Waste to Energy: a Case Study in a City of Nigeria

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Abstract

Nigeria has vast potential to generate renewable and sustainable energy from various sources such as biomass, solar, hydropower, wind, wave and tidal. For instance, Nigeria generates a huge amount of municipal solid wastes (MSW) across its cities without effective mechanism for utilising them. Potentially, these wastes can be utilized as feedstock for the production of biogas which can then be used to generate different forms of energy such as electricity, cooling and fertilizers as by-product. Considering the energy challenges associated with over-dependence on crude oil in Nigeria, it has become imperative for Nigeria to diversify its sources of energy generation in order to produce clean, stable, sustainable and affordable energy. This study examines the potential of organic fraction of municipal solid waste for combined electric power and cooling generation in the City of Port-Harcourt, Nigeria. The results from this study has shown that the energy from OFMSW in the city has the capacity to increase power generation to about 88% (466 MW) of the peak load demand which represent an increment of 41% in the current capacity of electrical power generations; and the project is economically feasible as the power generated can be sold at N22 per kWh with a payback period of 4.29 years.

Key words: Municipal solid waste, biogas, power and cooling

1. Introduction

Municipal Solid Waste (MSW) is a type of waste that consists of everyday items such as food waste, paper, plastics, vegetable matter, textiles, glass and metals which are generated from domestic households, commercial premises and industrial sites (Sha'Ato et al, 2007). Proper management of the municipal solid waste in terms of collection, use and disposal is essential in order to prevent environmental pollution. In essence, Poorly managed MSW can become sources of major environmental concerns such as air and ground water pollution, smoke toxic given off during open burning, health threatening infectious diseases and atmospheric contamination. For instance, greenhouse gases such as carbon dioxides (CO_2) and methane (CH_4) which promote global warming are produced from decomposing wastes at the dumpsites. In addition, the process of waste decomposition also brings about microbial activities which breed rodents, insects, houseflies, mosquitoes and worms which cause infectious diseases such as malaria and typhoid (Ogwueleka, T. C., 2009 and Alaba, O. A. et al, 2009).

A huge amount of municipal solid waste is generated across various cities in Nigeria, unfortunately, these waste are poorly managed as there are no effective mechanisms or methodologies for their proper disposal (Kofoworola, O. F. et al, 2007). Nigeria generates about

74,428.85 tonnes of municipal waste per day, of which over 60% of the wastes compose of organic materials (Imam A., et al, 2008). As illustrated in Figure 1, the wastes are mainly disposed of by open burning and landfilling which degrades air quality and pose hazard to the environment (Kofoworola, O. F. et al, 2007). Potentially, municipal solid waste can be utilized as feedstock for the production of energy. Various forms of technologies for the conversion of MSW to different energy forms are widely available and mature. These technologies include anaerobic digestion, combustion/incineration, gasification and pyrolysis (Royal Commission Report, 2004).

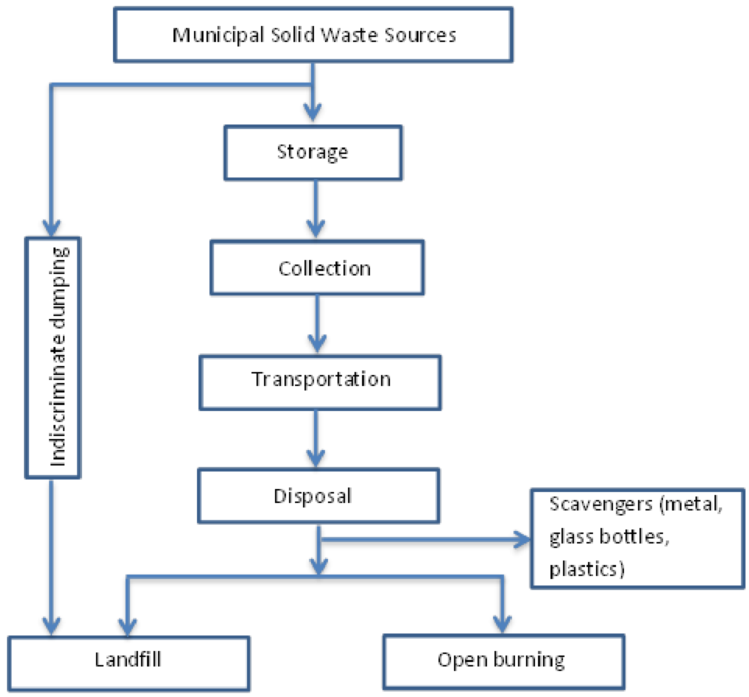

Figure 1: Flowchart of MSW management in Nigeria (Kofoworola, O. F. et al, 2007)

On the other hand, despite being one of the leading producers and exporters of crude oil in the world, Nigeria is still being faced with enormous energy challenges; Nigeria currently produces only about 4000MW of electricity which is far less than the estimated demand of 12,000MW (Tokede, W. et al, 2013). This situation has given rise to frequent and prolong power outages due to load shedding. Consequently, about 49% of the Nigerian population have no access to electricity and others who do have access suffer interruptions on a daily basis. The use of private fossil fuel-based generators to produce electricity has become a very popular and inevitable means of power generation in the country; this practise causes noise pollution, air quality degradation and greenhouse gases emissions which give rise to global warming and climate change (George, E. O. et al, 2012).

The aim of this study is to investigate the quantity, composition and characterization of municipal solid waste generation in the City of Port-Harcourt; and to carry out a feasibility study on the conversion of the organic fraction of the municipal solid wastes (OFMSW) into energy (district cooling and electric power) using ECLIPSE simulation software. The objective is to reduce leachate and greenhouse gases emissions caused by anaerobic respiration of poorly managed municipal solid waste, and to promote the production of clean, renewable, sustainable and affordable energy through anaerobic digestion of OFMSW in Nigeria.

2. Methodology

The methodology used for this study is a technical and economic evaluation: first of all, a detail investigation of the available resources and their components/characteristics of the OFMSW from the city; secondly, design of whole system and selection of the components of the system, including the anaerobic digester(s), engine generators and the cooling machines; thirdly, computational simulation of the processes of waste-to-energy using ECLIPSE software, which is based on the principle of energy and mass balance of any thermal/chemical processes; finally, an economic estimation to evaluate the potential of utilisation of OFMSW for the generation of power and cooling for the city.

3. Waste Resources from the Study Area

3.1 The Study Area

Port Harcourt is the capital city of Rivers State in the Niger Delta region of Nigeria. The city has an area of 360 km^2 ($140m^2$), it lies on coordinates 4.75^{o}N 7.00^{o}E along the Bonny River. Port Harcourt has a population of 1,947,000 based on 2012 population estimate (Wikipedia 2015). Due to Crude oil discovery in the area in 1956, Port Harcourt has since then grown into a centre for huge commercial and industrial activities giving rise to urbanisation and modernization. Several oil companies and other multinational firms have their offices in the city (Wikipedia 2015). The climate in Port Harcourt is tropical monsoon featuring two seasons which are rainy seasons and dry seasons, the average temperatures in the city ranges between 25^{o}C – 28^{o}C. As a result of the climate conditions in the city temperatures are relatively high and space cooling is usually required throughout the year to maintain thermal comfort in homes and offices (Weather Network, 2015).

3.2 Waste Generation in the City

A huge quantity of municipal solid waste is generated in Port Harcourt metropolis, as shown in Figure 2. Table 1 show MSW generation in major cities in Nigeria, a total of 117,825 tonnes per month of municipal solid waste is generated in Port Harcourt (Ogwueleka, T. C., 2009). These wastes which is managed by River State Environmental Protection Agency end up in landfills or open burning; this practice give rise to poor environmental conditions ranging from obstruction of traffic flow, blockage of drainages which causes flooding, water pollution, air quality degradation, health hazards and greenhouse gases emission (Ajie, U. E. et al, 2014 and Igoni, A. H. et al, 2007).

Figure 2: MSW being evacuated from roadside in Port Harcourt (Ajie, U. E. et al, 2014)

3.2.1 Moisture Content

The oven drying method was used to determine the moisture content of the waste to be 65.2%; this is as a result of the nature of food (fresh) consumed in the study area and climate (rainfall) as well. The drying of the waste was carried out at a temperature of 77°C (Igoni, A. H. et al, 2007).

Table 1: MSW generation in some major cities in Nigeria (Ogwueleka, T. C. 2009, Igoni, A. H. et al, 2007, Amber, I. et al, 2012)

City	Population	Waste generation per month (Tonne)	Density (kg/m^3)	Kg /capital /day	Agencies
Lagos	8,029,200	255,556	294	0.63	Lagos Waste management Authority
Port-Harcourt	1,947,000	117,825	300	0.6	Rivers State Environmental Protection Agency
Onitsha	509,500	84,137	310	0.53	Anambra State Environmental Protection Agency
Kano	3,248,700	156,676	290	0.56	Kano State Environmental Protection Agency
Ibadan	3,078,400	135,391	330	0.51	Oyo State Environmental Protection Agency
Nsukka	100,700	12,000	370	0.44	Enugu State Environmental Protection Agency
Kaduna	1,458,900	114,433	320	0.58	Kaduna State Environmental Protection Agency

3.2.2 Characteristics of the MSW

The chemical properties of the waste such as moisture content, volatile solid content and fixed carbon were obtained using the standard proximate analysis, and the ultimate analysis was used to determine the proportion of chemical elements such as Carbon (C), Hydrogen (H), Oxygen (O), Nitrogen (N) and Sulphur (S) in the waste. The results are shown in Table 2. The proximate and ultimate analyses were carried out for both the MSW and the organic fraction of the MSW. The percentage of carbon in the waste that is biodegradable was obtained as 80.6%; the Kiely mathematical definition method was used for the this data (Ogwueleka, T. C. 2009 and RCEPR, 2004).

Table 2: Proximate and ultimate analysis of OFMSW in Port Harcourt (Ogwueleka, T. C. 2009)

Proximate analysis (wet)					
	Food Waste (Weight %)	Wood/Leaves (Weight %)	Plastic (Weight %)	Paper (Weight %)	Textiles (Weight %)
Ash content	4.80	0.80	2.30	6.00	7.00
Fixed carbon content	4.0	15.00	2.40	9.10	16.20
Volatile matter content	26.00	65.00	95.00	78.00	69.00
Moisture content	65.20	19.20	0.30	6.90	7.80
Ultimate analysis (Dry)					
	Food Waste (Weight %)	Wood/Leaves (Weight %)	Plastic (Weight %)	Paper (Weight %)	Textiles (Weight %)
Carbon content	51.00	49.00	56.00	47.00	59.00
Oxygen content	39.00	42.00	26.00	45.00	19.00
Hydrogen content	7.40	6.00	6.00	7.30	6.00
Nitrogen content	2.30	1.20	-	0.60	5.40
Sulphur content	0.30	0.10	-	0.10	0.20

3.2.3 Physical Composition of the MSW

The composition of the MSW is analysed in terms mass (%), mass (kg), initial volume collected (m^3), volume of compacted density (kg/m^3), compacted sample volume (m^3), and density of initial collection (kg/m^3). The result is tabulated in Table 3 below.

Table 3: Composition of MSW sample in Port Harcourt (Ogwueleka, T. C. 2009)

Components of waste	Mass (%)	Mass (kg)	Initial collected Volume (m^3)	compacted sample Volume (m^3)	Initial collected density (kg/m^3)	Compacted sample density (kg/m^3)
Organic Components						
Food waste	29.2	43.5	0.14	0.12	310.7	362.5
Paper	12.4	18.5	0.21	0.17	88.1	108.8
Plastic	9.9	14.7	0.24	0.23	61.3	63.9
Wood/leaves	8.4	12.7	0.05	0.04	254.0	317.5
Textiles/leather/rubber	7.6	11.4	0.08	0.06	142.5	190.0
Miscellaneous organic	1.8	2.7	0.02	0.01	135.0	270.0
Inorganic Components						
Metals	17.2	25.6	0.13	0.12	196.9	213.3
Glass	13.5	20.1	0.11	0.08	182.7	251.3
Total	100	149.2	0.98	0.83	171.0 (average)	222.2 (average)

3.3 Electric Power Supply in Port Harcourt

There is a clear mismatch between power generation and load demand nationwide in Nigeria, and Port Harcourt is not exempted. This situation has given rise to load shedding regime because electric power supply is insufficient and inadequate. Presently, electric power supply to the stands around 250 MW against the estimated peak load demand of 530 MW (Ministry of Power, 2015). However, if the municipal solid wastes can be properly managed, they can be sustainably utilised as feedstock to produce energy for the city. Through anaerobic digestion of the organic fraction of the municipal solid waste (OFMSW), biogas can be produced which can be used to power an internal combustion engine (ICE) to generate electricity and the heat recovered from the system can be used to operate an absorption system for district cooling (RCEPR, 2004 and Demirbas, A. 2001).

4. Theoretical Determination of Biogas and Energy Yield from the Waste

The Buswell equation is commonly used to calculate biogas and energy yield from waste given the chemical elements percentage composition, empirical formula and atomic weight of the waste; the equation is given as:

$$C_cH_hO_oN_nS_s + \frac{1}{4}(4c - h - 2o + 3n + 2s)H_2O \rightarrow \frac{1}{8}(4c - h + 2o + 3n + 2s)CO_2 + \frac{1}{8}(4c + h - 2o - 3n - 2s)CH_4 + nNH_3 + nH_2S \quad (1)$$ (Hidalgo, D., 2015)

Given that Port-Harcourt generates 3928 tonnes of municipal solid waste per day, and that the percentage of organic fraction of the municipal solid waste is 69.3%, it means that 3928 x 0.693 = 2722 tonnes of organic fraction of the MSW is generated in Port-Harcourt per day.

4.1 Empirical Formula

Considering the organic waste percentage composition which is 49.00, 7.35, 42.00, 1.45 and 0.20 for Carbon (C), Hydrogen (H), Oxygen (O), Nitrogen (N) and Sulphur (S) respectively, the compound element composition by weight (%) is therefore given as:

$$C_{49}H_{7.35}O_{42}N_{1.45}S_{0.2} \tag{2}$$

Assuming there are 100g of the compound element, and given their atomic weight (C=12, H=1, O=16, N=14, S=32), the empirical formula of the compound is obtained as:

$$C_{1260}H_{2269}O_{810}N_{32}S_{1} \tag{3}$$

4.2 Biogas Yield

By applying the Buswell equation, the biogas composition is obtained as: 699 CH_4, 561 CO_2, 32NH_3, 1H_2S; approximately 55.48 %CH_4:44.52%. Given 1000kg sample of the organic waste with moisture content of 65.20% and solid content of 34.80%, it implies that the moisture content in the waste will be 652kg and the solid content will be 348kg. Therefore, 179 kg CH_4 yield is obtainable from 1000 kg of the waste sample assuming 98% CH_4:2%CO_2 biogas upgrade using physical absorption method. Considering 2,722 tonnes of OFMSW per day, 48,7233 kg CH_4 per day is obtainable.

4.3 Power Generation Capacity of the Wastes

Given methane lower heating value (LHV) of 50,000kJ/kg (Von Mitzlaff, K. 1988), obtained methane in the biogas generated from the anaerobic digesters with the flow rate of 5.64 kg/s, and the electrical efficiency driven by gas engine of 40%, the power that may be generated from the biogas may be estimated as: 5.64 kg/s x 50,000 kJ/kg x 0.4 = 112800 kW = 112.8 MW.

5. Simulation, Results and Discussion

ECLIPSE software is utilised for the simulation of the cases. ECLIPSE was developed for the European Commission and has been used by the Northern Ireland Centre for Energy Research and Technology at the University of Ulster since 1986. It is a personal-computer-based package containing all of the program modules necessary to complete rapid and reliable step-by-step technical, environmental and economic evaluations of chemical and allied processes using generic chemical engineering equations and formulae including high-accuracy steam-water thermodynamics package for steam cycle analysis (McIlveen-Wright, D. R. et al, 2007).

5.1 Power generation

In order to realize the electric power generation a J920 FleXtra gas engine of 9.5 MW electric power output is used for the model. This equipment is designed to achieve a high electrical efficiency of 48.7%. Figure 3 shows the simulation programme in ECLIPSE and Table 4 shows the results.

Due to the amount of biogas that can be generated a total of 15 power generating sets and can be arranged in one site or in 15 different sites to provide 9.5 MW of electricity each, accounting for a total 142.6 MWe.

Table 4: Gas engine data

Fuel	0.390144	kg/s
CH_4 LHV (in Biogas)	50	MJ/kg
Heat	19.5072	MW
Electricity	9.507	MW
Efficiency	48.74	%

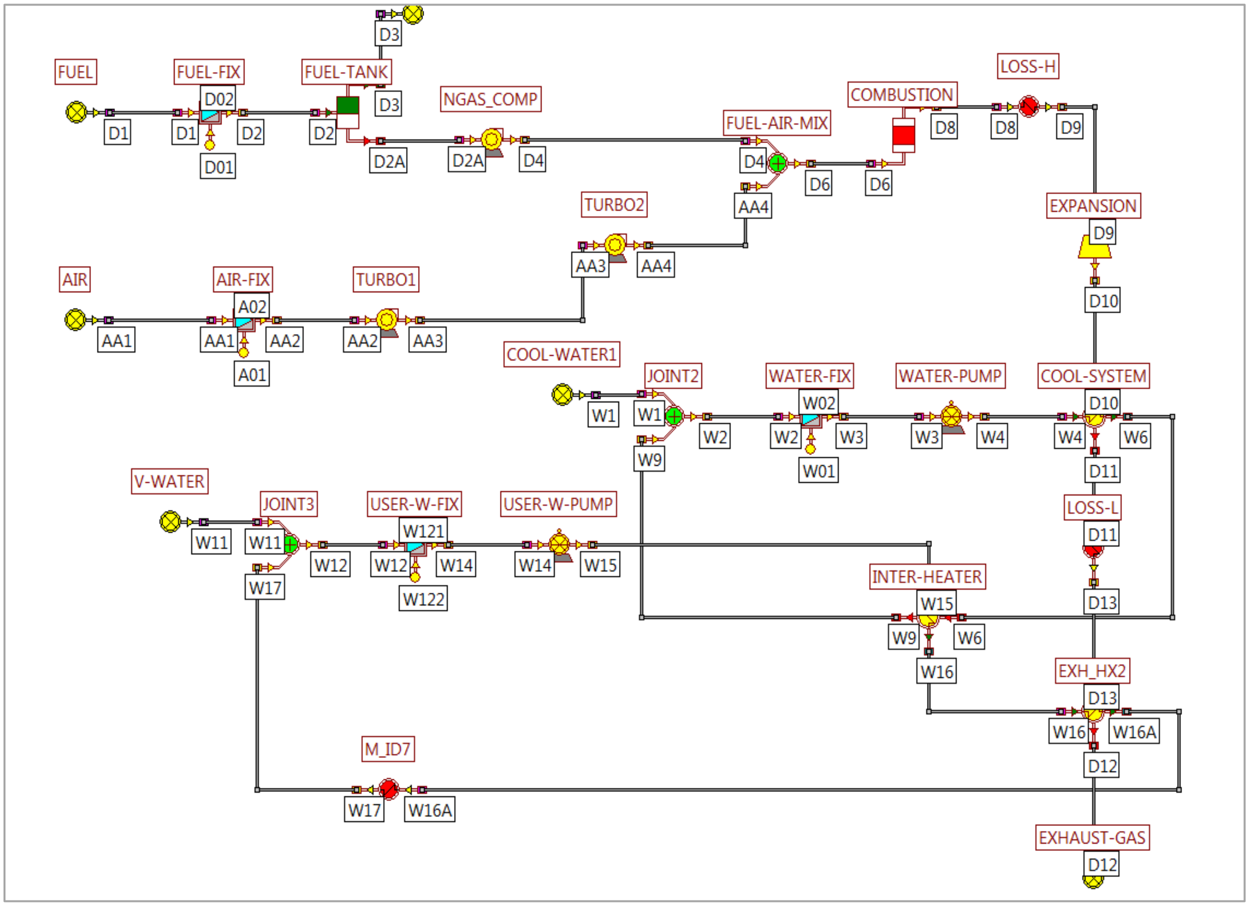

Figure 3: ECLIPSE process flow diagram of the gas engine

5.2 Cooling

In addition to the ICE engine a gas fired absorption chiller (Yazaki absorption chiller WC2T) can be coupled to the system using the recovered heat from the engine cooling system and the exhaust gas to heat the refrigerant generator in the chiller in order to produce cooling. Figure 4 shows the simulation programme in ECLIPSE and Table 5 shows the results. Each plant will have the capacity of 4.921 MW which would represent a total of 73.28 MW.

Table 5: Cooling capacity of the absorption chiller

Generator	**4921**	kW	Absorber	1796	kW
Evaporator	4820	kW	Condenser	5681	kW
COP	0.9795				

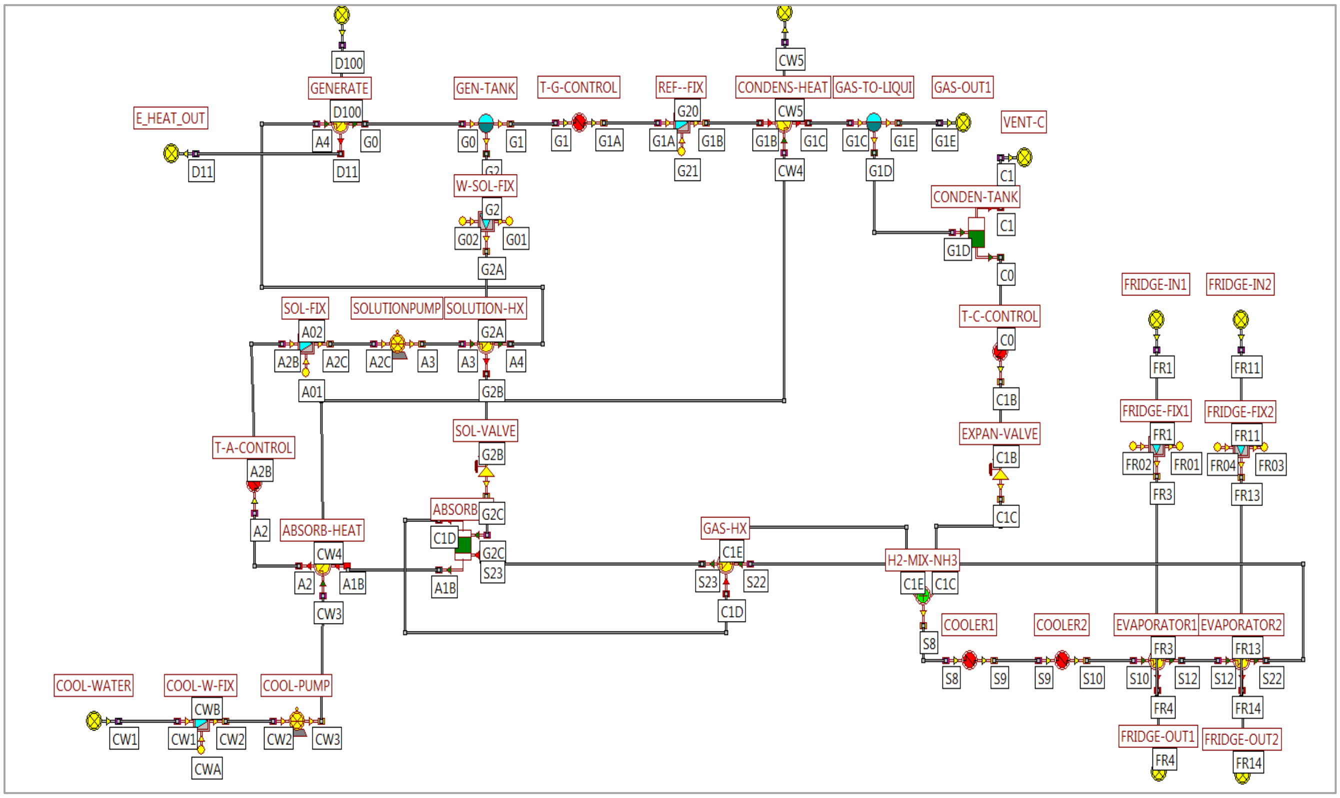

Figure 4: ECLIPSE process flow diagram for the gas-fired absorption chiller

5.3 Discussion

Based on the available quantity of OFMSW in the city and the simulations carried out, it can be seen that sufficient biogas can be produced to run 15 electric power generating sets which will provide 142 MW of electricity. In addition, the waste heat from the gas engines can be used to drive 15 sets of gas-fired absorption chillers to provide 73.82 MW of cooling in the area. The simulations shows that in addition to the power generation, the energy from the biogas produced from the OFMSW can be used to run the absorption chillers which will be able to provide 4.92 MW of cooling for each plant, making a total of 73.82 MW for the 15 sites. This implies that a total of 216 MW of electricity and cooling can be generated from the OFMSW produced in the city.

6. Economic Evaluation

The capital investment and operating cost of the project is estimated using the Department of Energy and Climate Change (DECC) cost estimations for AD technologies (DECC, 2011). The DECC cost estimations for anaerobic digestion cogeneration system relates to recently completed and on-going construction projects around the world, which was obtained based on consultation with the stakeholders of industry. The capital and operating costs estimates for the AD cogeneration plant is given in Table 6.

Table 6: Capital and operating cost estimates for AD cogeneration plant (DECC, 2011)

	Capital Cost		Operating Cost	
£'000/MW	2010	2015	2010	2015
High	6,260	6,121	630	639
Median	4,000	3,911	263	267
Low	2,147	2,099	98	99

6.1 The Project Cost

Assuming the average cost of 2015 estimates for this project, the capital investment cost for the plant will be £3,911,000 per MW and the operating cost will be £267,000 per MW. The total cost of the entire project (15 plants x 9.5 MW) is calculated in Table 7.

Table 7: Total project cost

Plant Capacity (MW)	9.5		
Number of Plants in the Project	15		
	Capital Cost (£)	Operating Cost (£)	Total Cost (£)
Per MW	3,911,000	267,000	4,178,000
Per Plant (9.5 MW)	37,154,500	2,536,500	39,691,000
Total Project Cost (15 plants)	557,317,500	38,047,500	595,365,000

6.2 Annual Earnings

Based on the current electricity tariff reviewed by National Electricity Regulatory Commission (NERC) in April 2015, the average price of electricity in the city of Port Harcourt is N25 (£0.083) per kWh (NERC 2015). From section 4.3, it is seen that the project has the capacity to generate a total 216,000 kW of power per day which is equivalent to 216,000 kW x 24 hours = 5,184,000 kWh per day. This implies that the project is able to generate income of 5184000 kWh x N25 = N129, 600,000 (£432,000) per day which is also equivalent to £157,680,000 per year assuming 365 days in a year and N300 to £1 exchange rate.

6.3 Payback Period

The payback period of the project can be calculated using the formula:

$$Payback\ period = \frac{Initial\ investment}{Cash\ inflow\ per\ period}$$

$$Payback\ period\ (years) = \frac{£595,365,000}{£157,680,000\ per\ year}$$

$$Payback\ period = 3.78\ years$$

From economical point of view, this project is feasible; it is even possible to generate power that could be sold at a cheaper rate based on this technology. For instance, assuming the project decides to sell electricity at a cheaper rate of N22 per kWh, the payback period is calculated below as 4.29 years which is still reasonable since the plant has a lifespan of 20 years.

$$Payback\ period = \frac{595{,}365{,}000}{\left[\left(\frac{5184000 \times 22}{300}\right) \times 365\right]} = 4.29\ years$$

This implies that the project can offer electric power at 12 % reduction in the current price, which will enable low income families to afford power as a way of reducing energy poverty.

7. Conclusions

As earlier stated in section 2.3, only about 47% (250 MW) of the peak load power demand (530 MW) is presently generated in the city of Port Harcourt. However, this study has shown that the energy from OFMSW in the city has the capacity to increase power generation to about 88% (466 MW) of the peak load demand which represent an increment of 41% in the current capacity of electrical power generations. Also, this system will serve as a sustainable method for municipal solid waste management in the city, mitigating the environmental hazards caused by poor waste management.

The project may offer an alternative energy solution to generating clean, renewable and sustainable energy, free of greenhouse gases emissions, and other environmental contamination caused by the use of fossil fuel in conventional power plant, and provides cooling using the waste heat from the engine generators and saves the electrical power used in vapour compression cooling systems.

Finally, The results from this study has shown that the energy from OFMSW in the city has the capacity to increase power generation to about 88% (466 MW) of the peak load demand which represent an increment of 41% in the current capacity of electrical power generations; and the project is economically feasible as the power generated can be sold at N22 per kWh with a payback period of 4.29 years.

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