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Energy Recovery from Municipal Solid Waste in the Port Harcourt Metropolis, Nigeria

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Abstract

This research presents an energy recovery from municipal solid waste (MSW) in Port Harcourt metropolis, Rivers State. The main focus is to investigate the conditions of renewable municipal solid waste (MSW) generated in Port Harcourt and to properly evaluate the minimum quantity of electricity that can be made from the MSW on a daily basis using the combustion pathway. The data used to assess the availability of the fuel (MSW) were obtained from waste dumpsites controlled by Rivers State Waste Management Agency (RIWAMA). The various parameters for the combustion chamber, which utilizes mass combustion in stoker crate furnace, were selected for the amount of MSW generated in Port Harcourt and operated at different steam saturation pressures within (20 – 45) bar, with a fuel consumption rate of 11.88kg/s. Analytical tools were used to analyze the combustion characteristics of the chemical compositions of the waste generated. The result revealed that for every kg of MSW combusted, 6.63kg of air is required for complete combustion generating an optimum flue gas mass flow of 87.63kg/s and temperature of 400ºC. The flue gas of mass flow ranging from 70.37kg/s - 87.63kg/s produce steam within the range of 9.2134kg/s – 9.8482kg/s at different steam pressures and stack temperatures. These indicate a resultant average net power output of 4.47MW of electricity when retrofitted to a steam turbine plant. This work thus showed that there are huge potentials in generating electrical energy from MSW in Port Harcourt, employing appropriate technology.

Keywords - *Combustion, Electricity, Energy Recovery, Mass flow, Municipal Solid Waste, Power Output.*

I. INTRODUCTION

The production of municipal solid waste has increased tremendously in recent years as a result of increased commercial activities and modernization that characterize the western world after the second half of the 20th century, along with the industrialization of the developing countries. It is a phenomenon expected to expand rapidly in the future, making the problems of waste disposal and waste management, key issues for present and future generations [1]. As a result of this fast-growing and The ever-increasing rate of municipal solid waste production, its accumulation is becoming a major problem. Consequently, a more sustainable and acceptable waste management scheme becomes vital for every society. In recent times, due to environmental, financial, and social considerations, more rational waste management is considered necessary. The willingness to minimize the accumulated waste, along with the increased energy demand has led to the development of the third-generation waste management systems. Such systems are the Waste to Energy facilities, which are preferred by society because they are environmentally friendly.

The ever increasing demand for energy for societal development is complemented by a variety of energy sources. Large scale energy utilization has led to a better quality of life and foster all-round development associated with many critical problems [2]. The most prominent of these is the pollution to the environment in various forms contributing to global warming and climate change [3]. The National energy supplies are at present, almost entirely dependent on fossil fuels and firewood, which are depleting fast [4]. Hence, with the fast depleting rate of fossil fuel, it is expedient to explore alternative energy sources, systems, and technologies for sustainable development to at least substitute an appreciable amount of conventional energy to mitigate the harmful effect to a reasonable extent.

Municipal Solid Waste (MSW) is produced daily all over the world, and it is a renewable energy resource with the potential to produce energy via Waste to Energy (WTE) plants while also reducing the volume of waste. Wastes are an important source of energy presently used in the generation of electricity and, at the same time, making the environment clean. WTE can address the twin issues of land use and pollution from landfills and the well-established environmental perils of fossil fuels known as greenhouse gas emissions (GHG). Benefits of WTE include waste volume reduction, sanitation and detoxification, stabilization, and energy recovery. The technologies that exist to produce energy from wastes are anaerobic digestion, combustion, gasification, and landfill gas to energy.

The German Advisory Council on Global Change (WBGU), put it that “Energy is universally acknowledged to be the mainstay of industrial society". The increased world population and the quest to improve living conditions as well as global economic growth have resulted in a continuous increase in energy demand. Without an adequate supply of energy, the stability of the economic order and the political structure of a society are in jeopardy [13]. Hence, energy both its production and its use in an environmentally safe manner is a platform for broader economic growth and improves the quality of life of people around the world [6]. In developing countries, the energy situation is very diverse, per capita energy consumption is far less than in the industrialized countries. In Africa, per capita consumption of energy remains very low, while energy demand and intensity have increased sharply (European Commission, 2002). An estimated 1.6 billion people or about one-fourth of the world population have no access to electricity and must rely on other sources for energy. Of this figure, about 50% is located in South Asia (35% in India alone), 32% in Sub-Sahara Africa and 14% in East Asia (not including China)

It is well known that MSW can be used to generate electricity. Since the early 1970s, it has been reported that the use of the biodegradable component in MSW to generate biogas can also be used to generate electricity with positive environmental implications, such as the reduction of greenhouse gas emissions from sanitary landfills and the replacement of highly polluting energy sources (oil, coal and natural gas) [7]. In all the cases, energy recovery is possible with an addition of supplementary fuel since the values in the study area fall below the 7.50 MJ/kg to 12.00 MJ/kg, an acceptable recommended range suggested by Whiting, (2002).

Port Harcourt has always been described as the garden city of Nigeria in the past due to its natural green plants and beautiful flower resources. However, in recent years the once beautiful city has lost its garden city status as a result of industrialization, oil and gas activities, and poor waste management schemes. Despite the strategic position of the city, there is still an epileptic power supply due to inadequate power generation and distribution. Ogaji *et al.*,[8] investigated the municipal solid waste (MSW) generated in Port Harcourt. They found it in large quantities, but some remain as litter in parts of the municipality. They also opined that refuse is mostly buried, but some reckless open-burning is done by residents, thereby poses environmental hazards to the city. They also found that waste collected from different receptacles and dumpsites in the city of Port Harcourt consisted of 66.6% volatile solids, 13.5% fixed solids, 19.1% liquid, and 0.8% other components. The average biodegradability fraction of the waste was reported as 0.807, with a carbon-to-nitrogen ratio of 27:1 while the energy content of the MSW was calculated as 7.25 MJ/kg.

Per capita generation of solid waste in Port Harcourt has been reported to range from 0.66-1.25 kg/cap/day, and the characteristics of the waste comprise organic matter, plastics, metal, nylon, glass, and others [9] [10]. Igoni *et al*. [10] reported 69.3% of MSW in Port Harcourt as organic content and opined that the energy content of refuse generated in Port Harcourt gave 1.733kcal/g which is sufficient for biochemical conversion to yield gas and heat for electricity. This high percentage of organic content in the waste stream in Port Harcourt and its suburbs can be harnessed for energy generation.

This work, therefore, examines the possibility of generating energy in the form of electrical power from MSW generated and collected in Port Harcourt metropolis using combustion pathway. It showcases an effective utilization of renewable municipal solid waste (MSW) generated in Port Harcourt for energy recovery within the specification of environmental conditions

A. Study Area of Experimental Engine Description

Port Harcourt is a cosmopolitan city in the Niger-Delta area of southern Nigeria and a hub of oil and gas activities. The location geographic coordinates in World Geodetic System (WGS 84) lies on 4°45′0″ and 4.75 N and 6°50′0″ and 6°83′3″ E , experiencing an average temperature of 24°C, the relative humidity of 97% [11].

II. MATERIALS AND METHOD

A. Description of the Proposed MSW-fueled Steam Power Plant

The power plant is designed to generate electric energy through direct combustion of Municipal Solid Waste. The plant schematic diagram is shown in Fig. 1.

The flue gas with enough heat energy exiting the combustion chamber is channeled to the boiler to produce high-pressure steam by heating saturated water flowing into it from the pump. The flue gas during the process loses its heat to the boiler, and it goes through a cleaning system before it is being released to the atmosphere via the stack.

B. Process of Municipal Solid Waste Collection in Port Harcourt

Municipal Solid Waste (MSW) is generated by virtually every household, business, and industrial sites in Port Harcourt metropolis as human activities are carried out in these places. These wastes are usually bagged and dumped in receptacles at designated temporary dumpsites, traditionally situated along major roads where refuse collection trucks can easily access. After that, the dumped MSW is collected and transported to permanent dump sites for disposal by contractors of the waste management agency of the municipality. Presently, municipal solid wastes are collected from five (5) local government areas of Rivers state namely, Port Harcourt City, Obio-Akpor, Oyigbo, Eleme and Ikwerre local government areas and disposed at three (3) different permanent dumpsites of Igwuruta, Eliozu, and Rumuolumeni currently operated by the waste management agency.

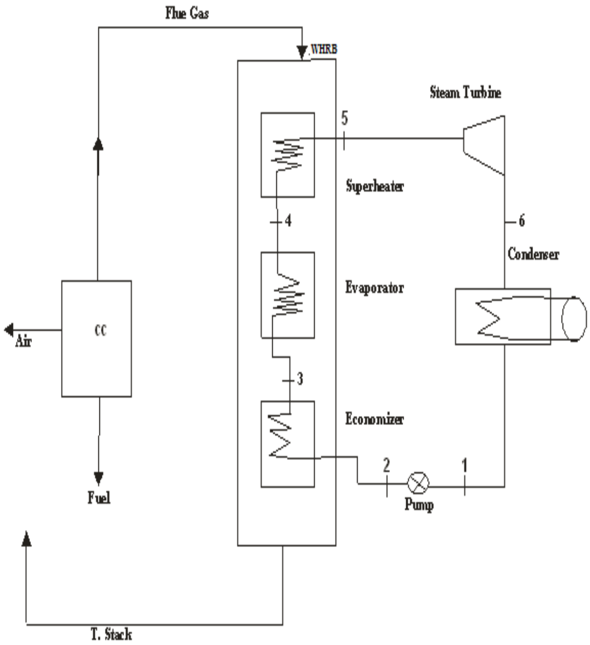

Figure 1 Schematic Diagram of the Proposed Municipal Solid Waste-Fueled Power Plant [12].

C. Mass Flow of Municipal Solid Waste Collected in Port Harcourt

To determine the mass flow of MSW collected in Port Harcourt, three (3) dumpsite presently operated by the waste management authority were visited. Field surveys of these dumpsites were undertaken twice a week (Tuesdays and Thursdays) for four weeks. Rumuolumeni dumpsite was visited each Tuesday while Igwuruta and Eliozu dumpsites were visited on each Thursday. During these surveys, the site manager and the desk officer in charge of records and statistics of each dumpsite were interviewed. The personal observation was also made to ascertain the validity of their records.

From interviews and site inspection conducted, it was revealed that the mass flow of municipal solid waste to each dumpsite is determined based on the available weighing material at each dumpsite. At Igwuruta and Rumuolumeni dumpsites, the mass flow is determined based on the type and number of trucks or compactors that deliver waste each day. Two types of compactors are used by MSW collection contractors of the Waste Management Authority (RIWAMA), namely, single-axle trucks which usually compact MSW up to 2.0 tonnes (2000kg) to 2.5 tonnes (2500kg) when fully loaded and double axel trucks which when fully loaded and compacted delivers between 4 tonnes (4000kg) to 5 tonnes (5000kg) of MSW.

Interviews and surveys at Igwuruta dumpsite revealed that about 28 to 35 trucks normally deliver MSW to each dumpsite during the day. In contrast, between 53 and 60 trucks deliver MSW to the dumpsite at night. Hence disposal of MSW to the above-mentioned dumpsite is mostly done during the night hours. Of these numbers of vehicles that deliver MSW to each dumpsite, forty-three (43) are single axle fully loaded trucks while thirty-eight (38) are double axel fully loaded trucks. At Rumuolumei dumpsite, it was estimated that between twenty-six (26) to thirty-two (32) trucks usually deliver MSW to the dumpsite during the day while at night 45 to 53 trucks do deliver MSW to the dumpsites. More so, out of the minimum of 71 trucks for a day 30 trucks are reported to be single axles, whereas 41 vehicles are double axel. Conversely, the mass flow of MSW at Eliozu dumpsite is done with the weighbridge installed at the entrance of the dumpsite. Each truck goes over the weighbridge as it comes in with MSW and the weight of the truck with its contents is recorded. On returning from the dumpsite, after tipping, it goes over the weighbridge, and the weight of the empty truck is recorded. Thus, the weight of the MSW is calculated by subtracting the weight of the empty truck from the weight of the loaded truck. Records available at Eliozu dumpsite and values estimated for Igwuruta and Rumuolumeni dumpsites are calculated and used to determine the mass flow of MSW (fuel) for the plant. Table 4.1shows the quantity of MSW collected and transported to the three dumpsites by contractors of the municipal waste management agency. The data covers the period between January 2016 and June 2016, and it indicates that the fuel is available for possible conversion to electric power.

D. Physical Composition of the Municipal Solid Waste

Surveys at each dumpsite revealed that MSW generated in Port Harcourt have different physical compositions. It was observed that each truck contained similar physical components, mainly organic and inorganic. The organic components, which are basically combustible materials, were observed to be food wastes, paper, wood, leaves, plastics, and miscellaneous organic materials, while the inorganic components which are mainly non-combustible materials were observed to be metals, glass, and ceramics.

To determine the percentage of combustible and non-combustible components of the MSW, wastes bins were used to collect the MSW and loaded to 10 kg by measuring on a weighing scale. The measurements were done for five (5) different trucks at each dumpsite. The weighed MSW is then sorted, and each component weighed separately to determine their masses based on combustible and non-combustible materials. The average percentage composition of the combustible materials of the MSW as evaluated and used in the MSW combustion analysis is 69.7%.

E. Combustion and Energy Recovery from Municipal Solid Waste (MSW)

The organic components of MSW contain elements such as Carbon, Hydrogen, Nitrogen, Oxygen, sulfur, and moisture. The Oxygen contained in the fuel gives a negative contribution to the demand for Oxygen for combustion. The ash does not participate in the combustion process. Thus, for the theoretical combustion reaction of MSW, the equations of reaction are expressed as;

$$C + (O_2 + 79/21N_2) \rightarrow CO_2 + 79/21N_2 \quad (1)$$

$$H_2 + 0.5(O_2 + 79/21N_2) \rightarrow H_2O + 0.5(79/21)N_2 \quad (2)$$

$$S + (O_2 + 79/21N_2) \rightarrow SO_2 + 79/21N_2 \quad (3)$$

Excess air is however, required for complete combustion of combustible part of MSW. In this case, equations (1) to (3) are expressed as follows;

$$C + [1+K](O_2 + 79/21N_2) \rightarrow CO_2 + [1+K]79/21N_2 + KO_2 \quad (4)$$

$$H + [1+K](O_2 + 79/21N_2) \rightarrow 0.5H_2O + [1+K]79/21N_2 + [0.75+K]O_2 \quad (5)$$

$$S + [1+K](O_2 + 79/21N_2) \rightarrow SO_2 + [1+K]79/21N_2 + KO_2 \quad (6)$$

where K is the fraction of excess combustion air.

1. Mass Balance in the Combustion Chamber

Considering the mass balance in the combustion chamber, as shown in Figure 2:

$$M_{in} = M_{out} \quad (7)$$

$$M_a + M_f = M_{fg} + M_{mt} + M_{ash} \quad (8)$$

$$M_a = (M_{fg} + M_{mt} + M_{ash}) - M_f \quad (9)$$

$$M_{fg} = (M_a + M_f) - (M_{mt} + M_{ash}) \quad (10)$$

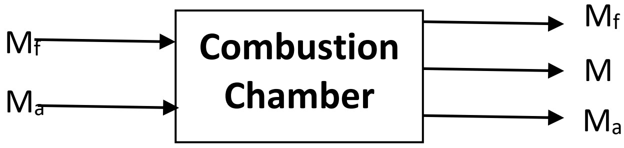

Figure 2. Mass Balance in Combustion Chamber

The theoretical amount of air which is the amount of Oxygen required per kilogram of MSW divided by the amount of Oxygen in the air is calculated taken that percentage of Oxygen in the air is 23.3% as follows;

$$M_{a,T} = (M_{O,H}\gamma_H - M_{O,C}\gamma_C + M_{O,S}\gamma_S + M_{O,O}\gamma_O)/23.3 \quad (11)$$

Where $M_{a,T}$ is pure air, γ is the percentage of an element in the chemical composition of the Municipal Solid $M_{O,H}$ $M_{O,C}$ $M_{O,S}$ Waste, and $M_{O,O}$ are the masses of Oxygen in hydrogen, carbon, sulfur, and Oxygen, respectively.

The percentage of an element in the chemical composition of municipal solid waste in Port Harcourt (γ) on wet basis analysis is calculated using the relation,

$$\gamma = \gamma_{dry}(1 - \gamma_{mt}) \quad (12)$$

where γ is a fraction of element in chemical composition on a wet basis, γ_{dry} is a fraction of element in chemical composition on a dry basis, and γ_{mt} is a fraction of water (moisture) in an original sample of the MSW.

The values obtained, as presented in table 4.2, is based on previous work on proximate and ultimate analyses of MSW in Port Harcourt done by Igoni *et al*. (2007).

$$M_{a,T} = (8\gamma_H - \gamma_O + \gamma_S + 32/12\gamma_C)/0.233 \quad (13)$$

$$M_{a,T} = (3\gamma_H - 0.3750\gamma_O + 0.3750\gamma_S + \gamma_C) \times 11.4449 \quad (14)$$

with excess air,

$$M_a = [1+K](3\gamma_H - 0.3750\gamma_O + 0.3750\gamma_S + \gamma_C) \times 11.4449 \quad (15)$$

Mass of flue gas per kilogram of fuel is found by substituting equation (13) into equation (10).

$$M_{fg} = (3\gamma_H - 0.3750\gamma_O + 0.3750\gamma_S + \gamma_C) \times 11.4449 + (1 - \gamma_{ash} - \gamma_{mt}) \quad (16)$$

with excess air,

$$M_{fg} = [1+K](3\gamma_H - 0.3750\gamma_O + 0.3750\gamma_S + \gamma_C)\times 11.4449 + (1-\gamma_{ash} - \gamma_{mt}) \quad (17)$$

Calculation of the combustion air supplied and the mass of flue gas from the combustion chamber is done using the elemental composition of MSW in Table 1. The percentage of air varies between 15 and 30% for most utility boilers (Nag, 2008), while 30% excess air is assumed for this work.

F. Energy Analysis

In this analysis, the first law of thermodynamics, which asserts that energy cannot be created or destroyed, is applied to examine the quantity of heat exchanged between the components and their surroundings. Thus, the performance of the thermal system in the form of first law efficiency is presented. The major components of the system are treated as control volumes; hence the sum of all the energy entering the system must be equal to that leaving the system.

III. RESULTS AND DISCUSSION

A. Result Analysis

The result of the investigation of municipal solid waste (MSW) generated within the Port Harcourt metropolis is shown in Table 3. The data gathering was based on the report from Rivers State Waste Management Agency (RIWAMA) Port Harcourt and dumpsite visitation. The result presented was for a period of 12months and three dumpsites.

Table 1 Net Mass of MSW collected in Port Harcourt from January to December 2017.

Month	Dump Sites			
	ELIOZU (Kg)	IGWURUTA (Kg)	RUMUOLUMENI (Kg)	TOTAL (Kg)
Jan.	10,038 ,400	11,22 5,000	16,145 ,200	37,408,600
Feb.	9,068, 200	13,18 3,200	15,814 , 000	38,065,400
March	11,325 , 000	15,01 5, 000	14,234 ,300	40,574,300
April	10,062 ,300	13,03 4, 000	16,215 , 000	39,311,300
May	13,456 , 000	14,03 4, 000	17,034 , 000	44,524, 000
June	8,915, 100	10,81 4, 000	17,242 , 000	36,971,100
July	12,419 , 000	17,23 5,200	20,180 , 000	49,834,200
Aug.	10,584 , 000	16,15 2, 000	17,324 ,300	44,060,300
Sept.	14,813 , 000	15,82 1,300	18,232 , 000	48,857,300
Oct	9,654, 300	17,04 3, 000	17,251 , 000	43,948,300
Nov	8,053, 000	10,52 1, 000	13,020 , 000	31,594, 000
Dec	9,308, 200	12,03 4, 000	15,241 , 000	36,583,200
Annual Net Mass of MSW				491,732, 000

(Source: Rivers State Waste Management Agency, 2016)

The estimated net mass of MSW (Table 1) is given as 491,732000 kg/yr. The combustible portion of the waste that has been found during field investigation is 69.7%. The combustible part of the MSW is used for the design analysis to determine the mass flow rate of the fuel (MSW). The result show for plant running of 8000hours annually, the required mass flow of the fuel (MSW) is 41.3tonnes/hr (11.88 kg/s), as shown in Fig. 3.

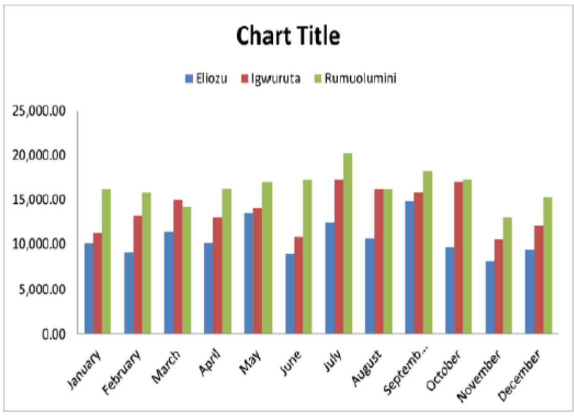

Figure 3. The plot of Waste Generated per Month in Port Harcourt City

The result shows that for the net MSW of 491732000kg/yr with 69.7% combustible, the MSW burning rate ($\dot{M}_f$) gives 11.88kg/s. using the relation

$$M_a = [1+K](3\gamma_H - 0.3750\gamma_O + 0.3750\gamma_S + \gamma_C)\times 11.4449$$

Given that γ_{dry} = 5.6%, and γ_{mt} = 19.88%, γ_H= 4.49, γ_{dry} = 52%, γ_{mt} = 19.88%, γ_C = 41.66%

Given that γ_{dry} = 34.2% and γ_{mt} = 19.88%, γ_O= 27.41%, γ_S = 0.11%, γ_{ash} = 41.66%
Therefore, the mass flow of air $\dot{m}_a$=78.7kg/s.

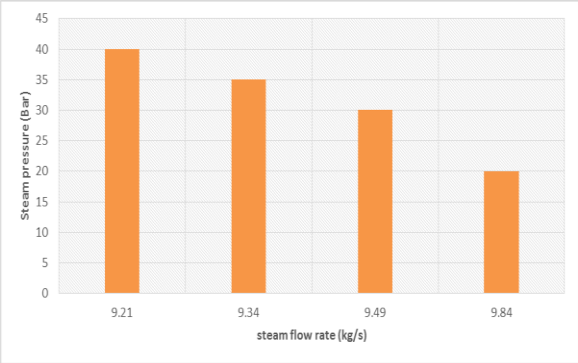

Figure 4. The plot of Steam Generation after Different Steam Pressure for Energy Recovery

The analysis further revealed that every 11.88kg/s of the MSW combusted requires 78.7kg/s of complete air combustion to produced 87.63kg/s of flue gas at the temperature of 400ºC. The flue gas of the range of (70.37kg/s - 87.63kg/s) produces steam of the range of (9.2134kg/s – 9.8482kg/s) using a retrofitting technology at different steam pressure and stack temperature as shown in Fig. 4. It was also observed that an average of the net power output of 4.47MW of electricity could be generated from the net MSW of 49132000kg/yr generated within the Port Harcourt Metropolis.

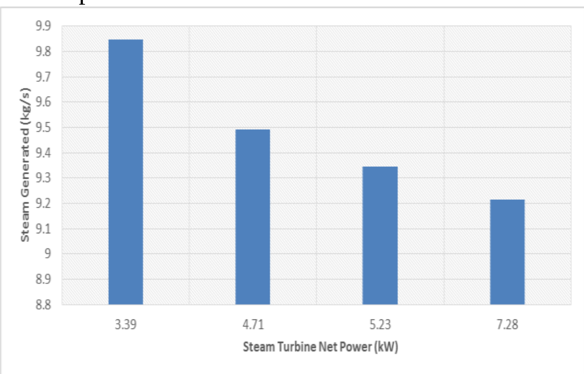

Figure 5. The plot of Steam Turbine Power Net against Steam Generated at Different Waste Mass

The result is shown in Fig. 5 gives the performance trend for energy extraction from the combustion of the MSW. At different temperature and pressure, the steam generated were plotted as indicated in Fig. 4, and the superheated steam was used to create power through the steam expander (turbine), and the net output is shown in Fig. Five accordingly.

III. CONCLUSION

Recovery of energy in the form of electric power presents a more suitable way of managing MSW, which most times are presently either littered on streets or dumped in non- sanitary landfills. Although the conversion of MSW into energy in the form of electric power has not been very successful in Nigeria, efforts are being made to utilize the potential in such conversion sequel to the persistent power problem affecting various sectors of the economy.
The following conclusions were made from the research:

i. The results obtained in this work suggest that the stand-alone MSW- fuel power plant in Port Harcourt and other cities of Nigeria is feasible and viable, hence private and public investors should invest in the project.
ii. The energy lost in the flue gas from the stack can be channeled to other useful purposes.

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