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*The Optimization Of Biomass-Based Energy Generation In Integrated Systems In Isiala Mbano Local Government Area: A Cross Disciplinary Approach*

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***ABSTRACT:*** *This study focused on the optimization of biomass-based energy generation in integrated systems in Isiala Mbano Local Government area, Nigeria. The study was carried out in response to the growing need for sustainable energy solutions for communities that are off-grid in this local government area; out of 39 communities, 9 communities have no access to power supply especially when you move deeper into these communities. The study aimed at integrating two renewable energy sources to meet the region's total daily electricity demand of 6310kWh, of which only 3500kWh/day is available from the output of PV system and biomass energy system, leaving a daily energy deficit of 2810kWh. The research utilized MATLAB simulations to carry out the optimization process, and found out that increasing biomass utilization to 4010kWh/day will resolve the energy shortfall. This study provided a technical feasibility of hybrid systems by offering a replicable strategy for energy sustainability in Nigeria.*

Keywords: Energy optimization, Biomass, Solar energy, Simulation, Modeling

## 1.0 Introduction

One of the most important sources of renewable energy is one generated from organic remains, generally known as biomass. This source of energy is available in abundance and contains a neutral carbon level which makes its usage favorable to the environment. Many sources of energy have been economically exploited just to fulfill the rising demand for power. While this is being sorted for, there is an increased primary reliance on fossil fuels by industrialized countries leading to environmental degradation, thereby causing a negative impact on people and accelerating climate change. The energy generated from biomass is regarded as "bioenergy", a special biomass such as animal waste, kitchen waste, in short any organic remains, is utilized as the substrate for the generation of this energy (Giwa et al., 2016).

However, the optimization of energy generated from biomass follows a complex decision making techniques – several factors such as feedstock selection, conversion technology, and operating parameters of the biomass-to-energy converting system have to be considered. The maximization and optimization of biomass energy performance is essential for improving power generation efficiency, and this has led to the development of various optimization techniques in biomass energy systems so as to enhance operational efficiency and overall performance (Masoud et al., 2025). The development of these optimal techniques for the maximization of energy yield from biomass systems remains a significant challenge.

## 1.1 Research Questions

This research aims to identify and develop the most suitable mathematical model and optimization technique for the maximization of the energy yield from a biomass-to-energy system. While focusing on this aim, the proposal will attempt to answer the following research questions:

1. What are the existing optimization techniques for the maximization of energy yield in a biomass-to-energy system?
2. What is the best proposed technique for the maximization of energy yield in a biomass-to-energy system?
3. What are the challenges or drawbacks affecting the optimization of a biomass-to-energy system?

## 1.2 Objectives of the Research

1. To analyze the factors affecting the production of energy from biomass.
2. To develop a mathematical model for the optimization of energy yield from biomass.
3. To validate the mathematical model by utilizing experimental biomass data.
4. To carry out a comparison with other traditionally developed non-optimized systems.

## 2.0 Literature Review

This section will review some of the previous studies carried out by various researchers on the optimization of biomass-to-energy systems.

Studies have shown that the major reasons for optimization approaches are to lower investment costs, operating costs, and maintenance costs, while increasing the reliability of the system and reducing emissions (Masoud et al., 2025). Biomass, which is not as popular as solar energy, is an important renewable energy source. Its operation faces several challenges which includes; technological know-how, economical constraints, and reliability constraints which can hinder its expansion (Wu and Pfenninger, 2023). Biomass-to-energy is a process that requires a high level of technicality which has a high impact on energy generation, overall efficiency, and profitability of the plant (Onwumelu, 2023). (Eteiba, et al., 2018) researched on the optimization of a hybrid system that comprises an off-grid PV/Biomass hybrid system which has different batteries. Various optimization techniques and models where applied so as to maximize the efficiency of the system. The study only performed optimization on the specific system sizing e.g PV panels, batteries, and a biomass unit, for a hybrid system, but the study didn't develop an advanced optimization techniques such as nonlinear programming and real time adaptive models, to improve the output, cost, efficiency, and the reliability of the biomass-to-energy system. A rigorous mathematical model has to be developed to be able to optimize the efficiency of the biomass-to-energy system before its incorporation with the PV system.

(Mariam et al., 2019) proposed a mathematical model for the optimization of renewable energy systems stressing on energy sources from biomass and $CO_2$ emissions. They considered villages that are off-grid in the city of Chile and decided to sort for a solution to this energy problem. They proposed a mathematical optimization model which uses a CPLEX optimizer to generate the necessary amount of energy while minimizing the cost of energy. (Euttamarajah et al., 2019) carried a study to maximize energy efficiency within a heterogeneous network which included various types of networks, energy data from renewable energy sources with their information were coordinated synchronously between base stations. The outmost aim of these studies was to minimize the total cost of generating energy from biomass and other renewable energy sources using different optimization approaches. In a study carried out by (Ritwik, 2025), it investigated the enhancement of bioenergy production and its optimization using a smart enzyme engineering, they study delved into the use of Artificial Intelligence (AI) to enhance the production of bioenergy by introducing automation in enzyme engineering leading to the development of bioenergy solutions which will enable precise, rapid, and cost-effective design of catalytic systems or enzymatic systems. Several studies have been carried out to develop various optimization technique for biomass to energy conversion, till this day, there have not been any effective and universally accepted solutions for the maximization of a biomass-to-energy renewable system (Muhammad, 2022).

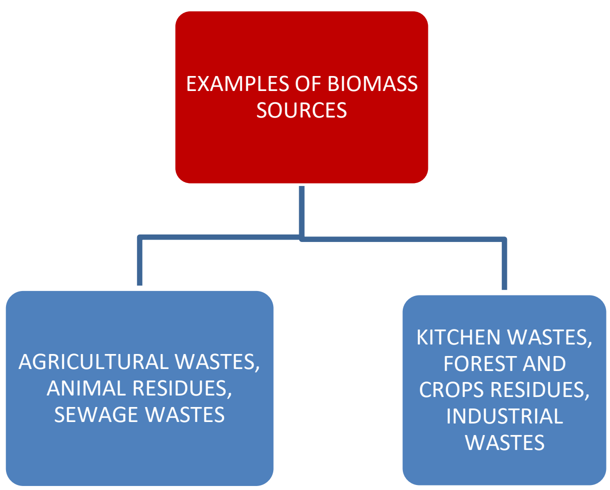


Figure 1: Diagram showing the various Biomass sources.

Further research is ongoing with the aim of developing an acceptable mathematical model for the optimization of the energy efficiency of a biomass-to-energy system while reducing cost and increasing its reliability. This study aims to propose a mathematical method that will align with the current research on energy optimization of renewable energy systems.

## 3.0 Mathematical Model of the Renewable Energy Systems

This section explains the proposed model design, mathematical sub-models and formulas, with the mathematical optimization model.

The success of this proposed research if implemented, will assist in enhancing the energy generation in Nigeria which is classified among the developing the countries of the world. There are several small towns and villages in Nigeria outside the electricity grid.

In a study carried out by (Ilo et al., 2019) on the optimization of Nigerian power system distribution using distributed generation, the study suggested the total installation of distribution lines that clusters to all houses in the small villages and towns. This is not totally realistic due to the low amount of power generated by the power distribution company of Nigeria. The small towns and villages generate an enormous amount of organic wastes which can be very useful in carrying out a biomass-to-energy conversion process. The integration of this renewable energy system into its power generation will help to easily produce enough energy for distribution to the small villages and towns in the local areas of the country. The major concern of this integration is the optimization of this renewable energy generation system, as the already available power generation system has been functional and serving for a long period of time, making its operation reliable and slightly efficient.

The proposed system includes a Biomass to energy system integrated with a PV-system for the energy generation for the small towns and villages in Nigeria. The PV system is the generation of energy from the sunlight (solar energy) whiles the biomass to energy system involves the conversion of organic wastes into reusable energy either by anaerobic digestion or aerobic digestion.

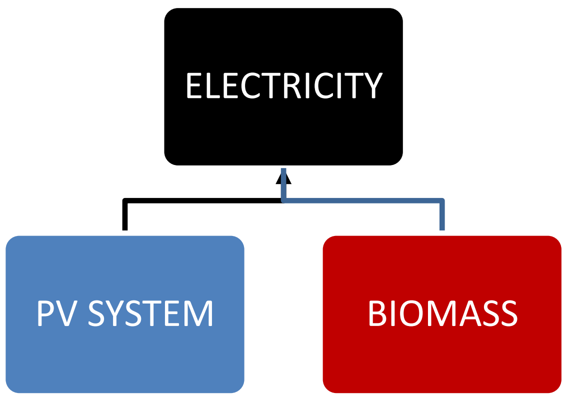


Figure 2: Diagram of proposed renewable energy system that integrates solar energy and energy from biomass to produce electricity.

The integration of these energy sources comes with several considerations of factors that will improve the functionality of the systems. The small and local towns in Nigeria generate a great amount of organic wastes from the high level of agricultural activities and its involvement by virtually all the indigenes of such small town and village. Nigeria already has a favorable weather condition, which makes the integrated solar energy system a better option. The mathematical model of optimization will be designed to integrate two renewable energy systems present in the given location, taking in account the advantages and disadvantages of each system.

### 3.1 Power Generated by the Biomass-to-energy System and PV System.

The power generated by a biomass-to-energy system is given by;

$$P_{BM} = R_g(q_w - q_B) \qquad \text{(Hamilton, et al., 2019)} \qquad (1)$$

Where;

$P_{BM}$ is the power of the biomass-to-energy system (kWh)
$R_g$ is the overall efficiency of the biomass-to-energy system.
$q_w$ is the amount of biomass available per kg
$q_B$ is the amount of biomass required per hour.

The efficiency of a biomass-to-energy system is given by;

$$\text{Efficiency} = \frac{Energy\ output}{Energy\ input} \text{ X } 100\% \qquad (2)$$

The power generated by a PV system is given by;

$$I_s = I_bF_b + I_dF_d + F_r(I_b + I_d) \qquad \text{(Li et al., 2019)} \qquad (3)$$

Where;

$I_s$ is the total solar radiation (kWh/m$^2$)
$I_b$; $I_d$ are the direct irradiation and diffuse solar radiation (kWh/m$^2$)
$F_b$, $F_d$, $F_r$ are the tilt factors for the beam, diffuse and reflected parts of solar radiation.

The efficiency of a photovoltaic (PV) solar system is given by;

$$\text{Efficiency} = \frac{\textit{Panel Power Output}}{\textit{Total Solar Power Input}}\ X\ 100\% \qquad (4)$$

The total power generated by the combined system is represented by $P_T(t)$ at any time t and $T_E$ defines the amount of energy from the two sources Ɛ {1,2}.

### 3.2 Mathematical Optimization Model

The mathematical optimization model to be used will be the Constraints Satisfaction Optimization Problem (CSOP) model. The system only consists of two renewable energy sources which make it much easier. The aim of the optimization is to minimize the cost of energy (COE), while maximizing the satisfaction of energy demands and maintaining the resource availability and equipment capacity limits.

Let:

ί Ɛ {1,2} where 1 denotes biomass, and 2 denotes PV system

j Ɛ {1,2} where 1 denotes electricity, and 2 denotes cooking

N = the number of households

$C_j$ = the amount of energy demanded by households for consumption type j (in kWh/year)

$T_E = N\sum_{j=1}^{2} C_j$ = the total energy demand

$P_{ji}$ = the amount of energy generated for consumption type j from main source ί

$M_{ji}$ = combined cost per kWh for consumption type j from the main source ί

$V_{ji}$ = the total cost of production per kWh for consumption type j from the main source ί

$R_i$ = the efficiency of the energy source ί

$D_i$ = the availability of the required resources for energy generation by the two renewable sources e.g daily solar radiation, daily biomass in kg/day which is converted to kWh/day.

$T_i$ = total number of units or devices for energy source ί

The objective function for the minimization is the Cost of Energy (COE).

$$\text{Equation for minimizing COE} = \frac{\sum_{j=1}^{2}\sum_{i=1}^{2}(M_{ji}+V_{ji})\ x\ P_{ji}}{T_E} \qquad (5)$$

The equations of the constraints to be considered are as follows;

Satisfaction of the energy demand for each type of consumption, given by;

$$\sum_{i=1}^{2} P_{ji} \geq C_j x N \quad \forall j \ Ɛ\ \{1,2\} \qquad (6)$$

The process do not exceed the available source of energy and efficiency

$$\sum_{j=1}^{2} \frac{P_{ji}}{R_i} \leq D_i \qquad \forall ί\ Ɛ\ \{1,2\} \qquad (7)$$

Positive value of energy production is given by;

$$P_{ji} \geq 0 \qquad \forall j \in \{1,2\}, i \in \{1,2\} \qquad (8)$$

The proposed system is a simplified system, which has two sources and two demand types. The systems can only generate energy for electricity and for cooking.

The above mathematical modeling presents the results of the proposed optimization model applied in the integrated system for the minimization of cost of energy generation and maximizing the amount of energy generated to satisfy the energy demand of consumers.

The implementation of this optimization model in an integrated system of biomass to energy and PV systems will help in generating enough energy for small towns and villages in the local areas that are off grid in Nigeria.

## 4.0 Results and Discussion

This section will present the result of the proposed optimization model of the integrated renewable energy systems which will be considered for usage in Isiala Mbano Local Government area, in Imo State, Nigeria, as well as its management and requirements for proper administration, in satisfying the energy demand.

### 4.1 Case Study: An Off-grid Region in Isiala Mbano, Imo State.

Isiala Mbano is one of the local government areas in Imo state which is made up of several rural communities, with an estimated population of 198,000 residents (Ogbonna et al., 2021). Most of the communities in this local government area are off the national grid; they can stay months, years without having any form of power supply, instead, they rely on energy generated from fossil fuels e.g kerosene, fireword, and small gasoline generators for cooking and lightening. Most of these communities practice a high level of agricultural activities leading to the production of enormous amount of agricultural residues such as cassava peels, poultry droppings, palm oil husks, and household food waste; all these wastes generated are considered valuable feedstock for biomass-to-energy conversion process. The average solar irradiation in Isiala Mbano is estimated to be between 3.5 to 7 kWh/$m^2$/day (Humphrey et al., 2022), while the general agricultural waste output in the area of study is estimated to be between 8,000 to 10,000 kg/day; this was ascertained after careful observation of their farming activities and market system. The average household demand for a typical rural area in Nigeria is 0.986 kWh per day (Sunday et al., 2019). This makes Isiala Mbano a potential area for the implementation of the proposed system. The table below shows the energy data for Isiala Mbano.

Table 1: Energy data distribution in Isiala Mbano

| S/N | Framework | Value | Unit |
|---|---|---|---|
| 1 | Population | 198,000 | Persons |
| 2 | Amount of biomass yield | 8,000-10,000 | Kg/day |
| 3 | Average solar irradiation | 3.5-7.0 | kWh/$m^2$/day |
| 4 | Average household demand | 0.986 | kWh/day |
| 5 | Percentage of communities that are off-grid | 25 (Source: physical survey) | % |

### 4.2 Resources and Load/Demand Evaluation and its Management

Isiala Mbano local government area comprises of 39 autonomous communities spread across 12 political wards (Wikipedia). Out of these 39 autonomous communities, about 9 of them are partially off the national grid; most of them have access to the national grid but when you keep moving deeper into these communities you will discover that there are no sign of power distribution in the hidden areas of these communities. Ezumuoha is one of the communities in Isiala Mbano; the outer part of this community has access to power supply while the inner part of the community has no access at all; this can also be likened to the other 8 communities mentioned earlier (list of communities in isiala mbano and their population, click: www.townsvillages.com/ng/isiala-mbano/).

All communities having areas without access to power supply are all classified to be off-grid areas. We were able to identify 9 of such communities in the study area. This makes up 25% of the total autonomous community of Isiala Mbano local government area. The combination of the two renewable energy sources is basically for the production of electricity which can be used for cooking and lightening of the environment. The number of households in the 9 communities that are off-grid is estimated to be 2560.

Total Energy demand (TE) = 0.986 kWh/day x 25% x 2560

= 6310kWh/day

Amount of energy generated from biomass per day = 2333.33kg/day x 1.5kWh/kg

= 3,500kWh/day

Amount of energy generated from PV system = 5kWh/day x 460m$^2$ of panels

= 2300kWh/day

Energy deficit to be optimized = (6310 – 3500 – 2300) kWh/day

= 510kWh/day

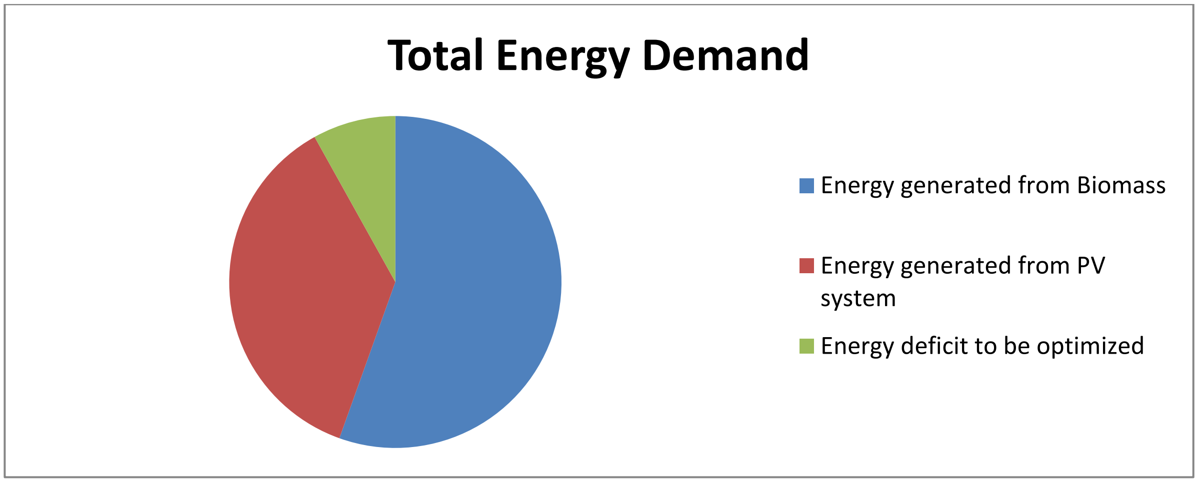


Figure 3: total energy demand.

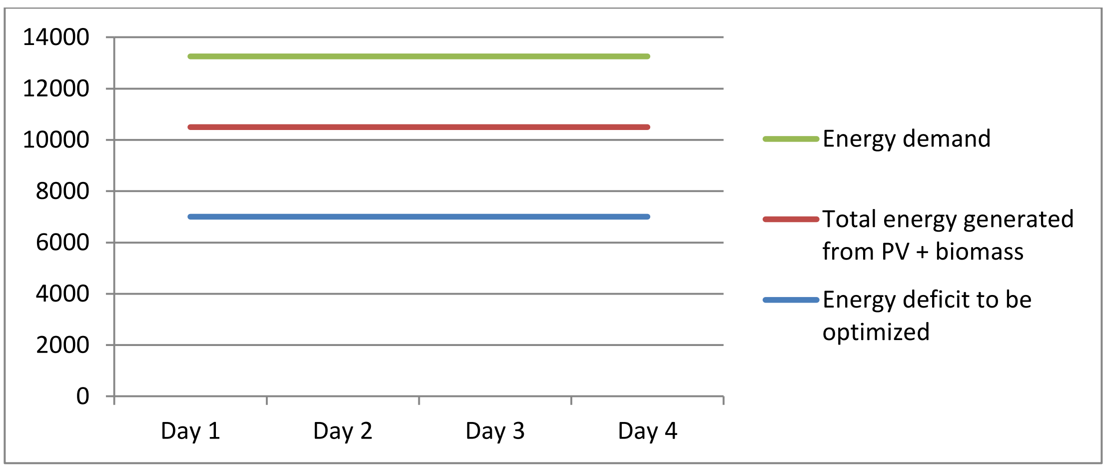


Figure 4: a line graph showing the comparison between the energy demand and its generation in a period of 4days

The optimized hybrid system will require the installation of a biomass plant, a PV system, and a battery storage system.

### 4.3 Discussion

The data of the optimized hybrid system was used to carry out a simulation and modeling test using the MATLAB software, and it was discovered that the total energy demand of 6310kWh/day was met using the hybrid system. The cost of energy per hour was discovered to be N198 kWh/day compared to the charge on the amount of electricity consumed by every household which is slated N225 kWh/day by Nigerian Electricity Regulatory Commission (NERC). The system showed a high level of reliability as a result of the integrated renewable energy sources. The system can be easily maintained and its energy output can be increased by adding more panels to the PV system. There is a lesser emission of $CO_2$ into the atmosphere.

## 5.0 Conclusion

The proposed integrated energy system demonstrated the feasibility and benefits attached to meeting the energy demands of the communities that are off-grid in isiala mbano local government area. The mathematical and computational process aimed at optimizing the hybrid system was successful; the proposed system was validated after analyzing its data in MatLab software. The research achieved its aim of meeting the energy demands of those communities in the rural areas, reducing the cost of accessing energy, and maximizing the renewable energy resource while preserving sustainability. Future work should look at the impact of AI-driven predictive models for forecasting demands and ream time optimization so as to meet up with the load demand.

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