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Assessment of hybrid solar photovoltaic-diesel systems for mini-marts in rural commercial applications

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Abstract:
In the quest for sustainable energy solutions, this study analyses the hybrid solar photovoltaic (PV)-diesel generator system's feasibility for reliable electricity supply to a mini-mart in Ajase-Ipo, Nigeria. Utilizing HOMER software, the system was modelled and optimized with a focus on both technical and economic factors. The optimal configuration comprises a 10.2 kW solar PV system, 8 batteries, a 6-kW converter, and a 10-kW diesel generator, meeting the annual energy demand of 29,200 kWh. The system's technical performance is highlighted by a capacity utilization factor of 17.9% and a performance ratio of 82.16%, demonstrating the efficiency of the solar PV system. However, heavy reliance on diesel fuel, with an annual consumption of 5,632 litres, leads to a high levelized cost of energy (LCOE) of ₦306.16 per kWh. This underscores the need for strategies to reduce diesel dependency and improve long-term economic viability through improved solar capture and optimized battery storage. The system also demonstrates significant environmental benefits, with CO_2 emissions reduced by 8,614 kg annually, alongside reductions in other harmful pollutants such as CO, SO_2, and NO_x. These findings reinforce the potential of renewable energy to provide a more sustainable, cost-effective, and environmentally friendly solution for electricity generation in similar contexts.

Keywords: Hybrid renewable energy; Solar photovoltaic; Battery storage; Diesel generator; Optimisation; Off-grid electrification

1. Introduction

Nigeria, despite its abundant hydrocarbon resources, faces significant challenges in providing reliable electricity to rural areas. The majority of rural households are disconnected from the national grid, relying heavily on diesel generators for power supply [1, 2]. However, the environmental impact and economic instability has significant implications due to fluctuating fuel prices, which create financial uncertainty for rural households and small businesses, hindering economic growth and exacerbating poverty. Additionally, poor infrastructure makes transporting diesel to remote areas costly and difficult, often making the transportation expenses higher than the fuel cost itself [3].

Hybrid Renewable Energy Systems (HRES), incorporating solar photovoltaic (PV), wind, and battery storage, offer a promising solution [4, 5]. These systems have demonstrated potential in addressing the limitations of standalone renewable energy sources, such as their intermittent nature. To overcome this challenge, battery storage systems are often integrated to provide backup power during periods of low resource availability [2, 6]. While battery storage systems are crucial for overcoming intermittency, their initial cost can be a barrier to wider adoption of renewable energy solutions [7–9].

A growing body of research explores the application of HRES, often involving combinations of different alternative energy sources [10–12]. Some studies focus on specific applications, such as solar PV/battery storage systems for powering healthcare facilities [13–15]. Others investigate the use of renewable energy sources (RES) in university campuses to achieve long-term cost reductions [7, 9]. In all this, a hybrid power system combining solar PV, diesel generators, and battery storage have emerged as viable solutions for rural electrification. Studies such as [2, 16] underscore their potential in reducing fuel dependency and lowering costs compared to diesel-only systems. While the relatively low cost of conventional power generation compared to PV

systems can influence the overall cost of electricity (COE) [6], the impact of fluctuating fuel prices remains significant. Moreover, recent research suggests that microgrids powered by renewable sources like wind and solar can be optimised to effectively replace fossil power plants [17].
Other researchers have demonstrated the successful deployment of hybrid systems in various contexts. [18, 19] highlighted their benefits for rural health centres in India, while [6] showcased their applicability across different climatic regions. [20] emphasised the influence of diesel prices and battery storage on system performance in Jordan, emphasising the potential of hybrid systems to address energy access challenges in rural areas. Additionally, hybrid systems have been successfully implemented for the electrification of a disaster management basement located in Tehran, Iran, where reliable power is crucial during emergencies [21].
Also, reports abound on the application of HRES in rural African communities. [22] explored the feasibility and benefits of integrating solar PV panels with diesel generators in Lubumbashi, DR Congo, to address energy deficits and promote sustainable economic development. The effectiveness of solar-diesel hybrid mini-grids in reducing costs and emissions for refugee camps in Rwanda, is exemplified by [23]. Results indicates that a combination of solar PV with diesel generators and battery storage, can improve energy access and provide economic and environmental benefits. This study among others underlines the importance of utilising RES like PV panels and batteries due to their cost-effectiveness and environmental advantages, especially in regions where diesel generators are prevalent [24, 25].
In addressing the power needs of rural areas, HRES have emerged as a promising solution for providing reliable and sustainable power to rural areas, particularly in regions like Nigeria [26]. In integrating solar PV, wind, battery storage, and sometimes diesel generators, HRES offer environmental and economic benefits [27, 28].
These studies collectively highlight the significance of RES in ensuring energy security and reducing costs. Notably, RES adoption has demonstrably addressed energy supply issues in critical areas like mobile telecommunication base stations [29], rural schools [30], irrigation systems [31], health facilities [10, 32, 33] and commercial centres [34–36]. However, research on RES applications in rural commercial centres remains limited.
This gap is particularly concerning as many rural communities lack access to the national grid, relying heavily on diesel generators for their energy needs. This dependence on diesel not only adds to the environmental burden but also creates challenges due to price volatility and potential supply disruptions. Therefore, exploring the use of RES to support rural businesses is of paramount importance.
This study focuses on the application of HRES for powering mini-marts in rural areas, addressing the limitations of traditional diesel-powered systems. By combining the strengths of solar PV, battery storage, and diesel generators, we aim to develop an optimal system design that maximises energy efficiency, minimises costs, and reduces environmental impact. A case study of a specific rural Nigerian community will provide a replicable model for promoting sustainable energy solutions in similar off-grid areas.

2. Methodology

This study utilises the HOMER software-based framework shown in Fig. 1 to provide the optimal energy solution. HOMER simulates various system configurations, considering both technical and economic factors. It then selects the best system based on two key metrics: the lowest total net present cost (NPC) and the lowest LCOE. To achieve this analysis, HOMER accepts weather data, including solar irradiation, as part of the input parameters for the software.

2.1 Study site and load profile

Ajase-ipo, a thriving commercial hub located along the Ilorin-Omu Aran Road in Kwara State, Nigeria, is the focus of this study. The town boasts a bustling market and enjoys relative access to basic amenities like water, good roads, schools, and healthcare. Its commercial importance attracts residents from surrounding communities. However, a sig-

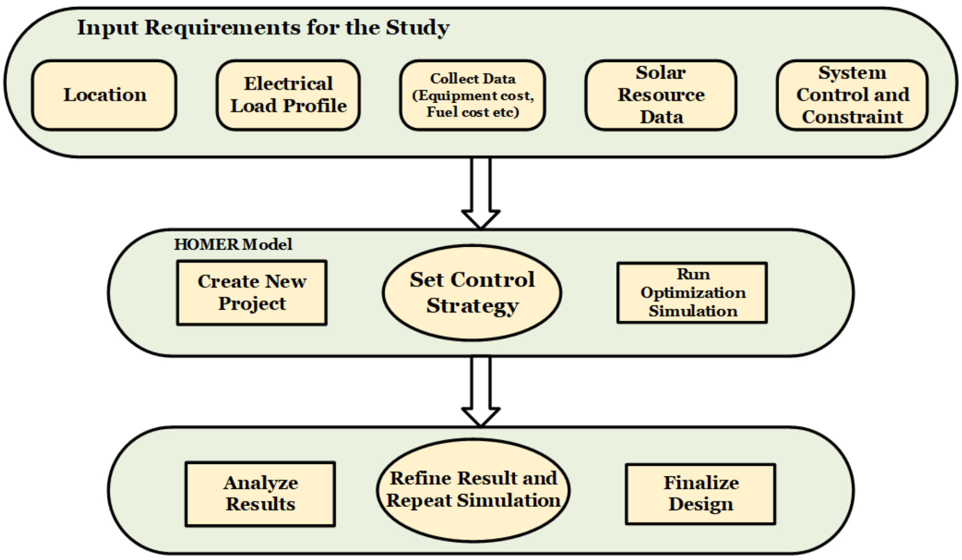

Figure 1. HOMER implementation framework.

Figure 2. Map indicating the study area.

nificant challenge is the lack of reliable electricity supply from the grid, forcing most businesses to rely solely on expensive and polluting diesel generators. Given Ajase-ipo's strategic location and limited grid supply, solar photovoltaic (PV) technology presents a promising solution. A hybrid solar PV-diesel generator system could complement diesel generation, reducing reliance on fossil fuels and enhancing the sustainability of commercial activities. This study focuses on a mini-mart business enterprise that serves as a primary source for groceries for the town's residents. Fig. 2 illustrates a map of the study area. The mini-mart has an average daily energy demand of 80 kWh, with a peak load of 6.06 kW.

2.2 Solar resource assessment

This study focuses on solar as the primary RES. To analyse its resource availability throughout the year, irradiance data was extracted from NASA website with HOMER software. These data contain the necessary solar irradiation for the chosen location.

Fig. 3 depicts the global solar energy resource for Ajase-Ipo, obtained from NASA's website. It shows the average solar radiation, and clearness index for the year.

3. Modelling of studied system

This study proposes a hybrid energy system utilising both solar and diesel generator as the energy sources as illustrated in the schematic representation shown in Fig. 4. Although the solar resource is intermittent by nature, it is primarily used to relief the diesel generator as the primary power source. To manage energy flow within the system, batteries are employed for storage, while a converter handles any necessary electricity conversion between the storage and the load. For optimal design using HOMER software, various input parameters are required. These parameters include the number of units for each component (solar panels, batteries, converter), along with detailed cost breakdowns, equipment lifetimes, and other relevant specifications.

3.1 Solar PV

The solar PV modules used in this study typically have a capacity of around 0.3 kW. The estimated capital cost of a single panel is about ₦80,000. The operation and maintenance (O&M) cost is estimated to be minimal, around ₦500 per year per panel. The module's output derating factor is 88%. The lifespan of these modules is expected to be up to 25 years.

The rated power output of a PV module is typically expressed under Standard Test Conditions (STC), which are defined as:

$$P_{PV} = P_{PV} \times f_{PV}\left(\frac{G_T}{G_{T-STC}}\right)(1-\alpha(T_c - T_{c-STC})) \quad (1)$$

In equation (1), P_{PV} represents the rated power output of the PV module, f_{PV} is the PV derating factor, and G_T is the solar irradiance on the module at the current time. G_{T-STC} is the reference irradiance at STC. The temperature coefficient of power α, set at 0.5, corrects for temperature effects. T_c is the PV cell temperature at the present time, and T_{c-STC} is the cell temperature at STC, set at 25 ºC. An optimal tilt angle of 22° has been used in this study, as suggested by [37], which analysed conditions for a nearby city.

3.2 Diesel generator

Considering the total peak load of 6.06 kW, a diesel generator of 10 kW is selected to account for current load and possible future expansion to it. For cost analysis purposes, an average fuel price of ₦1200 per litre is assumed throughout the simulation. The 10 kW DG incurs a capital cost of ₦1,500,000.00, a replacement cost of ₦1,500,000.00, and an O&M cost of ₦25 per hour. The generator connects to an AC output and has a 15,000-hour operational lifetime. It

Table 1. Typical electrical loads considered for the mini-mall.

appliance/equipment	quantity	rating (Watt)	total Wattage
Lighting (interior)	10	20	200
Lighting (exterior)	10	50	500
Refrigeration units	2	350	700
Freezer	2	680	1360
Entertainment systems (televisions, decoders etc)	-	-	500
Fans for ventilation	4	75	300
Security systems & cameras	8	50	400
Air conditioner	1	1500	1500
Computers and printers	2	350	600
Total estimated Wattage			6060

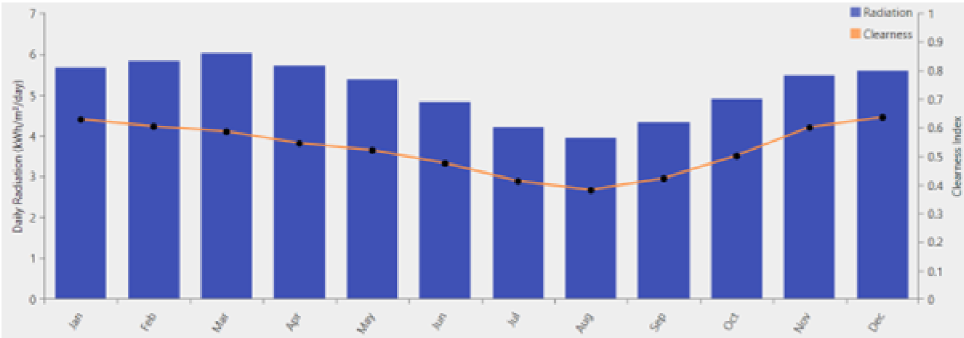

Figure 3. Average monthly solar radiation and clearness index of the study location.

is important to note that this generator operates with a minimum load ratio of 25% of its capacity. HOMER estimates the hourly fuel consumption of the diesel generator using a linear fuel curve model, as defined by equation (2) [38]:

$$F = F_{0,DG}Y_{DG} + F_{1,DG}P_{DG} \tag{2}$$

where, is the $F_{0,DG}$, $F_{1,DG}$, Y_{DG}, and P_{DG} represents diesel generator's fuel curve intercept coefficient, fuel curve slope, rated capacity, and electrical output of the diesel generator respectively.

3.3 Energy storage

The proposed hybrid system incorporates a Trojan SAGM 12 205 battery. It is a 12 V system with a maximum capacity of 219 Ah and is expected to deliver a total throughput of 2,285.10 kWh over its 15-year lifespan. To account for long-term costs, capital expenditures are set at ₦588,293.32 per battery, with replacement costs estimated at ₦588,293.32 and annual O&M costs at ₦0. The amount of energy stored in the battery is computed using equation (3).

$$B_c = \frac{L_D \times B_A}{\eta_B \times DoD \times V_{\text{DC}}} \tag{3}$$

where L_D is the electrical load to be supplied, B_A are the days of battery autonomy, η_B is the round-trip efficiency of the battery, DoD is the depth of discharge, and V_{DC} is the nominal voltage of the system.

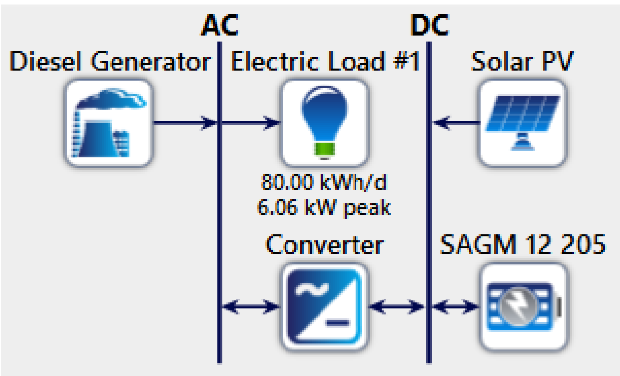

Figure 4. Schematic of the system setup.

3.4 Converter

To ensure proper power flow within the proposed hybrid system, converters are necessary. These converters handle the conversion of electricity between AC and DC, as required by different system components. The capital cost considered ranges from ₦1,250,500.00 to ₦2,790,700.00 for the difference sized of converter considered in the study. The converter is assumed to operates with an efficiency of 95%, signifying a potential 5% energy loss during the conversion process (inverter and rectifier combined). HOMER selects a converter size that can handle the maximum power output of the system:

$$P_{conv} = \frac{P_{\max}}{\eta_{inv}} \tag{4}$$

$$\eta_{inv} = \frac{P_{output}}{P_{input}} \tag{5}$$

4. Results and discussion

Simulation results from HOMER indicate an optimal system with 10.2-kW solar PV system which include 8 batteries including a 6-kW converter system and a 10-kW diesel generator system. This design has a huge economic implication due to a high dependency on fossil fuels. Table 2 presents the cost implications of the different components of the

Table 2. Cost implications of the different system components of the design.

component	capital (₦)	replacement (₦)	O&M (₦)	fuel (₦)	salvage (₦)	total (₦)
diesel generator	1,500,000.00	1,779,733.36	547,635.01	22,660,343.06	-5,516.71	26,482,194.72
solar PV	2,720,000.00	0	0	0	0	2,720,000.00
system converter	1,650,000.00	59,797.53	0	0	-2,182.87	1,707,614.66
battery	4,706,346.56	372,281.86	0	0	-16,436.65	5,062,191.78
system	**10,576,346.56**	**2,211,812.76**	**547,635.01**	**22,660,343.06**	**-24,136.23**	**35,972,001.15**

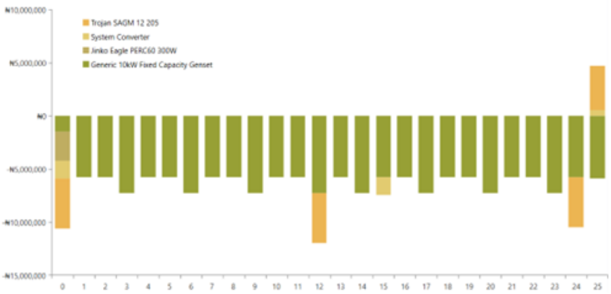

Figure 5. Cashflow of the system for the project lifespan.

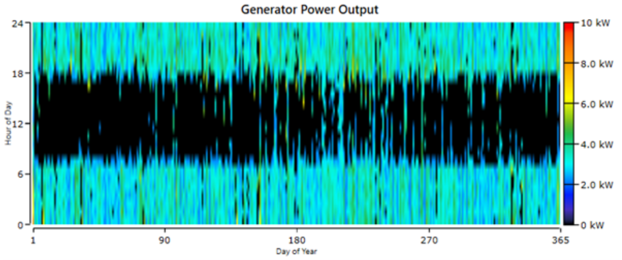

Figure 7. Disel generator operating pattern proportionate fuel consumption.

system over the project life cycle. The total NPC of the system is ₦35,972,000, with fuel costs of diesel generator accounting for the largest portion (₦22,660,343). While the LCOE (COE) of ₦306.16/kWh is higher than the highest existing tariff plan from the grid, strategical approach aimed at reducing fuel consumption will be crucial for long-term economic viability. The capital cost of the system at ₦10,576,346.56 appears reasonable, considering the inclusion of solar panels and batteries which usually take up a huge portion of the initial capital. However, maximising the solar energy capture and optimising battery storage capacity could further decrease reliance on the generator, leading to substantial cost savings over the system's lifetime.

The cash flow for the duration of the system life cycle is illustrated in Fig. 5. It is evident that the negative cash flows for the diesel generator represent ongoing fuel costs, highlighting the significant operational expenses associated with the operation of the diesel generator system. While the solar PV system incurs no operational costs after the initial investment, the battery system requires periodic replacement, as indicated by the negative cash flow in years 12 and 24. This emphasises the importance of battery life and maintenance in the overall system economics. The fluctuating cash flows for the diesel generator and battery system underscore the need for careful financial planning and analysis to assess the long-term viability of the hybrid system.

With an energy demand of 29,200 kWh/yr, the proposed system successfully met the entire requirements with no unmet load albeit at the expense of a high dependence on fossil fuels. The electrical summary reveals only 35.8% renewable energy contribution, with diesel consumption reaching 5,632 litres per year. This translates to the high fuel cost identified earlier. The average monthly energy production is shown in Fig. 6.

The diesel generator operated for 5,444 hours annually, consuming 5,632 litres of fuel. This equates to an average daily fuel consumption of 15.4 litres, accounting for approximately 62% of the year's operating hours. The high fossil fuel consumption of 5,632 litres per year results in a mean electrical efficiency of only 33.8%. Fig. 7 shows that most fuel consumption occurs when PV output is either low or unavailable. The high fixed generation cost (₦305/hr) and marginal generation cost (₦248/kWh) contribute to the substantial annual fuel cost of ₦22,660,343. The extensive operating hours and high fuel consumption underscore the inefficiency and unsustainability of relying heavily on fossil fuels. Furthermore, the economic burden of diesel fuel is exacerbated by fluctuating fuel prices, leading to unpredictable operational costs. This unpredictability complicates financial planning and strains budgets, particularly in remote or underserved areas where economic resources are limited.

Nevertheless, the dependency on diesel generators during periods of low or no PV output emphasises the need for a more balanced and integrated energy solution. The intermittent nature of solar energy necessitates a storage system, addressed in this study by batteries at a significant financial cost (₦4,706,346.56). This indicates that while RES, such as solar PV, can significantly reduce fossil fuel consumption, their effectiveness is highly dependent on adequate energy storage solutions. Fig. 8 illustrates the battery system's state of charge, revealing a charging pattern where batteries are nearly full most of the day. The figure highlights a scenario where low battery charge is avoided based on supply from the diesel generator. Observations from a typical 24-hour period (3 am June 25 to 2 am June 26) in Fig. 9 show that the battery state of charge dropped from about 95% at 5 am to 5% at 9 am due to the non-availability of the diesel generator and low solar radiation from the solar PV. A similar trend is observed between 12 noon and 3 pm the same day, with an improved state of charge following the continuous availability of the generator thereafter. This underscores the need for an effective energy management system to optimise production from different sources.

Despite the generator's dominance, the solar PV system demonstrates the potential for increased renewable energy

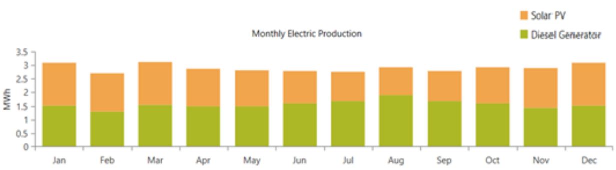

Figure 6. Average monthly electricity production of the hybrid system.

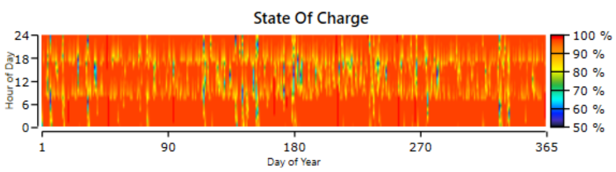

Figure 8. Dmap plot of Battery system state of charge throughout the year.

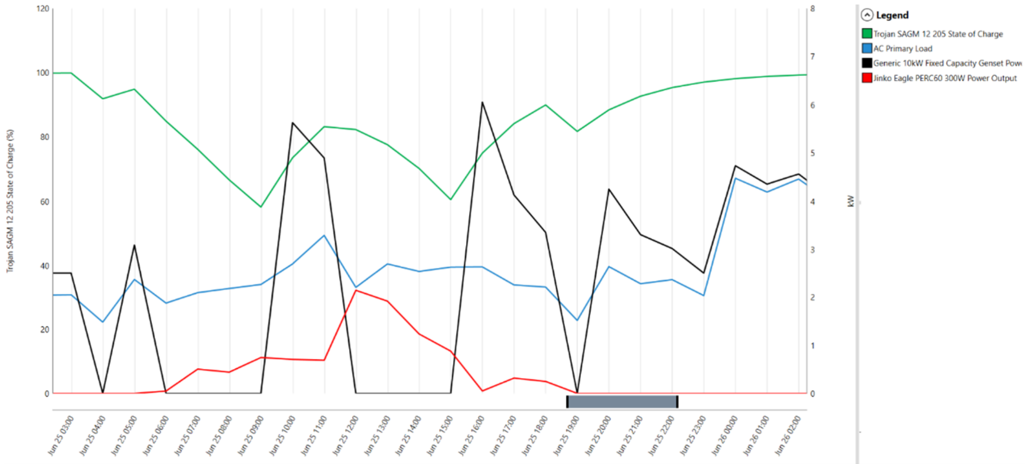

Figure 9. Battery state of charge relative to PV and generator osutput, and load served over a 24-hour period from 3 am June 25 to 2 am June 26.

use. With a rated capacity of 10.2 kW and annual production of 15,989 kWh, the PV system achieves a capacity utilisation factor of 17.9%. This suggests that under optimal conditions, solar energy could contribute a much larger portion of the business energy needs. With a performance ratio of 82.16%, this system shows high efficiency in energy production, indicating optimal performance under varying conditions. The battery bank of the optimal system, however, offers limited storage capacity, with an annual throughput of only 1,550 kWh. This translates to a 3.15-hour autonomy suggesting a need for a more cost-effective storage solution for deeper integration of renewable energy.

The effect of the solar PV degradation on solar energy production over the 25-year lifespan of the system is shown in Fig. 10. The system initially production of 15,989 kWh/year which account for 46% of total generation in its first year drops to 14,176 kWh/year (42.5% of production), representing a total reduction of approximately 11.35% from the initial output. This degradation pattern is typical for solar PV systems, which generally experience a decrease in efficiency due to factors like weathering, material fatigue, and reduced solar cell performance. Despite the drop, solar panels remain effective in generating substantial energy throughout their lifespan.

4.1 Environmental impact and carbon savings

The hybrid system incorporating solar PV offers significant environmental benefits compared to traditional diesel-only systems. As illustrated in Fig. 11, the deployment of the 10.2 kW solar PV system, significantly reduces the emission of harmful pollutants. Specifically, the system demonstrates considerable environmental benefits, especially in reducing carbon dioxide (CO_2) emissions—a major driver of climate change. With the inclusion of solar PV, CO_2 emissions decrease from 23,327 kg per year without solar PV to 14,713 kg per year, representing an annual reduction of 8,614 kg. This underscores the system's contribution to mitigating global warming. Beyond CO_2, the solar PV system also reduces emissions of other harmful pollutants. Carbon monoxide (CO) emissions drop from 176 kg per year to 111 kg per year, a savings of 65 kg annually. Unburned hydrocarbons decrease from 6.43 kg per year to 4.05 kg per year, particulate matter from 10.7 kg per year to 6.75 kg per year, sulfur dioxide (SO_2) from 57.2 kg per year to 36.1 kg per year, and nitrogen oxides (NO_x) from 201 kg per year to 126 kg per year. These reductions highlight the solar PV system's positive impact on air quality, contributing to cleaner energy generation and advancing environmental sustainability goals. The carbon savings, combined with the decrease in other pollutants, emphasise the critical role of renewable energy in reducing the environmental footprint of energy systems.

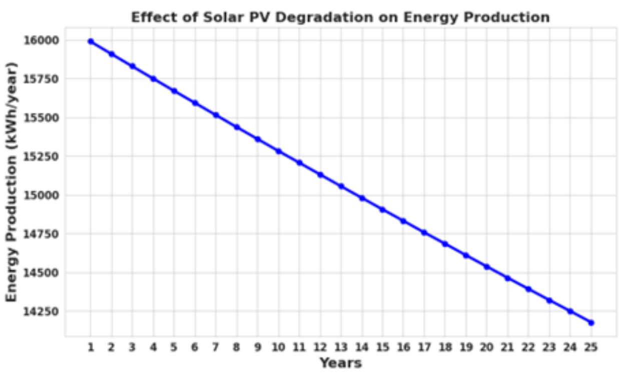

Figure 10. Solar PV degradation effect on energy production.

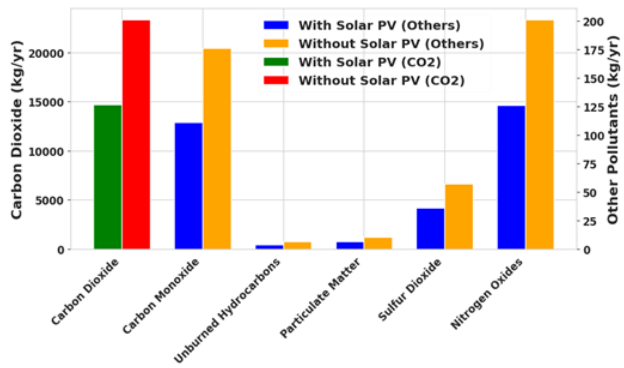

Figure 11. Emission Reductions with the hybrid Solar PV system.

5. Conclusion

This study demonstrates the potential of hybrid solar PV-diesel generator systems for mini-marts in regions with limited or no access to grid electricity. It emphasises the importance of optimising RES designs to maximise renewable energy integration. The proposed 10.2 kW solar PV system, complemented by a 10-kW diesel generator, provides a reliable energy solution that meets the annual demand of 29,200 kWh. While the initial design satisfies energy needs, its long-term economic sustainability is contingent upon reducing dependence on fossil fuels. Strategies to address this challenge include increasing solar capacity and exploring alternative battery technologies to enhance autonomy and decrease reliance on the diesel generator. Future research should focus on identifying cost-effective battery storage solutions that maximise renewable energy utilisation and promote long-term economic viability. Additionally, investigating demand-side management strategies could further mitigate the dependence on diesel generators, ultimately leading to a more sustainable energy solution for similar applications.

Authors Contributions
All authors have contributed equally to prepare the paper.

Availability of Data and Materials
The data that support the findings of this study are available from the corresponding author upon reasonable request.

Conflict of Interests
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.

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