and NPC by 88%, 30.6%, and 30.5%, respectively (Figure 6). The renewable fraction, which is the proportion of renewable energy sources in total system power produced, was
determined to be 92.9%. This result shows that when coupled with the extra energy provided by the diesel system, the system produces more energy from renewable sources.

The results also show that the dispatch strategy had a significant impact on the renewable penetration rate. Load Following was found to be the best dispatch strategy for the proposed system, as shown in Table 4. The optimized system generates 13,323 kWh of energy per year, while the solar PV system contributes approximately 12,628 kWh per year, accounting for approximately 94.8% of total production (Figure 7). Between October and May, when solar energy is plentiful, the PV solar system generates the majority of its energy, whereas production is minimal in June, July, August, and September (rainy season). The obtained results indicate that during the rainy season, when solar radiation is at its lowest, DG can meet the school’s electric demand (Figure 7). The diesel plant system provides 5.22% (696 kWh/year) of the extra electricity. The results indicate that the optimized system’s COE is higher than both the present global electricity pricing and the national grid energy tariff (about $0.022/kWh), which is primarily generated by hydropower plants. However, given the country’s electricity shortage (<45% coverage) and rural areas’ low electricity usage (<29% coverage), as well as the fact that the country’s hydropower potential is not being fully utilized to meet energy needs, particularly in rural areas, this cost should not be a deciding factor. Figure 7 depicts each component’s monthly power generation.

According to the cash flow summary shown in Figure 8, capital costs account for the majority of the total system cost, which is approximately $28,947.39. The DG accounts for approximately 50.44% system cost, generic flat plate PV accounts for 25.9%, converter accounts for 14.92%, and the system battery accounts for 8.74%. The high capital cost was due to the money spent on the installation of the PV system and the purchase of the DG. The initial cost of the PV array is high, at $7496.56 for the capital and $64.61 for operation and maintenance, but the replacement cost, fuel cost, and salvage value are all $0.00, implying that the total NPC of the PV array over the project’s lifespan is $7561.17. In the case of the diesel generator, its initial cost is high with a capital cost of $14,600.00, and also have a high O&M cost of $962.58, with cost of fueling at of $1683.57, salvage value of $3274.69, totaling an NPC of $20,520.84. This implies that though renewable energy components may have high initial cost but their operation, maintenance, and fuel cost is low as compared to diesel systems, which is consistent with other studies (Saheli et al., 2019). Figure 8 also present the contribution of the major components to the cash flow in terms operating cost; replacements cost and salvage value of the components.

As a consequence, the rated capacity of PV is 7.5 kW (Figure 9), with a mean output of 1.44 kW and a capacity factor of 19.2%. The entire annual PV energy output was determined to be 12,628 kWh, with 4,473 operating hours and a levelized cost of 0.0463 $/kWh. As illustrated in Figure 9, energy production is greatest during times of intense solar radiation hitting the earth’s surface, which occur between October and April. Due to the country’s cloudiest time and rainy season, the shortest duration of radiation occurred between June and August, and solar PV power production was lower than in other months.

Figure 10 depicts the distribution of diesel generator power production. As a result, electricity generation is relatively high throughout the summer months of June to September, because PV power generation is at its lowest during this time. The generator in this power system produces a average power production of 2.05 kW and a minimum electrical output of 1.83 kW, with an annual electrical production of 696 kWh. The amount of diesel fuel consumed per year is approximately 303 liters and its total operational hours is 392 hours per year.

To confirm the findings of this study and to provide stakeholders with a global perspective, a comparative analysis of similar studies performed in Ethiopia and other countries utilizing
HOMER was conducted. According to the data in Table 5, the COE of the PV/diesel/battery storage system used in this investigation is comparable to that of similar studies. The small variation in COE may be attributable in part to the fact that the various studies used a variety of hybrid configurations. While the economics of such projects are site dependent, the study gives further insight for project evaluations.

3.2. Environmental analysis
When assessing the viability of renewable and non-renewable hybrid systems, it is essential to evaluate the quantity of greenhouse gas (GHG) and pollutant emissions produced, since these emissions are directly linked to global warming. In this study, emissions are associated with the burning of diesel fuel. Annual diesel consumption and emission factors based on density, carbon, and sulphur contents, as well as a low heating value, are the two primary components needed for emission calculation. Environmentally friendly was determined to be the best configuration since it generated the fewest polluting gases when compared to the PV/diesel system (Table 6). Additionally, as compared to the PV/diesel system (worst case), the optimum system saved about 8031 kg/year of CO₂ gas emissions from being discharged into the surrounding air. The table indicates that carbon dioxide (CO₂) is the primary pollutant that contributes to unhealthy atmospheric air in this area, followed by carbon monoxide, while particulate matter contributes the least to overall pollutant emissions (Table 6).

3.3. Sensitivity analysis
The optimized configuration was subjected to sensitivity analysis by varying some variables that could have a direct impact on the cost and overall performance. The following parameters were examined in this section: solar radiation, the price of diesel fuel, and battery minimum State of Charge (SOC_min).

3.3.1. Solar radiation
The level of global solar radiation (GSR) received by a place determines how long the PV system will take to fulfil the load demand. Solar radiation decreases DGs operating hours and fuel consumption rate, and vice versa. Furthermore, the amount of energy generated by solar PV systems is reliant on the amount of solar radiation and intensity, which means that altering this parameter may have an effect on the system’s operating performance and cost. The yearly average global solar radiation was raised from 5.71 to 6.40 kWh/m²/day in this case at intervals of 0.14 kWh/m²/day.

The effects of changing solar radiation on the COE and NPC are shown in Figure 11, which demonstrates that when the global solar radiation level is increased from 5.71 to 6.40 kWh/m²/day in the optimized system, the NPC and COE drop by 2.62 and 2.63%, respectively. The amount of the reduction in NPC and COE may be explained by the drop in fuel use, as shown in Figure 12, as well as the cost of diesel. Additionally, when the GSR rose, so did the renewable penetration rate. The findings clearly demonstrate the effect of these factors on both the total cost of the system and the cost of electricity.

3.3.2. Fuel price
The effect of varying the price of diesel fuel on the COE and NPC is shown in Figure 13, which shows that when the price of diesel fuel is increased from 0.43 to 1.06 S/L in the optimised system, the NPC and COE rise by 5.18 and 5.17%, respectively. Increases in the price of gasoline result in a nearly linear increase in the NPC and COE values (Figure 13). Moreover, as shown in Figure 14, the optimum system used more fuel as the price of gasoline rose. For example, when the price of gasoline climbed from 0.43 to 1.06 S/L, overall fuel consumption grew by about 202.98 L/year, while the renewable portion dropped by around 12.8 % from the initial penetration (92.85%).
3.3.3. Battery minimum state of charge (SOC\textsubscript{min})

The SOC\textsubscript{min} of a battery system is the lowest charge level at which the storage system is never pulled. The majority of rechargeable storage batteries are not designed to be completely discharged; otherwise, they may suffer irreversible harm. Typically, the battery’s SOC\textsubscript{min} is set between 30% and 50% to prevent an extreme discharge that may harm the battery bank and to prolong the battery’s life (Lambert et al., 2006). This study examined the effect of increasing the SOC\textsubscript{min} from 20% to 45% in 5% increments on the hybrid system’s operational performance and overall cost. Increases in SOC\textsubscript{min} have an effect on total NPC, COE, renewable percentage, and rate of fuel consumption, as shown in Figures 15 and 16. The findings indicate that raising SOC\textsubscript{min} from 20% to 45% increases the NPC and COE by 5.63 and 5.62%, respectively, while maintaining a stable renewable percentage. When the battery’s SOC\textsubscript{min} drops below 30% or 35%, the system increasingly depends on the DG to fulfill load demand, as shown by the rise in yearly litres of fuel used. Furthermore, the results indicate that raising the SOC\textsubscript{min} presents a major environmental issue, since additional carbon emissions would be generated directly as a consequence of the diesel plant’s fuel consumption.

4. Conclusion

The purpose of this study is to evaluate the viability of using PV, DG, and battery HES to power an isolated rural school facility in Gara Godo village, Wolaita zone, Ethiopia using HOMER software. During the simulation process, different system configurations combining PV, DG, and battery storage generation were analyzed to find the most appropriate and least costly alternative while taking into account the environmental impact of each system scheme. With a NPC of $32,019 and a COE of $0.254/kWh, the hybrid system with 7.50 kW of PV panels and 11 unit batteries, 7.30 kW of DG capacity, and a 6.60 kW power converter is the most financially feasible choice for this school. The optimal system’s COE was slightly higher than Ethiopia’s current grid energy price ($0.022/kWh), which was primarily generated by hydropower plants. However, hydropower potential is not being fully utilized to satisfy the country’s energy needs, particularly in rural areas. As a result, the solar PV off-grid hybrid system is believed to be the optimal option for electrifying Ethiopia’s remote rural communities. Furthermore, the area has a high potential for renewable energy developments, with a RE penetration rate of 92.855%, which has reduced the operating hours and fuel consumption of the diesel plants to 340 hours per year and 303 L of fuel; thus, this system is environmentally friendly because it contributes to the maintenance of a clean and safe atmosphere through the use of low-pollutant fuels. According to the sensitivity analysis carried out on the ideal design, NPC, COE, fuel consumption, and renewable fraction are sensitive to the variation in all the considered sensitivity parameters. This study serves as a model for proving the techno-economic feasibility of Ethiopia’s solar development. Solar PV and other renewable energy sources like wind, biogas, and hydropower in rural Ethiopia require more study to establish their viability. Future research can be undertaken using a variety of combinations and components. Additionally, computational techniques can be used to optimize hybrid systems.

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