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Evaluating the impact of industrial loads on the performance of solar PV/diesel hybrid renewable energy systems for rural electrification in Ghana

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ABSTRACT

Access to reliable electricity remains a significant challenge in many rural communities worldwide. Off-grid solar PV hybrid renewable energy systems (HRES) have emerged as a viable option for rural electrification. However, rural communities' lack of productive load often limits their effectiveness. This study aimed to assess the impact of agro-processing productive loads on the performance of off-grid solar PV HRES for rural electrification. Hybrid Optimization Multiple Energy Resource (HOMER) software was used to perform a techno-economic analysis of a solar PV/diesel HRES. The study findings showed improvement in the rural community's load factor and solar load correlation with the integration of the productive load. Subsequently, increasing the renewable energy fraction in solar PV/diesel HRES reduces the levelized cost of energy (LCOE), making electricity generation more cost-effective for rural electrification in Ghana. Comparatively, the improved LCOE was found to be substantially higher than the End User Tariff of all residential consumers on the national grid, even under high PV penetration and full capital cost subsidy cases. The study provides valuable insights into the role of agro-based productive loads in enhancing the performance of rural off-grid solar HRES.

Introduction

Energy is a key resource for the socio-economic development of every country. In fact, energy is indispensable for the global community to attain the United Nations Sustainable Developmental Goals. Access to electricity improves education and health, reduces poverty, and positively impacts human developmental indices [2,22,43]. Therefore, rural electrification is a vital requirement in bridging the gap in the quality of life between rural and urban areas [65]. Although providing access to electricity is a top priority for many governments, yet still the majority of the global population lacking electricity are rural dwellers in developing countries [22,46,47,52,66].

Rural electrification is a critical global challenge, especially in developing countries [39]. This challenge has led to a wide gap between urban and rural electrification levels, particularly in sub-Saharan Africa (SSA) [41]. For instance, in Ghana, the electrification rate for urban areas is 94.7 %, while that of rural areas is 74 % [81]. Several factors have contributed to the wide gap between electrification rates in rural and urban areas. Some of these factors are the long distances from existing grid networks to rural communities, inaccessibility of locations, high cost of electricity, low energy consumption profiles, low paying capacity of rural dwellers, etc. [22,24,41,48,73]. These reasons, among others, make rural electrification a difficult task for utility companies, and it is sometimes perceived as a risky venture by various stakeholders in the power sector [22,53]. Therefore, countries are unlikely to attain total electricity coverage by extending national grids only [19,22].

Renewable energy (RE) based off-grid power systems are viable options for rural electrification [2,36,42,41,46,53,56]. Thus, in most Sub-Saharan countries, RE-based off-grid generation technologies offer cheaper rural electrification than conventional technologies such as diesel gensets [17,52]. Nevertheless, small-scale off-grid power systems in rural areas face key challenges such as poor electricity demand and low load factor [52]. For example, Das et al. [28] reported low annual average rural load demand and a low load factor of 255 kWh/day and 0.189, respectively. Li et al. [45] observed a load factor of 0.12 for rural load. Murugaperumal and Raj [53] also observed load factors of 0.3755 and 0.1199 for primary and secondary loads of typical rural communities, respectively. Das et al. [26] estimated a primary load of 248 kWh/day with a load factor of 0.23 for a rural community. Likewise, Apichonnabutr and Tiwary [10] reported an estimated annual average daily

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load and a load factor of 277.98 kWh/day and 0.23, respectively. Several other studies reported low electricity demand and poor load factors for rural areas [34,35,65,70].

The typically low electricity demand and load factor of rural areas mainly arise from the reason that rural electricity consumption is driven by domestic applications [17,42,36,52]. Thus, the load profiles tend to have high evening peaks and little or no consumption during the day [9,18,20,28,52,76].

The consequences of the low demand and load factor include low system capacity utilization, poor reliability, high electrification cost, high tariffs, and low financial returns on rural electrification systems [34,35,42,36,48,73,52,64,65]. The problem of poor power system performance is compounded by intermittent renewable energy sources, such as solar energy, for rural electrification projects [52]. A typical challenge is that the peak electricity production pattern usually does not match the load profile [20]. Hence, extra investments in mitigation measures, such as backup storage technologies, are required [52].

In some instances, due to the high cost of storage batteries, the small size of installations, and tariff subsidies provided to grid-based electricity, the per-unit cost of off-grid solar solutions could be substantially higher than those of grid-based electricity [17,73,48]. Comello et al. [25] reported a levelized cost of electricity (LCOE) of 0.380 USD/kWh for a rural community using solar mini-grids with a battery compared to 0.062 USD/kWh for the central grid. Likewise, a study in SSA reported a higher cost of off-grid solar PV systems of 0.830 USD/kWh, compared to that within 0.080 USD/kWh and 0.160 USD/kWh for the conventional grid [73,48]. Hence, although RE-based off-grid systems present viable solutions to meet the electrification needs of rural communities, affordability remains a key concern for rural customers [17,52,73,48].

In this regard, the productive use of rural electrification is among the proposed solutions to improve the electricity profile of rural communities and subsequently make off-grid rural electricity operations more cost-effective and sustainable [17,73,48]. For instance, it has been shown that integrating productive use in rural electrification improves the viability of off-grid projects by improving the electricity demand, especially during off-peak hours [19]. Alfaro et al. [9] alluded that peak and base demand greatly impact the LCOE. Subsequently, the changes to the load demand profile through the connection of rural residential demand to productive loads during off-peak hours could significantly change the cost to the residential sector. The authors recommended using industrial facilities as a load curve management tool to improve the LCOE of electricity supply to residential customers.

Similarly, Blum et al. [20] observed improvements in the daytime consumption and the daily energy demand of a rural residential profile by integrating productive users. The improvement resulted in a higher capacity factor of the power system and, subsequently, reduced the cost of electricity. It has also been suggested that the viability of rural electrification projects could be improved by progressively subsidizing the tariffs of the poor residential users based on the improvement of those of commercial users [73,48]. The study of Alfaro et al. [9] showed that integrating residential and productive sectors into rural electrification projects not only favors residential consumers but also opens opportunities to offset costs for both sectors. Likewise, Moner-Girona et al. [52] reported that, generally, multi-user PV systems have increased performance that reduces electricity costs among the various final users.

Studies also show that the cost of off-grid and mini-grid systems is directly impacted by the size of the system based on economies of scale [4,52]. Hence, the improvement in the energy demand of rural communities due to productive loads could considerably reduce the costs of off-grid RE-based power systems. The studies by [65,66] associated the LCOE reduction of rural communities with the improvement in load factor due to the integration of productive electricity usage for agro-processing and other commercial activities. By improving the load factor, it has been observed that systems that are initially uneconomical for a given load factor could become economical at the improved load factor [42,36]. Alfaro et al. [9] alluded that integrating productive activities into the load demand directly impacts the performance indices of rural electrification projects, such as the load demand characteristics, capacity factor, energy storage capacity, and others.

According to Asuamah et al. [12], productive energy use improves the economic sense of investments in electrification systems. In view of this, the productive consumers could serve as anchor loads to enhance the investment's financial stability and cost recovery [22,66]. Also, through power purchase agreements with productive consumers, some financial risks associated with rural electrification projects could be reduced [34,66]. Existing works suggest that the economic viability of large off-grid PV systems often depends on the presence of productive activities in rural communities [52]. Besides, studies show that productive users are willing to pay higher prices for electricity to obtain a reliable supply [8,73,48]. Thus, in some instances, productive loads are a key consideration for undertaking rural electrification projects [17,34,49].

Similar to the situation in several other SSA countries, poor load factor and low demand are present challenges facing off-grid solar PV-based rural electrification projects in Ghana [2,12]. For example, Adaramola et al. [2] reported poor load factor and low load demand of 12.26 % and 104 kWh/day, respectively, for a typical rural community in Ghana. Also, it has been reported that many customers of rural communities in Ghana are within the lifeline tariff block (i.e., consuming up to 30 kWh/month). Consequently, the major utility companies of the country have raised concerns about the adverse effect of the low load factors and low demand on the economic viability of rural electrification projects in the country.

Infact, several studies confirm the adverse impact of rural communities' poor load factor and low energy demands on the sustainability of RE-based rural electrification projects in Ghana. For example, Adaramola et al. [2] revealed that compared with the end-user tariff of 0.10 USD/kWh for lifeline customers on the national grid, beneficiaries of PV-based mini-grid system could pay 200 % more, even under full-grant finance conditions for maintenance of the system. Likewise, Odoi-Yorke et al. [54] showed that even at 100 % capital subsidy, consumers on off-grid hybrid RE-based electrification system could pay up to 32 % higher than the tariffs charged to the lifeline customers who are connected to the national grid. The findings of other studies on the feasibility of off-grid RE-based rural electrification projects support the argument that even at 100 % capital subsidy, the LCOE of these projects does not attain parity with those of the national grid [7,23].

Leaning on evidence in the existing literature that productive loads could improve the performance of rural electrification systems, this study explores improving the sustainability of solar PV-based rural electrification projects through productive consumption within the context of a developing SSA country, Ghana. The findings of previous studies highlight the need for such a study, as the unproductive use of electricity is a significant challenge to Ghana's rural electrification projects. For example, based on investigations, Bukari et al. [22] showed that low productivity and industrial use are the topmost barriers to deploying mini-grids to remote areas on technical criterion bases. Although Adaramola et al. [2] recommend the daytime use of electricity for productive activities to enhance the sustainability of rural electrification projects, yet still, Asuamah et al. [12] recently revealed that the main application of electricity in typical rural communities in Ghana is for unproductive uses. It is worth mentioning that some previous studies on Ghana's rural electrification systems factored existing productive loads such as those used for health and education purposes and commercial activities (e.g., barbering salon, drinking bars, grocery shops, cold stores, etc.) in the analyses of system performance [2,12,55].

Nonetheless, to the best of the authors' knowledge, the role of industrial loads on the performance of RE-based off-grid rural electrification systems within the context of Ghana has not been clearly investigated. Industrial loads have peculiar characteristics compared to those of the other productive loads considered in previous works, with respect to profile stability, daytime usage, among others [37,40,71,77].

Besides, in Ghana and many other African countries, due to the existing differential tariff systems employed by utility regulatory bodies, the tariff structure applied to industrial loads differs from those of other commercial loads and the residential sector [1,5,60,61].

To highlight the differential tariff system of Ghana, Fig. 1 presents the historic average End User Tariff (EUT) of various consumers and the cost of delivered power in Ghana from 2014 to 2020.

(LV = low voltage, MV = medium voltage and HV = high voltage)

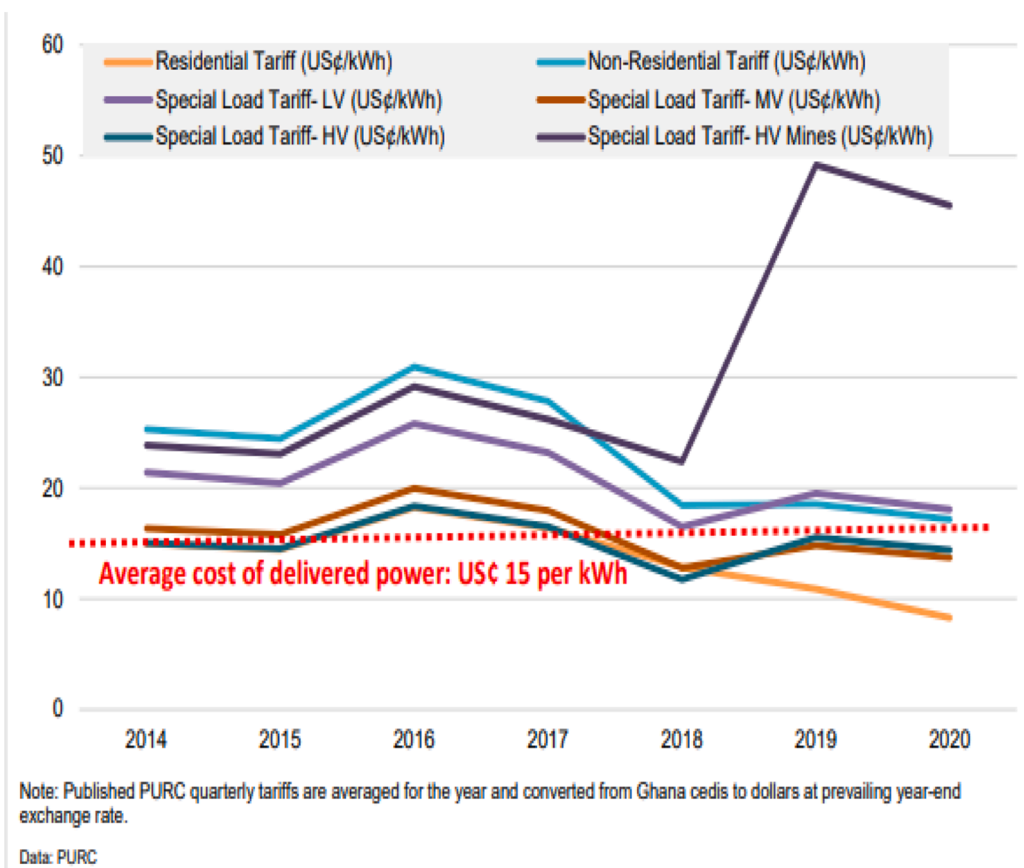
Historically, between 2014 and 2020, the residential sector has been among the lowest-paying end-user tariff consumers (average 0.14 USD/kWh). This energy consumption charge is paid in addition to a fixed service charge of about 1.19 USD/month. The non-residential customers paid an average end-user tariff of 0.23 USD/kWh and a fixed service charge of about 2.32 USD/month. Also, Fig. 1 reveals that the non-residential consumers, special load tariff (SLT)-LV and SLT-HV mines consumers in Ghana pay much higher tariffs than the average delivered cost of power of 0.15 USD/kWh. On average, over the past two decades, electricity tariffs increased by 9.6 % per year, and it is regarded that the industry paid to subsidize residential consumers due to cross-subsidy being implemented in Ghana.

Consequently, the industry pays higher tariffs than domestic users [61]. Therefore, Ghana's electricity tariff structure has been described as punitive, discouraging consumption and negatively impacting business costs, hence necessitating restructuring [60]. According to Acheampong et al. [1], the breakdown of the differential tariff pricing structure for various consumer classes in Ghana is very interesting and nuance. Nevertheless, Ghana's current tariff structure reflects a developing electricity market similar to those in other SSA countries, applying different treatment to electricity customers [5].

The peculiar characteristics and electricity tariff structure of industrial loads highlighted above compared to those of other productive loads factored in previous studies on rural electrification systems necessitates investigating the performance of rural electrification systems with integrated industrial loads in Ghana. Thus, to add to existing scanty works on the productive use of off-grid RE-based rural electrification projects in Ghana, here in this study, we focus on the role of agro-processing industrial load in improving the economic viability of solar PV-based rural electrification project of a residential dominated rural community. In addition, there is evidence in the existing literature that matching solar power production with load demand could improve the performance of solar PV integrated power systems [67,75,78]. Thus, this study further explores the changes in the load profile of the rural community with the integration of the industrial load with respect to its alignment with solar power production through solar-load correlations. It is anticipated that the outcome of this study could be helpful to various stakeholders in the power industry in planning and developing sustainable off-grid RE-based electricity projects for rural communities, particularly in Ghana and other SSA states.

Methodology

This section highlights the approach used to achieve the study goal. It outlines the various stages adopted in the HOMER software required to model the proposed hybrid renewable energy system (HRES).



(LV =low voltage, MV = medium voltage and HV = high voltage)

Fig. 1. Average EUT of various consumers and cost of delivered power in Ghana from 2014 to 2020.
Adopted from [1]

Hybrid optimization multiple energy resource (HOMER) software

This study used HOMER software to perform a techno-economic analysis of the solar PV/diesel/battery off-grid HRES. HOMER software is selected because it is a powerful tool for designing and optimizing HRES by modeling various energy resources and determining the most cost-effective and efficient mix of resources, system size, and storage capacity. Fig. 2 shows the framework of the HOMER software with respect to the input requirements and expected outputs [70].

Solar resource

The solar resource data of the study area (Mankramso community) was obtained using HOMER's online retrieval system linked to the NASA website. Fig. 3 displays the daily average monthly solar irradiation and clearness index of Mankramso. The community has an average solar irradiation of 5.08 kWh/m^2/day. The community's maximum and minimum solar irradiation are observed to be 5.72 kWh/m^2/day (February) and 4.36 kWh/m^2/day (July), respectively. Also, the monthly clearness index varied between 0.43 (in July) and 0.58 (in February).

Daily load demand

The study focused on a typical rural community and industrial load profile to evaluate the resilience of the proposed HRES. A typical rural community load demand was adopted from an existing study in literature, whereas the industrial load profile was obtained from an existing industry in Ghana.

Rural community load demand. This study selected Mankramso as the rural community for the proposed off-grid solar PV-based rural electrification project. The community is located in the Offinso North District of the Ashanti Region of Ghana (latitude 7° 24.8 N and longitude of − 1° 0.8 W). Mankramso community has an estimated total human population of 1,892, with an average household size of 5 people [54]. This community was selected because it is over 7.0 km from the national grid, and presently, electricity access is challenging.

In a related study, Asuamah et al. [12] reported a breakeven distance between the standalone mini-grid and grid extension of 1.11 km for the Nkrankrom rural community in Ghana. Thus, Mankramso's distance from the national grid makes it a potential candidate for an off-grid rural electrification scheme. Also, Mankramso is an agricultural-based community that aligns with the agro-processing industry activities considered in this study. The community could improve the livelihood of its dwellers by engaging in farming activities to produce raw materials for the agro-processing industry. Fig. 4 displays Mankramso's estimated twenty-four-hour load profile.

The daily energy demand of the community is estimated to be 263 kWh. The twenty-four hourly load demand for Mankramso was assessed through a field survey that identified the type of electrical appliances the people intended to use if they had electricity. Using a demand profile based on the actual measured energy consumption of the community could yield a better study outcome. Nevertheless, estimating the load profile of rural communities through surveys has been employed in several related studies[12,47]. Also, the load profile does not give seasonal variations in the load demand of the rural communities. However, the variations in the load profile were synthesized using the HOMER Pro software employed in this simulation study.

It is worth mentioning that this rural community has been employed in a previous study. Hence, a detailed description of the load profile is readily available in Odoi-Yorke et al. [54]. From Fig. 4, it is observed that the load profile of Mankramso has two peaking periods. The first high load demand occurs within periods of 6: 00 h to 11: 00 h, whereas the second very high load demand occurs within the hours of 16:00 h to 21: 00 h. This occurrence of the very high electricity demand of Makramso in the night hours is similar to those of other rural communities reported in existing literature[9,18,46,47].

Fig. 5 shows that the electricity consumption of Mankramso is mainly driven by domestic applications (52 % of total energy demand). Various studies similarly observed that rural loads are predominantly driven by domestic loads [17,42,36,47,52]. Table 1 displays the top five electrical appliances that drive the electrical energy demand of the rural community.

Concerning electrical appliances in Table 1, electricity use for domestic lighting and watching TV predominates. These loads contributed 36.5 % to the very high peak loads of the community during the night hours (Fig. 4). Likewise, Das et al. [28] observed that the demand for electricity for domestic lighting contributed considerably to the high peak demand at night (18: 00 to 23:00 h) in rural loads.

In addition to the load profile obtained through the field survey, this study factored community water pumping as a deferrable load in the load demand of the Mankramso rural community. Deferrable loads, such as those used for water pumping, potentially improve the load profiles of

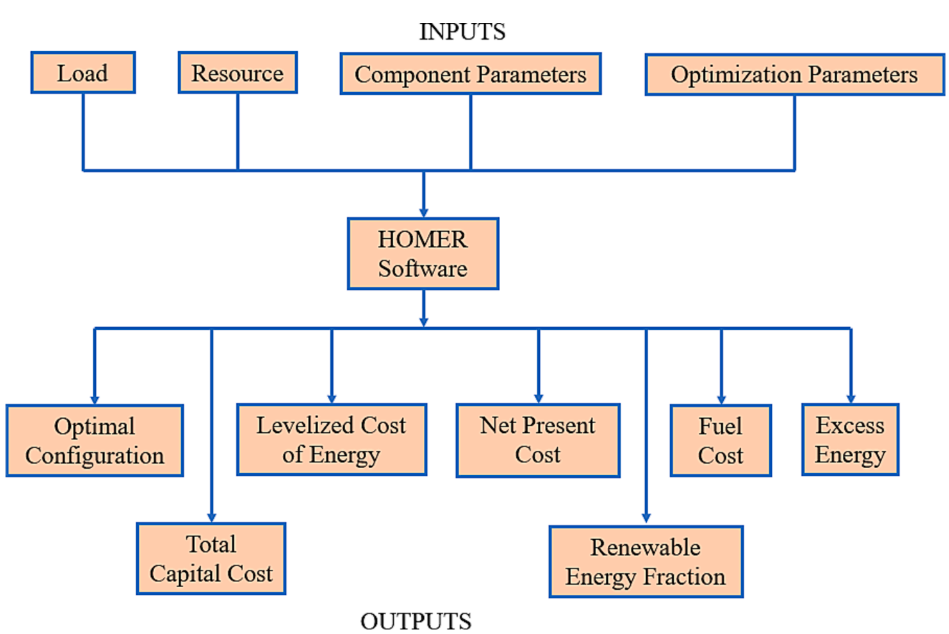


Fig. 2. HOMER architecture based on inputs and outputs [70].

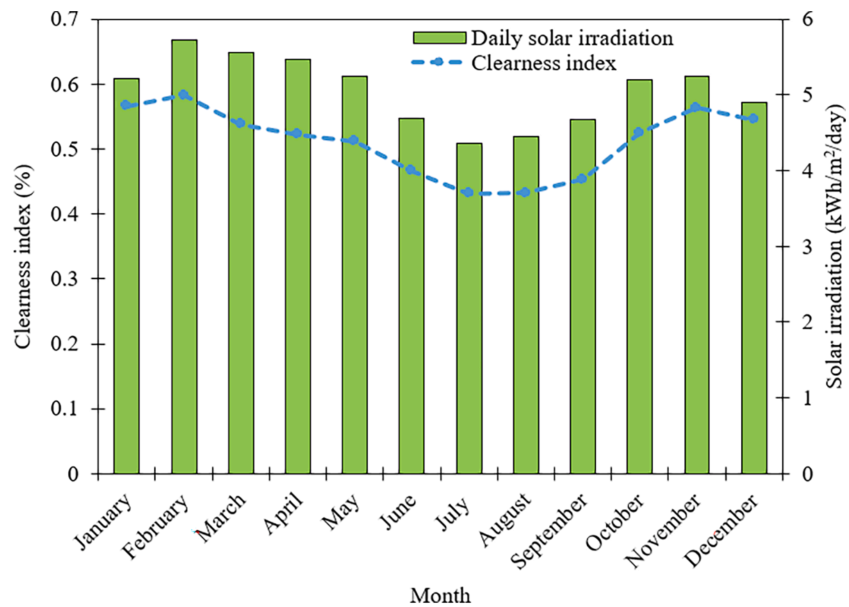


Fig. 3. Daily average monthly solar irradiation and clearness index of Mankramso.

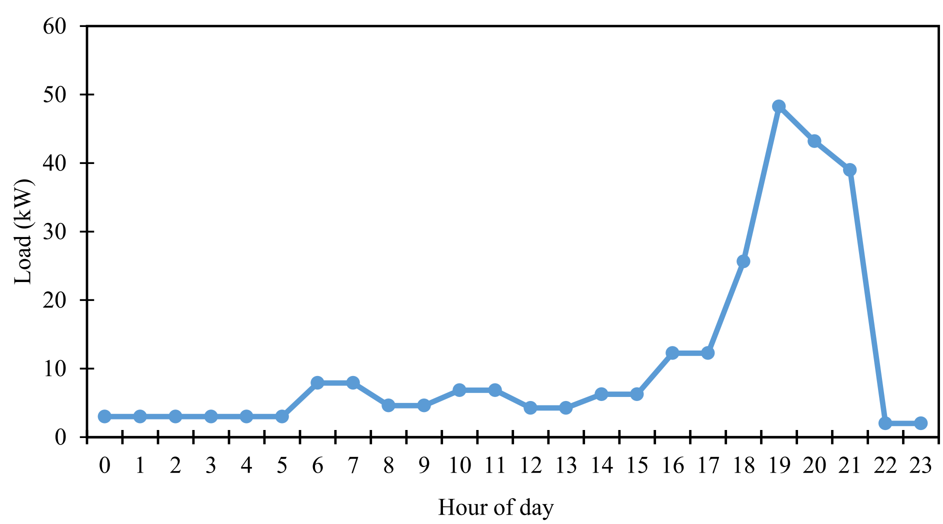


Fig. 4. Hourly daily load profile of Makramso rural community (Odoi-Yorke, Abaase, et al., 2022).

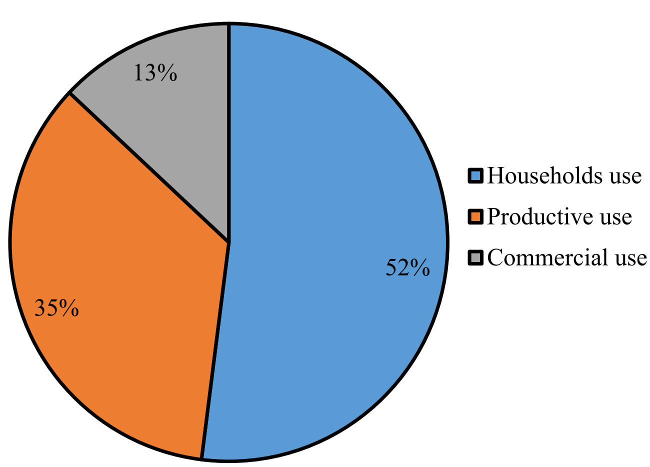


Fig. 5. Load demand of the various consumer categories in Mankramso [55].

Table 1
Top five electrical appliances that drive energy demand of the rural community.

Consumer	Load	Hours of the day	AC loads (kWh/d)
Household	Bulbs	18:00 – 22:00	48
Household	Television	19:00 – 22:00	48
Productive use (Cold store)	Deep freezer	00:00 – 23:00	28.8
Productive use (Small business)	Refrigerators	00:00 – 23:00	28.8
Productive use (Small business)	Milling machine	08:00 – 14:00	24

rural communities [30]. The daily energy demand (E_{demand}) required for pumping water is estimated using Eq. (1) [80]:

$$E_{demand} = (C_{pump})(H_{pump}) \quad (1)$$

Where C_{pump} is the power rating of the water pump and H_{pump} is the water pump operating hours.

The hours required for water pumping are computed as follows:

$$H_{pump} = \frac{D_{water}}{F_{rate}} \tag{2}$$

Where D_{water} is the daily water need, and F_{rate} is the flow rate.

Table 2 provides salient factors to estimate the rural community's daily energy requirement for water pumping. The estimated daily water pumping hours and daily energy demand for water pumping in Mankramso are 10 h and 50 kWh, respectively (Table 2).

Industrial load demand. This study considered the industrial load demand of Kingdom Premium Fruit Limited (KPFL). The company is located at Bortianor in the Ga South municipal assembly of the Greater Accra Region of Ghana at a latitude of 5° 516 north and a longitude of −0° 334 west. KPFL was selected because it is an agro-processing industry and could make it suitable for being located in a rural community as the industrial load. Also, the selection of KPFL was based on the willingness of the company to provide the authors with relevant data for this study. The authors admit that several other factors are considered in the company's siting. However, currently, high electricity tariffs and power supply instability are major challenges hampering the activities of industries in Ghana [1]. According to Alfaro et al. [9], integrating residential and productive sectors of rural electrification projects opens opportunities to offset costs for both sectors.

KPFL processes fruits such as mango and pineapple into juice for local and international markets. The company employs about 200 workers and has an average weekly production of about 1.4 million liters of mango and pineapple juice. With a workforce of about 200 employees, KPFL could be categorized as a large-scale enterprise [32,58]. At the time of this study, the company operates only during weekdays (24 h/day) and all year round. In this regard, the company ran two daily work shifts (i.e., day and night shifts) to ensure continuous operation and maximize productivity. Fig. 6 displays some of the major fruit processing machines KPFL uses in the agro-processing operations.

Fig. 7 displays the daily hourly load profile of the company for a typical day (measured on the 10th March 2022). The daily hourly load of KPFL measured on the 10th March 2022 under consideration is due to the availability of the data for this study. This hourly load demand profile of the company was obtained from historical energy consumption data of the company measured by the Electricity Company of Ghana (ECG) for electricity consumption billing purposes. The profile yields a cumulative daily energy demand of 932.5 kWh. Fig. 7 shows that energy consumption is high and stable between 9.30 h and 21.30 h. However, load demand drops considerably between 12: 30 h to 13: 30 h to the lowest hourly demand of 23.1 kWh daily. This considerable drop is due to the reason that, within the period, several loads of the company are shut down for lunch break.

Table 2
Salient parameters considered for estimating daily water demand.

Parameter	Value	Comments/Remarks
Average water required per person	50 L	Typical water needs recommended by the world Health Organization [79].
Household size	5	Data obtained from Odoi-Yorke et al. [54]
Number of households	400	Data obtained from Odoi-Yorke et al. [54]
Average solar irradiation	5	Obtained from HOMER's online retrieval system linked to the NASA website.
Water storage capacity for 1 day	100 m^3	Assumed value deduced using the average water required per person, household size, and total households
Water storage autonomy	2	Typical solar water pumping tanks are designed to store water for at least 2–3 days [80]
Power rating of the pump	5 kW	Author assumption based on available pumps in the local market
Flow rate of pump water	20 m^3/h	Estimated water flow rate from the pump based on water storage capacity and average peak sun hours
Energy demand	50 kWh/d	Estimated daily energy demand required for water pumping using Eq. (1)
Water pumping hours	10 h/d	Computed using Eq. (2). The actual water pumping hour is 5 h/d. However, adding 1 day of water storage autonomy increased the pump hours to 10 h/d.

Subsequently, on a daily basis, there is a considerable drop in the load demand during the company's lunch break periods. Similar industrial load demand patterns were observed by [51,77]. Using aggregated daily hourly energy demand measured over a relatively longer period would have made the study more robust compared to the single day considered in this study. Unfortunately, obtaining a longer measured daily hourly profile of the industrial consumer was challenging.

It is worth recalling that this study aims to investigate the impact of industrial loads on rural electrification projects. In view of this, the study proposes three cases, namely, case 1 (typical rural community load with deferral loads for water pumping), case 2 (KPFL industrial loads), and case 3 (combined load profiles of case 1 and case 2). Fig. 8 displays the twenty-four-hour weekday load profiles for three study cases. As previously indicated, during the study period, KFPL exclusively operated on weekdays temporarily. However, to comprehensively assess the total daily load demand of the community with the integrated industrial load, the weekday load demand of KFPL was extrapolated to include weekend load demand for the techno-economic analysis. From the authors' perspective, this approach provides a more accurate representation of the industry's long-term operations and the load demand of the community.

Proposed system configuration and governing equations

This section presents the governing equations that model components such as PV modules, diesel generators, batteries, and power converters. It also provides equations to determine the salient output, such as levelized cost of energy (LCOE), net present cost (NPC), renewable energy fraction, etc.

Hybrid renewable energy system configuration. The study considers a hybrid off-grid power system comprising solar PV, diesel generator, and battery storage technology for the rural community. Fig. 9 displays the proposed hybrid off-grid system configuration adopted in the HOMER software. Solar PV was considered the major renewable energy technology for the proposed off-grid rural electrification system because Ghana is in the sunbelt and has high solar power generation potential [12]. Thus, solar PV is a key technology in the plans and policies of the Government of Ghana in the deployment of mini-grids as off-grid electrification systems in areas that cannot be practically electrified through the national grid [22].

Moreover, among the various renewable energy technologies, solar has become the most preferred form to promote the productive use of energy [12,21]. Solar PV has been identified as a robust RE technology for productive use [66]. These properties of PV are in sync with the aim of the study, which seeks to promote the productive use of rural electrification systems to enhance sustainability.

Proposed hybrid renewable energy system governing equations. This section outlines the governing equations incorporated into the HOMER software to model the proposed system components. It provides relevant governing equations for the solar PV module, battery, diesel generator, and power converter.

Solar PV output power. HOMER computes the solar PV system power output (P_{pv}) using Eq. (3) [69]:

$$P_{pv} = Y_{PV} D_{PV} \left(\frac{R_t}{R_{,tSTC}}\right) \left[1 + \alpha_P (T_c - T_{c,STC})\right] \tag{3}$$

where Y_{PV} denotes the rated capacity of the PV array at standard test conditions (STC) (kW), D_{PV} denotes PV derating factor (%),R_t denotes solar radiation incident on the module surface (kW/m^2), $R_{,tSTC}$ denotes

Fig. 6. Major fruit processing machines for production.

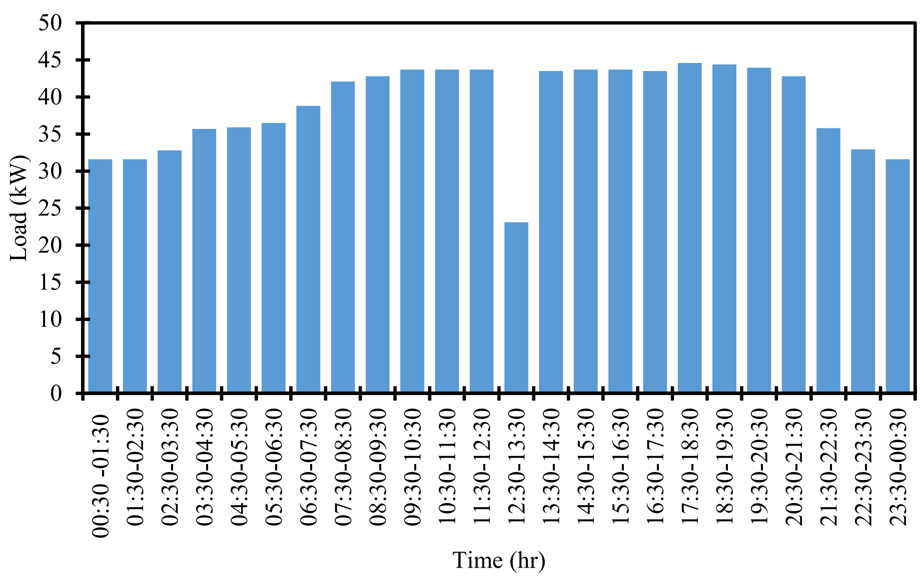


Fig. 7. Daily hourly load demand of KFGL for a typical day (10th March 2022).

incident solar radiation at STC (1 kW/m^2), α_p denotes temperature coefficient (%/m^2), T_c denotes PV cell temperature (°C) and $T_{c,STC}$ represents PV cell temperature under STC (25 °C).

Diesel generator. The diesel generator fuel consumption rate is determined as follows [11,13]:

$$F = F_{Coeff}DG_{Cap} + F_{cs}P_{DG} \tag{4}$$

Where F represents the fuel consumption rate (L/hr), F_{Coeff} represents generator fuel curve intercept coefficient (L/hr/kW$_{rated}$), DG_{Cap} represents the generator rated capacity (kW), F_{cs} represents the generator fuel curve slope (L/hr/kW$_{output}$) and P_{DG} represents the generator output power (kW).

Battery storage bank. Surplus power is fed to the battery. Eqs. (5) and (6) represent the excess power fed to the battery bank at an hour (t) [50]:

$$E_{Batt}(t) = E_{Batt}(t-1) + E_{Excess}(t)^{*}\eta_{Batt}{}^{*}\eta_{conv} \tag{5}$$

$$E_{Excess}(t) = E_{AC}(t) + E_{DC}(t)^{*}\eta_{conv} - E_{Demand}(t) \tag{6}$$

Where $E_{Batt}(t)$ represents the excess charge that feeds the battery, $E_{Excess}(t)$ represents energy from resources after meeting the load demand, $E_{Batt}(t-1)$ represents the battery bank capacity in the preceding state, $E_{AC}(t)$ represents the total generator output power, $E_{DC}(t)$ is the total power generation from a DC source, η_{Batt} is battery charging efficiency, η_{conv} denotes converter efficiency and $E_{Demand}(t)$ denotes total energy demand.

On the other hand, if the demand is more than a generation, the excess demand is met through the battery bank. Eqs. (7) and (8) represent battery bank storage capacity at the hour (t).

$$E_{Batt}(t) = (1-\sigma)E_{Batt}(t-1) - \left[\frac{E_{Deficitdemand}(t)}{\eta_{DischargeBatt}{}^{*}\eta_{conv}}\right] \tag{7}$$

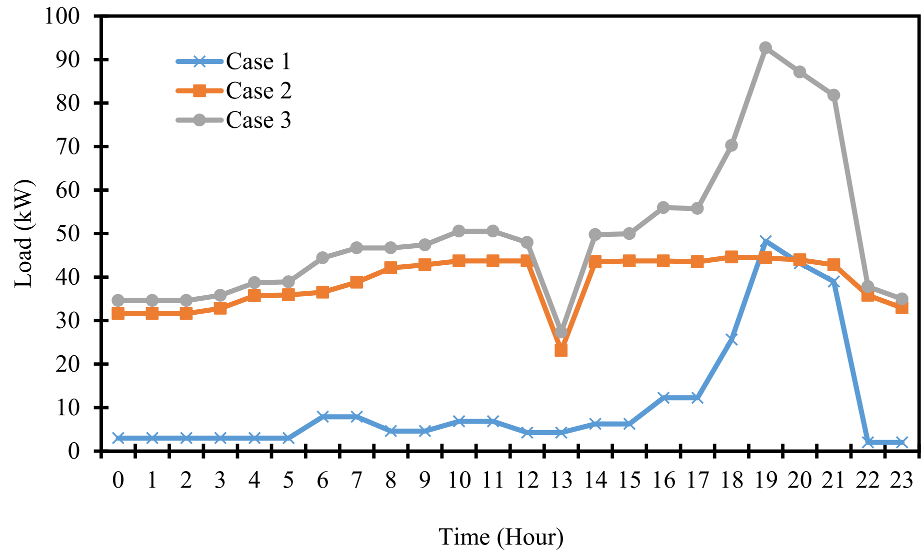


Fig. 8. Daily load profile for study cases.

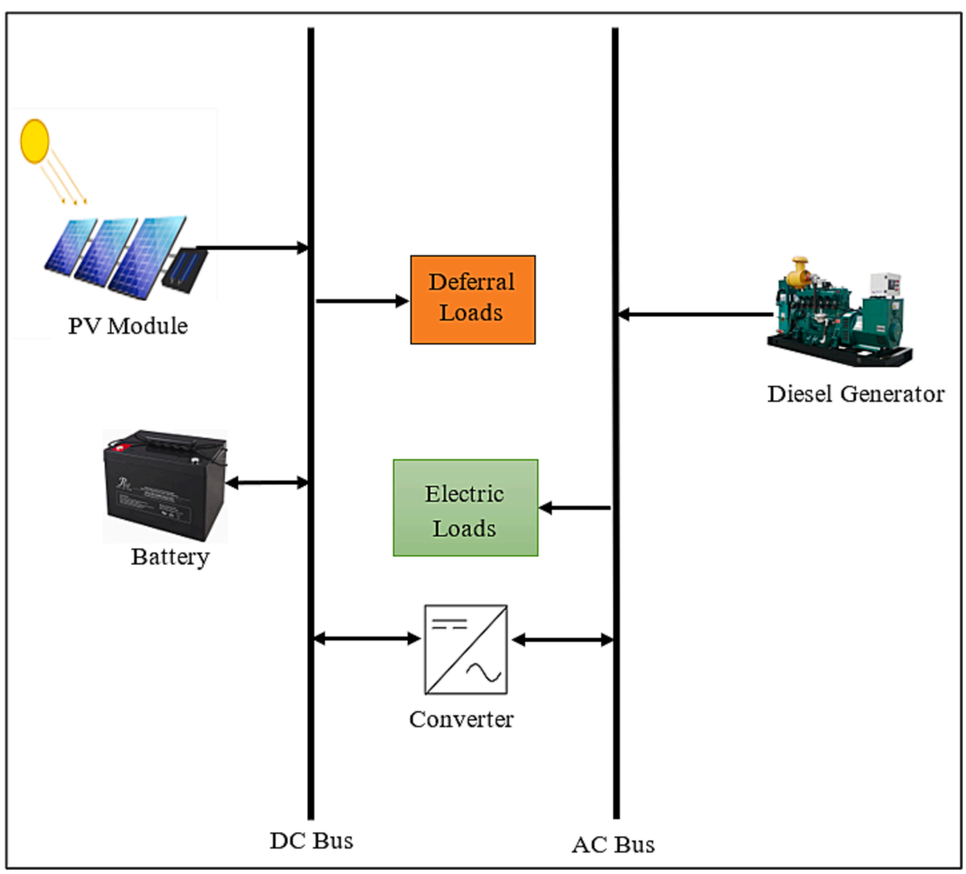


Fig. 9. Proposed system configuration for Mankramso community.

$$E_{Defictdemand}(t) = E_{Demand}(t) - [E_{AC}(t) + E_{DC}(t) * \eta_{conv}] \quad (8)$$

Here, $E_{Deficdemand}(t)$ denotes the total deficit load demand, σ represents the hourly self-discharging rate, and $\eta_{DischargeBatt}$ is the battery discharging efficiency.

The battery autonomy (A_{batt}) and battery lifetime (R_{batt}) are computed by HOMER based on Eqs. (9) and (10), respectively [54]:

$$A_{batt} = \frac{N_{batt} V_{nom} Q_{nom} \left(1 - \frac{q_{min}}{100}\right)\left(24 \frac{h}{d}\right)}{L_{prim,ave}\left(1000 \frac{Wh}{kWh}\right)} \quad (9)$$

Where N_{batt} denotes battery quantity, V_{nom} denotes nominal battery voltage, Q_{nom} denotes nominal battery capacity, and q_{min} denotes minimum battery state of charge. $L_{prim,ave}$ represents the average electric load.

$$R_{batt} = \min\left(\frac{X_{batt}Y_{lifetime}}{Z_{thrpt}}, R_{batt,f}\right) \tag{10}$$

where X_{batt} denotes the number of batteries in the battery bank, $Y_{lifetime}$ denotes a battery's lifetime throughput, Z_{thrpt} denotes an annual battery throughput, and $R_{batt,f}$ denotes battery float life.

Power converter. The power converters (P_{conv}) capacity should be more than the total electrical power emitted in both directions, as shown in Eqs. (11) and (12) [74]:

$$\eta^{CON}_{AC/DC} \cdot [DG_p(t)] \leq P_{conv} \tag{11}$$

$$\eta^{CON}_{DC/AC} \cdot [BATT_P(t) + PV_p(t)] \leq p_{conv} \tag{12}$$

where, $DG_p(t)$ denotes the diesel generator power output, $BATT_P(t)$ denotes battery output and $PV_p(t)$ denotes the PV power output, respectively. The inversion unit (conversion from DC to AC) and rectification unit (conversion from AC to DC) are denoted by ($\eta^{CON}_{DC/AC}$) and ($\eta^{CON}_{AC/DC}$), respectively.

Components technical specifications, cost, and simulation parameters

This section presents the components' technical specifications, cost, and simulation parameters to model the HRES. In view of this, Table 3 presents the technical specifications of the proposed HRES components. Also, the capital, replacement, and operating and maintenance (O&M) costs for each component are summarized in Table 4. Likewise, Table 5 presents the relevant simulation parameters to envisage the resilience and performance of the proposed HRES for rural electrification.

System's key performance metrics and definitions

In this study, the primary system performance metrics considered are the net present cost (NPC), levelized cost of energy (LCOE), and renewable energy (RE) fraction. In addition, the load factor (LF) is used as the performance metric for the consumer's load demand pattern.

Table 3
Summary of component's technical specifications.

Component	Parameters	Value
Solar PV module	Manufacturer	Jinko solar
	Nominal maximum power	505 kW
	Maximum power voltage (Vmp)	41.5 V
	Maximum power current (Imp)	12.17 A
	Open circuit voltage (Voc)	49.04 V
	Short circuit voltage (Isc)	12.89
	Module efficiency	20.40
	Operating temperature	−40℃∼+85℃
	Temperature coefficient of Pmax	−0.35 %/℃
	Temperature coefficient of Voc	−0.28 %/℃
	Temperature coefficient of Isc	0.048 %/℃
	Nominal operating cell temperature (NOCT)	45 ± 2℃
	Lifespan	25 years
Battery	Nominal voltage	6 V
	Nominal capacity	1 kWh
	Maximum capacity	167 Ah
	Roundtrip efficiency	90 %
	Maximum charge current	167 A
	Maximum discharge current	500 A
	Initial state of charge	100 %
	Minimum state of charge	40 %
	Throughput	3,000 kWh
	Lifespan	5 years
Power converter	Rectifier relative capacity	100 %
	Converter efficiency	95 %
	lifespan	15 years
Diesel generator	Fuel curve intercept	3.25 L/hr
	Fuel curve slope	0.236 L/hr/kW
	Minimum load ratio	25 %
	Carbon content	88 %
	Lower heating value	43.2 MJ/kg
	Density	820 kg/m^3
	Lifetime	10,000 h

Table 4
Summary of component cost data for simulation and optimization.

Component	Cost	Value	Comments/source
Diesel generator	Capital	525 USD/kW	Average data deduced from similar recent studies in Ghana by [11,13,55].
	Replacement	509 USD/kW	Average data assumed from similar recent studies in Ghana by [11,13,55].
	O&M	0.028 USD/op. hr	Average data deduced from similar recent studies in Ghana by [11,13,55].
	Fuel	1.257 USD/L	The actual price of diesel at the time of study was 1.143 USD/L [33]. Nevertheless, an extra 10 % was added for transportation and delivery costs.
Solar PV array	Capital	1,100 USD/kW	Assumed value from [11,13,54]
	Replacement	0 USD/kW	PV module lifespan equals project lifespan
	O&M	10 USD/kW/yr	Assumed value from [11,13,54]
Battery	Capital	310 USD/kWh	Average data from a recent study in Ghana [11,13,54]
	Replacement	253 USD/kWh	Average data from similar studies in Ghana [11,13,54]
	O&M	7 USD/kWh	Cost deduced from similar recent studies in Ghana [11,13,54]
Power converter	Capital	392 USD/kW	[11,13,54]
	Replacement	300 USD/kW	[11,13,54]
	Maintenance	6 USD/kW/yr)	[11,13,54]
Water pump	Capital	2,776 USD/kW	The cost of a solar pump in the Ghanaian market [38]on June 2022 using an exchange of 1 USD = 7.1441 [15 15]
	O&M	5 USD/kW/yr	Authors' assumption based on consultation with local suppliers and vendors

Table 5
Key parameters for simulation and optimization.

Component	Parameter	Value	Source/ remarks
Solar PV	Tilt angle	10°	Typical optimal values for Ghana are within 10° to 15°
	Panel azimuth	180 degrees south	Typical value due to the location of the study area
	Derating factor	80 %	[13]
	Ground reflectance	20 %	[54]
Economics	Project lifetime	25 years	Typical project lifespan for similar projects in the literature
	Discount rate	10 %	Data from [11,13]
	Inflation	10 %	Data from [11,13]

Net present cost (NPC). The NPC (C_{NPC}) indicates the present value of all costs incurred in the project's lifetime minus the present value of all revenue earned over its lifetime and is given as follows [54]:

$$C_{NPC} = \frac{X_{ann,tot}}{CRF(r, P_{proj})} \tag{13}$$

Where $X_{ann,tot}$ denotes the total annualized cost ($/yr), and CRF represents the capital recovery factor. CRF is given by Eq. (14)

$$CRF(r,N) = \frac{r(1+r)^N}{(1+r)^N - 1} \tag{14}$$

where r represents the real discount rate, and N represents the project lifetime in years.

Levelized cost of energy (LCOE). The LCOE is a financial metric used to assess the cost-effectiveness of different energy sources over their lifetime. It is calculated by taking the total cost of a given energy system, including its construction, operation, and maintenance costs, and dividing that by the total amount of energy produced over its lifetime as expressed in Eq. (15) [54]:

$$LCOE = \frac{\sum_{t=1}^{n} \frac{CAPEX_0 + OPEX_t}{(1+r)^t}}{\sum_{t=1}^{n} \frac{EP_t}{(1+r)^t}} \tag{15}$$

Where $CAPEX_0$ and $OPEX_t$ are the system's total capital expenditure and operation and maintenance expenditure, respectively. EP_t denotes the total energy generated in kWh in year t.

Renewable energy (RE) fraction. It is the total power generated from renewable energy sources and is determined as follows:

$$RF = \left(1 - \frac{\sum P_{DG}}{\sum P_{renew}}\right) \times 100 \tag{16}$$

Where P_{DG} is the generator output power and P_{renew} is the power from renewable energy sources.

Load factor. The load factor is defined as the ratio of the average to the peak load, as shown in Eq. (17):

$$LF = \left(\frac{L_{ave}}{L_p}\right) \tag{17}$$

Where L_{ave} and L_p are the average load demand and peak load demand, respectively.

Pearson correlation coefficient test and p-value

As earlier indicated, this study also explores the changes in the load profile of the rural community with the integration of the industrial load with respect to its alignment with solar power production. Here, the match between solar power production and load demand is measured through solar-load correlations. Eq. (18) is applied to determine the correlation between solar power production and load demand [29]:

$$P_c = \frac{n\sum ab - (\sum a)(b)}{\sqrt{[n\sum a^2 - (\sum a^2)][n\sum b^2 - (\sum b^2)]}} \tag{18}$$

Where P_c is the Pearson correlation coefficient, n is the number of observations in the dataset, a is the solar power production values, and b is the load demand values. The p-value determining correlation significance was calculated using the t-distribution (TDIST) function in Microsoft Excel. It is worth mentioning that a statistically significant correlation is shown by a $p\text{-value} < 0.05$.

Results and discussions

Load profile and factor

This study used three different load profiles to assess the performance of PV/diesel/battery HRES for rural electrification (Fig. 8). The study load profiles were classified as follows: Case 1 comprises pure rural loads with deferral loads (water pump), Case 2 mainly consists of industrial loads, and Case 3 combines Case 1 and Case 2 load profiles.

Table 6
Study cases load factor (LF).

Load type	Case 1	Case 2	Case 3
No daily or hourly noise	0.23	0.87	0.54
10 % daily and 10 % hourly noise	0.16	0.60	0.37

Table 7
PV output power against load profile.

Load profile	Pearson coefficient	p-value
Case 1	−0.260*	0.00
Case 2	0.162*	0.00
Case 3	0.097*	0.00

* Correlation is significant at the 0.05 level (2-tailed).

Table 6 presents the load factor for each load profile. It is worth mentioning that 10 % daily and 10 % hourly noise were added to the load profiles, as presented in Table 8. This noise accounts for daily, monthly, and seasonal variations in electricity use.

It can be observed in Table 6 that Case 1 exhibited the lowest load factor among the three cases in both situations with and without noise factored in the load profiles. The result of the poor load factor of the rural load (Case 1) is similar to those reported in related studies [2,27,44,59,72]. This result is attributable to the reason that there is low daytime demand because rural communities are mostly farmers who spend the day on the farm and use energy in the evenings. The low load factor implies a wide gap between the peak load and average load, consequently, idling capacity for most of the day. On the other hand, the best load factor of 0.87 observed in the pure industrial load is attributable to the considerably stable profile of the industrial load throughout the day (Fig. 7).

The low-load factor in Case 1 could be improved through demand side management (DSM) techniques such as load shifting from evening hours, where demand peaks to daytime usage. However, Table 1 of this study and the outcomes of other related studies [3] reveal that occupancy-dependent loads, such as TV and bulbs, dominate rural loads. These loads have low shifting flexibility and, thus, present little opportunity for load-shifting DSM techniques. Nevertheless, the almost three-fold improvement in the load factor, as observed in Case 3 compared to that in Case 1, presents the alternative of using industrial facilities as load curve management tools to improve rural load profiles, as

Table 8
Summary of base scenario technical, economic, and emission output for different load profiles.

Parameter	Case 1	Case 2	Case 3
PV capacity (kW)	65	140	185
Generator capacity (kW)	72	65	140
Battery capacity (kWh)	130	500	600
Power converter capacity (kW)	55	59	103
Electricity production (MWh/yr)	138.864	355.287	467.393
Electricity consumption (MWh/yr)	104.850	340.399	445,180
Excess electricity (%)	18.6	0.02	0.25
Renewable energy fraction (%)	50	50	50
Unmet electric load (%)	0	0	0
Capacity shortage (%)	0	0	0
Generator production (MWh)	51.513	167.146	218.779
PV production (MWh/yr)	87.351	188.140	248.614
Generator operation hours (hr)	2,051	5,222	4,978
Battery autonomy (hr)	9	10	9.44
Diesel consumption (L/yr)	18,550	54,900	73,368
NPC (USD/kWh)	1,139,042	3,233,244	4,614,018
LCOE (USD/kWh)	0.435	0.380	0.415
Operating cost (USD/yr)	38,599	114,676	164,317.6
Initial capital (USD)	147,063	366,355	506,079
Fuel cost (USD/yr)	23,317	69,009	73,368
CO_2 emissions (kg/yr)	48,557	143,706	192,048

suggested in [9]. This approach of improving the load profile could be relevant in rural loads with less opportunity for load shifting. Similarly, other studies observed improvements in the daytime consumption and daily energy demand of a rural residential profile with the integration of productive users [20].

This study further explores the changes in the load profile of the rural community with the integration of the industrial load with respect to its alignment with solar power production through solar-load correlations. Thus, the result of the solar-load correlation coefficients and p values for various load demands obtained via statistical analyses are presented in Table 7. The solar-load correlation coefficients measured the relationship between PV power generation and electrical load demand.

The two-tailed statistical tests at $p = 0.05$ indicate that all the correlation coefficients for Case 1, Case 2, and Case 3 were significant. The negative solar-load correlation coefficient implies a significant mismatch between solar power production and load demand in Case 1 and Case 2. According to Blum et al. [20], a challenge that arises with the mismatch between peak solar electricity production pattern and the load profile is that extra investments are required in mitigation measures such as backup storage technologies [52]. The mismatch also causes redundancy when the storage battery is fully charged during the daytime when solar power generation peaks [57].

On the contrary, with the integration of the industrial load, there was a significant improvement (at $p = 0.05$) in the alignment of the load demand and solar power production. The industrial load exhibited the best alignment with solar power production. The alignment of solar production and load demand could reduce the need for a storage facility, which is an expensive component of solar PV systems in Ghana [30].

Earlier studies indicated that integrating residential and productive loads potentially brings mutual benefits to multiple users [9,52]. However, the results obtained in this study, with respect to load factors and solar-load correlations, suggest that the integration favors the residential load profile over the industrial profile. Specifically, while the integration improved the load factor and solar-load correlation for the residential community, it adversely affected both the load factor and solar-load correlation of the industrial load.

Performance of hybrid renewable energy systems

The HOMER algorithm searched for the best solution from the sizes considered for the given load profile. This is done by performing hourly energy balance calculations for different configurations. HOMER selected the best systems based on the lowest net present cost. Table 8 shows the best system configuration recommended by HOMER for the base scenario.

The base scenario optimal system sizing configurations are as follows: Case 1 (65 kW of PV, 72 kW of diesel generator, 130 kWh of battery storage, and 55 kW of converter); Case 2 (140 kW of PV, 65 kW of diesel generator, 500 kWh of battery storage and 59 kW of converter); and Case 3 (185 kW of PV, 140 kW of diesel generator, 600 kWh of battery storage, and 103 kW of converter). It can be noted in Table 8 that the study cases' optimal HRES sizing configurations have a 0 % capacity shortage and unmet loads. The implication is that the study cases' optimal HRES sizing configurations can meet the desired electrical loads without any electricity deficit throughout the year. The instability of national power grids is a major challenge in developing countries, and the result of a 0 % capacity shortage agrees with the suggestion in [52] that off-grid RE-based systems could alleviate the situation of power instability. The results also show that the capacities of the HRES components (PV modules, batteries, generators, and converters) vary in each Case. This variation is due to the different electricity demands for each study case. Higher electricity consumption requires increasing component capacities to produce enough electricity to meet the loads without any capacity shortage. The share of electricity production (diesel and solar PV) from the proposed systems is shown in Fig. 10.

It is also worth noting that PV dominates electricity generation throughout the year in all three cases investigated. The dominance of solar PV in the generation mix suggests that solar resources are readily

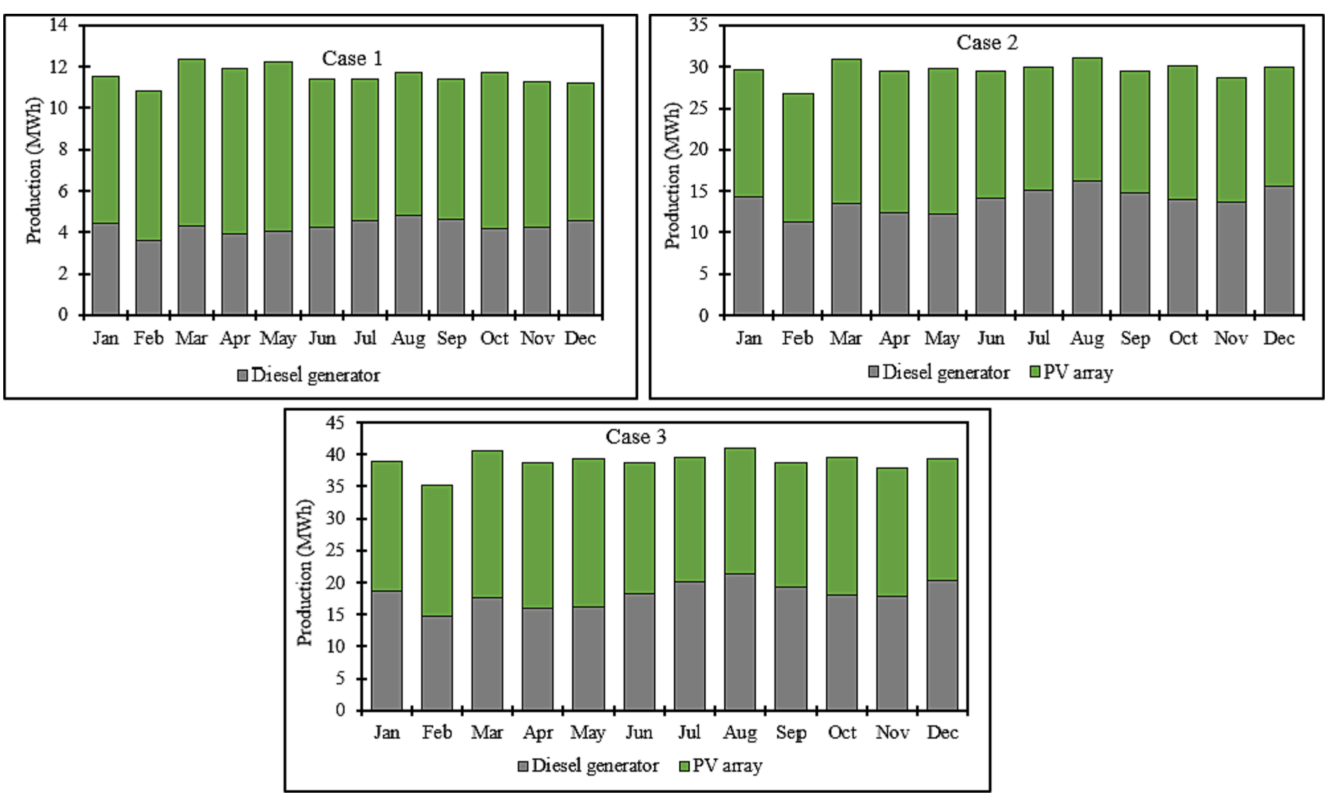


Fig. 10. Share of electricity generation from energy sources for the base scenario.

available. Also, it is more economical to meet the load demands with solar PV than diesel generators for most of the year for conditions under the designed considerations. These results agree with other studies that RE-based off-grid generation technologies could offer cheaper rural electrification than conventional technologies such as diesel gensets [17,52].

From an economic viewpoint, LCOE is a useful performance indicator for comparing the cost of electricity from various power systems. Thus, it is a critical indicator for decision-making on electrification projects. The results show that the hybrid solar PV system for industrial loads (Case 2) has the lowest LCOE. In fact, the LCOE of Case 2 is 9 % lower than that of Case 3 (pure rural loads plus industrial loads) and about 14 % lower than Case 1 (rural loads only). The result of the best LCOE observed in Case 2 could be related to its better load factor and better match with solar power production (as implied by the best correlation in Table 7) compared to the other load profiles [67,75,78].

It can also be seen in Table 8 that the renewable fraction (RF), which accounts for the share of solar PV penetration in electricity generation, is equal for the study cases. Likewise, the battery autonomy for the study cases is the same. The study chose the same RE fraction and battery bank autonomy for an easier and more direct comparison of the results between the three study cases. This means that the impact of other factors on the results can be evaluated without the confounding factor of different RE fractions and battery autonomy. It can be seen that, though the RE fraction and battery autonomy are the same, the excess energy generation for the study cases are different. The results show that in Case 1, excess energy generation is about 18.6 % compared to 0.02 % and 0.25 % in Case 2 and Case 3, respectively. Case 1′s higher excess energy generation can be attributed to the mismatch between solar generation and load demand, as implied by the negative solar load correlation. Thus, the solar produced was not used due to the low daytime demand, and a lot more storage was required per unit load demand to store energy for night use. Storage batteries are expensive and adversely affect the system's cost and LCOE. Another reason for the worst LCOE observed in Case 1 is perhaps due to the so-called redundancy, which causes the clean solar power to go to waste when the storage battery is fully charged during the daytime when solar power generation peaks [57].

The result of Solar fraction in all cases is the same; however, the best and worst LCOE exhibited by Cases 2 and Cases 1, respectively, aligns with the assertion in the study of Afonaa-Mensah et al. [6]. The assertion is that load profile improvement enhances the impact of solar power absorption on the economic benefits of PV-integrated systems.

Alfaro et al. [9] showed that the peak demand and base demand greatly impact the LCOE and could account for the better LCOE observed in Case 2 than in Case 1 and Case 3. Likewise, the changes to the load demand curve through the combination of rural residential demand and industrial loads could account for the considerable reduction in the LCOE of Case 3 compared to that in Case 1. As power systems benefit from economies of scale [4,52], the bigger size of the power system due to increased load demand in Case 2 and Case 3 compared to Case 1 could be another reason for their better results of LCOE compared to the Case 1.

These results of the least LCOE in Case 2 suggest that utilizing solar energy for industrial purposes could be more cost-effective than residential and rural electrification in Ghana. The reason is that industrial loads are more stable throughout the day, and energy generated from solar PV could be utilized efficiently to meet the loads. That cannot be said for rural loads, which exhibit a poor load profile, where much energy is mainly consumed in the evening when sunlight is rarely unavailable for energy generation. Rural consumers should consider improving daytime energy use to achieve a cost-effective LCOE for solar PV-based electrification projects. This improvement could be achieved by integrating industrial into rural loads, as demonstrated in this study. Nevertheless, the levelized cost approach of comparing power systems has some limitations. For instance, according to Bhattacharyya [17], LCOE is a one-dimensional indicator despite its wider use and fails to account for other considerations beyond costs. In the context of NPC economic indicator, Case 1 showed the least among all the cases. The higher NPC in Cases 2 and 3 is attributed to increasing component capacities and capital costs.

Generally, it is widely recognized that transitioning to a more sustainable energy system with a higher share of renewable energy is crucial for mitigating climate change and reducing greenhouse gas emissions. Therefore, increasing the RE fraction can decrease the reliance on fossil fuels, a major contributor to global carbon emissions. In view of this, the study modeled two other PV/diesel/battery HRES with 70 % and 90 % RE fractions (Fig. 11). The percentage of RE fractions chosen is based on the assumption that the base scenario was 50 %. The aim is to envisage the performance of the HRES when solar PV penetration increases for the study cases. It also aims to assess the performance of the load profiles' resilience when the share of RE is higher.

Fig. 11 shows that the LCOE decreases with increasing RE fractions in the study cases. For example, in Case 1 (pure rural loads + deferral loads), LCOE declines by only 14 % and 34 % for a RE fraction of 70 % and 90 %. Similarly, in Case 2 (industrial loads), LCOE significantly decreases by about 19 % and 43 %, adopting a RE fraction of about 70 % and 90 %. In addition, the LCOE for Case 3 (rural load + industrial loads) reduces by 21 % and 45 % when RE fractions of 70 % and 90 % are incorporated into the electricity generation mix.

The substantial decrease in LCOE might be attributed to diesel generators' lower fuel, operation, and maintenance costs. The higher reduction impact of increasing renewable on LCOE obtained in Case 3 compared to Case 2 is attributable to the greater daytime demand in the combined rural and industrial load as compared to that in the pure industrial load; hence, the greater amount of solar power was utilized to meet the demand without the need for storage.

In view of this, it can be further noted from Fig. 12 that NPC, operating costs, and fuel costs decrease as the study cases' RE fraction increases. These results suggest that integrating a higher proportion of renewable energy sources can reduce total system installation, operation, and maintenance costs. On the other hand, the initial cost rises as the RE fraction rises. The high initial cost might be due to increasing solar modules and battery capacity. The observation that the initial cost increases with higher RE fractions highlights an important trade-off. While the long-term benefits of reduced operational and fuel costs are evident, the higher initial investment required to accommodate increased solar modules and battery capacity might pose financial challenges, especially in resource-constrained regions. This result signifies that stakeholders and decision-makers would require higher upfront costs for the system's installation (as the size of the power system increases), which could deprive the system of its attractiveness.

The study LCOE obtained is compared to the currently approved end-user tariff (EUT) for residential Ghanaian consumers, highlighted in Table 9. The objective is to determine the cost-effectiveness of the proposed system for rural electrification projects in Ghana. The comparison is focused on Case 1 and Case 3 since this study aims to investigate the resilience of improving rural loads' characteristics (load factor and solar-load correlation) through industrial loads for rural electrification projects. Ghana's Public Utilities Regulatory Commission (PURC) categorizes residential electricity consumers into four blocks (Table 9).

It can be observed from Fig. 11 that the LCOE of the base scenario (50 % RE fraction) obtained for Case 1 and Case 3 are 0.435 USD/kWh and 0.415 USD/kWh, respectively. Similarly, at a 70 % RE fraction, the LCOE of Case 1 and Case 3 are 0.377 USD/kWh and 0.336 USD/kWh, respectively. Furthermore, a RE fraction of 90 % reduces the LCOE of Case 1 and Case 3 to 0.308 USD/kWh and 0.262 USD/kWh, respectively. It can be seen that Case 1 and Case 3 LCOE are considerably higher than EUT for all residential customers in Ghana, even under high PV penetration levels presented in Table 9. It is worth mentioning that the average LCOE (0.373 USD/kWh) for Case 1 and (0.337 USD/kWh) for Case 3 is about 146 % and 141 % higher than the EUT paid by lifeline

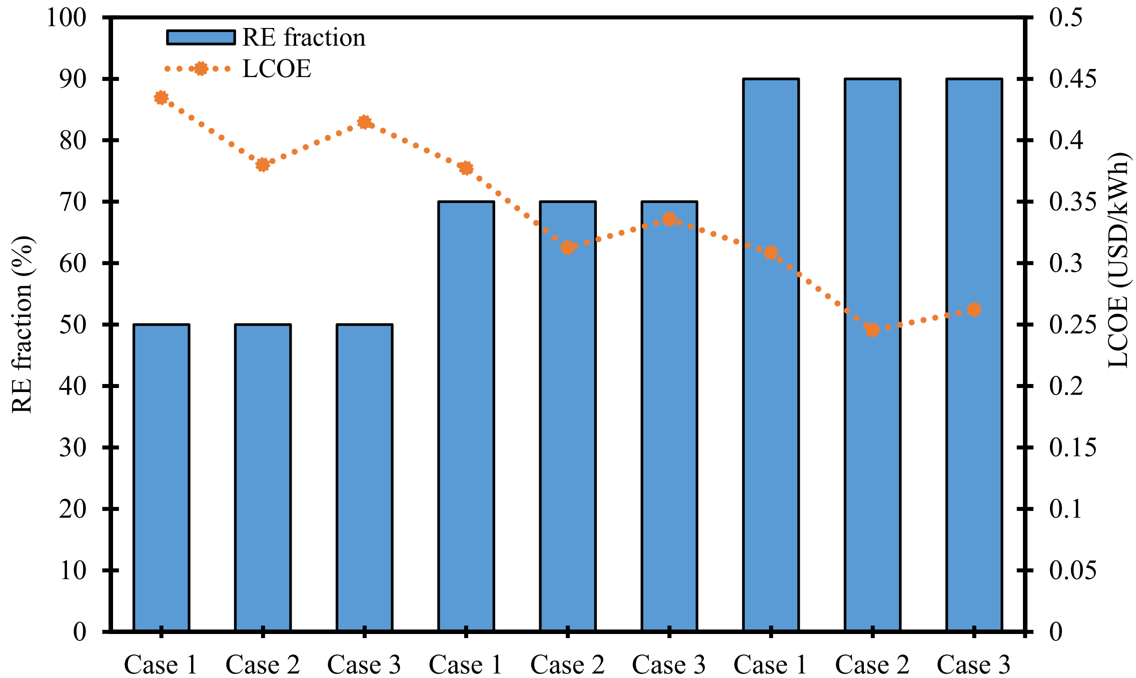


Fig. 11. Effect of RE fraction on LCOE for the different load profiles.

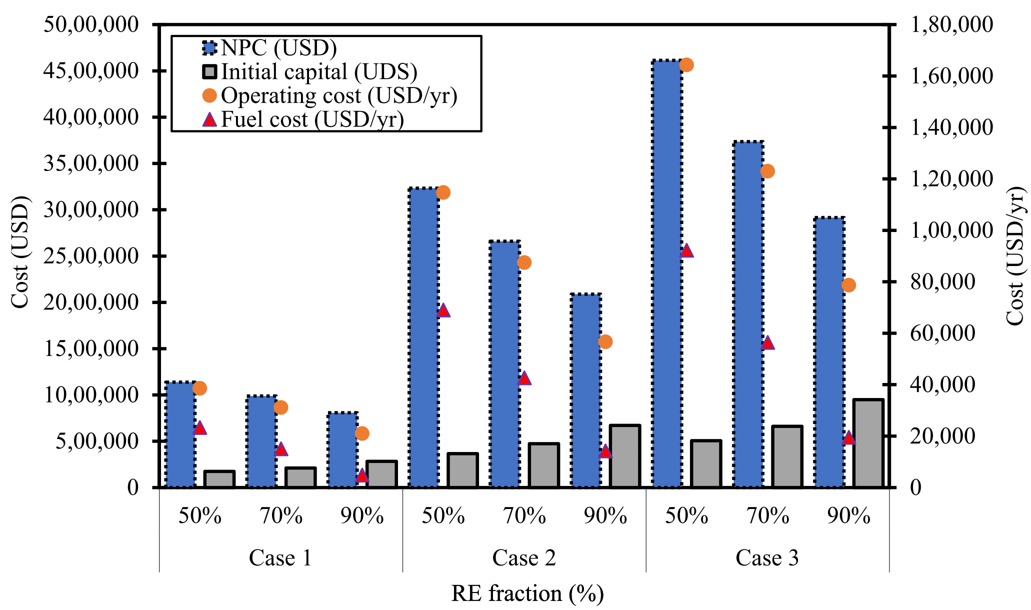


Fig. 12. Effect of RE fraction on system cost indicators.

Table 9
Ghana's approved electricity tariffs for residential customers [63,62].

Sector	Customer	Electricity consumption category (kWh)	Tariff charged (GH ₵/kWh)	Tariff charged (USD/kWh)[a]
Residential	Lifeline, exclusive	0 – 30	0.645	0.058
	Other	31 – 300	1.427	0.128
	Other	301 – 600	1.853	0.167
	Other	600+	2.058	0.185

[a] Computed using an exchange rate of 1 USD = 11.129 GH₵, obtained from the Bank of Ghana database using September 1, 2023, as the end-user tariffs approval date.

consumers, who reside mostly in rural areas. In fact, the Case 1 average LCOE is about 98 % and 76 % higher than the tariff consumers paid in the 31–300 and 301 – 600 categories, respectively. Likewise, Case 3 average LCOE is approximately 90 % and 65 % more than the tariff paid by consumers in the 31–300 and 301–600 categories, respectively. Notwithstanding, lifeline and other residential consumers pay an extra service charge. The service charge is about 0.191 USD/month for lifelines and 0.964 USD/kWh for other residential consumers [63,62].

With respect to the result of higher LCOE of the proposed compared to EUT of the grid, it has been argued that comparisons with conventional grid system tariffs may not be valid, as those do not usually reflect the true cost of power generation in many countries in SSA [16,68]. Besides, several studies have shown that the average EUT is considerably lower than the average electricity production cost in Sub-Saharan Africa

[1,4,16]. It could, therefore, be observed that the approved increment of about 27.15 % in recent tariffs of Ghana by the PURC is nowhere near the 148 % initially put forward by power utilities to enable the sector to survive [60,61].

Nevertheless, the LCOE results obtained in this study imply that based on the prevailing economic factors, design parameters, and considerations of this study, PV/diesel/battery hybrid systems are not an attractive investment choice for rural electrification in Ghana compared to grid electricity. A recent study by Acheampong et al. [1] found that Ghana's electricity is more expensive than its neighboring countries, such as Nigeria and Cote d'Ivoire, in 2018–2019. However, the study cases' LCOE, which varies from 0.262 USD/kWh to 0.435 USD/kWh, is comparable to the LCOE obtained in similar studies in other countries, as presented in Table 10, based on similar assumptions used.

Table 10 also shows that the LCOE (0.15 USD/kWh) obtained by Aziz et al. [14] is substantially lower than that obtained in this study. The reason is that the system has a lower RE fraction (about 41 %) and a high capacity shortage of about 3 %. A capacity shortage accounts for the electricity deficit available throughout the year. Higher capacity decreases the system's total net present cost. This is because the power capacity required to meet the electrical load demand is neglected, which tends to decrease the component cost. Studies show that with SSA, productive users in rural areas are willing to pay higher prices for electricity to obtain ensured reliable supply [8,73,48]. The result of the 0 % capacity shortage obtained in this study implies a more stable and reliable power supply and could be attractive to some productive users.

The results above have shown that the system LCOE is not competitive compared to the grid tariff for residential customers. Therefore, the study further examined the effect of capital subsidies on the LCOE for Case 3, as shown in Fig. 13. The 0 % corresponds to the reference case for system deployment without subsidies. It can be noted from the figure that, though the system is responsive to capital subsidies, the LCOE is still expensive compared to the average residential EUT. For example, with a 100 % subsidy, the LCOE is about 93 %, 67 %, and 45 % higher than the residential EUT at RE fractions of 50 %, 70 %, and 90 %, respectively. This suggests that customers would be paying a higher tariff rate for electricity produced by the system than the grid tariff. These findings coincide with similar studies by Odoi-Yorke et al. [54], Agyekum and Nutakor [7], and Adaramola et al. [2] in Ghana, where hybrid energy systems' LCOE was higher at the grid tariff with a 100 % capital subsidy. However, this study's 45 % higher than the grid tariff is more promising for solar RE-based rural power systems than the 200 % obtained in a similar study by Adaramola et al. [2] after 100 % capital subsidy under similar solar penetration levels. It is worth emphasizing that, despite the wide use of LCOE in comparing the cost of electricity of various systems, LCOE has been criticized for emphasizing costs while failing to capture other relevant power system issues [17]. Notably, emission taxation has not been factored in this study. In a related study, Eduful et al. [30] alluded that the absence of emission taxation in Ghana is a major contributing factor to why the LCOE of both grid-tied and off-grid PV-based electrification schemes have not attained parity with that of the national grid.

The effect of the RE fraction on CO_2 emissions for the study cases is illustrated in Fig. 14. Generally, CO_2 emissions are expected to reduce when diesel generator operating hours decrease and solar PV penetration increases. It is worth mentioning that this general trend can be observed in Fig. 14. As the RE fraction increases from 50 % to 90 %, CO_2 emissions consistently decrease across all load profiles (Case 1, Case 2, and Case 3). However, CO_2 emissions reduction is not uniform across different load profiles. For example, in Case 1, the reduction from 50 % RE to 90 % RE is substantial (from 48,556.73 $kgCO_2$ to 10,114 $kgCO_2$), while in Case 3, the reduction is less pronounced (from 192,048 $kgCO_2$ to 40,678.48 $kgCO_2$). This variation suggests that the impact of increasing the RE fraction depends on the specific load profile and the local energy demand characteristics. The reduction in CO_2 emissions is due to a drastic reduction in diesel generator operating hours. These results suggest hybrid solar PV systems with higher RE fractions significantly cut CO_2 emissions. However, a high upfront cost is required to achieve CO_2 emission reduction for solar/diesel HRES systems, as shown in Fig. 12. Thus, the choice of RE fraction could be tailored to local load profiles and energy demand. Rural electrification projects must consider load diversity to optimize their renewable energy systems. The results indicate that increasing the RE fraction in these systems can positively impact reducing CO_2 emissions, aligning with global sustainability goals.

Conclusion

Access to reliable and sustainable electricity in rural areas of developing countries remains a pressing global challenge. This study investigated the impact of agro-based productive load on solar PV/diesel HRES performance for rural electrification in Ghana, a developing country. HOMER software was used to investigate the performance of solar PV/diesel HRES based on the following load profile: Case 1 (rural loads + deferrable loads), Case 2 (industrial loads only), and Case 3 (rural + deferrable + industrial loads).

The findings indicate that integrating productive use loads into the community load demand improves the rural load profile's load factor and solar load correlation. The improved load profile reduces the LCOE, making the solar PV/diesel HRES more attractive. However, the improved LCOE was substantially higher than the EUT of all residential consumers on the national grid, even at high PV penetration and full initial capital cost subsidy scenarios. This suggests that under the present EUT tariff of residential customers on the national grid, integrating productive loads only may not be enough to attain the cost parity of off-grid PV/diesel/battery HRES with that of the national grid, even under high RE penetration and capital subsidy levels. Thus, further interventions may be required to improve the affordability and financial attractiveness of solar PV/diesel/battery HRES for rural electrification in Ghana.

In addition, increasing RE fractions reduces LCOE and CO_2 emissions but increases initial capital cost significantly. The decreasing trend in LCOE with higher RE fractions is promising for rural electrification in Ghana. Lower LCOE makes electricity more affordable and accessible to remote communities. Lower LCOE, driven by higher RE fractions, may contribute to the long-term sustainability of rural electrification projects. It can attract private sector investments, improve project viability, and ensure continued operation and maintenance of systems. However, local load profiles should inform the specific choice of RE fraction, and a balanced approach considering environmental and economic goals is

Table 10
Similar studies on PV/diesel/battery hybrid systems proposed for rural electrification.

Author(s)	Location	Peak load (kW)	Load demand (kWh/d)	Load factor (%)	Renewable fraction (%)	LCOE (USD/kWh)
Pedro & Juan [59]	Ecuador	13.98	89.91	0.27	80	0.359
Sankoh et al. [72]	Sierra Leone	30	165	0.35	87	0.336
Aziz et al. [14]	Iraq	401.66	5413	0.56	41.3	0.15
Ladu et al. [44]	South Sudan	180.46	778.25	0.17	85.1	0.238
Fodhil et al. [31]	Algeria	4.5	47	0.48	93	0.37
Das & Zaman [27]	Bangladesh	74.34	350	0.33	80	0.32

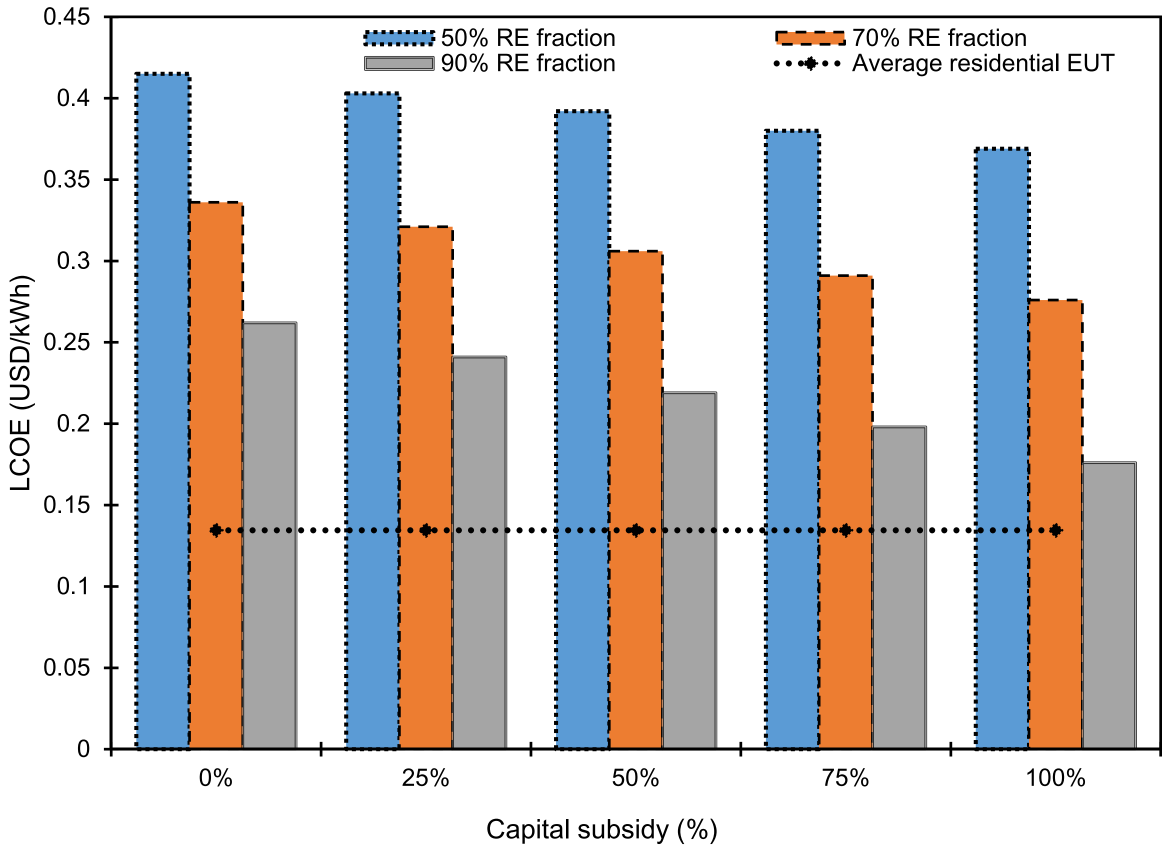


Fig. 13. Effect of capital subsidy on Case 3.

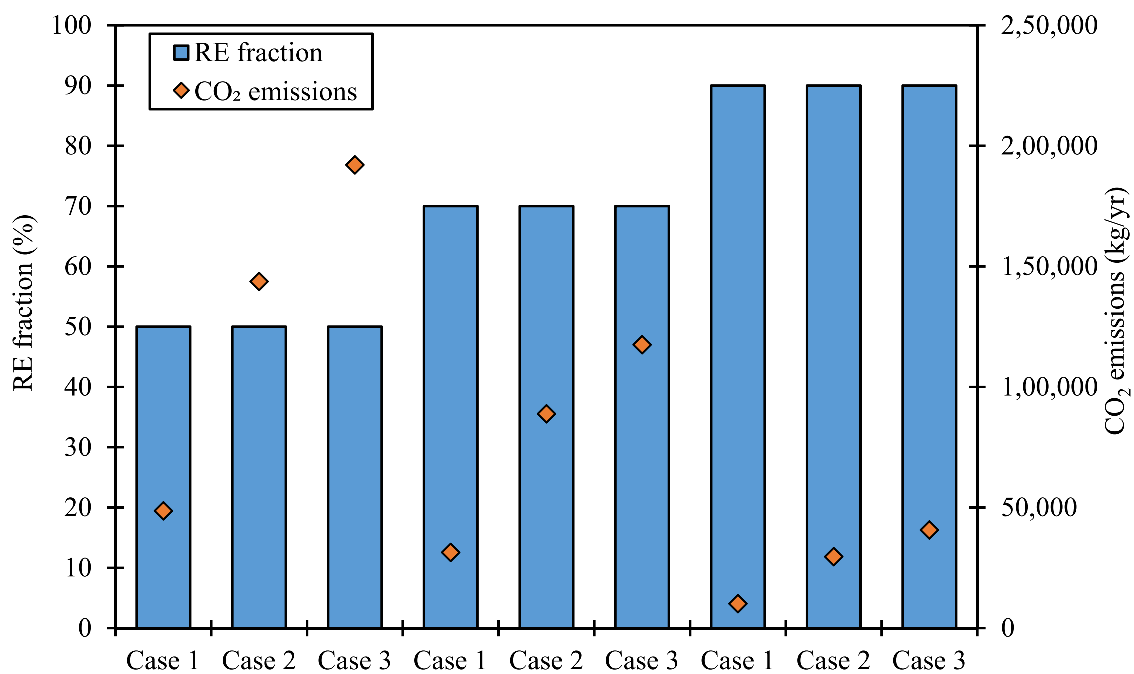


Fig. 14. Effect of RE fraction on CO_2 emissions for different load profiles.

essential for long-term success. Government policies should consider the findings to promote the integration of higher RE fractions in rural electrification projects. Subsidies, incentives, and regulatory support can further reduce the LCOE and promote the adoption of renewable energy systems. The study findings could be useful to policymakers and other stakeholders in the energy sector of developing countries in improving the economic viability of off-grid HRES for rural communities.

CRediT authorship contribution statement

Stephen Afonaa-Mensah: Writing – review & editing, Writing – original draft, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Flavio Odoi-Yorke:** Writing – review & editing, Writing – original draft, Visualization, Validation, Methodology, Formal analysis, Data curation, Conceptualization. **Issah Babatunde Majeed:** Writing – review & editing, Writing – original draft.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

The data that has been used is confidential.

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