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Techno-economic comparison of standalone solar PV and hybrid power systems for remote outdoor telecommunication sites in northern Ghana

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ABSTRACT

Telecommunication services have continued to evolve to meet the ever-changing bandwidth demand requirements. The electricity grid network of Ghana is faced with challenges, including low voltages, a lack of quick fault response teams, and the proximity to specific locations. Using diesel generators to address the shortfall in grid supply is expensive and has implications for greenhouse gas emissions. This study evaluated the technical and economic benefits of using a standalone solar photovoltaic (PV) system, hybrid (Solar PV/diesel), conventional diesel generators (DG), and grid extension to power an off-grid outdoor telecommunication site. Power solutions configurations were simulated using hybrid optimization of multiple electric renewables (HOMER). The study found the optimum design to be a standalone solar PV/battery system with 56.3 kW solar PV array and Sixty (60) pieces of 12 V SAGM batteries of 135 Ah. The optimum design had a net present cost (NPC) of US$ 88,176.00 and a cost of energy (COE) of US$ 0.321/kWh. The COE and the NPC of the optimum system were approximately 50% less than the design with DG only, which could significantly impact service tariff and improve access to digital connectivity. The COE from the solar PV/battery system is not competitive with the grid power supply (COE = US$0.12). However, considering the electric distance limit or breakeven distance of 4.51km for grid extension, the solar PV/battery is preferred. Therefore, the stakeholders in providing power solutions to off-grid locations should consider solar PV technology.

Keywords

Telecommunication, off-grid sites, Standalone solar PV, HOMER, electric distance limit, grid extension

INTRODUCTION

The International Telecommunication Union (ITU) estimates that 3.7 billion people in 2020 were utterly cut off from the internet (digital communication systems) and left out of tapping into the technology's transformative power advantages. These figures require urgent attention in the wake of the COVID-19 pandemic as connectivity has been tagged the "hidden hero" globally in managing the spread of the deadly virus. The dependence on information and communication technologies (ICTs) networks and services has irrevocably reinforced the significant contribution of connectivity to our society's survival (Martins, 2020). ICT infrastructure networks allowed us to work remotely, stay in touch with relations, online schooling, collaborative research, etc., to prevent the world's unthinkable shutdown (Pokhrel & Chhetri, 2021; Shahzad et al., 2020; UCLG, 2020). It is unequivocal that access and connectivity are cardinal to sustaining our "new normal" during and in the post-COVID-19 world. Aside from the estimated populace completely cut off from the digital space, many developing countries struggle with expensive, unreliable, and slow connectivity challenges that disadvantaged them during the COVID-19 crisis(International Telecommunication Union, 1999; Sambuli, 2016). Africa and Commonwealth Independent States (CIS) regions, according to the ITU facts and figures report 2020, are facing an enormous gap in access to mobile-broadband networks of 23% and 11%, respectively (International Telecommunication Union, 2020). These challenges in digital connectivity have several dimensions and require a wholesome approach to address. However, access to power is fundamental to finding a solution to ensure nobody is left behind in the universal digital connectivity campaign. Access to electricity in Africa is faced with technical, political commitment, and financial issues identified by Brew-Hammond (Brew-Hammond, 2010). These challenges have seen significant improvement leading to increased electricity access in some African sub-Saharan regions, as reported in the African Energy Outlook 2019. These improvements are noticeable in a few countries in the sub-region, such as Kenya, Senegal, Rwanda, Ghana, and Ethiopia. In Ghana and Kenya, the electricity access rate as of 2019 was almost 85%. Grid connections have accounted for most progress in Africa over the last decade, but off-grid systems have rapidly increased deployment to augment grid extension challenges (International Energy Agency, 2020; Kumi, 2017b; USAID, 2020; World Bank, 2019). There are, however, unelectrified areas due to the high cost of grid extension and remoteness.

Globally, mobile telephony has the most intriguing success stories of technology diffusion. Compared with fixed-line telephony, it achieved phenomenal subscribers in a short period and became a household technology (Bento, 2016; Kalba, 2008; Kauffman & Techatassanasoontorn, 2005). Since the introduction of mobile cellular services into Ghana by Mobitel in 1992, it has immensely enhanced Ghana's economy. Telecommunications services have become an integral component of the daily lives of Ghanaians, from traditional voice calls to the payment of utility, data services, medical advice, and mobile money services (banking) (Chris et al. 2002; Haggarty, Shirley, & Wallsten, 2005; Osei-Owusu, 2015; Osei-Owusu et al., 2002). The country's telecom industry services consist of fixed-line services, mobile 2G/3G/4G, and Internet Service Providers (ISPs). Currently, there are four 2G/3G/4G active, licensed operators in Ghana. Mobile Telecommunication Network (MTN) has over 50% of the market share in voice and data services as of the first quarter of 2020 (National Communication Authority- Ghana, 2020). The country has a vibrant commercial telecommunication industry providing the platform for innovative services. The capacity, coverage, and availability of their infrastructure were tested in the wake of the pandemic. Power availability is directly tied to the performance of the telco and users.

The services provided serve a considerable populace, positively impacting broader economic growth and contributing significantly to government finances(GSMA, 2019). As of 2016, Ghana's mobile penetration rate stood at 131.9%, according to the National Communication Authority-Ghana (2019). Estimates of the mobile penetration rate of 2020 stood at 140% and are expected to increase due to the pandemic's increased demand for mobile connectivity (Statista, 2020). The recorded mobile penetration rate does not mean all Ghanaians own a mobile phone; instead, an individual could own multiple subscriber identity modules (SIM). According to Groupe Speciale Mobile Association (GSMA) intelligence, the country has the highest mobile penetration in the West African sub-region, surpassing others in the region with an adoption rate of 55%, higher than the regional average 44.8% at the end of 2019.

Ghana's Telecom infrastructure, such as towers and power systems, are either owned or operated by the Mobile Network Operator (MNO) or licensed tower companies (National Communication Authority- Ghana, 2018); the latter is prominent. As of 2012, there were 5,583 tower sites in the country, with 638 sites, approximately 11%, deployed in off-grid areas. One of the main challenges for these telecommunication companies in providing reliable and broader coverage is access to an uninterrupted power supply. Telcos operators achieve continuous power supply by running diesel generators and backup batteries. In Ghana, an average of 1,300 liters of diesel is consumed monthly by an off-grid site against 450 liters for grid-connected cell sites(Green Power for Mobile, 2012). Apart from being expensive to operate, diesel generators (DG) also have the disadvantage of greenhouse gas emissions with implications for global climate(Höök & Tang, 2013; Johnsson et al., 2019; Williams, 2002; Wuebbles & Jain, 2001). Studies have estimated that about 2-3% of the world's energy consumption is on Information and Communications Technology (ICT), contributing to about 3% of the total CO_2 emissions (Anayochukwu & Nnene, 2013; Cunliff, 2020; Höök & Tang, 2013; Johnsson et al., 2019; Lu, 2018). The continual powering of these ICT appliances and infrastructure on unclean energy sources directly impacts the environment. Rising fossil fuel prices, fuel spillage, fuel pilferage, and the short life span associated with DG use from the frequent start and shut down procedures are challenges confronting MNO and tower companies(Tebepah, 2015).

Ghana has a high access rate to grid electrification, at approximately 85% in 2019. Remote communities that have not been connected yet may remain so for the foreseeable future due to the high cost of extending the grid to these communities, where productive use opportunities are currently limited (Kumi, 2017a; Ministry of Energy, 2017.). The potential to use renewable energy resources for electrification of rural and remote communities has been espoused largely in literature with confirmatory findings (Aboagye et al., 2021; Brown & Hewitt, 2006; Opoku et al., 2020). The country is located along the equator and positioned to receive significant solar irradiance. The average solar irradiation ranges from 4 to 6 kWh/m² per day, ideal for harnessing to create isolated/grid-connected power systems to meet isolated communities' load demands or supply the grid. The potential has been identified and supported by Ghana's renewable energy policy, which focuses on improving cost-effectiveness and creating favorable regulatory and fiscal regimes for RE. It further seeks to support local research and development to reduce costs and promote solar PV power technology in its renewable energy master plan and action plans (ECREEE, 2015; Ministry of Energy, 2019).

Renewable energy systems offer a solution that involves replacing part or wholly diesel generators with renewable energy sources as the main power supply for tower sites. Powering a cell site with solar PV can be achieved totally (standalone) or partially (using a hybrid of electricity from the grid, diesel generator, or other renewable energy technologies). Hybrid systems use more than one energy source, thereby taking advantage of the benefits of those energy sources. Several combinations of conventional and renewable power system configurations are implemented for telecommunication purposes worldwide. Renewable power options adopted are dependent on resource availability at the site (Anayochukwu, 2013; Anayochukwu & Ndubueze, 2021; V. Ani, 2017). In the northern part of Ghana, annual solar radiation averages approximately 5.57 kWh/m^2/day throughout the year (Energy Commission, 2018). While wind speeds are relatively high in the harmattan season (between December and March every year), there are no ground measurements to confirm wind resource viability for commercial electricity generation(Essandoh et al., 2014).

Techno-economic comparison of standalone solar PV/ hybrid(diesel/wind) feasibility studies has been conducted in countries with unreliable grid networks in the African sub-Saharan extensively in Nigeria, using hybrid optimization for multiple electric renewables (HOMER). Lanre demonstrated in a study that hybrid(solar PV, batteries, and diesel) could supply the electricity requirement of a health facility in Nigeria for an off-grid community (Olatomiwa et al., 2018; Olatomiwa & Mekhilef, 2015). In Nigeria, Ani (2016) conducted a solar PV/hybrid system feasibility for a residential home; the finding suggested that the load could be supplied with a hybrid solar PV/batteries/diesel generator with the least net present cost (NPC). Feasibility studies have been carried out exploring solar PV, wind, and diesel generators as a hybrid system to power remote telecommunication sites in Nigeria, suggesting that the hybrid system was the optimum design. These studies further suggested a reduction in carbon-dioxide (CO_2) released into the environment. The economics of systems played in favor of hybrid systems over the system's life cycle. However, the hybrid systems had the highest initial capital investment compared with conventional diesel generators. In these studies, the numeral values of parameters of comparison varied significantly due to varied load sizes and system pricing (Anayochukwu & Ndubueze, 2013; Babatunde et al., 2019; Olatomiwa et al., 2015). Similar feasibility studies in Malaysia with HOMER comparing standalone and hybrid systems showed that the hybrid system was sustainable, economical, and environmentally-friendly (Alsharif & Kim, 2016; Alsharif et al., 2015; Halabi, Mekhilef, et al., 2017; Hossain et al., 2017).

In Ghana, studies on the feasibility of renewable energy systems solutions have considered electrification of remote or island off-grid communities, with results suggesting the promising utilization potential. However, challenges ranging from techno-economics to socio-technical need to be addressed to reap the benefits of renewable energy solutions(Bukari et al., 2021; Gyamfi et al., 2015; Kemausuor & Ackom, 2017; Nuru et al., 2021). A feasibility study on a hybrid mini-grid renewable energy system (consisting of solar PV and biodiesel generators) in Wa East district by Adaramola et al. in 2017 using HOMER computer application software showed a COE of US$ 0.76/kWh from the system at full cost (Adaramola et al., 2017). In recent times, a standalone hybrid mini-grid system (solar PV/battery/converter) feasibility study for an off-grid community of Nkrankrom in the Bono region with HOMER showed COE as US$ 0.107/kWh making it the preferred choice over grid extension to the community.

The feasibility study results conducted by Quansah et al. on powering an outdoor base transceiver station (BTS) in the Eastern region suggested a 48% saving on COE from a standalone diesel power solution with a hybrid (diesel/solar PV (Quansah et al. 2017). Furthermore, in an attempt to explore competitive alternate sources of power to power a telecommunication site by Odoi-Yorke & Woenagnon, (2021) using HOMER for a solar PV/fuel cells hybrid system, the results show that the levelised COE (LCOE) produced by the PV/fuel cell hybrid system is about US$0.222/kWh. This LCOE outshines the current average grid tariff (US$ 0.25 /kWh) paid by grid-connected telecom base stations. Although many other studies have been reported on powering telecommunication sites in other parts of the country, there were no published studies in our study area to the best knowledge of the authors. This study went further to compare the proposed power solutions to grid extension referenced to the electric distance limit (EDL)/breakeven distance.

Has this unfortunate turn of events favoured renewable energy potential to provide power to remote telecommunication sites in Ghana's northern parts? This paper performed a techno-economic analysis of a standalone solar PV, hybrid power systems, and grid extension option to determine if the current rising fuel prices and the reducing cost of solar PV system components have affected previous studies' results. The findings suggested that a standalone solar PV power solution is affordable compared with other solutions (hybrid, diesel only, and grid extension) and would enhance universal access to reliable digital connectivity towards attaining sustainable development goals. The study's outcome suggested a paradigm shift for researchers and stakeholders in the industry of the previous findings. It contributed to the scientific literature on the prospects and benefits of deploying renewable energy. In the wake of the COVID-19 pandemic, a revisit to past research findings is key to informing policy and regulation development to accelerate renewable energy in Ghana and countries with similar climatic conditions.

MATERIAL AND METHODS

The study employed a non-intrusive energy audit technique to generate load profiles used in HOMER software. HOMER software is an excellent techno-economic feasibility studies tool suitable for this study objective as used in similar studies. It is a computer-based model used in micropower systems design and compares the cost of energy from different power generation technologies. As seen in the literature, HOMER is widely used for techno-economic studies of renewable energy systems and performs calculations with high accuracy. It can model systems' physical behavior and compare design options based on their technical and economic merits. (HOMER Energies, 2021).

HOMER simulates systems' operation by making the energy balance calculation for each of the 8760 hours in a year. The model's primary inputs were monthly solar insolation, cost of components, diesel price, daily load profile, and other economic parameters. A list of configurations sorted based on the Net Present Cost (NPC) were presented. However, the system configuration based on TNPC could vary depending on selected sensitivity variables. The software repeats the optimization process for every selection of sensitivity variables. In this study, the sensitivity variables were fuel price, discount rate, and cost of solar system components. The optimal solution from HOMER for a renewable energy system is the feasible system with the lowest TNPC(Gilman & Lilienthal, 2006).

Study area

Ghana's Northern part is characterized by low laying landscape with few escarpments and savannah vegetation. The region's climate is relatively dry, with a single rainy season in May and ends in October. The amount of rainfall recorded annually varies between 750 mm and 1,050 mm. The dry season starts in November and ends in March/April, with the highest temperatures recorded towards the end of the dry season (March-April) and the lowest temperatures recorded in December and January(Cudjoe et al., 2013). The dry season features dust that could settle on solar panels. A previous study on the effect of dust on solar panels' performance showed a significant portion of solar radiation blocked by dust particles(Styszko et al., 2019). The study community is Keto - Daboya in the North Gonja district (lies between Lat 9° 39' 01" N, Long 1° 23' 23") in the Savannah Region of Ghana. The community is along the Daboya river, a tributary to the White volta. Access to communities in these catchment areas is characterized by inadequate network coverage and bad road conditions and is usually cut off in the rainy season.

Solar resource assessment and input

The average annual solar irradiance in the region is 5.57 kWh/m^2/day, with monthly averages provided in Table 1. The study area's estimated solar energy potential is 2,033 kWh/m2/year based on the detailed solar data. From December to early February, the Sahel's harmattan winds significantly impact temperatures in the region, causing a variation between 14˚C at night and 40˚C during the day(Cudjoe et al., 2013). These temperatures are within the operating temperature of 47˚C for flat plate solar panels.

TABLE 1. Average global horizontal solar irradiance of the study area

Month	Clearness Index	Daily radiation (kWh/m^2/Day
January	0.607	5.44
February	0.607	5.842
March	0.591	6.058
April	0.569	5.984
May	0.563	5.843
June	0.548	5.596
July	0.478	4.9
August	0.473	4.913
September	0.51	5.242
October	0.592	5.777
November	0.641	5.819
December	0.628	5.476

Furthermore, the region under study has a good clearness index. The clearness index measure approaches the optimum value of 1, indicating that more solar radiation can penetrate the atmosphere to fall on the solar PV panels. Its value increases under clear, sunny conditions and decreases under cloudy conditions. Considering the effect of temperature on panels' output, HOMER computes the PV array's output power as shown in Equation 1.

$$P_{PV} = Y_{PV}\, f_{PV}\left(\frac{\bar{G}t}{\bar{G}t,STC}\right)[1 + \alpha_p (T_c - T_{c,STC})] \quad \text{………………………………………….. (1)}$$

Where:

P_{PV} is the output power, Y_{PV} is the rated capacity of PV array under standard conditions [kW], f_{PV} is PV$_{derating}$ factor [%] which represents effect of dust falling on panels, wiring losses, shading, ageing, etc. ranging from 0.5 to 0.95, $\bar{G}_t$ represents the solar radiation incident on the PV array in current time step [kW/m^2], $\bar{G}t$, STC is the incident solar radiation at standard test conditions (STC)[kW/m^2], α_p is temperature coefficient of power [%/˚C], T_c PV cell temperature in current time step [˚C] and $T_{c, STC}$ is PV cell temperature under standard test conditions [25˚C](Islam, Akhter, & Rahman, 2018). A monocrystalline solar panel was used in the simulation due to the excellent efficiency of an average value of 16.4% at standard test conditions.

Solar resource input for simulation

This part requires information on the solar resource available on the site to model, simulate, and assess the performance of a system. HOMER software downloaded the site's solar resource from the National Aeronautical Space Administration (NASA) Surface Meteorology satellite. The area receives an annual daily average of 4.9 kWh/m^2 to 6.058 kWh/m^2 of global sun irradiation. This choice was made because there was no publicly available found data on solar radiation measured from the ground were available for the specified site (Asuamah et al., 2021)

Electric load demand of site

To minimize the effect of error in load estimation of the study, a non-intrusive energy audit technique was employed at existing sites to generate the load profile. The electric load demand at a site depends on its capacity, active traffic, and additional functions. A hop/hub site linking other sites via a microwave transmission radio or fibre optic systems or both would have higher power consumption compared to a terminal site. This assertion might not always be accurate as a terminal site installed in a densely populated community might have several base transceiver stations impacting its power consumption considerably. To check this uncertainty of terminologies, the study considered the electric load demand of ten (10) outdoor cell sites base transceiver station (BTS) (2G/3G) of a telecommunication operator. An outdoor site does not necessarily mean the site is a hop/hub or terminal site but refers to the provision of shelter space with air cooling systems to control equipment temperature. The absence of air-cooling systems (air conditioners) in outdoor sites reduces its electricity demand making it the preferred choice in modern telecommunication site design. Good load forecasting is crucial to the design of power systems. Electricity demand estimation was based on ratings of equipment. The criteria for the selection of sites are presented in Table 2.

Table 2. Selection criteria for sites

Selection criteria
Outdoor site
BTS 900/1800/Node B
Transmission radio
Standby diesel generator

An outdoor site BTS 900/1800/Node B single cabinet with three (3) sectors each and two (2) plesiochronous digital hierarchy (PDH) microwave radios for transmission was selected for the study. The aforementioned equipment constituted the main equipment of the site with an additional auxillary load such as power outlets, aviation warning lights, and security floodlights, as summarized in Table 3.

Alternating Current (AC) loads on a direct current (DC) source power requires an inverter for conversion, introducing losses in the process. A DC load is preferred for an optimum solar PV system; however, this is not the case in some sites. Air conditioners for shelter are usually AC load, and their motors require a high startup current, about three (3) to five (5) times its rated current. The site selected for the study is a modern outdoor BTS using DC fans for cooling, thereby eliminating the energy cost of air conditioners. A rectifier is required in a hybrid (Solar PV/diesel generator) system to convert AC from the generator to DC. Table 3 shows details of equipment of the selected site with the power rating of the equipment.

TABLE 3. Load estimation of outdoor (900/1800/Node B) cell site

Power equipment description	Rated Power (W)	Quantity	Duration of usage (h/day)	Daily power (Wh/day)
BTS (900/1800/Node B)	2640	1	24	63,360
PDH transmission radio	125	2	24	6,000
Aviation warning light	15	2	12	360
Security/flood lights	100	1	12	1,200
			Total	**70,920**

Daily load curve input estimation

The main loads of a telecom site (BTS and PDH transmission radio) run continuously for 24 hours per day, with varied power consumption. The energy consumption of the BTS is linked to traffic processing. The traffic profile varies for sites depending on the demographics. For example, an urban center, especially in educational institutions where students patronize promotional calls (voice and video) and data packages, will vary significantly compared to a farming community. BTS's energy demands reduce by 80 - 85% during idle periods as most sectors are off, leaving the baseband unit for signaling(ZTE Corporation, 2003). The BTS solemnly operates at rated capacity; therefore, the rated power used in the study will account for the system's tolerance. Auxiliary loads such as lighting used during certain day hours (6:00 pm -6:00 am) were factored into the hourly load profile. The tolerance or error margin will account for the stochastic powering of measuring instruments and computers for corrective and preventive maintenance. The load profile of an outdoor site is shown in Figure 1.

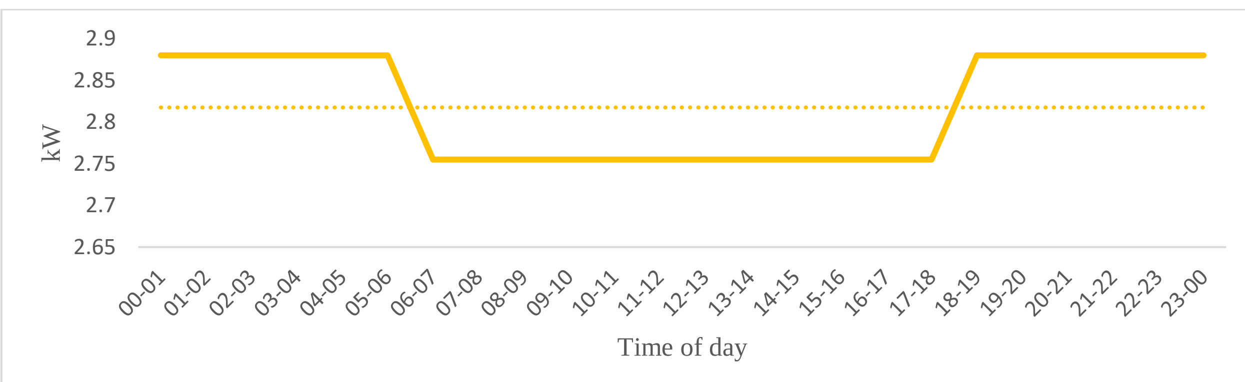

FIGURE 1. DC hourly load profile

Economic input variables

Mobile Network Operators (MNO) and Tower Companies lease land or rooftop of buildings for site construction for five (5) years with options to renew. In this study, area or space for construction is assumed to have been acquired and therefore not considered economic input for the power system. However, the land/space allocated for a site intended to use solar PV systems must be adequate to accommodate the installation. Currently, the leased land area is typically 100m^2 or 144m^2, which houses the tower, shelter/cabinets, diesel generator (DG), etc. This setup limits space for solar PV panel installation. The system fixed capital cost in HOMER includes the capital cost of equipment, installation labour cost, replacement cost, operation and maintenance (O&M) cost, transportation cost, and additional components cost. The economic constraints set for the simulation were; the inflation rate of 7.9%, annual interest rate of 16%, as stated by the Bank of Ghana(Bank of Ghana, 2020). The cost curve was taken to be linear; thus, as component size increases, the component's price increases, and vice versa. A typical system life span of 25 years was assumed for the study.

Prices of diesel generators vary greatly from manufacturers, brands, and features. Diesel price per liter considered for the financial analysis was the average price from September 2019 to January 2020, with a 10 % adjustment for transport to the site estimated at GH₵ 5.94 per liter, equivalent to US$ 1.0925/liter at the prevailing exchange rate(Bank of Ghana, 2020). Other diesel prices used for the sensitivity analysis were based on the country's diesel price history(Statista, 2022). Table 3 shows the cost used in the simulation of the system.

TABLE 3. Economic inputs variables for components of systems

Components	Size	Capital cost (US$)	Replacement cost (US$)	O&M (US$/year)	Source
Diesel Generator	10 kW	3,000.00	3000.00	263	(MANTRAC, 2022)
Flat plate Monocrystalline Solar PV	1kW	750.00	750.00	5	(HTC Ghana, 2021)
Storage Battery SAGM 12 135	12 V /200 Ah	339.00	300.00	5	(Yeboah et al., 2021)
System converter	5 kW (48V)	867.00	800.00	-	(Yeboah et al., 2021)

Economic indicator – Levelized cost of energy (LCOE)

This indicator is computed as the average cost per kWh useable electrical energy produced by the system under study using the following equation in HOMER (Quansah et al., 2017).

$$LCOE = \frac{Cann,tot - Cboiler\ E\ thermal}{Eprim,AC + Eprim,DC + Edef + E\ grid,sales} \quad (2)$$

Where;

$C_{ann,tot}$ is the total annualized cost [$/yr], c_{boiler} is the boiler marginal cost [$/kWh], $E_{thermal}$ is the total thermal load served [kWh/yr], Eprim,AC is the AC primary load served [kWh/yr], E_{prim},DC is the DC primary load served [kWh/yr], E_{def} is the deferrable load served [kWh/yr], and $E_{grid,sales}$ $E_{grid,sales}$ is the total grid sales [kWh/yr]. Terms that do not apply to this study were set to zero (0) in equation (2) by HOMER in the model.

Grid extension estimates to community

The grid extension cost in Bono region of Ghana was estimated at US$ 10,607.3/km by Yeboah et al. (2021) based on the study conducted by Longe et al. (2014) for an off-grid community with mountainous terrain called uMhlabuyalingana in South Africa of $20,000/km for 11 kV line extension. Yeboah et al. (2021) argued that their estimation was lower because the site/area under study had a good terrain without mountains. The challenges associated with mountainous terrain are expected to increase the extension cost. This study adjusted the estimate of Yeboah et al. (2021) by 10% to cater for the difference in location and river crossing. The resulting estimate for the 11kV was US$11,668.03/km with an operation and maintenance price of US$260. The Savannah region which is the study area region, is characterized by a low-laying landscape and savannah vegetation.

HOMER system simulations

The HOMER software's simulation process addresses the uncertainties associated with renewable energy sources, load demands, and input variables. It is achieved in three folds of tasks: simulation, optimization, and sensitivity analysis. Firstly, it determines whether the system is feasible and calculates its net present cost (NPC). It considers the system viable if it can adequately feed the load (electrical power in this instance) and meet any other constraints specified. Secondly, it performs multiple simulations on different system configurations using the Graham algorithm. It estimates the system's life-cycle cost as the total cost of installing and operating the system over its lifetime. The best possible or optimal system configuration is the one that satisfies the user-specified constraints at the lowest Total Net Present Cost (TNPC). Finally, it assesses the effect of uncertainties of variables beyond the designer's control, such as interest rates, system component cost prices, and fuel prices, by performing several optimizations under given assumptions to assess the extent of changes in the designer's inputs. It executes different combinations of these defined input parameters in Table 3 and optimal configuration combination with the least TNPC determined. It also determines the excess electricity generated by the energy sources when the minimum output surpasses the system's load demand and energy storage facilities. A limitation of HOMER is that it does not model electrical transients or other dynamic effects, which would require much smaller time steps.

Operating strategy of systems

The current design configuration for most grid-connected sites is grid-battery-DG, with the battery and DG serving as a backup power source due to the unreliable grid supply. None of the on-grid sites were initially designed to run solely on the grid or grid-battery hybrid power system. The study considered powering a new off-grid telecom outdoor site on;

1. Solar PV with backup batteries as a standalone system
2. A hybrid system comprising solar PV and a diesel generator with backup batteries.
3. Grid extension to the site

The telecom load requires uninterrupted power to ensure continuous network service; therefore, there was no deferrable load. The standalone system uses a backup battery to remedy the intermittent nature of the solar PV system. Figure 2 illustrates the schematic diagram of the power solutions simulated. The four system configuration scenarios considered were as follows;

1. A standalone solar PV system.

2. A hybrid system with a cycle charging strategy (CCS) is used. In this dispatch strategy, the generator is operated to serve the initial load at full output power. The surplus electrical power produced goes into charging the battery bank.
3. A DG with backup batteries as a base case for comparison.
4. Grid extension

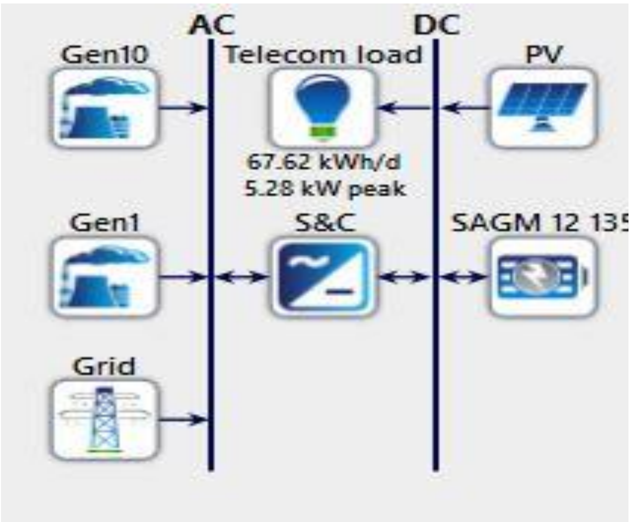

FIGURE 2. Schematic diagram of the power system configuration in HOMER.

Input variables for sensitivity cases

The Intergovernmental Panel on Climate Change (IPCC) report showed that the trend of solar systems costs over the last 30 years had seen more than a 10% annual decrease; however, it is still not competitive with conventional power systems(IPCC, 2012). The sensitivity analysis of solar system components was done with a 10% decreasing multiplier based on the IPCC report on solar PV system components such as PV panels, converters, and batteries. Sensitivity analysis performed on fuel price was based on the rising trend (Statista, 2022). It was carried out to investigate the behaviors of the proposed systems under uncertainties. Table 4 shows the sensitivity ranges considered in the study.

TABLE 4. Sensitivity variables ranges used for analysis

Input variables	Unit	Ranges of sensitivity
Price of diesel	$/L	1.0925, 1.25
Component cost	*	1, 0.9
Discount rate	%	16, 10
Load annual growth	%	25
Solar radiation monthly scale average	%	30

RESULTS AND DISCUSSIONS

This section presents and discusses the study's findings in the form of tables and figures geared toward the study's objectives. The discussions would follow the lines of technical and economic comparison of the study's system scenarios regarding the performances of the conventional diesel generator's base system. The results capture the system configurations' economic, technical, and GHG emissions, standalone PV, hybrid (PV/DG), grid extension, and DG from HOMER.

Optimization results

HOMER results are presented in two parts; the sensitivity cases and optimization results. The optimization results showed that all the systems models considered by HOMER were feasible and capable of meeting the load specified under all settings. The results were presented based on each category's best and presented the best among the categories at the top of the list. The system with the least Net present Cost (NPC) is the best. Figure 4 illustrates the optimization results of the study generated by HOMER from the simulation. A standalone solar PV system comprising 56.3 kW solar PV, 60 pieces of SAGM 12V 135Ah batteries having NPC of US$ 88,176.00 at the cost of energy of US$ 0.321/kWh. The choice of system to meet an off-grid load; thus, solar PV/battery system is the same as in previous studies (Asuamah et al., 2021; Longe et al., 2014). However, there are variations in figures, for example, COE with those studies. This variation could be due to the cost of components and load size with the current research. It is interesting to note that previous studies suggested that hybrid systems were the best to meet the load demand of telecommunication sites, as aforementioned in the introduction of this work. Apart from the difference in system type, the COE of this study is less than the findings in the work of Quansah et al. (2017) for a telecommunication site in Ghana. It further suggests that decreasing solar PV and rising fuel prices in the wake of COVID-19 have impacted the results of previous studies. If this trend continues, it would make investment in solar PV systems competitive. . According to Ghana's Energy 2020 Energy outlook, the average end-user tariff as of the end of 2019 was GHp 71.6, an equivalent prevailing rate of US$ 0.12/kWh (Commission, 2020) for electricity supplied from the national grid. Therefore, COE from the standalone solar PV/battery system is still high compared to COE for grid-connected cell sites. It further suggests that the solar PV/battery system is not competitive in the grid-connected areas but suitable for remote locations.

PV (kW)	Gen10 (kW)	Gen1 (kW)	SAGM 12 135	S&C (kW)	Dispatch	COE ($)	NPC ($)
56.3			60		CC	$0.321	$88,176
21.7	10.0		50	3.79	LF	$0.505	$138,826
19.5		10.0	60	4.56	LF	$0.511	$140,523
	10.0		18	7.67	CC	$0.672	$184,675
		10.0	18	8.23	CC	$0.673	$184,969
2.54	10.0	10.0	4	4.48	LF	$0.697	$191,663
2.24	10.0	10.0		4.69	CC	$0.700	$192,521
	10.0	10.0	1	4.70	LF	$0.711	$195,439
	10.0	10.0		4.73	CC	$0.712	$195,689

FIGURE 4. Optimization results generated by HOMER for scenarios being compared

Cost summary and comparison of systems

Table 5 summarizes the three proposed configurations' simulation results for comparative analysis with the DG system as the base system.

TABLE 5. Comparative analysis of proposed configuration

Description	Parameter	System Configurations		
		Standalone Solar PV	*Hybrid (Solar PV & Diesel Generator)*	*Diesel Generator*
Cost Summary	Cost of Energy (COE) (US$)	0.321	0.505	0.672
	Net Present Cost (US$)	88,176.00	138,826.00	184,675.00
	Operating Cost (US$)	2,677.00	9,305.00	15,653.00
	Initial Capital (US$)	58,351.00	35,163.00	10,298.00
Compare economics with DG as the base case system	Present Worth (US$)	107,513.00	56,864.00	-
	Annual worth (US$/yr)	9,651.00	5,104.00	-
	Return on Investment (%)	23.5	22.7	-
	Internal Rate of Return (%)	28.7	28.4	-
	Simple Payback (year)	3.34	3.39	-
Electrical	Generic flat plate PV (kWh/yr)	93,348	35,908	-
	DG (kWh/yr)	-	10,952	27,536
	Excess Electricity (kWh/yr)	66,426	20,562	16.4
	Unmet load (kWh/yr)	17	21.7	17
	Capacity shortage (%)	23.1	24.6	24
	Renewable Percentage	100	76.6	0
Emission	Carbon Dioxide (kg/yr)	0	13,676	26,067
	Carbon Monoxide (kg/yr)	0	103	197
	Unburnt Hydrocarbons (kg/yr)	0	3.77	7.18
	Particulate matter (kg/yr)	0	6.27	12
	Sulfur Dioxide (kg/yr)	0	33.6	64
	Nitrogen Oxides (kg/yr)	0	118	224
Battery	Autonomy (hr)	28.6	23.8	8.58
	Expected lifespan (year)	6.25	8.32	1.97
Fuel Summary	Total fuel Consumed per year (L)	-	5235	9,978
	Average Fuel per day (L/day)	-	14.3	27.3
	Average Fuel per hour (L/hr)	-	0.598	1.14

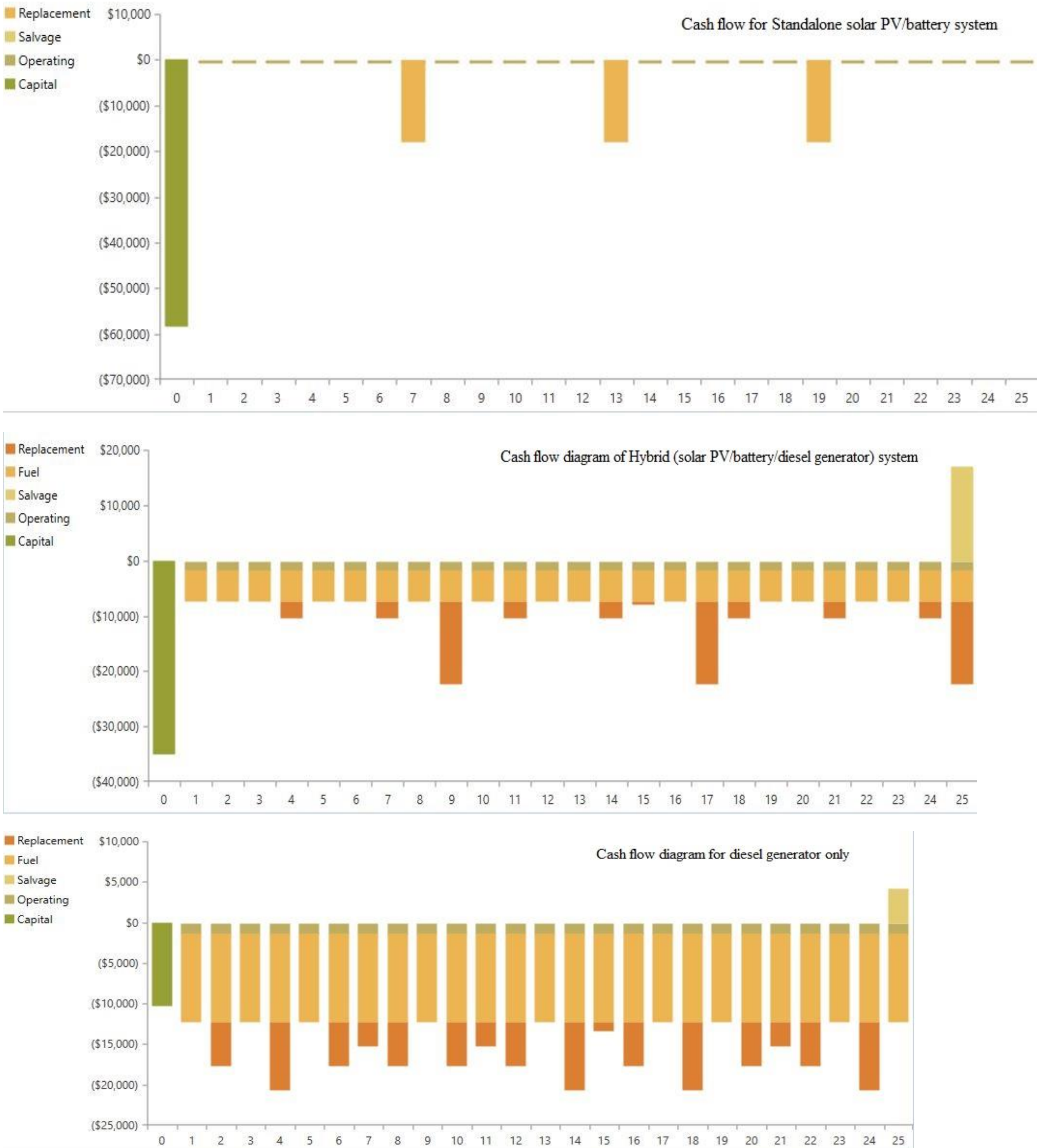

FIGURE 5. Cash flow comparison of the simulated systems

Summary of economic analysis

The results summarized in Table 5 show the feasible systems comparing their cost summary values, economics compared with a diesel generator as a base system, the electrical parameters, emissions, batteries, and fuel summary where applicable. The comparison gives an insight into the economics of the systems from HOMER for decision making and the implication of choice. Figure 5 illustrates the systems' cash flow trend in the optimization results, which suggest the diesel generator solution's continuous and high operating cost. The standalone solar PV system had the highest initial capital, battery quantity, and operating cost. Sustaining the site load solely on solar PV would require more panels and batteries to generate and store power. It has implications on the initial capital and system replacement cost, thereby increasing its life cycle cost. The standalone PV system's running cost is low because there is no additional cost incurred in fuel purchase for running the system. The popularity of DG in the current sites is explained by the attractively low initial capital, proven technology, and stable power generation. However, the operating cost is high, mostly attributed to fuel purchases. The high quantity of fuel consumed by DG has a corresponding effect on GHG emissions. Although technically viable, the economics of the DG system suggests it's not the best among the options available. The NPC and COE of DG are about twice the cost of the standalone solar PV system.

The study area is characterized by dust in the dry season, which is about half the year. The presence of dust in the atmosphere reduces radiation reaching the panel, thereby affecting power generation from the panels. To assess the impact of dust on the system, the sensitivity of a reduction in solar radiation resource showed an increased COE and TNPC as radiation reduced. The increase in cost is from increased capacity to supply the load demand. This information is vital in developing a maintenance schedule for the solar PV systems to ensure competitive system cost, long life span, and sustainability. Although load growth is essential in system design consideration, the solar PV system's modular nature addresses the challenge. It also suggests that new sites could be designed with solar PV power solutions.

Grid extension breakeven distance analysis

The addition to the study is the comparison of the proposed power solutions with grid extension to the site. The cost associated with grid extension was compared to determine the distance at which grid extension is better than the isolated power solution, called the breakeven distance. The breakeven distance, or Electric Distance Limit (EDL), between a standalone power solution and grid extension was determined and summarized in Table 6 in this investigation. This means that for an isolated power solution to be more cost-effective and efficient, the distance from the nearest grid network must exceed the EDL. Although the country has achieved impressive electricity access, there are still communities with proximity to the nearest grid network of over ten (10) km. The distance between the Keto community to the Daboya, the district capital with a grid substation, is 18 km, greater than the breakeven distances of all the systems considered. Furthermore, the cost of grid connection continues to rise. In contrast, the market's price of renewable energy sources continues to fall, making a stronger case for electrification of off-grid sites with standalone solar PV systems competitive.

Table 6. Electric Distance limit for grid extension to the site at Keto

Proposed system	Breakeven distance (km)
Standalone Solar PV/battery	4.51
Hybrid - Solar PV/battery/diesel generator	8.28
Diesel Generator only	11.69

Green House Gas (GHG) emissions of systems

Combustions of fossil fuels by DG emit harmful gases and particulate matter that negatively affect the environment. The GHG emission levels are shown in Table 5. In terms of GHG emissions from the systems, the standalone system is considered clean since its operation does not emit GHGs. The results summarized in Table 5 show that the standalone system has zero emissions, as solar PV does not emit any GHG. The hybrid system also has a medium emission from low fuel consumption. DG usage contributes 26,067 kg/year of Carbon dioxide from the combustion of 9,978 L/year of diesel. These figures represent an insignificant portion of the $MtCO_2e$ unit of measure; however, the numbers increase when these figures are scaled to the total number of sites running on diesel generators. Data on fuel-related emissions from the Environmental Protection Agency (EPA) shows an annual increase of 2.1% from 1990 to 2016(EPA, 2019). The increase is attributed to fossil fuel combustion from the country's electricity and transport sectors. There is, therefore, the need for conscious efforts to minimize fossil fuel use and commit more to the use of renewables in the commitment to fight climate change(Abokyi et al., 2019).

Other positive impacts of the availability of electricity to the community

Aside from the benefits derived from services of connecting to the digital space. The network availability in the Keto community has other benefits for the locals. The network signals would extend to neighboring communities that stand to benefit and facilitate the general wellbeing of the inhabitants. The results also suggested significant excess electricity from the proposed system. The excess electricity with appropriate arrangements with the locals could power floodlights near the site to support night studies for students and phone charging.

CONCLUSION

The study found that a standalone solar PV/battery system was the most economical option for powering an off-grid telecommunication site. Although the system choice has an initial high investment cost, the NPC is the least. The base case system has the least initial capital cost but has the highest TNPC, operating cost, and COE. In addition to the economic benefits of the standalone solar PV/battery system, it has a minimal environmental impact on the environment as it does not emit greenhouse gases in operation. Therefore, there is a need for government intervention in the form of subsidies and waives if solar PV technology is to achieve parity in COE.

The power solution choice is different from previous studies, with a COE from the solution approximately 50% less. In comparison with the cost of grid extension to the site, the breakeven distance was about four times the distance to the community of Keto in the North Gonja District, further making a substantial augment for renewable energy power solutions

Renewable energy technologies should be promoted for cell sites, in line with the government's policies to promote renewable energy, as in Ghana's Renewable Energy Law and the Renewable Energy Masterplan. Heavy dependence on fossil fuels continues to increase humanity's carbon footprint. Solar PV/hybrid systems will reduce the national electric load to augment the deficit in generating capacity even in grid-connected areas. Therefore, there is a need to invest in renewables to meet today's needs without affecting the survival of future generations. Sustainable development is achieved with a balance of the economy, society, and environment. The study's findings further promote universal access to digital connectivity and contribute to the fight against climate change.

Limitations of study

The variation of electricity consumption with seasons and traffic was not factored in this study. Although the study's objectives have been achieved by the methods employed, there is a need for the simulation to be conducted using intrusive load profiling to capture the variation of electricity consumption with varying traffic at the site. In the long run, off-grid viability is contingent on a variety of other issues, including the availability of spare parts, maintenance personnel, security of batteries, and insurance, which were not examined in this study.

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Declaration of competing interest

The authors declare that they do not have any competing interest

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