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Feasibility analysis of an off-grid photovoltaic-battery energy system for a farm facility

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ABSTRACT

Renewable energy plays a very important role in the improvement and promotion of environmental sustainability in agricultural-related activities. This paper evaluates the techno-economic and environmental benefits of deploying photovoltaic (PV)- battery systems in a livestock farmhouse. For the energy requirements of the farm to be determined, a walkthrough energy audit is conducted on the farmhouse. The farm selected for this study is located in southern Nigeria. The National Renewable Energy Laboratory's Hybrid Optimization Modeling for Electric Renewable (HOMER) software was adapted for the purpose of the techno-economic analysis. It is found that a standalone PV/battery-powered system in farmhouse applications has higher economic viability when compared to its diesel-powered counterparts in terms of total net present cost (TNPC). A saving of 48% is achievable over the TNPC and Cost of Energy with zero emissions. The results obtained show the numerous benefits of replacing diesel generators with renewable energy sources such as PV-battery systems in farming applications.

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1. INTRODUCTION

Access to energy which is clean, reliable and affordable (especially electricity) is essential to the sustainability of modern civilization [1, 2]. This is because access to energy is vital and connected to many of the major opportunities and challenges experienced across the globe. Access to clean energy is essential to the creation of more jobs, mitigation of climate change as well as sustainable food production. Access to adequate and clean energy is therefore paramount to economic success as well as positive human health outputs. In order to achieve this, the United Nations has emphasized the indispensability of affordable and clean energy for all through item 7 on the sustainable development goals (SDG) [3]. Working towards achieving reliable, clean and affordable energy is essential because it has a connection with all other SDGs. As such, concentrating on widespread access to energy, energy conservation, energy efficiency and most especially, the increased penetration of renewable energy in the global energy mix would ensure sustainable societies and create resilience to environmental challenges such as climate change [4].

Currently, about 1 billion people lack access to electricity worldwide. Responsible for more than 50 % of this population is Sub-Saharan Africa (SSA) [5, 6]. Consequently, homes and businesses are typically faced with unreliable electricity services. This scenario inflicts significant limitations on commercial activities, delivery of public services, and standard of living. Due to the low electrification rates in rural communities in Nigeria, many businesses located in rural communities are faced with adequate energy access challenges [7, 8]. For the alleviation of the effect of unreliable access to grid-connected electricity, many homes and business resorts to using captive diesel and gasoline generators [9]. This method of electrification has many challenges associated with it. Some of these include fluctuations in fuel pump prices, incessant scarcity of fuel products, exposure to toxic fumes, fire outbreaks, wear and tear [10-12], etc. Apart from these, the cost of energy is usually higher. This is because the cost involved in servicing and maintaining this form of electricity generation is high and consequently not profitable for many business owners. Hence, alternatives to fossil powered electricity generation is paramount.

In the recent past, the Nigerian government has pledged increased investments into the agricultural sector in Nigeria [13]. This is expected to boost the Gross Domestic Product (GDP) and create more employment opportunities among the youths. As a result of this, the number of entrepreneurs venturing into livestock farming is on the increase. Livestock farming requires electricity for its basic daily operation. Some of the energy-consuming activities on a livestock farm include water pumping, lighting, refrigerating, and other office activities. Traditionally, due to lack/inadequate electricity in Nigeria, livestock farms are either powered by gasoline or diesel generators. In order to avoid the bottlenecks and negative consequences exhibited by this means of energy production, the adoption of small-scale renewable energy technologies must be explored. Some of these technologies include Photovoltaic (PV), wind turbines, and biomass. As alternatives to fossil-fuelled generators, research into the use of renewable energy technologies for electricity production has been conducted and presented. However, the majority of renewable energy research efforts in SSA have only being directed towards meeting the basic energy needs for household applications [14-17]. Some of these researches have also been extended to meeting the energy needs of remote telecom base stations [18-20] and rural healthcare centres [6, 21-23]. Little research efforts have been extended to powering livestock farming in Nigeria.

The aim of this research is to elucidate the technical, cost and environmental viability and effectiveness of replacing captive diesel and gasoline generators with PV facility. This study, therefore, presents the techno-economic and environmental analysis of adopting a PV-battery energy system for powering a typical remote livestock farmhouse in Nigeria. This technology is selected due to its modularity and technological maturity in the Nigerian market. The results of these analyses would be effective in formulating informed policy for establishing off-grid livestock farms across Nigeria.

2. RESEARCH METHOD

The method used in this research is presented in this section as shown in Figure 1. The study was carried out between September 2017 and May 2018 in a typical remotely located livestock farm in Akinyele local government area of Oyo State, Nigeria. It method entails: calculation of daily water requirement, determination of total dynamic head (TDH) for pumping of water, estimation of hydraulic energy which is required daily to pump the water, extraction of available solar radiation of the site in terms of hours per day and calculation of the size of PV modules and batteries required based on the total load demand. The techno-economic analysis is implemented using Hybrid Optimization Modeling for Electric Renewable (HOMER). The details of the methodology are presented in the next sub-sections

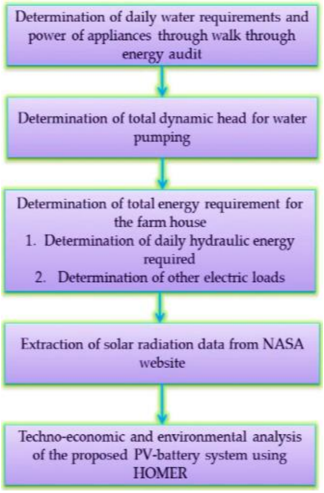


Figure 1. The methodology applied for the study

2.1. Walkthrough energy audit and determination of daily water requirement

From the audit, it was identified that the farmhouse consists of 1 administrative office and 3 rooms accommodation for the farm attendants on night shifts. The total number of birds is 5000 while the farm breeds 250 goats. Based on these information, the daily water requirement of the farm was estimated as shown in Table 1. The water requirements actually vary seasonally depending on the weather conditions (wet or dry). More water is used during dry weather conditions. The water requirement for the case study (based on the daily records from the farm) is given in Table 1. Water use on the farm is divided into three parts; the personnel on site, the birds and the goats on the farm.

Table 1. Estimated daily water requirement of the farm

S/N	Item	Quantity	Estimated water requirement (litre/day)
1	Birds (chicken)	5000	1705
2	Goats	250	4732
3	Personnel/ Visitors	8	1600
	Total		8037

2.2. Determination of TDH

The TDH (measured in meters) determines the effective pressure at which the pump must operate for the delivery of water. It consists of two parts; the vertical lift and the total frictional losses. The vertical lift is the addition of elevation, standing water level and drag down parameters. The frictional loss is the pressure that is required to overcome the friction in the pipes to the point of discharge. This is given as (1):

$$THD = TV_{lf} + TF_{loss} \quad (1)$$

where TV_{lf} is vertical lift and TF_{loss} is total frictional losses
Step 3: determination of hydraulic energy required daily:
This is obtained by using (2).

$$H_e = \rho \times V \times g \times THD \quad (2)$$

Based on calculations using (1) and (2), a 0.7 hp motor is needed, but a 1 hp motor is selected because of the possibility of getting the 0.7 hp motor in the market and because of future expansion on the farm. This is equivalent to 746 W.

2.3. Determination of radiation data

The location of the study receives a moderate solar radiance of approximately 6.16 kWh/m2/day and sunshine hour of about 6 hours daily. Figure 2 shows the monthly irradiance and a clearness index as obtained from the NASA website [24]. This data serves as metrological input to HOMER and it defines the operational capacity of the PV panels.

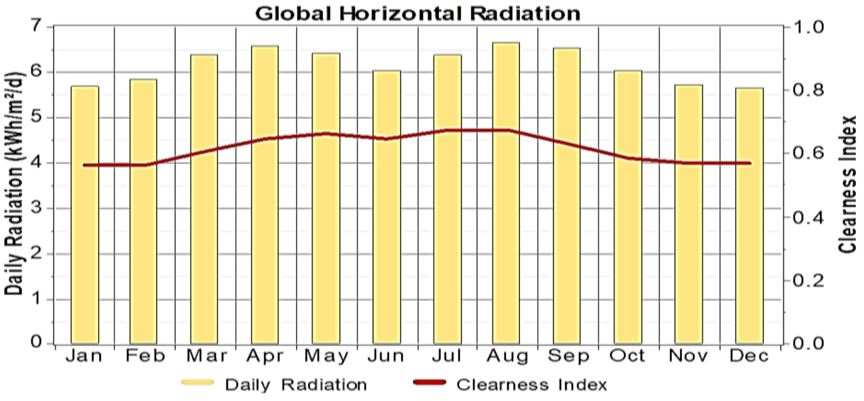


Figure 2. Monthly global irradiance on site

2.4. Techno-economic analysis

The analysis that is used for choosing the PV-battery configuration is based on the optimization process. This is done using the National Renewable Energy Laboratory's Hybrid Optimization Modeling for Electric Renewable (HOMER) software. HOMER a design and optimization software for microgrids and distributed energy generation systems developed by the national renewable energy laboratory (NREL) was employed to determine the economic and technical viability of the proposed system [25]. It has the capacity to stimulate the system behaviour for 8760 hours of the year by making sure the system objective and constraints are satisfied. It compares the cost of different possible configurations and returns the system with the least TNPC as the most viable. Input parameters into the software are given in Table 2. The equation used for computing the size of the PV, battery, the TNPC, and the LCOE is given in the next subsections.

Table 2. System component details [26]

Parameter description	Value	Parameter description	Value
PV		Battery	
Rated Capacity	1kW	Rating	4V,1900Ah
Derating Factor	80%	Round-trip efficiency	85%
Capital cost	$4.250.00	Capital cost	$269.00
Replacement cost	$4.200	Replacement cost	$260
Operational life	20 years	O & M cost	$5/yr
Ground reflectance	20%	Operational life	4 years
Converter		Diesel	
Rated power	1kW	Rated power	1Kw
Efficiency	90%	Capital cost	$280
Capital cost	$621.80	Replacement cost	$280
Replacement cost	$569	O & M cost	0.5$/hr
O & M cost	$3/yr	Operational life	15000hours
Operational life	15 years	Minimum load ratio	30%

2.4.1. PV system

The energy available for the PV array to deliver at a specific location is given by (3) [27].

$$\mathrm{Epv(t)} = \mathrm{H(t)} \times \mathrm{B} \times \mathrm{s} \times \eta_{\mathrm{pv}} \tag{3}$$

where: H(t) is hourly insolation (kWh/m^2), B is the surface area of the PV module (m^2), s is the factor of penetration, η_{PV} is the PV panel efficiency. The efficiency of the PV generator is given as [27]:

$$\eta_{\mathrm{PV}} = \eta_{\mathrm{r}}\eta_{\mathrm{cp}}\,[1 - a\,(\mathrm{T_d} - \mathrm{T_{dref}})] \tag{4}$$

where η_{r} is the efficiency of the reference module, η_{cp} is the efficiency for power conditioning, a is the temperature coefficient for the efficiency of the generator, $\mathrm{T_{dref}}$ is the temperature of the reference cell (°C), $\mathrm{T_d}$ is the temperature of the cell (°C) which is obtained from the temperature of the surrounding $\mathrm{T_s}$ (°C) and the sun's radiation (Ra) as follows:

$$\mathrm{T_d} = \mathrm{T_s} + \left(\frac{\mathrm{NTOC} - 20}{800}\right)\mathrm{Ra} \tag{5}$$

2.4.2. Battery capacity

HOMER uses (6) to calculate the storage capacity of the battery [28]:

$$B_{sc} = \frac{DL \times \mathrm{B}A_d}{\eta_{Ba} \times DoBD \times V_{sn}} \tag{6}$$

where DL, BA_d, η_{Ba}, DoBD, and V_{sn} are the demands of the load, days of battery autonomy, round-trip efficiency of the battery, depth of battery discharge and the system's nominal voltage respectively.

2.4.3. Economic analysis

a. Total net present cost (TNPC)

HOMER uses (7) to estimate the Total Net Present Cost (TNPC) [6].

$$TNPC = \frac{TC_{an}}{F_{cr}(i, X_{proj})} \tag{7}$$

TC_{ann} represents the total cost obtained annually, F_{cr} represents the capital recovery factor, i represents the interest rate (%), and X_{proj} is the lifetime of the project. For this work, the interest rate used is 12%, while the lifetime of the project is 25 years.

b. Levelised cost of energy (LCOE)

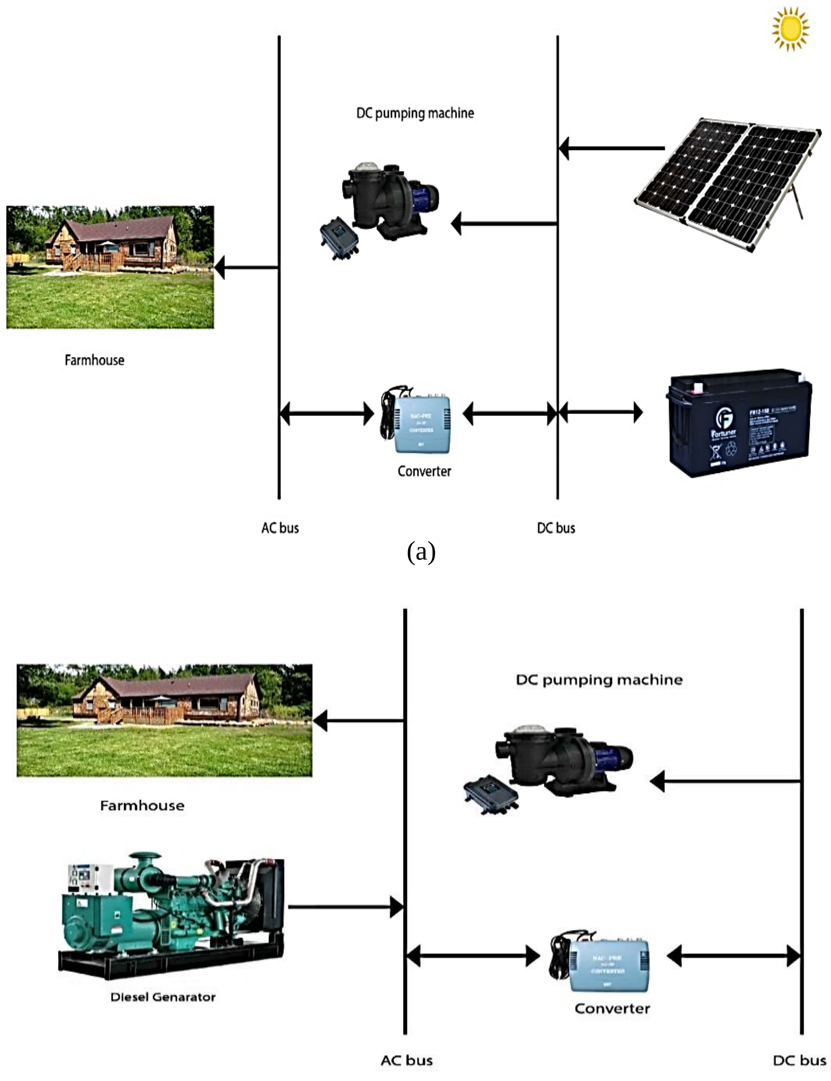
The levelised cost of energy (L_{COE}) is computed using (8) [6].

$$LCOE = \frac{TCGE_{ann}}{TDEM} \tag{8}$$

where $TCGE_{ann}$ Represents the total cost of annual electricity generation while $TDEM$ is the total electricity demand met by the source of electricity generation.

2.5. Configuration of the proposed energy system

The system arrangement for the PV only powered system and the diesel generator only is shown in Figure 3. The proposed energy system comprises of solar panel, batteries, converter, charge controllers and its accessories. The primary load is attached to the AC bus while the pumping machine is attached to the DC bus. The battery serves as backup storage to ensure an uninterrupted supply of power while the converter ensures energy flow between the water pump and PV as well as the battery charging. The technical and economic details of the proposed PV-battery energy system are presented in Table 2**.** These information serves as input data for the software.



(a)

(b)

Figure 3. Schematic diagram of simulations in HOMER: (a) PV only (b) diesel only

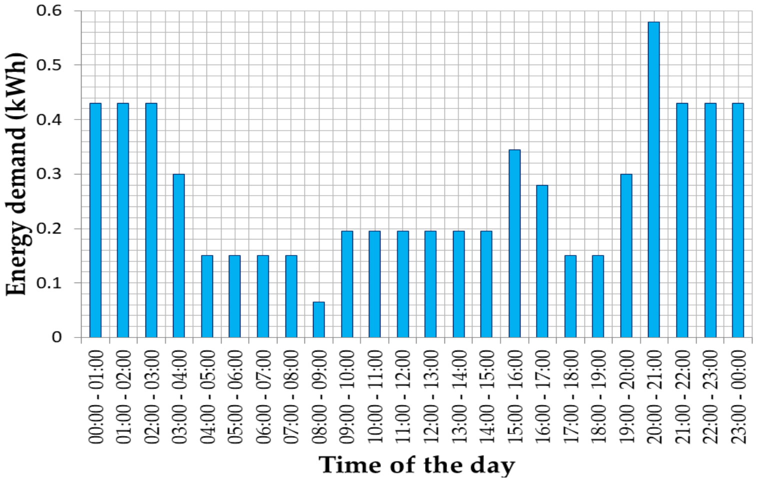
3. RESULTS AND ANALYSIS

3.1. Farmhouse load profile

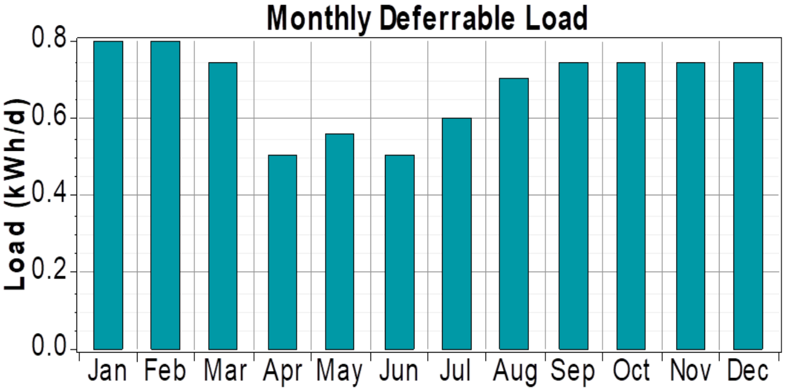
The breakdown of electricity use by appliances on the farmhouse (apart from water pumping) is presented in Table 3. Figures 4a and 4b present the load profiles of the farm (primary and deferrable). The total primary daily energy demand is estimated as 6.37Wh/day with the peak demand (0.58kW) occurring between 20:00 hours and 21:00 hours and the least (0.15 kW) occurring between 08:00-09:00 hours as shown in Figure 4a. Furthermore, according to Figure 4b, the highest deferrable energy demand is attributed to the month of January and February (about 800W).

Table 3. Power ratings and hours of use of other equipment

Load	Power Rating (W)	Hour/day	Number	kWh
CFL	15	12	10	1.8
Fan	65	15	2	1.95
TV	150	6	1	0.9
Refigirator	150	8	1	1.2
Computer	65	8	1	0.52
Total daily demand (kWh)				6.37



(a)



(b)

Figure 4. (a) Primary daily load profile (b) Deferrable monthly load profile

3.2. Energy system configuration

HOMER implemented an hourly time series simulation of possible energy system nomenclature. The output from this incus: annual electricity production, component size, economic (TNPC, LCOE), and the quantity of GHG emitted. The optimal configuration was selected based on the least TNPC. Table 4 presents the details of the results obtained. The best energy alternative consists of a 3kW PV array, 4 batteries, and 1kW converter and with 100% renewable fraction. The TNPC and LCOE for the diesel generator-only option of generation over the lifetime of the project are higher by 48% in contrast to the PV-only system. The results of the emissions resulting from the use of the diesel generator are given in Table 4. The emission quantified include carbon dioxide (CO_2), carbon monoxide (CO), unburned hydrocarbons (UHs), particulate matters (PMs), sulfur dioxide (SO_2), Nitrogen oxides (NOx).

The standalone “diesel-only” generator emitted 3897 kg of CO_2 annually while the PV system did not generate any air pollutants as shown in Table 4. Presented in Figure 5 is the cost comparison for the two energy alternatives. The capital cost of the PV-battery energy system is $14448 while the other costs are: operating cost-$248, TNPC is $17616, and LCOE is $0.535. For the diesel generator, the initial cost is $591, the operating cost is $2370, TNPC is $41855, and LCOE is 0.934. The cash flow summary with regards to the different cost components for the proposed system is given in Figure 6. It shows that the initial capital had the highest NPC ($14,500) followed by replacement cost ($5000), the operation cost contributed $1000 while the NPC of the salvage cost is negative. Since the proposed system does not have a captive generator, the value for the NPC of the fuel is zero. Based on the result presented in Table 5, in terms of the system components, the PV returned the highest cost ($14,881). This is followed by the battery ($1,902), while the converter had the least ($833).

Table 4. Performance evaluation of diesel only and PV powered system configuration

Technical			
Parameter	Diesel generator	PV powered	Unit
PV Panel size	-	3	kW
Generator size	1	-	
Power electronic converter size	0.5	1	
Batteries	-	4	No
Economic			
Initial capital cost	591	14448	$
Operating cost	2370	248	$
TNPC	41855	17616	$
LCOE	0.934	0.535	$/kWh
Greenhouse gas Emissions			
CO_2	3.897	-	kg/yr
CO	9.62	-	
UHs	1.07	-	
PMs	0.725	-	
SO_2	7.83	-	
NOx	85.8	-	
Electricity production			
Annual electricity Production	3.145	5.395	kWhr/yr
excess electricity	526	2.136	kWhr/yr
Unmet Load	0	0.00000041	kWhr/yr
Shortage capacity	0.00543	0.00543	kWhr/yr
Renewable fraction	0	100	%

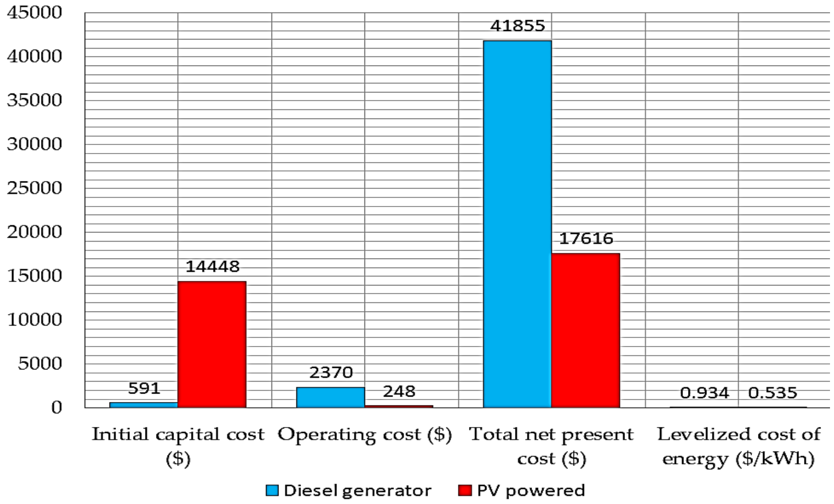


Figure 5. Economic comparison of diesel-only and PV system

Figure 6. Cash flow summary

Table 5. Breakdown of TNPC based on components' cost

Item	Capital ($)	Replacement ($)	O&M ($)	Salvage ($)	Total ($)
PV	12.750	3.976	384	-2.228	14.881
Battery	1.076	800	256	-230	1.902
Converter	622	259	0	-48	833
System	14.448	5.035	639	-2.506	17.616

The possibility of replacing diesel generators with a PV-battery system for electricity production on a farmhouse has been explored in this study. Results from the analysis show that the PV-battery energy system is viable with higher initial investment capital but lower operating cost, LCOE, and TNPC when compared to a diesel generator. An emission reduction was also achieved by replacing diesel generator with PV-battery system. The results of this study are consistent with the ones reported by Babatunde *et al.* [21], Akinyele [28], and Ohijeagbon *et al.* [29]. Meanwhile, Akinbulire *et al.* [14], Olatomiwa *et al.* [30], Ayodele and Ogunjuyigbe [19] and Adaramola *et al.* [31] gave a contrary result by stating that the inclusion of a diesel generator with the PV-battery system could mitigate the effect of intermittency of solar radiation resource. To the best of our knowledge, this is one of the pioneer techno-economic feasibility studies directed at adopting PV-battery system for livestock farms in Nigeria. Future research efforts could be geared towards methods that are flexible and cost-effective by which these technologies can be selected by users. Also, the inclusion biomass and wind turbine can be explored to see its effects on the system configuration and the cost of energy. Although the analysis of the study is case-specific, its methodology can be adopted globally.

4. CONCLUSION

This study elucidates the technical, economic and environmental viability of powering a farmhouse with a PV-battery energy system as against a diesel generator. This study discovered that the adoption of the PV-battery for powering a poultry farm is technically, economically and environmentally feasible and better than diesel only. It shows that the cost of energy while using the proposed energy system is lower and this, in turn, will lower the energy expenditure. This will consequently increase the overall profit of the business as the expense of energy decreases. Emissions to the atmosphere are also eliminated. This will help business owners and policymakers in making an informed decision as regards the deployment of PV-battery energy systems for agricultural-related purposes.

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