IMPROVING POWER OUTPUT GENERATION FROM BIOGAS PLANT USING SIMPLEX OPTIMIZATION TECHNIQUE

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Abstract

This paper presents improving power output generation from biogas using simplex optimization technique. This aim is to address the issues of poor power supply at Amapa community, Benue state due to low power generation capacity in Nigeria. To solve this problem, raw materials of pig dung, compost dung and poultry dungs were collected, hydrolyzed with water in a ratio of 50:50 and then feed to a biogas digester system which produced the desired biogas and converted to electricity by the internal combustion engine and synchronous generator. The problem of power optimization due to nonlinear behavior of the biogas was addressed using Simplex Optimization Model (SOM) and then implemented with Simulink. The result showed that at an average of 1.504cm^3 of biogas with SOM was able to generate average energy of 11.26MW and power equivalent of 3.13Kw/h. The result was also comparatively evaluated with a biogas generated with only cow dung (characterized), and new system without SOM respectively for ten operating hours. The average power generated by the respective biogas generators in Kw/h are 2.75 for the characterized, 2.85 for the new system without SOM and 3.13 for the new system with SOM. The percentage improvement achieved with the new system as against the characterized is 10% and 12.14% for the new system with SOM as against the characterized.

Keywords: Simplex Optimization Technique; Biogas; Digester System; Synchronous Generator

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1. INTRODUCTION

As at 19th of March, 2022, the estimated population of Nigeria is 206.1 million according to Worldometer (2022), however, the average power generation capacity to serve this population on daily basis is slightly above 4000MW (Agency Report, 2021). This is far too small and has remained a very big problem all over the country, as it has affected productivity on all sides of the economy. Today, energy has remained one of the most important factors to global prosperity and the need for the exploitation of new source of energy has remained a major topic for research discussion. In Nigerian for instance, the major source of energy is hydro and thermal. The availability of this energy sources are not constant, as the hydro is dependent on large abundance of water (raining season) for full generating capacity. The thermal on the other hand is dependent on resources which can produce the heat required for energy conversion, before power is generated. These resources too are not fixed, coupled with the aging generators, among other technical factors, all these have affected the capacity of power generation within the country. The optimization of the hydro generator performance is fully weather dependent as only raining season can improve water flow at the dams and rivers for optimal power generation, however on the thermal section, the generating capacity can be improved only if other variables which can produce heat are considered like coal for instance. These variables of power generation which are not constant make the generation power system in Nigeria not always available on demand and hence not reliable (Ilo, 2019).

According to (Mgbachi et al., 2018; Abba and Ilo, 2019; Tomothy et al., 2021; Ilo, 2017) among others, the need for the exploitation of other renewable sources to optimize power generation has remained the key solution to the sustenance of power in Nigeria. Biogas has been receiving increasing attention as an alternative to fossil fuels in solving the problems of rising energy prices, waste treatment/management and creating a sustainable energy development (Mgbachi et al., 2018). Biogas is a form of renewable energy generated from biological resources such as plants and animals, through anaerobic digestion process. This biogas has remained a vital product in the generation of energy in various developing and developed countries over the years with many advantages such as less pollution, cheap, availability among others when compared with the hydro, nuclear and thermal counterparts. Some of the methods employed to generate this biogas energy includes pig dung, pig compost, poultry waste, waste bins, among others, and have helped in power generation using various techniques such as (1) fuzzy logic, (2) genetic algorithm, and (3) simplex optimization approach (Florian et al., 2018; Bettina et al., 2021). However, the use of simplex optimization approach provided not only optimal power generation capacity, but also at low cost when compared with the other techniques. This approach will be considered in this research to generate a reliable, quality and cheap power supply for the people of Amapa community at Ape Local Government Area, Benue State Nigeria which has suffered poor power supply over the last few decades and as a result has affected their standard of living and overall growth.

2. LITERATURE REVIEW

Mgbachi et al., (2018) published a research Development of a Simplex Optimization Technique for Biogas Generation of Electrical Energy which used a simplex optimization model to improve electrical energy generation with cow dung. The result of the total energy generated was increased by 39.7% from 636.6MW to 889.49MW after optimization. However, improvement on this research was recommended for higher energy generation. According to Christian et al., (2014), the work on Biogas Plant Control and Optimization Using Computational Intelligence Methods adopted the application of Computational Intelligence (CI), Genetic Algorithms (GAs) and Particle Swarm Optimization (PSO) to solve the challenging problem of underlying highly nonlinear and complex digestion processes. The results of this research showed that there was an improvement of 20% in biogas production and substrate reduction can be achieved when compared with to conventional manual operation. Nevertheless, the application of simplex technique for this energy generation technology will improve the system, therefore, further research is recommended.

Florian et al., (2018) presented research on Process Optimization of Biogas-Based Power-to-Methane Systems by Simulation applied the ASPEN Plus simulator for the modeling of power-to-methane process setups consisting of catalytic methanation and membrane gas upgrading using biogas as carbon dioxide as source. This technique used four different process setups to assess influences of fermentation setup, recycling of membrane off-gas and multistage membrane gas separation as well as pressure. From the results of the simulation, it was shown that less energy is required for processes without off-gas recycling but it still leads to hydrogen losses of up to 25%. However, an improvement on this work is necessary to reduce the amount of gas loss in the process. Dodiek and Camilo (2013) presented research on the optimization for biogas power plants using automatic control of gas pressures. The study used Proportional-Integral-Derivative controller and programmable logic solvers to control the entire system pressure of a biogas gas reactor to generate energy. This approach despite the success is expensive as multi controllers are involved. Danijel et al., (2020) in Optimization Model for Biogas Power Plant Feedstock Mixture Considering Feedstock and Transportation Costs Using a Differential Evolution Algorithm proposed a model which involves an optimal mixture of different feedstock combination in a biogas power plant and also informs about the optimum transportation distance for each feedstock. This optimization procedure is performed on each scenario with methane production that costs about 0.75 EUR/m^3in 1 MWe biogas power plant. The cost of implementation of this technique is high, therefore, implementation of another technique that is cheaper is recommended.

3. METHODS OF ELECTRICITY GENERATION FROM BIOGAS

Biogas can be used in electricity generation through a biogas run generator. 1m^3 of biogas is equivalent to 0.5 to 0.6 liters of diesel or 6kWh. The biogas needs to be de-humified and purified before use in the prime mover (UNESCAP, 2007). Conversion of biogas to electricity involves converting dry biogas to mechanical energy within a controlled combustion system using a heat engine. The mechanical energy is used to generate electrical power from a generator that is coupled to the engine. For small scale biogas to electricity production, combustion engines are a better option because they have higher efficiency and low cost compared turbines of similar capacity (UNESCAP, 2007).The engine was used in a cogeneration mode where the heat was recovered from the cooling and exhausted for heating applications. This combined heat and power can increase thermal efficiency of the engine to as high as 90%. In an alternative design, a micro turbine was operated by burning biogas in a micro cogeneration. Mini cogeneration concept can be used to produce 5kW to 500 kW electricity with excess energy being fed to the electricity grid (UNESCAP, 2007). Figure 2.3 below is illustrating a biogas with power production capability, from figure 1, it is noted that to generate electricity from biogas at farm level, the system should be equipped with a prime mover like an internal combustion engine driving a synchronous generator. The synchronous generator ensures constant frequency generation. A carburetor, biogas purification system and the biodigester are other critical elements of the electricity generation system.

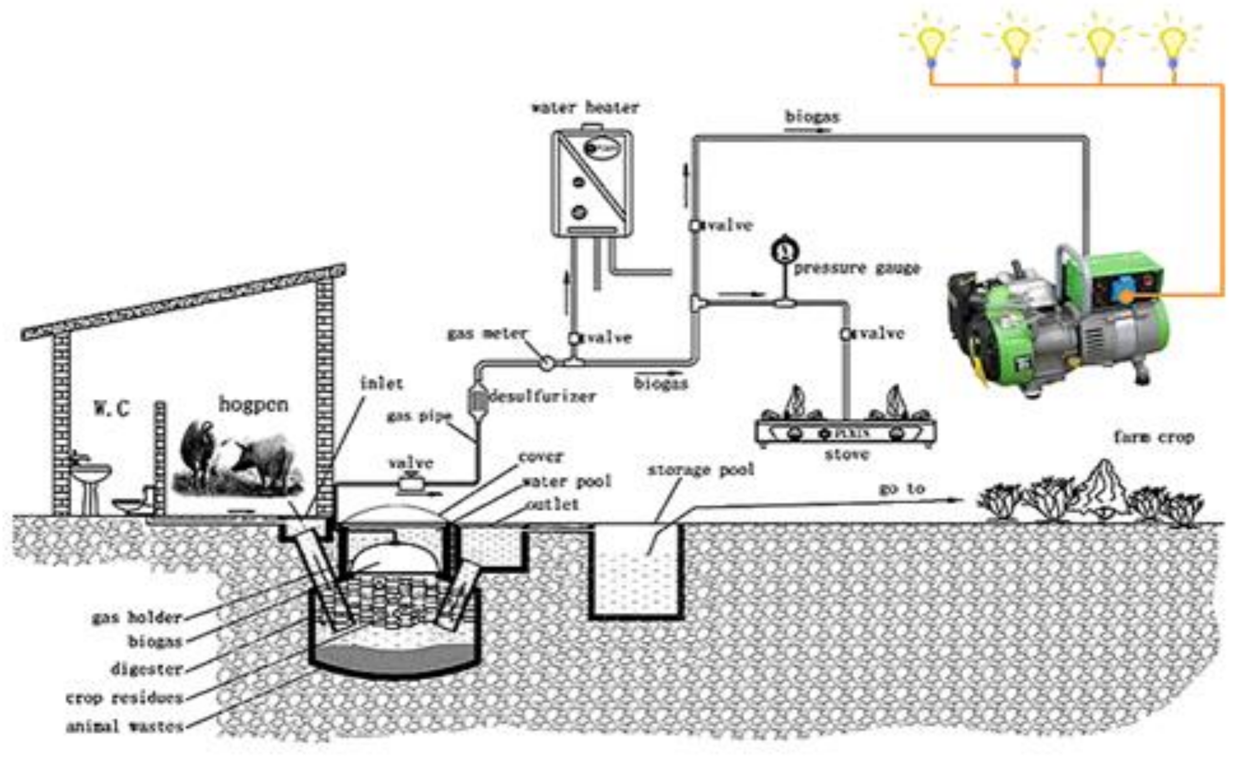

Figure 1 Biogas power generating process (Source: Green power, 2021)

3.1 Simplex Optimization Technique

Linear Programming (LP) is a minimization or maximization optimization problem with linear objective, linear equality and inequality constraints. The applications range from engineering, agriculture, transportation to food industry, manufacturing, etc. The foundation of LP dates back to the work proposed by Kantorovich (1939) where an optimization problem of production planning and organization was studied. Later, Dantzig, who is known as the father of LP, introduced the first general framework of LP and provided the basic primal simplex method for solving LPs since then, LPs and the simplex method have been greatly explored and have led to a large number of extensions. Specifically, the dual simplex method was proposed in 1954. The primal and dual simplex is the two main streams in the simplex methods. In 1972, a special LP WAS constructed which is an example and showed that the basic simplex method has exponential time complexity in the worst case. From that moment on, more research efforts turned to finding more efficient algorithms, either by improving the basic simplex method or by proposing new algorithms from other perspectives. In 1984, the interior point method (IPM) for solving LPs, which is also called as Karmarkar's algorithm, was proposed. This algorithm is the first practically feasible method that can solve LPs in polynomial time and has prompted many studies on the variants of IPM for solving LPs.

4. SYSTEM MODELLING

To model the mass of the energy sources used for the biogas generation, the relationship between the numbers of animals used for the production of the dung was considered and presented in equation 1;

$$M_o = N_a C_w \qquad 1$$

Where M_o is the mass of the dungs used. N_a is the total number of animals which produced the dung and the C_w is the solid waste per day in kg. The volume V_b of the fluid in the digester is given as equation 2;

$$V_b = R m_o \qquad 2$$

Where R is the relative biogas yield Mass from equation 2, m_o is the input. The mass of the animal dung undergoes hydrolysis with the volume of water to produce the flow rate as in equation 3;

$$v_f = \frac{m_o}{p_m} \qquad 3$$

Where p_m is the density of the dry fluid, and v_f is the flow rate from the digester. The volume of gas generated by the digester is given as in equation 4;

$$V_d = v_f t_r \qquad 4$$

Where v_f is the low rate of the digester fluid, t_r is the retention time of the fluid inside the digester. To determine the electrical energy (E) generated the model in equation 5 was used as in equation 5;

$$E = n H_b V_b \qquad 5$$

Where n is the efficiency of the engine, H_b is the heat of the per unit volume biogas combustion process. The power equivalent generated is presented as in equation 6;

$$P = \frac{E \; x \; CV \; x \; n}{860 \; x \; H_b} \qquad 6$$

Where E is the energy generated in equation 5, CV is the calorific values of biogas, other variables are defined in equation 5.

4.1 Simplex Optimization Model (SOM)

The need for optimization is to help maintain steady state in the amount of power output produced in equation 6 despite the nonlinear behavior of the amount of manure and hence biogas supply. The optimization technique ensured that stable power is produced, also it ensures economy in terms of capacity required in the procurement of the biogas. Over the years many solutions such as mixed-integer and interval linear-programming, lagrangian relaxation and quadratic programming, heuristic optimization methods, genetic algorithms, particle swarm optimization, simplex optimization etc. have been proposed to solve the optimization problems involved in energy generation (Araoye, 2021). The SOM according to Araoye (2021) not only is cheap and easy to implement, but is also very efficient in the addressing optimization problem relating to power generation. To this end, the SOM was adopted from Araoye (2021) and used to optimize the biogas plant. To compute the variable for the simplex optimization model, the new vertex is determined as equation 7;

$$V = M + d \tag{7}$$

Thus, the coordinated of the new vertex required adding the distance as equation 8;

$$d = M - W \tag{8}$$

Substituting d in equation 7 provides the model in equation 9 and 10;

$$V = M + (M - W) \tag{9}$$

$$V = 2M - MW \tag{10}$$

Hence the new vertex is given as in equation 11;

$$Vn = M + \alpha(M - W) \tag{11}$$

The midpoint regarding any number of variables is given as in equation 12;

$$M = M = \frac{1}{N}\sum_{j=1}^{n} V_j \tag{12}$$

Where N presents number of variables, *i* is the worst response vertex index, the vertex is j, NV is the new vertex, M is the best average vertexes, α is movement coefficient of the simplex, W is the worst vertex response. This process continuous for the next stage until the problem is solved, hence making it very effective for optimization solution (Araoye, 2018).

5. SYSTEM IMPLEMENTATION

The implementation of the system was achieved using power system toolbox, optimization toolbox and Simulink. The model of the biogas generated was used to configure the power system toolbox, the optimization toolbox was considered with the simplex optimization model. The engine model and synchronous motor model was adopted from Araoye (2018) was configured with the requirements in the table 1 and table 2 respectively. These systems alongside the toolboxes were used to implement the system developed with Simulink platform as shown in the figure 2;

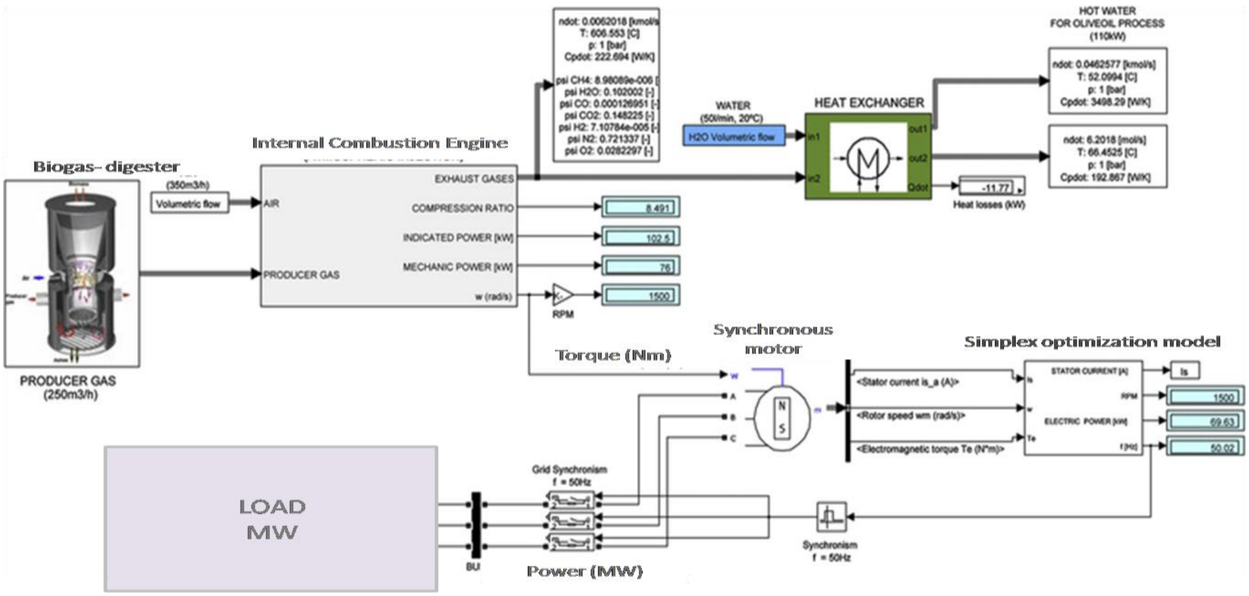

Figure 2: Simulink model of the Biogas generating system

TABLE 1: SYNCHRONOUS GENERATOR SPECIFICATION (Akpojaro et al., 2018)

Parameters	Type/value
Generator phase	Single
Pole	2
Slots number	26
field winding slot	20
Excitation winding slot	6
Voltage; frequency	220v; 50Hz
Speed rpm	3000
Excitation windings	80/single layer winding
Coil Gauge	21/22SWG
Coil excitation w indings	24/25SWG
Winding factor	1
Rotor windings	0.6kg
Power factor	1
Diameter of stator frame	389.3mm

Length of stator frame	303.6mm
Power	2.5MW/2.4KVA
Torque	7.957Nm

TABLE 2: ENGINE SPECIFICATIONS (Akpojaro et al., 2018)

Parameters	**Type/values**
Engine type	4 stroke
Compression ratio	9:1
Bore size	68mm
Stroke	44mm
Starter system	Recoil starter
Displacement	164cm3
Governor	Centrifugal mechanical
Net torque	10.4Nm
Net power	5.5HP
Maximum speed	3600rpm

The figure 2 presented the Simulink model of the new power generating system developed. The biogas digester when loaded with the animal dung collected and diluted generated the biogas which was feed to the engine model which used inter combustion process as shown in the heat exchanger to generate torque which drives the synchronous generator and produce the power feed to the bus and feed to the transformer which supplied the Nkalagu community.

6. RESULTS

This section presented the performance of the simulated biogas generator without the optimization model active. The result was generated with the mass of the animal dungs as modeled in equation 1 and diluted with the volume of water in equation 2 was feed to the digester to generate a biogas model in equation 4. The relationship between the gas generated, energy and equivalent power is presented in table 2;

TABLE 3: RESULT OF BIOGAS GENERATOR WITHOUT SIMPLEX OPTIMIZATION MODEL (SOM)

Time (Hr)	**Volume of gas (cm^3)**	**Energy (MJ)**	**Power generated (Kw/h)**
1	1.565	10.692	2.97
2	1.830	12.49	3.47
3	1.930	13.18	3.66
4	1.050	7.67	2.13
5	1.100	7.99	2.22
6	1.220	8.78	2.44
7	1.330	8.78	2.44
8	1.550	10.19	2.83
9	1.720	11.34	3.15
10	1.740	11.35	3.16

Average	1.504	10.25	2.85

The result generated with simulation for the new biogas power generating system was presented in table 3. From the result, it was observed that the $1.504cm^3$ of biogas generated was able to produce 9.91MJ of energy according to equation 5 and then power equivalent of 2.75Kw/h. The analysis of the volume of biogas generated during the testing period is presented in figure 3;

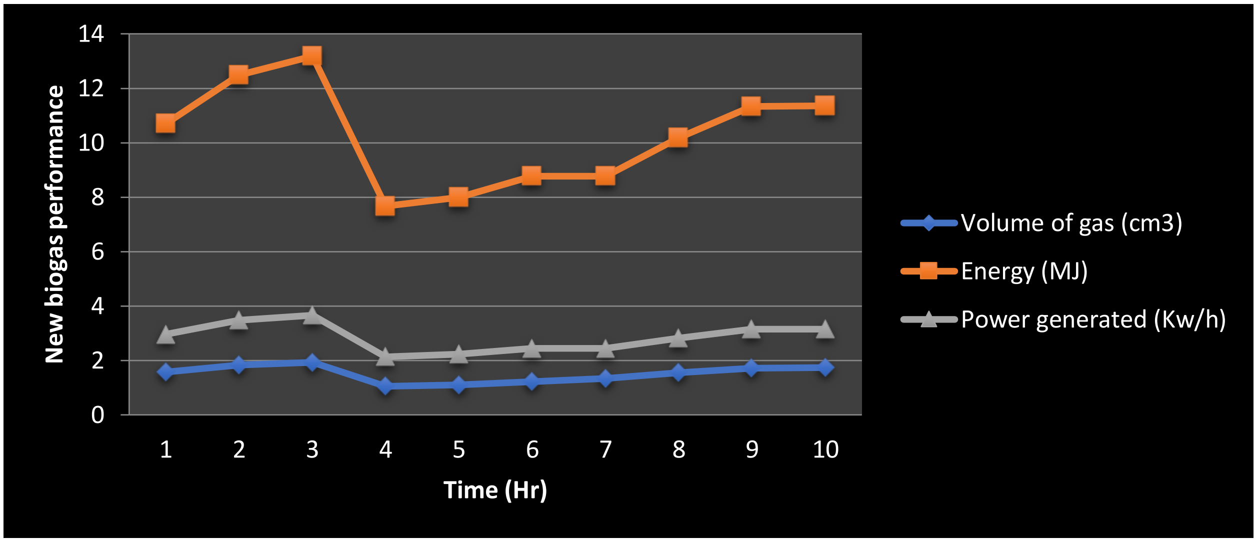

Figure 3: Result of the new biogas generator without SOM

The figure 3 presented the performance of the new biogas generator without optimization and from the result it was observed that the behavior of the biogas generated determined the energy rate converted and hence power output from the synchronous motor. The implication of the result showed that with the three different materials (poultry, compost and pig dung) used for the energy generation, the quality of power output was good but varies as the input biogas gas volume varies, hence justifying the need for optimization.

6.1 Result of the Biogas Generated

The result of the biogas generator developed was optimized with the SOM in equation 11. The result showed how the each of the SOM variables was used to generate new vertex and used to optimize the amount of power generated as shown in figure 4;

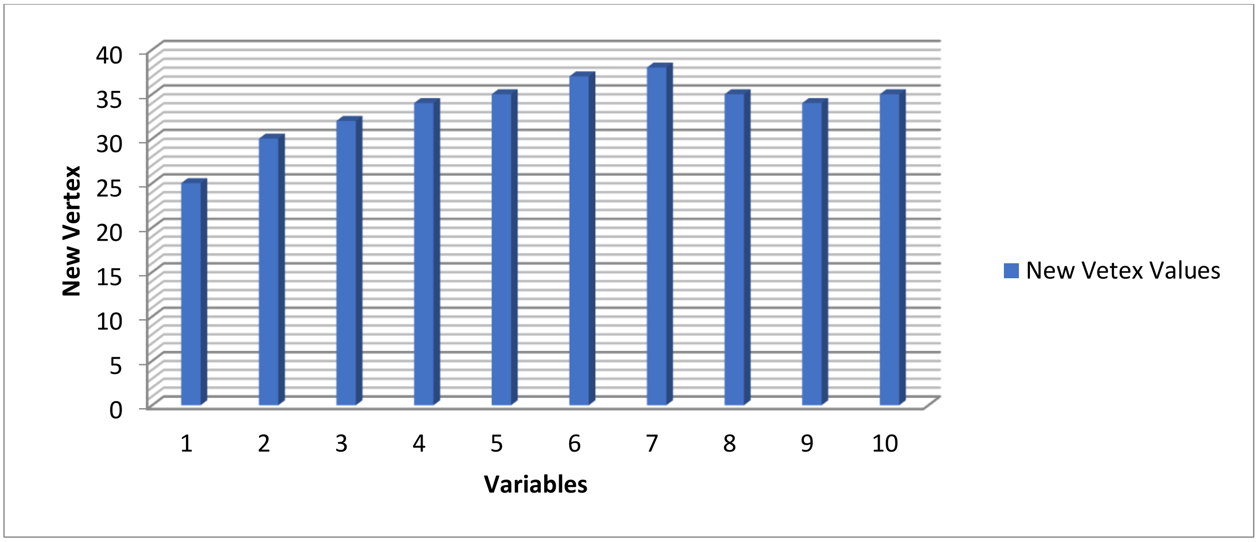

Figure 4: Result of the SOM

The figure 4 presented the performance of the optimization model developed and used to address the nonlinear impact of the biogas input on the generator output. The impact on the new biogas generator developed is presented in the table 4;

TABLE 4: RESULT OF THE GENERATOR WITH SOM

Time (Hr)	**Volume of gas (cm^3)**	**Energy generated (MJ)**	**Power generated (Kw/h)**
1	1.565	11.41	3.17
2	1.830	12.49	3.47
3	1.930	13.18	3.66
4	1.050	9.11	2.53
5	1.100	9.79	2.72
6	1.220	10.22	2.84
7	1.330	10.22	2.84
8	1.550	11.27	3.13
9	1.720	12.06	3.35
10	1.740	12.82	3.56
Average	1.504	11.26	3.13

The table 4.3 presented the performance of the new biogas generator with the SOM. The result showed that at an average of 1.504cm^3 of biogas generated, the SOM was able to achieve average energy generated of 11.26MW and power equivalent of 3.13Kw/h. The quality of the power generated was analyzed graphically as figure 5;

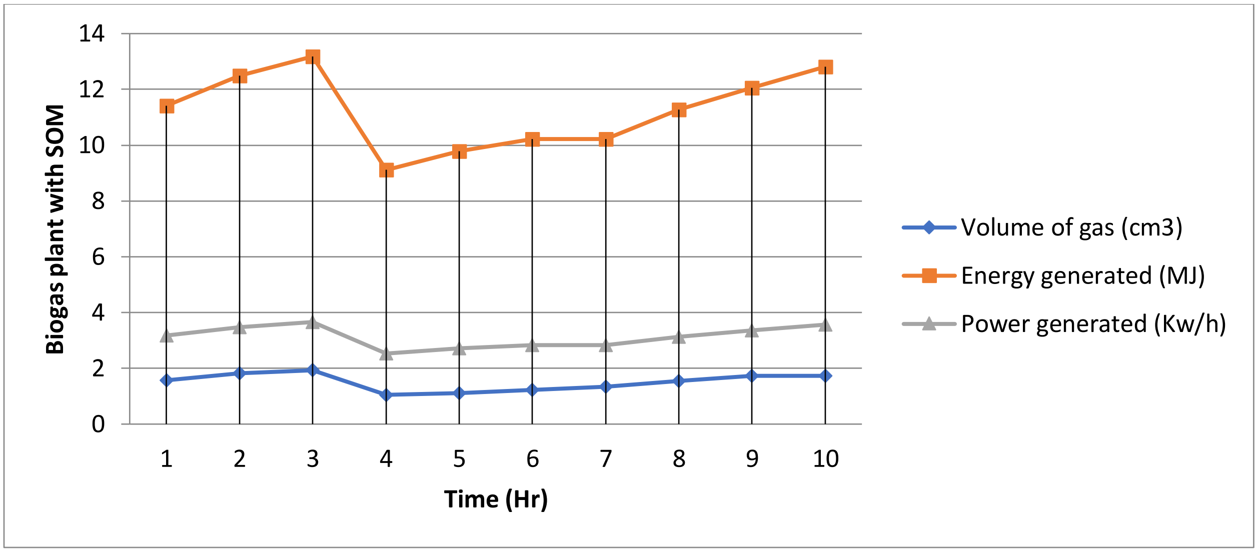

Figure 5: Biogas generator with SOM

The figure 5 presented the performance of the biogas generator with SOM. The result showed that the variation in the biogas volume has little impact on the energy equivalent and hence the power generated. The implication of the result showed that the variation in the biogas volume affected the power generated only slightly as shown in the corresponding curves, this was because the new vertex values generated by the SOM was used at each stage to balance power output.

TABLE 5: COMPARATIVE ANALYSIS OF POWER GENERATED

Time (Hr)	Power (Kw/h) with characterized	Power (Kw/h) with new biogas plant	Power generated (Kw/h) with new gas plant and SOM
1	2.87	2.97	3.17
2	3.35	3.47	3.47
3	3.54	3.66	3.66
4	1.93	2.13	2.53
5	2.02	2.22	2.72
6	2.24	2.44	2.84
7	2.44	2.44	2.84
8	2.83	2.83	3.13
9	3.15	3.15	3.35
10	3.16	3.16	3.56
Average	2.75	2.85	3.13

The table 5 presented the comparative power produced the biogas plant with pig dung as the characterized, pig, poultry and compost dung as the new system and the new system with SOM. The average power generated by the respective biogas generators in Kw/h are 2.85 for the new system without SOM and 3.13 or the new system with SOM. The percentage improvement achieved with the new system as against the characterized is 10% and 12.14% for the new system with SOM as against the characterized.

7. CONCLUSION AND RECOMMENDATION

The Nkalagu community over the years has suffered poor quality of power supply service by the Enugu Electricity Distribution Company (EEDC). The major cause of the problem has remained the poor capacity of power generation in Nigerian which has resulted to load shedding. To address this problem a mini gird was developed using raw materials collected from animal dungs and farm to develop a biogas generator which was able to process and generate electricity. The quality of the biogas generated was improved with SOM and the result showed that at an average of 1.504cm^3 of biogas generated, the SOM was able to achieve average energy generated of 11.26MW and power equivalent of 3.13Kw/h.

7.1 Recommendation

This system developed can be mass produced and deployed to other areas to optimize power generation in Nigeria

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