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Research Article

Techno-Economic Analysis of Waste-to-Suburban Cooking Energy Critical Infrastructure Development in Southwestern Nigeria

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Abstract

This study examined the techno-economic specifications for a Waste-to-Suburban Cooking Energy critical infrastructure project in Southwestern Nigeria. Technological and project economic data for the W2E project were obtained from strategic sources and energy project foresight/analysis framework used. The results showed residential upgraded biogas-for-cooking demand of approximately 10,243 m^3/month, and municipal solid waste (MSW) input of approximately 80 tonnes/month. The planned biogas plant had estimated costs of US $120,000, a throughput of almost 15,364 m^3/month and required 5 acres of land for construction. Project economic viability indicator estimates were: Initial Investment – US $256,500, annual profits – US $40,000, Net Present Value (NPV) – US $142,000, maximum payback period – 7 years, and annual Return-on-Investment (ROI) – 16%. Socio-economic benefits per month included the constant supply of cheap cooking fuel, comparative cooking energy cost savings (biogas-to-LPG usage) of US $3,810, and the elimination of almost 80 tonnes of MSW from the environment. The study concluded that the Waste-2-Biogas critical infrastructure project was technically, environmentally, and socio-economically viable, and was suitable for deployment across suburban Southwestern Nigeria.

Keywords

Waste-to-suburban cooking energy; critical infrastructure; energy planning/analysis; project planning and management; suburban energy consumption; waste-to-biogas; biogas-for-cooking energy; municipal solid waste (MSW); southwestern Nigeria

1. Background to the Study

Domestic energy consumption is a key component of the critical energy infrastructure essential for the effective functioning of modern societies [1]. Domestic energy consumption entails the total energy used for household activities – including heating, lighting and cooking [1]. Cooking energy, the focus of this paper, is important as a modern man not only needs to eat food several times each day, almost all their foods need to be cooked before consumption.

Unlike developed countries which display advanced cooking energy acquisition and distribution systems, utilizing modern cooking fuels (like liquefied petroleum gas (LPG), electricity, solar energy and biogas) [2, 3], in most developing countries, cooking energy (about 90% of their domestic energy consumption) is predominantly based on biomass energy sources such as wood, charcoal, animal dung, straw, and leaves [2-4]. So clearly modern societies have access to clean cooking – using cleaner fuels and energy-efficient modern stoves – which developing countries like Nigeria are struggling to achieve.

Clean cooking addresses household and ambient air pollution, resource efficiency and climate vulnerability, as well as many of the basic needs and development challenges of the poor, while also delivering climate benefits as espoused in the Sustainable Development Goals (SDGs) [5, 6]. Constraints to clean cooking include limited national capabilities for clean cooking technologies development and resource scarcity, disruption in distribution networks, technical inefficiencies, limited funding and high costs of clean fuels/technologies procurement, non-existence of basic modern clean fuels products supply infrastructure, population increase and poor societal value systems and activities, and government policies and regulations amongst others [6, 7].

Amongst the four modern cooking fuels identified – liquefied petroleum gas (LPG), electricity, solar energy and biogas – the development of biogas usage in addressing cooking energy demand helps address two key socio-economic development issues confronting a developing economy like Nigeria, namely, the provision of critical energy for cooking and the management of solid waste generation [8, 9]. Biogas is a renewable energy source or biofuel, being an energy-rich gas produced from the anaerobic decomposition or thermochemical conversion of biomass (raw materials such as agricultural, industrial and municipal organic waste, manure, plant material, sewage, food waste, and green waste) [10-12]. Biogas is composed of gases (basically methane, carbon dioxide and hydrogen sulfide), is environmentally friendly, and produces instant heat on the ignition, as well as a by-product (slurry) which is suitable as fertilizer [11, 13]. Furthermore, biogas has many utilization options, is storable, and far superior to other renewable energies; biogas plants can generate power continuously without requiring sun, wind and water [14].

In Nigeria, biomass energy from wood, crop residues, and dung is the primary energy source, especially in rural areas [15-17]. Despite biomass cooking fuel utilization being a significant constituent of national energy consumption, this utilization primarily results from an amalgamation of an individual or small-group consumption rather than a national policy measure [15, 17]. Nigeria's limited access to clean cooking results from policy and market failures. Addressing Nigeria's cooking energy demand with a sustainable biomass-to-power or waste-to-power initiative has had limited success [18-20]. This is ironic as bridging these two significant national challenges – providing adequate cooking energy and elimination of solid waste – are critical to Nigeria's national development aspirations, especially as the nation faces a rapidly growing population over 200 million, and the demands of urbanization and industrialization [21-23]. A fundamental challenge is that data on national cooking energy demand and organic waste generation are very poor, albeit it is estimated that 32 million tonnes of solid waste are generated annually with less than 30% of this waste collected – leading to severe ecological, environmental, health and developmental consequences to this inaction [24].

Unlike Lagos State, which generates about 13,000 metric tonnes in Nigeria, most States lack verified data on solid waste generation [25, 26]. Nigeria's waste generation, on average, comprises organic (food) (57%), paper & plastic (29%), glass (5%), metal (5%) and others (4%) [25, 27]. Across the country, Federal and State capabilities for waste management are very low, and there are very limited waste-to-wealth competencies [24, 25]. Consequently, domestic management of municipal solid waste (MSW) is a major concern; with residents exhibiting improper waste disposal across municipalities. 'Waste management' in Nigeria entails 'waste disposal' – the transportation of wastes from city centers to urban outskirts where the wastes are burnt in open dumpsites [25, 28, 29] – with the prominently practiced MSW techniques being open dumping, landfills, open burning, composting, and dumping into gutters, drainages, streams/rivers and open space [24-26, 29].

Factors attributed to poor waste disposal management and limited waste-to-biogas deployment in Nigeria include low investment in critical infrastructure, rapid population growth and uncontrolled urbanization, inadequate technical and managerial capabilities, the wrong attitude of the public towards solid waste management, poor planning, uncoordinated waste management system of innovation, poor waste collection, improper waste segregation, and inadequate waste transportation and poor policy and regulatory framework, amongst others [24-26, 29, 30].

The Federal Government and several State Governments have taken cognizance of the relevance of addressing the challenges of the cooking energy demand and waste management nexus, and in recent years, have promoted several government policy discourses and renewable energy policies/standards for its proper inclusion in national planning – including the Renewable Energy Masterplan, the various federal and state governments' Waste-2-Energy initiatives, the National Science, Technology and Innovation Policy, and the National Renewable Energy and Energy Efficiency Policy, amongst others [24]. Regrettably, these governments in Nigeria have found it difficult to institute and/or maintain the strong institutions and infrastructure required for efficient and effective biogas-to-cooking energy development, and durable strategic initiatives are non-existent at worst and ineffectual at best [24].

Recent policy efforts in Nigeria to strengthen decentralized public and private investments in Waste-2-Energy (W2E) initiatives in the country have generated much excitement [23, 31-34], albeit biogas-to-cooking energy development has not been as pronounced as waste-to-electricity initiatives [23, 24]. Despite the considerable public expenditure on the country's several Waste-2-Energy (W2E) initiatives, their performance indicators have been very poor [23, 24]. These inadequacies may be attributable to the ineffectualness of state agencies and their private sector service-providers to effectively analyze regional cooking energy demand to comprehensively plan and deliver these W2E initiatives. This study analyzed a proposed multi-million-naira centralized Waste-2-Biogas for Cooking Energy strategic initiative in a residential complex in the Moniya area of Ibadan, Oyo State, for appropriate project planning and implementation. The specific objectives were to ascertain cooking energy consumption in the suburb, determine the technical specifications for biogas utilization for cooking energy replacement, and determine the project economics of the Waste-to-Biogas initiative. This study is significant as it provides strategic intelligence and a template for the planning and implementing a critical Waste-to-Biogas initiative, with special reference to Southwestern Nigeria.

1.1 Overview of the Biogas-to-Cooking Energy Process

A biogas plant is a facility (or artificial system) that provides an oxygen-free environment where bacteria transform biomass into biogas (or turn waste into sustainable energy and fertilizers creating carbon-neutral energy), with the biogas production process precluding methane emissions and showcasing positive effects on the environment [35-37]. The oxygen-free transformation process is called anaerobic digestion, and the biogas plant may be called an anaerobic digester [36, 37]. Biogas is 100% renewable and carbon-neutral as its combustion does not produce carbon dioxide. The biogas can be used as cooking energy or it can be used to generate heat, generate electricity or both [37, 38]. Biogas facilities are part of the waste management system, and the residues are high-quality fertilizers, providing a suitable alternative to synthetic chemical substances [36, 39]. Some suitable biomass feedstock includes crop residues, agricultural material and wastes, industrial and municipal waste/sewage, food, paper, wastes, livestock manure, and seaweed [38, 39].

The biogas plant comes in different sizes and forms, and has three major components for the biomass-to-biogas conversion process [35-37, 40]:

i. The reception area where the raw (waste) materials arrive, is pre-treated and prepared for anaerobic digestion.
ii. The digester (or fermentation tank) is an air-tight, waterproof container with at least two openings – the inlet entry for the biomass/raw materials and the exit opening for the gas produced. This tank should be made of steel to withstand the corrosive by-products.
iii. The gas container which is hermetically sealed serves as a gas collector during the fermentation process, and has an outlet for the exit of gas for the production of heat and energy.

Biogas plants follow an automatic, straightforward process created to replicate the natural anaerobic digestion in an artificial environment, making biogas production simple and carbon neutral [38, 39, 41]. Figure 1 depicts the biogas plant operation process, while Steps 1 – 6 explain the process.

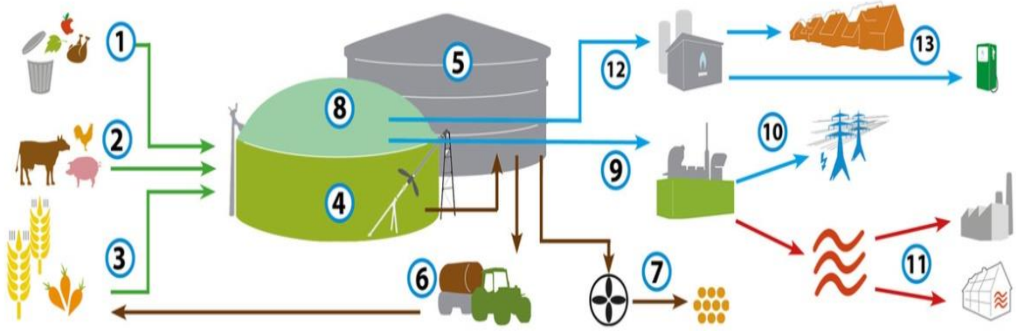

Figure 1 The Biogas Plant Operation Process [14].

1.1.1 Step 1 – Pre-Treatment and Filling the Digester (1, 2 and 3)

Multiple organic input materials, called substrates, are fed into the digester – including foodstuff remnants, fats/sludge, and renewable resources (corn, beets/grass, and manure/dung).

1.1.2 Steps 2 – The Fermentation Process (4)

Inside the fermenter, the substrate is heated to approximately 38-40°C, and decomposed by micro-organisms without light and oxygen. The organic matter is shifted severally to prevent layers from forming at the top and bottom of the tank.

1.1.3 Steps 3 and 4 – Production of Biogas and Pulling Out of Fermentation Residue (4, 5 and 8)

Step 2 final products are biogas with methane (the main component), carbon dioxide, water and hydrogen sulfide. After Step 2, the biogas and fermentation residues (digestate) produced are moved to their storage tanks for further utilization. The digestate is used as an environment-friendly, high-quality fertilizer. The biogas production process thus is a zero-waste system for eliminating waste while producing fertilizers.

1.1.4 Step 5 – Eliminating Impurities and Utilizing the Biogas and Digestate (6 – 13)

The biogas goes through a cleanup process, in which water, hydrogen sulfide, and impurities are removed to produce biomethane which can be burned in the combined heat and power (CHP) plant or generate energy (electricity) and heat. The electricity produced can be fed to the national grid, or set up as an off-grid system; the heat generated can be used for cooking, or building heating. Furthermore, the biogas produced may be supplied to the national grid or gas filling stations.

2. Methodology

The study utilized an energy planning and foresight analysis framework. A government-approved private residential complex in Moniya, Akinyele Local Government Area in Ibadan, Oyo State comprising 374 individual buildings was considered for this study. Each housing unit is a 3-bedroom apartment; with residents being predominantly middle-income public servants, well-educated (with at least a Master’s degree), and having a maximum family size of five.

In achieving Objective I (i.e., ascertaining cooking energy consumption in the residential area), a cooking energy audit of housing units in the residential area was conducted. This entailed (a) a walkthrough audit detailing source and heat energy requirement for cooking per day, per month, and per year by the individual households, (b) an estimation of average cooking energy requirement per household in the residential area, and (c) determination of biogas equivalence of the cooking energy consumption.

Achieving Objective II (i.e., determining the technological specifications for biogas utilization for cooking energy replacement) entailed (a) estimating biogas requirement for replacing the determined cooking energy consumption, (b) assessing the technical specifications of the biogas system such as design specifications, materiel demand, and land-space requirement for construction, and (c) calculating waste feedstock quantity for the biogas system.

In achieving Objective III (i.e., assessing the project economics of the Waste-to-Biogas initiative), data on costs (capital costs, land costs, operations and maintenance costs, energy costs, etc., measured in US dollars) over 25 years for the biogas system were obtained from primary and secondary sources such as manufacturers/equipment vendor and estate agents' price lists, project financial analysis reports, and other relevant literature.

In achieving Objective III (i.e., assessing the project economics of the Waste-to-Biogas initiative), the techno-economic specifications for the proposed biogas plant included initial investment/capital costs (the costs for the biogas plant, land, buildings & facilities and the cash in hand); annual operation costs (waste feedstock procurement, operations and maintenance, energy and utilities, and other costs like insurance, research and analysis); and annual estimated revenues from projected biogas sales. An energy project financial management template detailing the percentage of each cost item relative to the total initial investment/capital and operations costs was developed based on literature and expert opinion, manufacturers/equipment vendor and estate agents' price lists and project financial analysis reports [42-45]. The data obtained were analyzed using different analytical methods including chemical process calculations, energy project foresight/analysis techniques, descriptive statistics and comparative costs analysis. Project economic viability indices (levelised costs of biogas energy, Net Present Value (NPV), Payback Period, and Return on Investment) were determined.

Figure 2 depicts the process flow diagram for the production of the biogas and bio-fertilizer from the strategic W2E project, and provides the schematics for the chemical process calculations (material balance) executed.

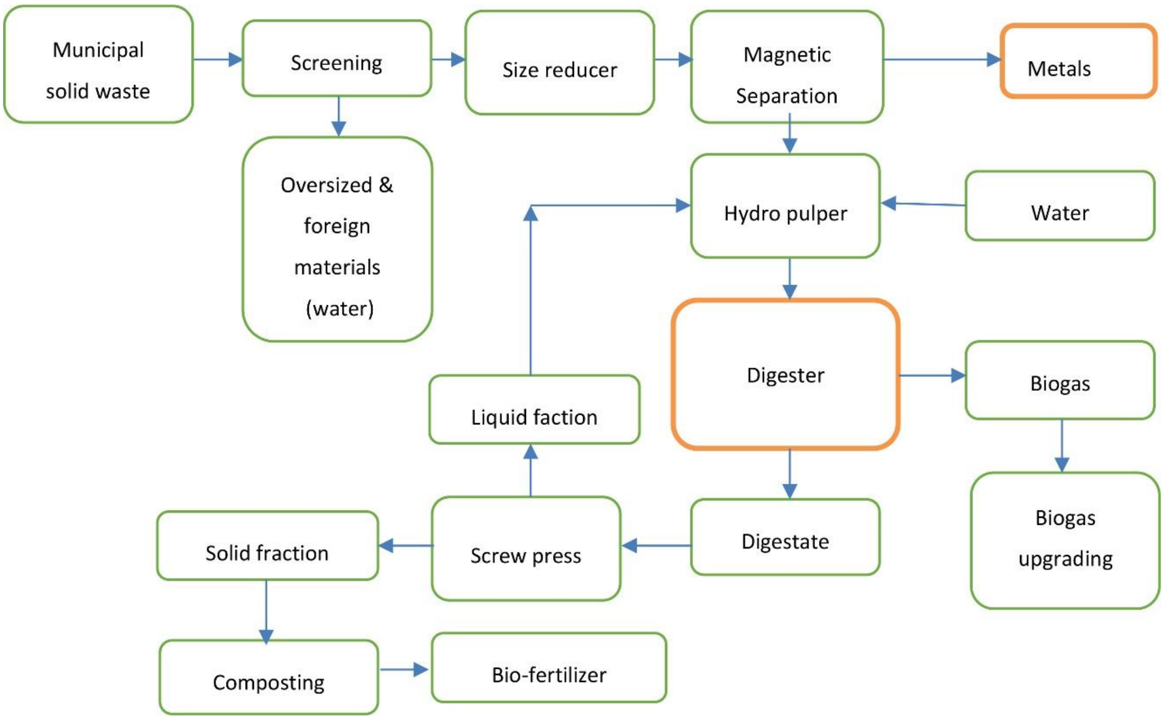

Figure 2 Biogas and Bio-fertilizer Production Process Flow Diagram.

3. Process Evaluation and Results

The calculations of the study are presented in this section.

3.1 Technological and Cost Specifications for the Waste-to-Cooking Energy Strategic Initiative

Liquefied Petroleum Gas (LPG) (77.63% of average cooking energy consumption) is the predominant cooking fuel in the study area, followed by Electricity (15.42%), Kerosene (4.54%) and Biogas (2.41%). The average number of meals and average monthly cooking gas consumption was estimated at 33,660 meals and 217,158,454.80 BTU respectively (see Table 1). The determination of upgraded biogas required to produce the equivalence of the total average cooking energy demand per month (217,158,454.80 BTU) is shown in Table 2 and estimated to be 10,242.60 m^3.

Table 1 Average Cooking Energy Consumption in the Selected Residential Complex (374 Housing Units) in Moniya, Akinyele LGA, Ibadan, Oyo State.

Average Number of Meals	Average Cooking Energy Consumption: Kerosene Litres (10^3)	Kerosene Joules (10^9)	Kerosene %	Biogas scf* (10^3)	Biogas Joules (10^9)	Biogas %	Liquefied Petroleum Gas (LPG) Kg (10^3)	LPG Joules (10^9)	LPG %	Electricity kWh (10^3)	Electricity Joules (10^9)	Electricity %	Total Joules (10^9)	Total %
Per Day: 1122	0.009	0.35	4.54	0.29	0.18	2.41	0.12	5.93	77.63	0.33	1.18	15.42	7.64	100
Per Month: 33,660	0.29	10.40	4.54	8.72	5.52	2.41	3.63	177.86	77.63	9.81	35.33	15.42	229.11	100
Per Year: 409,530	3.56	126.56	4.54	106.13	67.18	2.41	44.15	2,164	77.63	119.40	429.84	15.42	2,787.56	100

Where scf* = Standard cubic feet.

Table 2 Average Cooking Energy Consumption and Total Biogas Replacement Requirement in the Selected Residential Complex in Moniya, Akinyele LGA, Ibadan, Oyo State.

		Average Cooking Energy Consumption		
Housing Units	**Average Number of Meals**	**Joules (10^9)**	**Total Biogas Requirement Joules (10^9)**	**Total Biogas Requirement (m^3)**
374	**Per Day:** 1122	7.64	7.64	341.42
	Per Month: 33,660	229.11	229.11	10,242.60
	Per Year: 409,530	2,787.56	2,787.56	124,618.30

Table 1 shows the average daily consumption of cooking fuels across the 374 houses in the residential complex to be Kerosene (9 liters; SI Unit of energy – 0.35 gigajoules), Biogas (290.77 standard cubic feet (scf); SI Unit of energy – 0.18 gigajoules), Liquified Petroleum Gas (LPG) (120.97 kg; SI Unit of energy – 5.93 gigajoules) and Electricity (327.12 kWh; SI Unit of energy – 1.18 gigajoules); thus, giving an estimated total average cooking energy consumption per day of 7.64 gigajoules. LPG (77.63% of total average cooking energy consumption) is the predominant cooking fuel in the study area, followed by Electricity (15.42%), Kerosene (4.54%) and Biogas (2.41%). In a month, the total average cooking energy consumption was estimated at 229.11 gigajoules (see Table 1). The quantity of upgraded biogas per month required to produce the equivalence of this monthly total average cooking energy consumption per month (229.11 gigajoules) was determined, using a conversion table, to be 10,242.60 m^3 (see Table 2).

3.2 Chemical Process Calculations for Municipal Solid Waste Determination (Material Balance Analysis)

The material balance over the process lifecycle provides information on the quantities of raw materials consumed and the consequent products [46, 47]. Consequently, the material balance expression is:

$$\text{Materials In} - \text{Materials Out} + \text{Generation} - \text{Consumption} = \text{Accumulation} \quad (1)$$

The Biogas production process entails 3 units: the pre-treatment unit, the anaerobic digestion and digested treatment unit, and the biogas upgrading unit. Determining the Municipal Solid Waste (MSW) input entails a reverse process analysis from the upgraded biogas output, through the biogas upgrading unit, the digested treatment unit and the pre-treatment unit to the start of the process. The proposed biogas plant would have an estimated monthly biogas demand of 10,242.60 m^3 as the output target. It is assumed that the final (refined) biogas will contain 87.55% CH_4, 11% CO_2, 0.05% H_2S, 1% NH_3 and 0.4% H_2O (moisture) [48].

3.2.1 The Biogas Upgrading Unit Calculations

Thus The amount of biogas constituents from biogas production output of 10,242.60 m^3 can be estimated:

CH_4 = 0.8755 × 10,242.60 m^3 = 8.967.40 m^3;
CO_2 = 0.11 × 10,242.60 m^3 = 1,126.67 m^3;
H_2S = 0.005 × 10,242.60 m^3 = 51.21 m^3;
NH_3 = 0.01 × 10,242.60 m^3 = 102.43 m^3;
H_2O = 0.004 × 10,242.60 m^3 = 40.97 m^3.

The Hydroscopic Absorption (HA) Section. A waterscrubber enters a mixture of water and biogas into the HA section (See Figure 3). Of the total water entered in the HA section, 80% is absorbed (i.e., 80% of the moisture is removed in the HA section). Thus the 20% moisture left is equal to the moisture constituent of the refined biogas, which is 40.97 m^3.

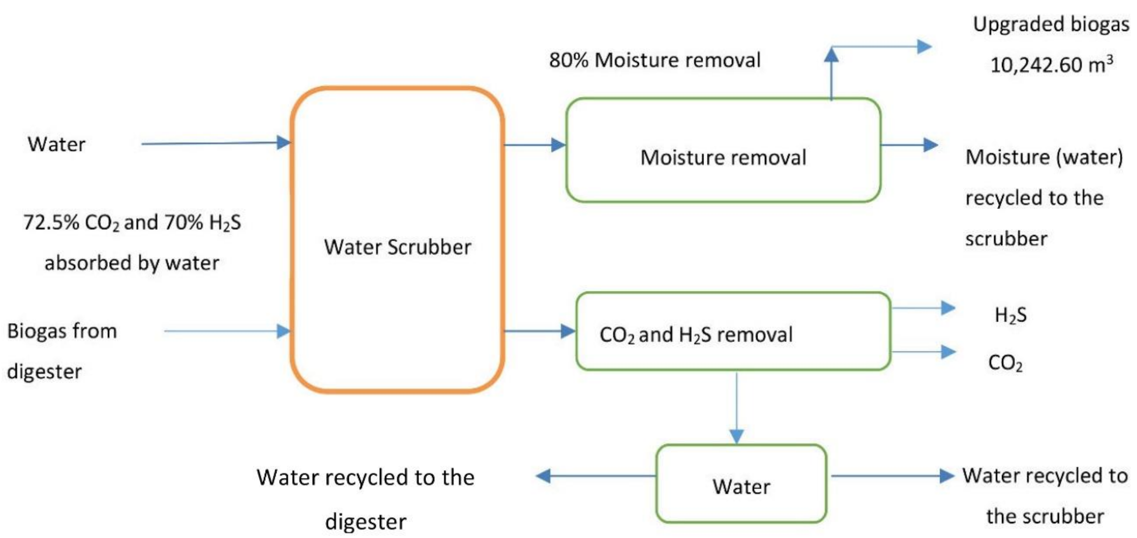

Figure 3 Biogas Upgrading Unit.

Total amount of water entering the HA section × 0.2 = 40.97 m^3.

Total amount of water entering the HA section $= \frac{40.97}{0.2}$
= 204.85 m^3.

Total amount of water absorbed in the HA section = 204.85 – 40.97
= 163.88 m^3.

Total amount of biogas entering the HA section = 10,242.60 + 163.88
= 10,406.48 m^3.

The Water Scrubbing Section. It is assumed that the water would absorb 72.5% CO_2 and 70% H_2S entered into the water scrubbing system [48](See Figure 3). This implies the 27.5% CO_2 left is equal to the CO_2 constituent of the refined biogas, which is 1,126.67 m^3. Similarly, the 30% H_2S left equals the H_2S constituent of the refined biogas, which is 51.21 m^3.

Thus,

Total amount of CO_2 entered into the water scrubbing section × 0.275 = 1,126.67 m^3.

Total amount of CO_2 entered into the section $= \frac{1,126.67}{0.275}$

$= 4,096.98$ m^3.

Total amount of H_2S entered into the water scrubbing section × 0.3 = 51.21 m^3.

Total amount of H_2S entered into the section $= \frac{51.21}{0.3}$

$= 170.70$ m^3.

Total amount of CO_2 absorbed by water $= 4,096.98 \times 0.725$

$= 2,970.31$ m^3.

Total amount of H_2S absorbed by water $= 170.70 \times 0.7$

$= 119.49$ m^3.

This absorbed amount of CO_2 and H_2S is removed from the section later.

The quantity of biogas from the digester entered into the upgrading unit:

Biogas quantity $= 10,406.48 + 2,970.31 + 170.70$ m^3

$= 13,547.49$ m^3.

Biogas quantity $= (10,242.60 + 163.88 + 2,970.31 + 170.70)$ m^3

$= 13,547.49$ m^3.

The material balance table for the process calculation is presented in Table 3.

Table 3 The Material Balance for the Biogas Upgrading Unit.

Input			**Output**		
Material		**Amount (m^3)**	**Material**		**Amount (m^3)**
1.	Biogas	13,547.49	1.	Biogas	10,242.60
			2.	Moisture	163.88
			3.	CO_2	2,970.31
			4.	H_2S	170.70
	TOTAL	**13,547.49**			**13,547.49**

3.2.2 Calculation of Anaerobic Digestion and Digested Treatment Unit

0.21 m^3 of biogas can be produced from 1 kg of organic waste [48, 49].

Thus,

1 m^3 of biogas can be produced from $= \frac{1 \times 1}{0.21}$

= 4.76 kg of organic waste.

And

13,547.49 m^3 of biogas can be produced from $= 4.76 \times 13,547.49$

= 64,486.05 kg

= 64,486.05 kg of organic waste.

Thus, 64,486.05 kg of organic waste would be required for digestion per month (See Figure 4).

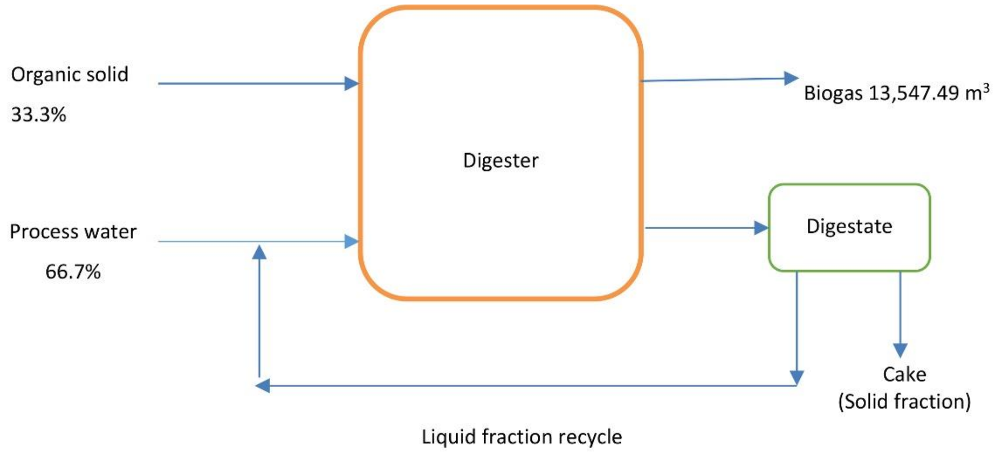

Figure 4 Anaerobic Digestion and Digested Treatment Unit.

For the optimum production of biogas from Municipal Solid Waste by anaerobic digestion in the digester, the required waste-to-water ratio is 1:2 [48, 49].

Therefore, the water requirement for digestion = 64,486.05 × 2
= 128,972.1 kg.

For biogas conversion according to Bhattacharjee *et al*. [48] and Aikhuele *et al*. [49],

1 m^3 biogas ≡ 1.3 kg biogas.

Consequently, 13,547.49 m^3 biogas ≡ 13,547.49 × 1.3 kg biogas = 17,611.74 kg biogas.

The total mass entering the digester = mass of the water requirement + mass of organic waste
= 128,972.1 + 64,486.05
= 193,458.15 kg.

The weight of the digestate = 193,458.15 – 17,611.74
= 175,846.41 kg.

The amount of cake (solid fraction of digestate) is 33.3% of the digestate [48] (See Table 4).

Table 4 The Material Balance of the Anaerobic Digestion and Digested Treatment Unit.

Input			**Output**		
Material		**Amount (kg)**	**Material**		**Amount (kg)**
1.	Solid organic waste	64,486.05	1.	Biogas	17,611.74
2.	Water	128,972.10	2.	Cake (solid fraction)	58,556.85
			3.	Liquid fraction	117,289.56
	TOTAL	**193,458.15**		**TOTAL**	**193,458.15**

Thus, the amount of cake = 175,846.41 × 0.333
= 58,556.85 kg.

The amount of liquid fraction is 66.7% of the digestate.

Thus, the amount of liquid fraction = 175,846.41 × 0.667
= 117,289.56 kg.

This liquid fraction is recycled into the digester to optimize the anaerobic digestion process.

The additional water required for the complete digestion, which is supplied from the hygroscopic absorption section is determined:

Additional water requirement = water requirement for digestion – digestate liquid fraction
= 128,972.1 – 117,289.56
= 11,682.54 kg.

The material balance table for the process calculation is presented in Table 4.

3.2.3 Calculation of Pre-Treatment Unit

In the hydro pulper, 5% light fraction and 7% heavy fraction of the waste would be removed. The light fractions are non-biodegradable contaminants such as textiles, wood, plastic film, string, etc. In contrast, the heavy fractions are non-biodegradable contaminants such as stones, large bones, batteries and metallic objects [50]. The pretreatment system is essential for separating different waste types and crushing the feedstock to optimal-sized fractions [14, 23] (See Figure 5).

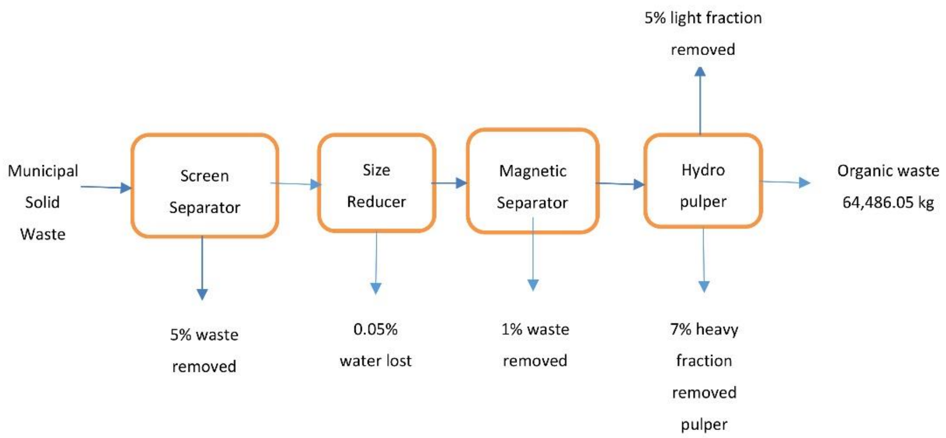

Figure 5 Pre-treatment Unit.

Thus, the total waste percentage removed in hydropulper = (5 + 7)%
= 12%.

The organic waste output of 64,486.05 kg = (100 – 12)% of waste entered into the hydropulper.

The amount of waste entered into the hydropulper $= \frac{64,486.05}{0.88}$
= 73,279.60 kg.

The amount of light fraction removed = 73,279.60 × 0.05
= 3,663.98 kg.

The amount of heavy fraction removed = 73,279.60 × 0.07
= 5,129.53 kg.

In the Magnetic Separator, 1% Metal Waste is Removed. Therefore, the organic waste metal separator output of 73,279.6 kg = (100 – 1)% of waste entered into the metal detector.

The amount of waste entered into the magnetic separator $= \frac{73,279.6}{0.99}$
= 74,019.80 kg.

The amount of waste removed in the magnetic separator = 74,019.8 × 0.01
= 740.2 kg.

<u>In the Size Reducer, 0.05% Waste is Lost.</u> Therefore, the waste size reducer output of 74,019.80 kg = (100 – 0.05)% of waste entered into the size reducer.

The amount of waste entered into the size reducer $=\frac{74,019.8}{0.9995}$

= 74,056.83 kg.

The amount of waste removed in the size reducer = 74,056.83 × 0.0005

= 37.03 kg.

<u>In the Screening Operation, 5% Waste is Removed.</u> Therefore, the waste screening operation output of 74,056.83 kg = (100 – 5)% of waste entered into the screening operation.

The amount of waste entered into the screen separator $=\frac{74,056.83}{0.95}$

= 77,954.56 kg.

The amount of waste removed in the screen separator = 77,954.56 × 0.05

= 3,897.73 kg.

The material balance table for the process calculation is presented in Table 5.

Table 5 The Material Balance of the Pre-treatment Unit.

Input			**Output**		
Material		**Amount (kg)**	**Material**		**Amount (kg)**
1.	Municipal solid waste	77,954.56	1.	Waste from screen	3,897.73
			2.	Waste removed from size reducer	37.03
			3.	Waste from magnetic separator	740.20
			4.	Light fraction from Hydropulper	3,663.98
				Heavy fraction from Hydropulper	5,129.53
				Organic fraction from Hydropulper	64,486.05
	TOTAL	**77,954.56**		**TOTAL**	**77,954.56**

3.3 Determination of Location and Land Area for the Municipal Biogas Plant

Ogundari *et al.* [43] have pointed out that the location of an industrial plant is a critical factor in its viability analysis, with factors like raw materials accessibility, end-user proximity, availability of labor, infrastructure and finance, as well as government regulations and policies, amongst others, being significant.

Increased government attention on municipal solid waste (MSW) management in Southwestern Nigeria (comprising Oyo, Ondo, Ekiti, Osun, Ogun and Lagos States), has stimulated public and private sector investments in Waste-2-Energy strategic projects in the geopolitical zone with a heightened increase in Ibadan, Oyo State is a strategic location in the area. Ibadan is the capital and most populous city in Oyo State, the second most populous city in Southwestern Nigeria (after

Lagos) and the largest city in the region (and indeed Nigeria) by geographical area. Ibadan has an estimated population of 3.65 million in its urban center and over 6 million in its metropolitan area. The city is only 119 km northeast of Lagos, Nigeria's economic hub, thus fostering the city's agricultural and industrial development and position as the second-largest economy in Southwestern Nigeria (and fourth largest in Nigeria). Ibadan's rapid population growth has spurred the growth of built-up areas and newly-developed residential complexes. A municipal solid waste management initiative affiliated with a newly-developed built-up area and residential complex in the Moniya, Akinyele Local Government Area of Ibadan, Oyo State was purposely selected in this study to determine the viability of its Waste-2-Biogas strategic project as an input to strategic environmental and power infrastructure planning in Nigeria's Southwest geopolitical zone.

3.3.1 Total Land Area Required for the Waste-2-Biogas Strategic Project

The land area for the Waste-2-Biogas project is dependent on the processing type, number of unit operations and processing capacity. It is estimated that a 200 m^3 biogas plant would require approximately 250 m^2 of land for construction [40].

The planned biogas plant has an estimated output of 10,242.60 m^3 per month. However, the plant design benchmark would be assumed to be estimated output plus 50%, which yields:

Plant design benchmark = 10,242.60 m^3/month + (10,242.60 × 0.5)
= 15,363.90 m^3/month.

Thus,

200 m^3 biogas plant would require 250 m^2 of land;

15,363.90 m^3 biogas plant would require $\frac{250}{200}$ × 15,363.90 m^2 of land
= 1.25 × 15,363.90
= 19,204.88 m^2 of land;

19,204.88 m^2 of land ≡ 4.7 acres (as 4047 m^2 ≡ 1 acre) or ~5 acres (30 plots @ 6 plots/acre).

3.4 Techno-Economic Analysis of the Municipal Waste-2-Biogas Project

The analysis of the project economics of the Municipal Waste-2-Biogas Project is critical to project investment decision-making. This section presents estimated costs based on the study methodology (see Table 6) and the study techno-economic analyses.

Table 6 Techno-Economic Assessment of a Municipal Waste-2-Biogas Project.

Costs	US $
Capital Costs	
15,363.90 m^3/month biogas plant	120,000.00
Land	90,000.00
Buildings + Facilities	24,000.00
Total Fixed Capital	**234,000.00**
Cash in Hand (100% of TOC)	22,500.00
Total Investment	**256,500.00**
Operating Costs (Annual)	**US$**
Waste Feedstock (12.5% of TOC)	2,800.00

Operations + Maintenance (57.5% of TOC)	12,950.00
Energy + Utilities (20% of TOC)	4,500.00
Others (10% of TOC)	2,250.00
Total Operating Costs (TOC)	**22,500.00**

3.4.1 Determination of the Initial Investment (Fixed Capital and Cash-in-Hand)

The calculations for the municipal biogas plant, land and buildings & facilities are presented.

Cost of the Municipal Biogas Plant. The total cost for a municipal biogas plant was assumed to be $1500/ton of waste feedstock [51]. The input municipal solid waste was estimated to be 77,954.56 kg (or approximately 80,000 kg or 80 tonnes) used in the process analysis.

Therefore, Municipal biogas plant costs = $1500 × 80
= US$120,000.

Cost of Land in Moniya, Akinyele LGA, Ibadan, Oyo State. A plot of commercial land in Moniya, Akinyele LGA, Ibadan, Oyo State was estimated to cost ₦1.25 million (Nigeria Property Centre, 2021). Which gives US $3,010.09 (@₦420 per Dollar at official bank rates as of July 1, 2022).

Thus, the cost of 5 acres (30 plots of land) = US $3,010.09 × 30
= US $89,285.71 (or ~US $90,000).

Cost of Building and Facilities. The cost estimates for ancillary structures (the buildings and facilities) were based on project experts' advice and determined at 20% of the cost of the Municipal Biogas Plant.

Thus, cost of Buildings & Facilities = 0.20 × US $120,000
= US $24,000.

Cash-in-Hand. This equals annual operating costs and is a working capital required to meet current, short-term obligations.

3.4.2 Determination of the Annual Operations Costs

The annual costs for waste feedstock were estimated at US $2,800 (field study). Other cost items were determined using the financial template discussed in the study methodology (See Table 6 for details).

The initial investment/capital costs were summed up to US $256,500 (comprising total fixed capital and cash-in-hand) while the annual operations cost was US $22,500.

3.4.3 Levelized Cost of Upgraded Biogas

The levelized cost of upgraded biogas (LCOUB) represents the average revenue per unit of upgraded biogas generated that would be required to recover the costs of building and to operate a biogas plant during an assumed financial life and duty cycle.

The study assumed that the value of the annual operating costs would be the same over the 25-year project lifespan and be equal to the first-year costs of US $22,500.

The total value of operating costs over the 25-year project lifespan = US $22,500 × 25

= US $562,500.

The Present value of a future sum of money is determined by discounting it at some chosen compound interest rate [43]. The equation represents this:

Net Present Value (NPV) = F(P/F, I, N), where F is the future cash flow, and (P/F, I, N) is the discounting factor or weighting factor (or a decimal number) that is multiplied by the future cash flow to discount it to the present value. Simply put, (P/F,I,N) is a conversion factor when computing the time value of money.

Thus, the NPV for the operating costs over a lifetime = F(P/F, I, N).

Where, F = US $562,500.

Number of years (N) = 1 year.

Interest Rate (I) = 10% (Commercial loan rate obtained from the CBN as at May 2022).

Thus,

Present value of lifetime operating costs = US $562,500 (0.9091)

= US $511.368.75.

Consequently,

$$\text{Levelized Cost of Upgraded Biogas} = \frac{\text{sum of costs over lifetime}}{\text{sum of upgraded biogas produced over lifetime}}$$

$$= \frac{\text{Initial investment} + \text{Operations costs over lifetime}}{\text{upgraded biogas}\,\frac{\text{produced}}{\text{month}} \times 12\,\frac{\text{months}}{\text{year}} \times 25\text{ years}}$$

$$= \frac{\text{US }\$(256{,}500 + 511.368.75)}{10{,}242.60\text{ cubic m/month} \times 12\,\frac{\text{months}}{\text{year}} \times 25\text{ years}}$$

$$\text{Levelized Cost of Upgraded Biogas} = \frac{767{,}868.75}{3{,}072{,}780}$$

$$= \text{US }\$0.25\text{ per m}^3.$$

3.4.4 Assessment of Annual Profit

Assuming retail price of upgraded biogas at US $0.50 per m^3,

Annual revenue = 10,242.60 m^3 × 12 × US $0.50/$m^3$

= US $61,455.60.

Annual profit = US $(61,455.60 – 22,500)

= US $38,955.60 (Approx. US $40,000).

3.4.5 Net Present Value (NPV) Analysis for the Waste-2-Biogas Infrastructure Project

The Net Present Value (NPV) is determined by the net cash flow over the project lifespan (25 years) discounted to the present less the Initial Investment [45, 51].

The study assumed that the value of the annual revenues would be the same over the 25-year project lifespan and be equal to the first-year revenues of US $61,455.60.

* Note that the economic value of the bio-fertilizer production is not considered in this paper.

NPV= Total revenues – Total costs

= Total project Annual Revenues discounted to the Present – Sum of costs over lifetime.

NPV= US $[(40,027.04*25) (0.9091)] – 767,868.75
= US $[(1,000,676) (0.9091)] – 767,868.75
= US $909,714.55 – 767,868.75
= US $141,845.80 or ~ US $142,000.

Since the NPV is positive, the project is viable.

3.4.6 Payback Period Analysis for the Waste-2-Biogas Infrastructure Project

The Payback Period Calculation was used for analysis [45, 51].

$$Payback\ Period = \frac{Initial\ Investment}{Annualized\ expected\ cash\ inflow} \tag{4.3}$$
$$= \frac{256{,}500}{40{,}000}$$
$$= 6.41 \text{ years or Approx. 6 years 5 months}$$

The Payback Period when the cost of land (land appreciates over time) is not considered:

$$\text{Payback Period} = \frac{144{,}000}{40{,}000}$$
$$= 3.6 \text{ years or Approx. 3 years 7 months.}$$

Consequently, payback period for the Waste-2-Energy infrastructure project was estimated to be in the range of 4 – 7 years.

3.4.7 Annual Return on Investment (ROI) Analysis for the Waste-2-Biogas Project

$$Annual\ Return\ on\ Investment\ (ROI) = \frac{Annual\ Net\ Profit}{Initial\ Investment} \times 100 \tag{4.4}$$
$$Annual\ Return\ on\ Investment\ (ROI) = \frac{40{,}000}{256{,}500} \times 100$$
$$= 15.59\%\ or \sim 16\%.$$

3.5 Socio-Economic Benefits of the Waste-2-Biogas Project in Moniya, Akinyele LGA, Ibadan, Oyo State State

The socio-economic benefits of the waste-2-biogas project in Ibadan, Oyo State were analyzed in this section (See Table 7). If the households in the residential estate were to depend on LPG for their cooking energy needs, they would need to spend a total amount of US $8,929.25 per month, compared to the US $5,121.30 which would have been spent if the households had depended on biogas only, resulting in energy costs savings of approximately US$3,810. Furthermore, the table revealed that LPG costs were almost 2 times the cost of biogas gas; thus, the Waste-2-Biogas initiative, with its delivery/usage of biogas, would guarantee constant biogas supply for cooking while also securing significant waste management services (elimination of about 80 tonnes of municipal solid waste) in the residential complex.

Table 7 Comparative Costs of Heating-for-Cooking for 1 Month in the 374-Unit Housing Estate: LPG vs Biogas.

Source of Heating for Cooking	**Heat Consumption (Joules × 10^9)**	**Total Fuel Requirements**	**Costs per Unit**	**Total Costs (US$)**
LPG	229.11	4,675 kg	US $1.91/kg	8,929.25
Biogas	229.11	10,242.60 m^3	US $0.50/$m^3$	5,121.30
Savings				**3,807.95 (or ~ 3,810)**
Biogas to LPG cost ratio:				**1:1.75**

In one month, the W2B project is expected to lead to cost savings of approximately US $3,810 per month (Approx. US $127 per day or US $45,720 per year) in the residential estate. On an individual household scale, these cost savings are US $0.34/day, US $10.18/month and US $122.18/year. In this study, LPG costs are estimated to be 1.75 times the cost of biogas, thus indicating that biogas usage as cooking energy is more viable than LPG usage.

4. Summary and Conclusion

This study examined the techno-economic specifications for a Waste-2-Biogas strategic initiative in Southwestern Nigeria as a significant option for cooking energy alternatives. A Technology Foresight Analysis framework for Waste-2-Biogas development comprising planning and strategic analysis methods was used.

The study determined that for the 374 housing units in the residential complex, the average cooking energy demand per month totaled 229.11 Gigajoules, from 4 sources – Kerosene (4.54%), Biogas (2.41%), LPG (77.63%) and electricity (15.42%). The estimated upgraded biogas to meet this cooking energy demand was 10,242.60 m^3 (361,930.80 cu ft). A material balance analysis determined that this upgrade biogas demand would require almost 80,000 kg of municipal solid waste (MSW) input. The planned biogas plant was determined to have a plant design benchmark of 15,363.90 m^3/month requiring a total land area of approximately 5 acres for installation, costing an estimated US $90,000. The municipal biogas plant itself was estimated to cost US $120,000.00. With total initial investment of US $256,500, annual total operating costs of US $22,500, levelized upgraded biogas costs of US $0.25 per m^3 and assumed upgraded biogas retail price of US $0.5 per m^3, annual revenue and annual profit projections were US $61,455.60 and 40,000 respectively**.** Project economic viability indices revealed **an** estimated Net Present Value (NPV) of US $142,000, a payback period of 4 to 7 years, and an annual Return on Investment (ROI) of approximately 16%, indicating a viable project. The socio-economic benefits of the W2B project every month included the constant supply of cheap cooking fuel, comparative cooking energy cost-saving estimates (Biogas to LPG) of US $3,810, and the elimination of almost 80 tonnes of municipal solid waste from the environment.

The study concluded that the Waste-2-Biogas for Cooking Energy critical infrastructure project was technically, environmentally, economically and socially viable, and was suitable for deployment across Southwestern Nigeria.

Author Contributions

This work is a sole authorship. The author contributed 100% to the work.

Competing Interests

The author has declared that no competing interests exist.

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