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Original Research Article

An Economic Evaluation of a Small-Scale Wood-Fired Gasifier for Decentralized Power Generation in Nigeria

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ABSTRACT

This study presents an economic evaluation of a small-scale biomass gasifier power plant (BGPP). The major aim was to evaluate the economics of coupling a small-scale wood-fired open-core downdraft gasifier to an internal combustion engine (ICE) for electricity generation using the levelized cost of electricity (LCOE). The gasifier was made using locally sourced materials in a workshop in Benin City, Edo State, Nigeria. The gasoline generator was obtained from a local market in Benin City. Results from the study show that the LCOE of the gasifier power plant was approximately ₦12.78/kWh$_{el}$ (electrical energy). This generation cost was much lower than that (₦82.81324/kWh$_{el}$) of generator fuelled with gasoline commonly utilized for electricity generation in Nigeria. This generation cost was also lower than the electricity tariff in some regions established by the Nigerian government in 2019. This indicates that the BGPP presents a more profitable alternative than gasoline for electricity generation in Nigeria in the absence of grid electricity. Hence, development of such power projects should be encouraged in Nigeria to ease the present electricity crisis in Nigeria, especially in the rural areas.

1. INTRODUCTION

With Nigeria currently experiencing inadequate supply of electricity, there is a great need for the application of renewable energy to complement the current fossil fuel-based power, which currently account for about 86% of the generated electricity in the country (NESISTATS, 2018). Though renewables such as the hydro and solar are already being deployed for power generation in Nigeria, there's need to increase the energy mix to include other renewables, which are readily available in the country. One of such resources is biomass, such as wood waste.

Globally, generating electricity from biomass is becoming an attractive renewable alternative (Mohapatra and Gadgil, 2013; Molino et al., 2016). Biomass use in gasifiers, especially of the fixed-bed downdraft type, has significant potential to provide electricity for regions that have no access to the electricity grid, especially in developing countries (Buragohain et al., 2012; Mal et al., 2015). Such electricity provision can enhance the development of these regions' economy and improve living standards of the inhabitants (Nouni et al., 2008) Biomass resources enjoys widespread geographical distribution and can support changes of load and power demand in power generation systems due to its ready availability (Mohapatra and Gadgil, 2013). For example, a significant volume of wood waste is generated annually from wood processing activities as well as municipal and industrial activities across cities in Nigeria (Aina, 2006; Francescato et al., 2008; Sambo, 2009; Akhator et al., 2016). These wood residues can be harnessed for bioenergy production to improve electricity availability in the country. Figure 1 shows wood processing activities and wood wastes in sawmills in Benin City. The effective use of biomass as feedstock for bioenergy projects would require readily available and quality biomass as well as low biomass and plant capital investment cost (Cambero et al., 2015).

Economic evaluation of biomass gasification power plant (BGPP) for electricity generation is pertinent to assess the economics of the technology. This provides an important information that will aid decision makers and investors in deciding to invest in such bioenergy projects. Several researchers have carried out economic analyses to assess the feasibility of such bioenergy projects with focus on unit cost of electrical energy generation (USD/kWh$_{el}$). Coronado *et al.* (2011) did a techno-economic study of a gasifier coupled to an ICE to generate electricity (15 kW$_{el}$) and produce hot water.

Figure 1: Wood processing activities and wood wastes in sawmills in Benin City (images by author)

They reported generation costs between 4.1 and 10 cUSD/kWh$_{el}$. Yagi and Nakata, (2011) studied CHP systems in Japan's rural regions. They evaluated economic feasibility based on plants' size, location, numbers and low generation cost. The optimal gasification power plant could generate 180 kW$_{el}$ at 19.1 cUSD/kWh$_{el}$.

This study evaluated the economics of a small-scale wood-fired open-core downdraft gasifier system coupled to an internal combustion engine for electricity generation. Compared to other gasification technologies, the downdraft gasifier is the most suitable option for decentralized heat and power generation because the syngas obtained from it contains very low amount of tar and particulates (Milne and Evans, 1998). Low tar content is desirable for smooth operation and longevity of internal combustion engines. This justifies the choice of this type of gasifier for the present study. This study combines previous studies on the generation rate and energy potential of wood waste in Benin City (Akhator et al., 2016; Akhator et al., 2017) and economic analysis with the aim of providing reliable information to assess the economic feasibility of small-scale biomass gasification projects for decentralized electricity generation in Benin Metropolis, which could also be useful to assess similar projects across Nigeria.

2. MATERIALS AND METHODS

2.1. Materials

The materials used for the study included a 5 kW_{th} (thermal power) wood-fired gasifier developed by the authors, a 2 kW_{el} gasoline generator, mixed wood wastes and gasoline. The gasifier was used to convert wood wastes to synthesis gas, while the gasoline generator was used to generate electricity using the produced synthesis gas and purchased gasoline as fuel on separate occasions. Several resources such as journal publications, periodicals, scholarly articles, newspaper publications, published and unpublished reports from government parastatals and agencies were also retrieved, examined and analysed for this study.

2.2. Methods

When considering the economics of biomass gasifiers coupled to internal combustion engines for electricity generation, three categories of cost are very crucial due to their influence on the cost of electricity generation. They are plant investment cost, biomass cost, as well as operation and maintenance (O&M) cost. Plant investment cost is determined by its commercial value. Either it is presented as a total cost (Quaak *et al.*, 1999; Buragohain *et al.,* 2010), or as cost of the individual components (gasifier, engines, etc.) of the plant (Wu *et al.,* 2002). The plant investment cost also include cost for civil works, piping, controls, etc.

Biomass cost is an important factor for the cost of energy generation, being the feedstock for the gasification power plant. This cost depends on biomass sources, transportation to site and pre-treatment requirements on site. Wood residues from wood processing activities in Benin City, Nigeria were used as feedstock in this study. These wood residues are considered useless materials and hence, are either disposed of or burnt in open air on wood processing sites. Therefore, the only cost associated with the fuel is transportation cost as the wood wastes are sun dried before used in the gasifier.

Operation and maintenance (O&M) costs include fixed and variable costs. For gasifier power plants, the fixed costs are mostly between 3-6% of total installation costs per year, while the variable costs are quite low, about 0.005/KWh (IRENA, 2018). Costs of labour, scheduled maintenance, parts replacement, and minor consumables such as lubricants, etc make up the fixed O&M costs. While, costs of ash disposal, unscheduled maintenance, equipment replacement and repairs, and incremental serving costs are the main components of variable O&M costs. Unfortunately, available data often combines fixed and variable O&M costs into a single number, thereby making it impossible to separate both costs (IRENA, 2018).

The study was carried out on a 5 kW_{th} downdraft gasifier system using wood residues as feedstock. The gasifier system was designed by the authors and developed using locally sourced materials in a local workshop in Benin City, Edo State, Nigeria in order to reduce the investment capital cost. It comprises a gasifier, an air cooler, a filter and an air blower. The thermal power output of the gasifier is of the order of 5kW, this will meet the needs of low electrical power of the order of 2 kW. Figure 2 shows the biomass downdraft gasifier system.

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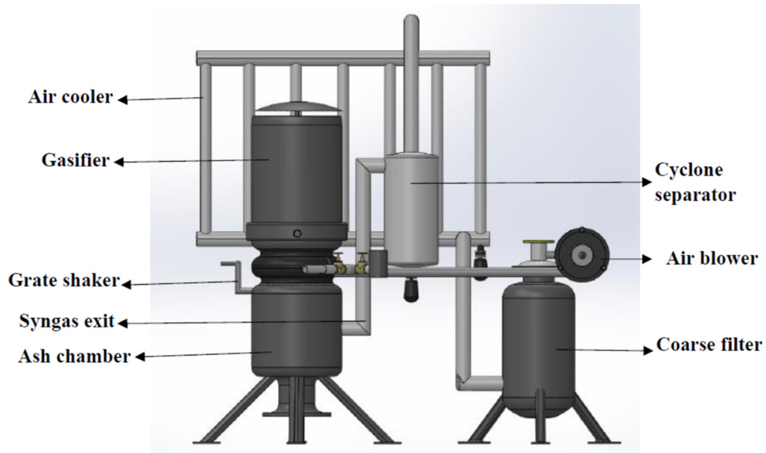

Figure 2: Schematic of the biomass downdraft gasifier

The gasoline generator was obtained from a local market in Benin City. The cost of electricity generated by coupling the gasifier system to a gasoline generator was evaluated. The cost of electricity generation was evaluated by considering the optimum performance of the biomass gasifier power plant which is expected to generated 2 kW_{el}. The life cycle cost of the electricity generation was determined by considering the present economic realities in Nigeria. Although, there are several options for evaluating the economic performance of bioenergy projects, the widely accepted indicator in the electricity industry, the levelized cost of electricity (LCOE), was applied in this study. LCOE determines how much money must be made per unit of electricity generated to recoup the lifetime cost of an electricity generation system. The discounted cash flow approach was used to estimate the LCOE of the biomass gasification power plant and it was compared with the retail price of grid electricity in Nigeria. The obtained LCOE was also compared with cost of electricity generation using the generator fueled with gasoline over the same period.

2.3. Calculation for the Levelized Cost of Electricity (LCOE)

The method used in the study has been used by several authors to evaluate economic feasibility and comparison of bioenergy projects. These authors include Quaak et al. (1999) for a World Bank project, Wu et al. (2002) in China, Buragohain et al. (2010) in India, Wei et al. (2011) in the United States, and Coronado et al. (2011) in Brazil. Input variables to the model are the plant electrical power output, investment capital cost, operation cost, lifetime of the plant, cost of biomass, and plant annual operation time. The aim of the model is to obtain the levelized generation cost of electrical energy (LCOE), which specifies how much a unit of electrical energy generated by the plant will cost. The calculation was carried out and some input parameters were assumed while others were obtained from literature. The input parameters for the calculation of LCOE are presented in Table 1. The step-by-step analysis is discussed thereafter.

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Table 1: Basic parameters and assumptions for economic evaluation

No.	Parameters	Value	Reference
	Investment cost of the gasifier power system (₦)		
1	Gasifier (5kW)	42, 800	Determined
	Cyclone	10,500	Determined
	Air cooler	12,000	Determined
	Filter	10,500	Determined
	Air blower	3,500	Determined
	Gasoline generator (2kW)	56,500	Market value
	Installation works	50,000	Determined
	Total	185,800	Determined
	Fuel		
2	Biomass consumption rate	3.4 kg/hr	Determined
	Wood waste availability in Benin City	335,460.04 tons per year	Akhator et al., (2016)
	Specific biomass cost	₦ 3.00/kg	Determined
	Gasoline consumption rate	1.11 L/hr	Determined
	Specific cost of gasoline	₦ 145.00/L	
3	Plant operation time		
	Daily (hours/day)	12	Assumed
	Yearly (days/year)	360	Assumed
4	Plant electrical power output	2 kW	Determined
5	Operation and maintenance cost	4.5% of plant investment cost	IRENA, (2018)
6	Discount rate	17%	NERC, (2012)
7	Technical lifespan of plant	5 years	Assumed
8	Lower heating value (LHV) of wood waste	19.85 GJ/t	Akhator et al., (2017)

Plant installation cost influences the generation cost via the investment cost (I_{tot}) distributed over the plant's lifetime (years) using an effective discount rate (r). Using the nominal post tax weighted average cost of capital (WACC) of 17% as the discount rate (NERC, 2012), the fixed payment per year was determined using Equation 1.

$$I_t = I_{tot} \times \frac{r \times (1+r)^n}{(1+r)^n - 1} \tag{1}$$

Where, I_t is the payment per year (N/yr), I_{tot} is the total invested capital for the power plant (N), r is the discount rate for the entire investments (%), and n is the lifespan of the plant (years). I_{tot} = N185, 800.00 (Table 1). Also, the fixed yearly payment can also be calculated by dividing the investment cost of the plant by its entire lifetime in years. This is valid when the investor has no debt to pay back for the project (Wei *et al.,* 2011). The specific cost of energy associated with the yearly payment of the plant investment cost was obtained by relating the yearly payment, I_t (N/yr) with the total amount of energy generated per year (kWh_{el}/yr), (which is the product of net electrical energy output and the operating hours per year), as shown in Equation 2.

$$I_{t,e} = \frac{I_t}{E_t} \tag{2}$$

Where, E_t is the yearly total electrical energy (kWh_{el}/yr).

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Annual cost of biomass ($F_{c,a}$ in N/yr) was calculated multiplying the biomass consumption rate (kg/h), biomass specific cost ($F_{c,s}$ in N/kg), and annual operation time ($t_{o,yr}$) together as shown in Equation 3.

$$F_{c,a} = m_f \times F_{c,s} \times t_{o,yr} \tag{3}$$

Annual specific cost of biomass ($F_{c,\,e}$) was determined by relating annual cost of biomass with the energy generated per year using Equation 4.

$$F_{c,e} = \frac{F_{c,a}}{E_t} \tag{4}$$

Reliable operation of a power plant over its lifetime depends immensely on adequate maintenance. However, plant maintenance periods depend on how long it is in operation per year. A detailed calculation of the O&M cost requires very specific information about variables, such as cost maintenance personnel as well as parts replacements and repairs, for any given plant. This information is not easily known. Nevertheless, for gasifiers, an operation and maintenance cost between 3 to 6% of the total plant cost per year was suggested (IRENA, 2018). An average O&M cost of 4.5% of the total plant investment cost, I_{tot}, was then used in this computation as shown in Equation 5.

$$O\&M_{c,a} = 0.045 I_{tot} \tag{5}$$

The specific O&M cost is obtained from Equation 6.

$$O\&M_{c,e} = \frac{O\&M_{c,a}}{E_t} \tag{6}$$

The levelized cost of electricity generation (LCOE) was then obtained by summing up all the aforementioned specific costs using Equation 7.

$$LCOE = I_{t,e} + F_{c,e} + O\&M_{c,e} \tag{7}$$

Equations 1 to 7 were also used to determine the cost of electricity generation for the generator fuelled with gasoline.

3. RESULTS AND DISCUSSION

Table 2 presents the respective annual specific cost per kWh_{el} obtained for wood waste and gasoline as fuel as determined by substituting appropriate values of the variables into Equations 1 to 7.

Table 2: Cost of electricity generation at 2kW for wood waste and gasoline

Cost variables	Wood waste (₦/kWh_{el})	Gasoline (₦/kWh_{el})
Investment cost	6.72157	2.043956
Fuel cost	5.1	80.475
O&M cost	0.967708	0.294271
LCOE	12.78928	82.81324

From the analysis done, an LCOE of N 12.78928/kWh_{el} was obtained with wood waste as fuel. With gasoline as fuel, commonly utilized as alternative means of electricity generation in Nigeria now due to grid electricity shortage, an LCOE of N 82.81324/kWh_{el} was obtained. This LCOE value is about 6 times more than the

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LCOE value obtained with wood waste as fuel. It was observed from the analysis that despite the fact that the investment cost for the BGPP was higher than that of the engine fuelled with gasoline, the LCOE value with gasoline as fuel was much higher than the LCOE value for the BGPP. This is an indication of how much effect gasoline price has on the cost of electricity generation. Hence, from the foregoing, the wood-fired gasifier power plant presents a more profitable alternative than gasoline fuelled gas engine for electricity generation in Nigeria.

It was also observed that the obtained LCOE of ₦12.8931/kWh$_{el}$ for wood waste as fuel is less than the current electricity tariff ₦30.98/kWh and ₦34.08/kWh set by NERC for residential customers with single phase (R2S) and three phase (R2T) respectively in Benin Distribution Company's franchise states as shown in Table 3. Hence, from financial point of view, this biomass gasification system will be profitable for electricity generation. Figure 3 presents the values of each cost category as a percentage of the total cost per generated electrical energy for the biomass gasifier power plant.

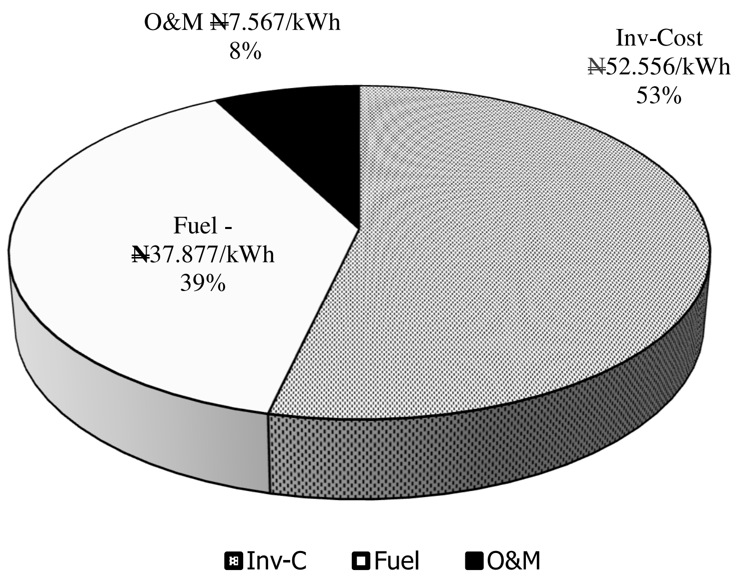

Figure 3: Composition of total life cycle cost

Table 3: Benin Discos tariff (NERC)

Class	2015	2016	2017	2018	2019	2020	2021	2022	2023	2024
R1	4.00	4.00	4.00	4.00	4.00	4.00	4.00	4.00	4.00	4.00
R2S	14.82	24.08	31.27	31.26	30.98	30.88	27.29	24.49	24.34	24.14
R2T	14.82	24.45	34.40	34.40	34.08	33.97	30.02	26.94	26.78	26.56
R3	26.52	38.56	40.46	40.46	40.08	39.96	35.32	31.69	31.50	31.24
R4	26.52	38.56	40.46	40.46	40.08	39.96	35.32	31.69	31.50	31.24
C1S	20.72	33.87	34.90	34.90	34.58	34.47	30.46	27.34	27.17	26.95
C1T	20.72	34.19	36.27	36.27	35.94	35.83	31.66	28.41	28.24	28.01
C2	24.65	40.67	38.11	38.11	37.76	37.64	33.27	29.85	29.67	29.43
C3	24.65	40.67	38.11	38.11	37.76	37.64	33.27	29.85	29.67	29.43
D1S	19.89	32.51	35.62	35.62	35.29	35.18	31.09	27.90	27.73	27.50
D1T	19.89	32.82	37.94	37.94	37.59	37.47	33.12	29.72	29.54	29.30
D2	25.84	38.56	39.29	39.29	38.92	38.80	34.29	30.77	30.59	30.34
D3	25.84	38.56	37.71	39.29	38.92	38.80	34.29	30.77	30.59	30.34
A1S	19.04	31.12	33.00	33.00	32.70	32.59	28.81	25.85	25.69	25.48
A1T	19.04	31.42	33.97	33.97	33.66	33.55	29.66	26.61	26.45	26.24
A2	19.04	31.42	35.27	35.27	34.95	34.84	30.79	27.63	27.46	27.24
A3	19.04	31.42	35.27	35.27	34.95	34.84	30.79	27.63	27.46	27.24
L1	19.62	32.07	36.26	36.26	35.93	35.81	31.65	28.40	28.23	28.00

3.1. Sensitivity analysis

With regards to the cost of electricity generation for biomass-based electricity generation, it is necessary to explore how the cost will vary with respect to some key variables. The considered variables were number of operating hours per year and cost of biomass. The annual operating hours was varied independently, while the cost of biomass was varied by a factor of ±200%, to ascertain the sensitivity of LCOE to their variation.

3.1.1. Effect of annual operating time

The effective operational time of a biomass power plant depends mainly on local electricity demand and the availability of residual biomass. For this study, the plant's annual operation time was varied from 4320 h/year to 7920 h/year, to cover a broader scenario that includes pessimistic and optimistic conditions. Figure 4 shows the effects of annual operational time on the value of LCOE for constant base parameters. It can be observed that LCOE decreases as annual operating time increases. This indicates that it is crucial to ensure the highest possible operation time for such plant, especially for high capital-intensive plants (Quaak et al., 1999)

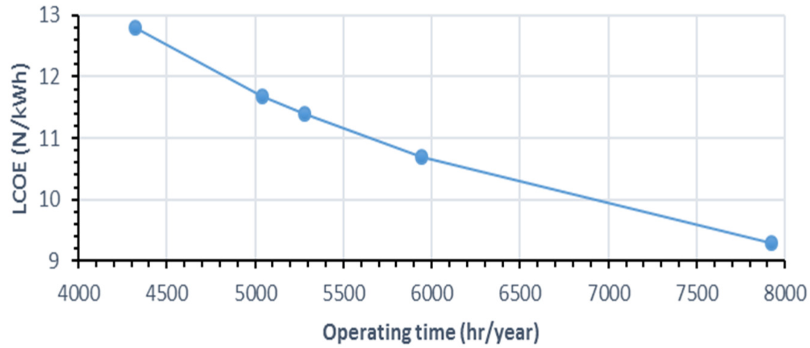

Figure 4: Effect of annual operating hours on LCOE

3.1.2. Effect of biomass cost

Wood wastes were used as the feedstock for the gasification power plant, this makes its cost strongly related to the LCOE. Biomass cost can vary significantly mainly due to its availability, transportation costs, and pre-treatment costs (Steubing *et al.,* 2014). Biomass cost has been identified as the most important cost after the specific investment cost of the plant (N/kWh$_{el}$) for biomass-based decentralized electricity generation (IRENA, 2018).

Installing the power plant close to sources of biomass, such as forest or wood processing industries, is an effective approach to reduce biomass cost, by avoiding or reducing transportation cost (Cambero et al., 2015). Another alternative is to use wood residues from wood processing industries. These residues have no commercial value and has lower pre-treatment requirements for gasification purposes (Yagi and Nakata, 2011). Biomass cost can also be reduced possibly by sun drying the biomass, where ambient conditions and storage capacity allows it. In the absence of sun drying, hot air from synthesis gas cooling in the power plant, or waste heat from the gas engine can be used for drying the biomass. These cogeneration schemes can increase the overall plant efficiency (Coronado et al. 2011; Yagi and Nakata, 2011). Figure 5 shows the sensitivity of LCOE to biomass (wood waste) cost. It can be observed that the LCOE has a positive correlation with changes in cost of biomass. This analysis was done by varying biomass cost using a factor of ±200% of the base biomass cost of N3/kg.

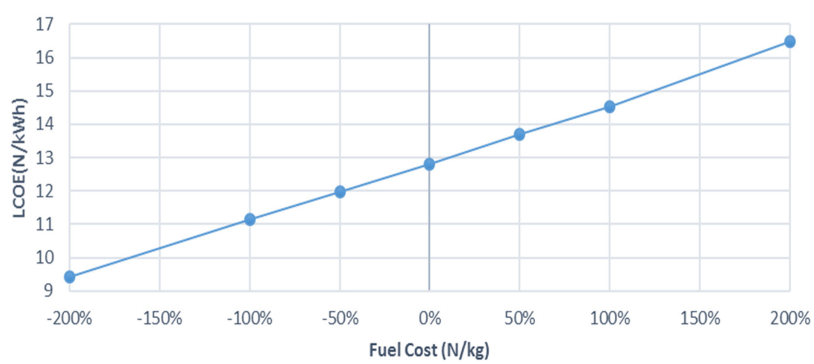

Figure 5: Effect of biomass cost on LCOE

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4. CONCLUSION

In this work, the economics of coupling a small-scale biomass downdraft gasifier system to an internal combustion engine for electricity generation was evaluated. The gasifier system was made using locally sourced materials in a local workshop in Benin City, Edo State, Nigeria in order to reduce the investment capital cost. While the gasoline generator (ICE) was purchased from a local market in Benin City. The study reveals that the gasifier power plant can generate electricity at a cost of approximately N 12.78/kWh_{el}. In comparison, this generation cost was observed to be much lower than the cost of generating electricity from a gasoline fueled generator over the same number of years. This generation cost was also found to be lower than the electricity tariff set by NERC for residential customers with single phase (R2S) and three phase (R2T) respectively in Benin Distribution Company's franchise states in 2019. From the economic assessment, it shows that the BGPP presents a more profitable alternative than gasoline for electricity generation in Nigeria in the absence of grid electricity. Hence, development and deployment similar biomass gasification power projects should be encouraged in Nigeria to ease the present electricity crisis in Nigeria, especially in the rural areas.

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6. CONFLICT OF INTEREST

There is no conflict of interest associated with this work.

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