TECHNO-ECONOMIC ANALYSIS OF HYBRID SOLAR PV/DIESEL POWER SYSTEM: CASE STUDY OF SUSTAINABLE AGRICULTURE

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Abstract: Remote and rural nature of agricultural activities establish their dependence on off-grid electricity. This study presents an optimal design of a hybrid solar photovoltaic (PV)/diesel power system for the support of irrigation farming and post-harvest cold storage activities in Kadawa village, Kano state of Nigeria. The Hybrid Optimization of Multiple Energy Resources (HOMER) software is used to conduct the techno-economic analysis of the proposed hybrid power system. Simulation results showed that the proposed system can be served by a 25 kW PV system and diesel generator of 10 kW. Other vital indicators in the result included the cost of energy (COE) and net present cost (NPC) which were subjected to sensitivity analysis. Sensitivity variables such as solar irradiance and diesel fuel price effect on this optimal system were conducted. Results show that integrating renewable energy into agricultural activities will go a long way in achieving food security.
Keywords: Net present cost, optimization, renewable energy, sensitivity analysis

Introduction

Modern agricultural practices have led to significant reduction in the number of malnourished people in some developing countries. However, one in every four persons still goes hungry in Africa. In Nigeria, a sizable number of agricultural products used to feed the populace come from remote and rural areas whose isolation means they have little or no access to power supply from the grid (Olatomiwa *et al*., 2015). Over the years, diesel-powered generators have been the only source of power to most rural communities to service essential social and economic activity like health and agriculture. However, concerns about the rising cost of fuel, the inherent effect of fossil fuel power generating station on the environment and the resultant climate change phenomena has brought to the fore the need to diversify the energy mix with particular interest in sustainable power generation methods (Shoeb *et al*., 2016). Consequently, these remote locations require a sustainable source of power to support and improve farming activities such as irrigation, storage and processing of harvested crops. In this regard, the sustainable development goals (SDG) set out by the UNDP includes, amongst other goals a target of zero hunger by 2030. Renewable energy technologies will be essential in ensuring that these targets are accomplished, particularly in a developing country like Nigeria. Although, a major challenge for some renewable energy source is the intermittent nature of the resources which is largely due to the associated variation in climatic condition (Shoeb *et al*., 2016). Hybrid systems which combine two or more renewable energy system or a blend of renewable energy system (RES) and fossil fuel generators can help to improve the reliability of power supply to support agricultural practices.

A number of studies have been reported that have either used a renewable energy source alone or a hybrid with conventional fossil fuel generators for support of rural loads and agricultural practices. An instance of such study is in Olatomiwa *et al*. (2015), which demonstrated the economic feasibility of hybrid power generation in six rural communities geographically spread across Nigeria. Findings showed that the optimal system for all sites under consideration is a PV/diesel/battery hybrid configuration. However, only the basic need of the rural communities was considered. Sen and Bhattacharyya (2014) proposed an optimal hybrid system for an off-grid village where the results show that RES generator is an economically viable substitute for extending grid services to a remote location. Phurailatpam *et al*. (2018) describes an optimization of a DC microgrid for rural applications that included agricultural load. The study shows that rural areas with partial grid connection will have a lower cost of energy (COE) when compared to an autonomous system.

Some researchers have studied the use of different energy sources for water pumping application (Mustafa *et al*., 2014; Nurunnabi and Roy, 2015; Rezk and Shoyama, 2014). Each of these works employed different energy sources which include, wind, solar PV, fuel cell, diesel and in some cases a hybrid of these sources. The results were positive for the use of renewable technology. However, Nabila et al., 2014 favoured the use of diesel generator over a PV system due to a lower COE. Though, this is the result of the unusually lower price of diesel fuel in Algeria at $0.2 /L. Shoeb *et al*. (2016) analysed a hybrid PV-Diesel mini-power system for remote location under various irrigation load conditions. Significant findings show that running the irrigation pump loads during the daytime with the solar PV contributing a significant fraction of the total energy generated resulted in reduced COE. Studies that have demonstrated the use of a combination of different renewable energy and diesel fuel generator technologies for different rural application is also presented in Bekele and Boneya (2012); Kaur and Segal (2017); Ranjevaa and Kulkarnia (2012); Ahmed and Fernando (2017).

From the highlighted literatures, hybrid renewable energy systems have shown to be a reliable and cost-effective method of supporting agricultural practices like irrigation system; particularly in remote and rural areas. However, most studies ignored the need for storage of farm produce and its electricity requirements. Considering the Nigerian government's efforts at diversifying the economy away from oil with special focus on agriculture, the number of farming activities being carried out in these rural areas is expected to increase. Hence, this paper aims to analyse a hybrid PV–diesel generator system that will not only support irrigation activities of farming, but will also include support for cold storage facilities to cater for the post-harvest operation of farming. This will assist the country’s food security drive and ensure farmers get more value for their investment using sustainable practices. The NPC and the COE are the key indicators of the most optimal solution to be considered. In addition, the impacts of variation in renewable energy sources and cost of diesel fuel were investigated and analysis of these variations on the NPC and COE was carried out.

Materials and Methods

Study area and solar energy resource potential

The area used for this study is the farm settlement of Kadawa with geographical coordinates of 11° 38' N, 8° 25' E. It falls within the Kano River Irrigation Project, Kano State, Nigeria and a hybrid PV-Diesel system is proposed to support agricultural activities (irrigation and cold storage). It is an area cultivated with vegetable crops which include onions, pepper and mostly tomatoes. This area accounts for about 70% of tomatoes consumed in Nigeria, however, about 40-50% of these is lost due to high post-harvest losses caused by poor handling, processing and preservation practices. When glut occurs in the market during the harvest periods, farmers are forced to either sell at very low prices or allow it to rot away. Currently, farming outside the raining season between April and September is practiced with irrigation where smallholder farmers use small petrol pumps to irrigate their lands from the existing branch and field canals water supply system. Even at that, farmers continue to suffer from various challenges ranging from the high cost of petrol/diesel, incessant maintenance of faulty pumps, etc. All these have resulted in low output irrespective of the farmer efforts. With an average daily radiation of 5.951 kWh/m^2/day, the location has a good potential for solar energy production. The average monthly solar radiation obtained from NASA surface meteorology and solar energy website is illustrated in Fig. 1.

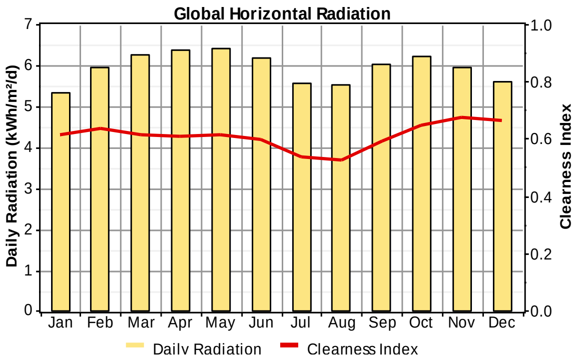


Fig. 1: Monthly average solar radiation data for Kadawa village

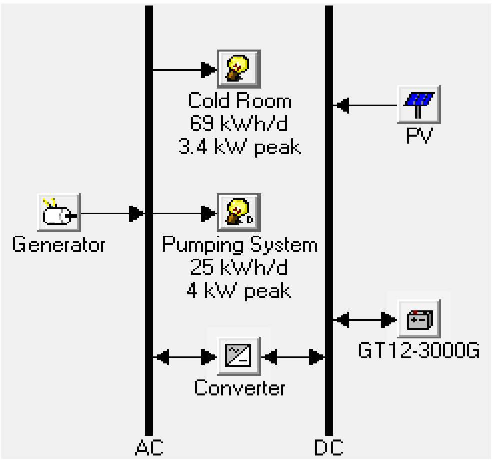


Fig. 2: Hybrid system schematic in HOMER

Hybrid system design

The schematic of the system setup is illustrated by Fig. 2. The system includes a PV array, Diesel generator, battery and converter. The power generated by the PV array is supplied to the pump system and cold room loads through the AC bus. The generator is used mainly as a backup power supply system for the cold room in days with cloud overcast and during maintenance of the PV array. Excess power from the PV array is stored in the battery bank which is used to meet the demand of the load when the PV is not generating at night. The converter serves as the Bidirectional Bridge between the AC bus and the DC bus. Input specification of the hybrid system components are outlined in subsequent section.

Load estimation

This study presents two load types in cold rooms for storage of harvested perishable crops and the water pumping system for irrigating farmlands. Fig. 3 shows the assumed monthly average electrical load profile of a typical cold room developed based on information from a manufacturer's catalogue. This profile includes the associated lighting load for the cold room with an estimated energy consumption of 69 kWh/day. In Homer, it is modelled as the primary load.

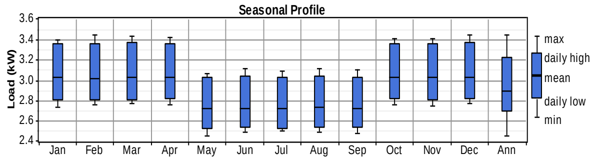


Fig. 3: Average monthly load profile

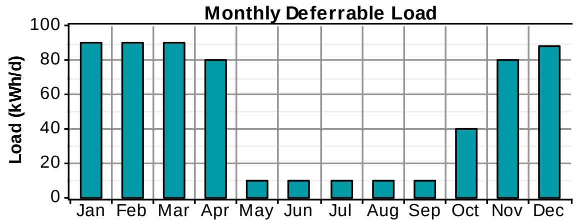


Fig. 4: Average monthly deferrable load profile

For the water pumping system, a 4 kW LORENTZ pump is specified. It has a maximum flow rate of 57 m^3/h and suitable for surface pumping application. Depending on the need of the farmers, the pumped water may either be sent to the storage tank or used to water the fields directly. This study assumes the farm settlement has a cluster of storage tanks with a combined capacity of 200 m^3. The electric load demand of the pumping system is a representation of the water demand by the farm which is required to adequately irrigate the crops. The irrigation period covers the months outside the rainy season (May-September) as illustrated in the average monthly deferrable load profile of Fig. 4.

PV array

The object of the proposed system is to ensure that the PV component of the system is able to supply its load requirements most of the time. A polycrystalline silicon PV module manufactured by Yingli solar having a peak power of 250 Wp at a voltage of 29.8 V and short circuit current of 8.92 A under standard test condition (STC) is selected. The lifespan of the PV module is 25 years with an initial installation cost of $1400/ kW including the cost of the charge controller. Electrical parameters of the solar PV module under nominal operating cell temperature are outlined in Table 1.

Table 1: Technical and cost parameters of PV module

Parameters	Value
Rated Power Pmax (W)	182.4
Voltage at Pmax Vmpp (V)	27.2
Current at Pmax Impp (A)	6.71
Open-circuit voltage Voc (V)	34.7
Short-circuit Isc (A)	7.21
De-rating factor (%)	80.7
Lifetime (Years)	25

Generator

Although the PV module will generate power during the day while at night the output will be zero, a hybrid system that includes a generator will take care of this condition and days when the PV array do not generate enough during the day. This will ensure that the loads are always served irrespective of the weather condition. Technical parameters and the associated cost of the diesel generator selected for this system is outlined in Table 2.

Table 2: Technical and cost parameters of diesel generator

Parameter	Value
Rated capacity (KW)	10
Capital cost ($)	555
Replacement cost ($)	555
Operation and maintenance cost ($/h)	0.5
Fuel price ($/L)	0.65
Lifetime (Hours)	15000

Battery

Storage batteries are required to store surplus energy from the PV output during the day for use at periods when the load demand exceeds the energy production level of the PV array. A 2 V, 2000 AH Gaston GT12-2000G batteries is used in this hybrid system. At a capital cost of $575, manufacturer data sheet shows that it has an average life span of 15 years.

Converter

The converter used for this system if manufactured by Sukam with an efficiency of 90% and lifespan of about 20 years. For this study, the capital cost for a 10 kW converter is $3000. Replacement cost is $3000 and operation and maintenance cost that is negligible. Technical and cost data of the converter are shown in Table 3.

Table 3: Technical and cost parameters of converter

Parameter	Value
Rated capacity (KW)	10
Capital cost ($)	3000
Replacement cost ($)	3000
Operation and maintenance cost ($/h)	0
Efficiency (%)	90
Lifetime (Years)	20

System simulations and optimization

HOMER software was used to simulate the system and determine the optimal value of the components. HOMER is a micro-power optimization tool that minimizes the NPC and the levelized COE of the system under consideration based on some techno-economic input parameters. NPC consists of all associated cost incurred in setting up the system during its useful life period taken as 25 years in this study. This cost includes capital cost, cost of replacement, fuel cost, etc. equation 1 gives the expression for calculating NPC in HOMER.

$$C_{NPC}=\frac{C_{ann,tot}}{CRF\left(i,R_{proj}\right)} \qquad (1)$$

Where $C_{ann,tot}$ is the total annualised cost, i equals interest rate, N is the project lifetime, in years and CRF is the capital recovery factor given by

$$CRF(i,N)=\frac{i(1+i)^N}{(1+i)^N-1} \qquad (2)$$

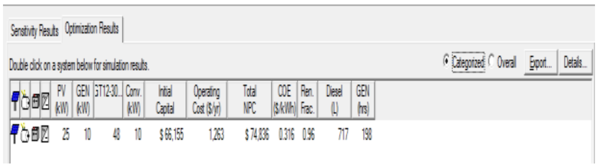
The levelized COE is expressed as

$$COE=\frac{C_{ann,tot}}{E_{served}} \qquad (3)$$

Where E_{served} is the total energy served by the system.

Results and Discussion

The result of the simulations carried out in HOMER gave an optimal system that balances the initial investment and operation and maintenance cost whilst minimizing the NPC. A hybrid system comprising of 25 kW PV array, 10 kW diesel generator, 48 storage batteries and 10 kW converter is the most economical configuration. The system will attract an NPC of $74,836, an initial capital of $66,155 and an operating cost of $1,263. Fig. 5 shows that all these economic indicators resulted in a COE of $0.316 per unit.



PV (kW)	GEN (kW)	GT12-30...	Conv. (kW)	Initial Capital	Operating Cost ($/yr)	Total NPC	COE ($/kWh)	Ren. Frac.	Diesel (L)	GEN (hrs)
25	10	48	10	$ 66,155	1,263	$ 74,836	0.316	0.96	717	198

Fig. 5: Simulation results of the hybrid system in HOMER

The average energy output of the hybrid system on a monthly basis is shown in Fig. 6 where it is evident that the power contribution of the diesel generator system only occurs for a few hours in some months while the PV system is the sole source of power for the major part of the year. In addition, 44,339 kWh/yr, which account for 96% of the annual energy produced is supplied by the PV system while the remaining 4% is contributed by the diesel generator system as shown in Table 4.

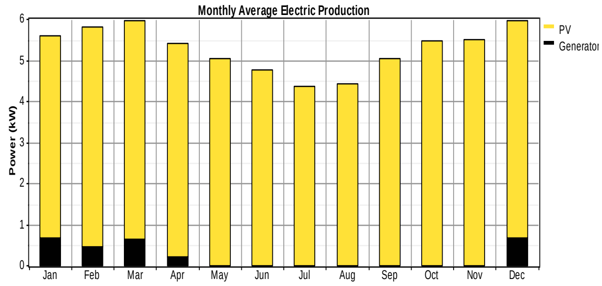


Fig. 6: Monthly average power output from the hybrid system

Table 4: Annual energy production and utilization of the hybrid system

		kWh/yr	%
Production	PV array	44,339	96
	Generator	1,949	4
	Total	46,287	100
Utilization	AC primary load	25,367	74
	Deferrable load	9,040	26
	Total	34,408	100
Quantity	Excess electricity	5,525	11.9
	Unmet electric load	0.0000143	0
	Capacity shortage	0	0

The cost analysis of each component of the optimal hybrid system is illustrated in Fig. 7. 49% of the total cost is spent on the PV modules followed closely by the cost of the storage batteries. The converter and diesel generator account for less that 15% of the total cost. Although the PV modules and battery components attract a chunk of the initial investment, the overriding interest of having a system that is environmentally friendly and sustainable in the long term cannot be downgraded.

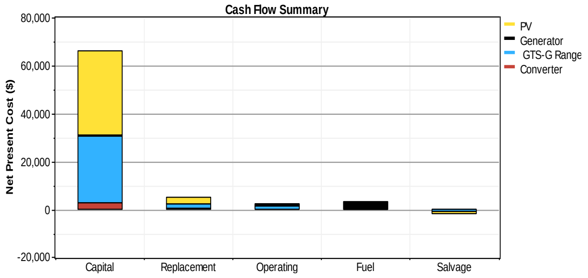


Fig. 7: Cost outlook of the hybrid PV–diesel system

The cash flow outlook for a lifespan of 25 years is illustrated by Fig. 8. It can be observed that the PV/battery component continues to attract the bulk of the cost even when the need for replacement arises. However, the need may not arise until after 20 years.

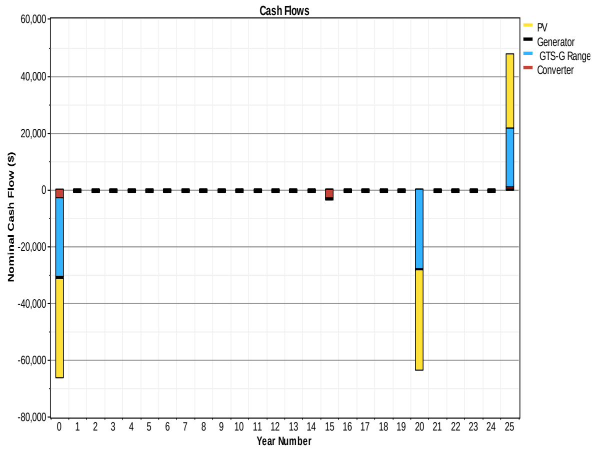


Fig. 8: Life cycle cash flow of the hybrid PV–diesel system

Sensitivity analysis

Although the system under consideration is optimal, however, the reality is that it will be subjected to a number of factors peculiar to the energy source (solar radiation and diesel). Consequently, the effect of changes in solar resource and diesel fuel prices is analysed by conducting a sensitivity analysis on the optimal hybrid system.

In the first scenario, the fuel price of diesel is fixed at $0.65 /L while a ± 20% variation is applied to the scaled annual average of the solar resource radiation at 5.95 kWh/m²/d. The effect of radiation on the optimal system design is shown in Table 5. When the incident solar radiation on the 25 kW PV array is reduced by 20%, the NPC, operating cost and COE increased while the renewable fraction decreased to 84%. This is caused in part by the increase in fuel cost due to the additional power production from the diesel generator to meet the load demand as shown in Fig. 9. However, with an increase of 20% in incident solar radiation, the system achieved a 100% renewable fraction with a drop in the NPC, operating cost and COE.

Table 5: Effects of solar irradiance on hybrid system cost

Global Solar kWh/m²/d	Total NPC $	Operating Cost $/yr	COE $/kWh	Ren. Fraction
4.76 (-20%)	83,915	1,263	0.355	0.84
5.95	74,836	2,584	0.316	0.96
7.14 (+20%)	71,443	769	0.302	1

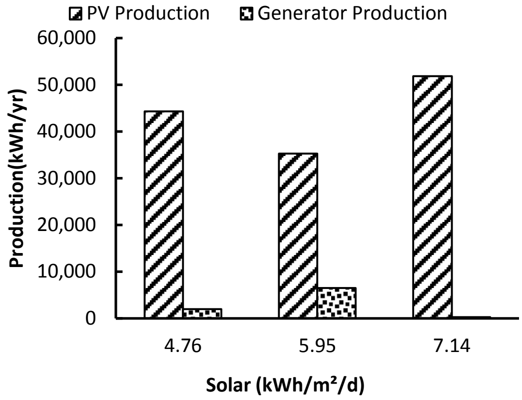


Fig. 9: Effects of solar irradiance on energy production

Table 6 represents the second scenario where the price of diesel rose from a minimum of $0.52 /L to $0.78 /L representing a ± 20% variation in price while the annual solar resource was fixed at 5.59 kWh/m²/d. It could be observed that there was a marginal increase in the value of NPC, operating cost and COE as the price of diesel fuel increases. However, the renewable fraction remained at the optimal system value of 96%.

Table 6: Effects of fuel price on hybrid system cost

Diesel Price $/L	Total NPC $	Operating Cost $/yr	COE $/kWh	Ren. Fraction
0.52 (-20%)	74,196	1,263	0.314	0.96
0.65	74,836	1,170	0.316	0.96
0.78 (+20%)	75,477	1,356	0.319	0.96

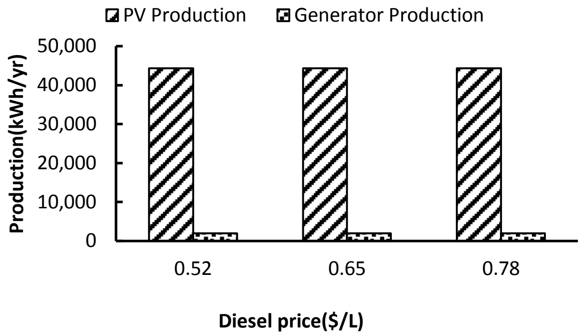


Fig. 10: Effects of fuel price on energy production

Energy production from both the PV array and the generator during a price increase in diesel remained unchanged as illustrated in Fig. 10. Further, examination shows that 44,339 and 1,949 kW/h of energy was produced from PV and diesel the generator, respectively. This value is also equal to the energy production when solar radiation is 4.76 kWh/m²/d and diesel price at $0.65 /L.

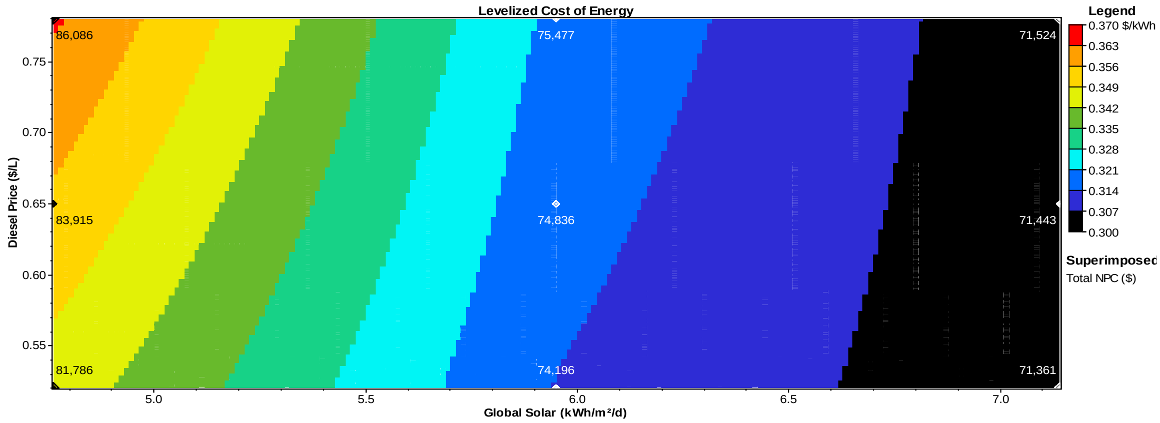


Fig. 11: Surface plot showing the effect of diesel price and solar irradiance on the cost of electricity

Finally, the ± 20% variation is applied to both the solar resource average value and the price of diesel simultaneously. Fig. 11 is a surface plot that illustrates the effect of these variations on the NPC and the COE for the optimal hybrid system. It is observed from the plot that the COE varies between a minimum $0.3 /kWh and $0.37 /kWh, while the NPC varies between $71,361 and $86,086. This value is dependent on the level of solar resource radiation and the price of diesel fuel.

Conclusion

This study presents an analysis of a hybrid PV-diesel power for irrigation system and cold room storage of harvested perishable crops in rural farming community of Kadawa, Nigeria. These two loads were modelled in HOMER as deferrable and primary loads respectively and simulations carried out. Results obtained produced a combination of 25 kW PV modules, a 10 kW diesel generator, 10 kW converter and 48 batteries as the optimal system configuration that has a combine energy output of 46,287 kWh/year. In addition, an initial capital cost and NPC of $66,155 and $74,836, respectively produce a COE of $0.316 /kWh. An analysis of the project lifecycle showed that some components will require replacement after about 20 years of operation. Furthermore, sensitivity analysis was conducted to understand the impact of solar resource and diesel price variation on the optimal system. Findings revealed that an increase in the solar resource reduces all associated costs for the optimal system while the increase in diesel price leads to a marginal increase cost with a renewable fraction that remains unchanged.

As a country plagued by unreliable power from the grid, this hybrid system can be a reliable source of energy for rural communities. If food security of Nigeria is to be guaranteed, the government adoption of this system for rural famers can help. Moreover, legislations that include tax exemptions for investors in renewable energy products and subsidy for low income rural famers to employ this system will further boost agricultural output. All these will go a long way in ensuring that the aim of the sustainable development goals in achieving zero hunger as proposed in this study is achieved, in addition to improving the yield of rural farmers.

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