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Bioelectric Power Potential Analysis of Agricultural Crop Residues: A Case Study of Nigeria

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***Abstract* - Nigeria belongs to the League of Nations in the growing economies list in the world and consequently, needed more infrastructural support from different developmental sectors such as the power. Insufficient electricity generation has been a major obstacle to the expected progression in the economic development indices. On a global scale, there has been a growing quest for increasing access to sustainable energy technologies, especially from renewable energy sources. Presently, Nigeria generates over 5000 MW of electricity for a population of over 200 million people. This has created serious techno-economic constrictions in the country. The country has vast potential for renewable energy especially biomass agricultural residues, but the residues have remained largely untapped. Therefore, this study analyzed the electrical potential of biomass agricultural residues in Nigeria. It also presents the varieties of technological perspectives that can be embraced to utilize the residues for power generation in the future. The research is to encourage the use of biomass residues for renewable energy based on sustainable technological approaches. The results obtained presented that as much as approximately 30 TWh of electrical energy can be generated annually from the seven different kinds of biomass agricultural residues investigated.**
***Keywords:* Crop Residue, Renewable Energy, Power, Industry, Nigeria**

I. INTRODUCTION

Global energy consumers have relied on different energy resources to satisfy their energy demands. In the last few decades, bioenergy from solid biomass wastes has been used extensively for heat energy in less efficient energy systems. From a modern technological context, bioenergy has gained the attention of stakeholders for heat and power generation. Several research publications have validated the techno-economic feasibilities of bioenergy for power generation but more policy and legislative supports are still required for sustainable investment in bioelectricity. In Africa, most especially in Nigeria, agriculture is a pivot for local economic development.

Therefore, the production of biodegradable agricultural waste materials is a common phenomenon. Considering the fact that the development of Renewable Energy Technologies (RETs) is currently occupying a centre stage of the interest of government and energy stakeholders, consequently, the utilization of agricultural biomass residues for power generation in rural communities could be an integral part of sustainable development. Most rural communities in developing countries especially in Africa are off-grid with constricted access to electricity. For a very long period of time, fossil fuels have been used to generate centralized electricity for large cities.

Unfortunately, rural communities are expected to rely on the extension of centralized power grids from the cities but it is usually not economically viable due to the long distance involved. The increasing anticipated depletion in the global reserve of fossil fuel has compelled nations to strive towards the exploitation of Renewable Energy (RE) for sustainable economic development and environmental benefits. In a global context, Nigeria is one of the countries making efforts toward the utilization of biomass for power generation as shown in Figure 1 [1].

The present rising global population is projected to impose a corresponding increase in energy demand [2-3]. The expected global aggressive socioeconomic development will make the exploitation of fossil fuels an insufficient source of energy for the future. From this perspective, the utilization of RE such as wind energy, solar energy, hydropower and biomass for electricity will be an inevitable task [4]. The application of biomass energy for electricity is strategically important in the quest for improving electricity generation through environmentally friendly technological mechanisms.

Apart from solar energy, wind energy and hydropower, bioenergy from biomass agricultural residues is another significant source of RE. The estimation of agricultural residues is usually the first step toward the utilization of agricultural bioenergy residues for power generation. The challenge of inadequate information about the potential capability of the different kinds of agricultural residues for power generation informed the core objective of this study. Therefore, this study presents the theoretical estimation of the potential of some selected agricultural biomass residues for power generation in Nigeria.

II. QUANTIFICATION OF THE SELECTED AGRICULTURAL RESIDUES

RE has a very critical role to play in the pursuit of sustainable development in Nigeria. The utilization of agricultural residues for renewable power generation is very important because the uncontrollable burning of biomass residues is harmful to the environment and human health. Agricultural residues are currently being burnt in open-air stoves for heating and such a practice results in emissions of harmful substances that can trigger cardiovascular infection in women and children's respiratory tracts. Therefore, the application of agricultural residues for power generation through modern energy technologies in Nigeria is very important. Nigeria is an agrarian country with great potential to produce agricultural residues for power generation. Unfortunately, the bioenergy database in the country is currently in a state of inefficiency. At different levels of engagement, the availability of research results for the support of the bioenergy subsector in Nigeria is quite limited. In the context of the main objective of this study, the production quantities of the selected crops and their estimated amount of residues are presented in Figure 2 based on the Food and Agriculture Organization (FAO) statistics covering the period of 2017-2021.

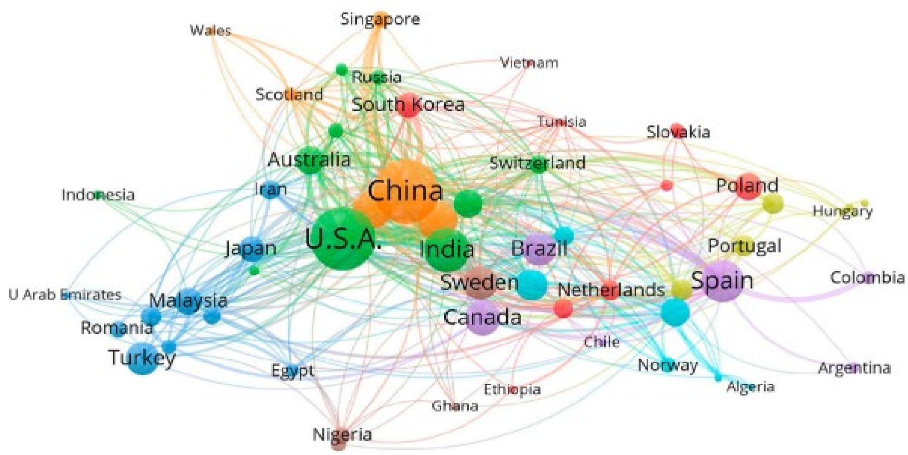

Fig. 1 Distribution of research activities on the replacement of fossil-based energy carriers with biomass and the Research interrelations between different countries

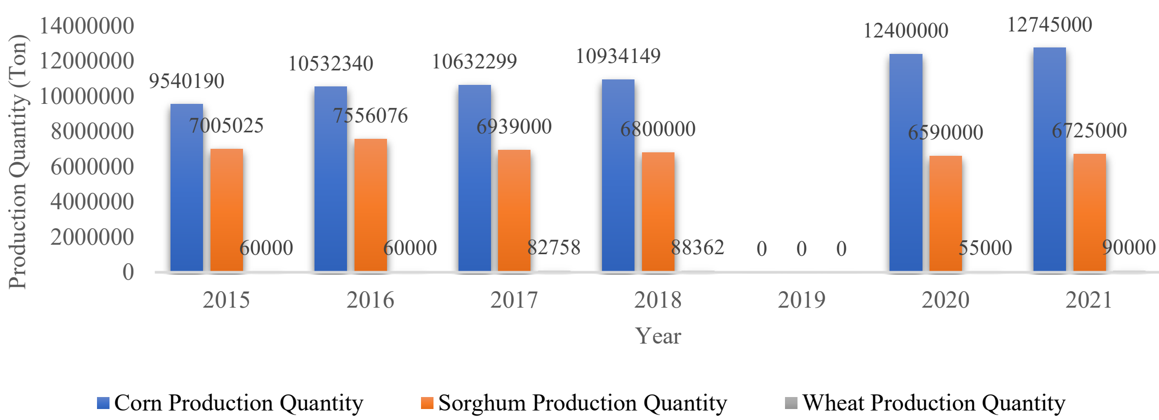

Fig. 2 Quantity of crop production in tonnes [5]

III. METHODOLOGY

Nigeria is located in West Africa with a land mass of 923,768 square km and a population of over 200 million people. The country is naturally endowed with a good proportion of land suitable for agricultural production. Production of cereals crops in any part of the country can be achieved with the nature of the soil and quality of rainfall in the country. Figure 3 illustrates a map of the country showing the agriculturally suitable land portion of the country. Although, the production of cereal crops is more noticeable in the northern part of the country and the crops can be grown in any part of the country. Cereal crops such as wheat, sorghum and corn are considered for the estimation explored in this study.

A. Estimation of the Potential of Crop Residues

The estimation of the potential of the residues from the selected crops involves the use of some important parameters. The utilization of agricultural crop residues for power generation usually contends with some other important applications such as application of animal feeding, enrichment of soil fertility, direct burning for cooking, and animal bedding. However, in a situation where it is possible to utilize the total amount of the residues generated which is usually a difficult task, the gross potential of the crop residues will be considered. There have been several studies about the application of both gross and recoverable potential of crop residues for power generation [6-8] considered as standard procedures. The computational procedure adopted by Mohammed *et al.,* [9] is applied in this study as shown in Eq. (1). The estimation was made based on the crop-to-residue ratio (CRR). CRR defines the quantity of residue present in the crop based on the comparative weight of the crop and the residue. Therefore, the values of the CRR used for the computation of the total residues from the selected crops are shown in Table I.

TABLE I CROP RESIDUES AND THEIR CRR

Agricultural crop	Residue Type	Range of CRR	Average value of CRR
Corn	Cob	0.27–0.57	0.40 [10,11-14,16,17]
	Straw	0.20–0.23	0.21 [10,12,13,16,17]
	Stalk	1.15–2.00	1.72 [11-14,16,17]
Sorghum	Straw	1.25–2.00	1.75 [19,13,18]
	Stalk	1.40–4.75	2.85 [11,13,16,18]
Wheat	Straw	1.20–1.50	1.30 [12-14,15]
	Husk	0.23–0.30	0.27 [12,15]

Fig. 3 Map of Nigeria showing the green areas for wet farming [19]

$$TQ_{Res} = P_Q \times CRR \times \delta \qquad (1)$$

where P_Q is the production quantity of the selected crop and δ= recoverability factor representing the percentage of the realistic amount of the residues used for the purpose of power generation. In this study, a value of δ = 0.4 indicating 40% of the residue was assumed to be available for power generation. This assumption presents that not all the biomass residues generated is available for utilization for electricity generation.

B. Estimation of Bioenergy Potential

The expression of Eq. (2) [20] is used for estimation of the bioenergy potential based on the recovery potential of the agricultural residues.

$$BEP_{Res} = \sum_{i=1}^{n} TQ_{Res} \times LHV_{Res} \qquad (2)$$

Where BEP_{Res} = bioenergy potential of a given crop residue (MJ), LHV_{Res} = lower heating value of the residue (MJkg^{-1}) and n = the number of crops.

The Electric Power Generation (EPG_{Res}) potential of the residues can be expressed as follows.

$$EPG_{Res} = BEP_{Res} \times \sigma_{elect} \qquad (3)$$

Where σ_{elect} denotes the electrical power efficiency of the internal combustion engine.

C. Determination of Lower Heating Values

A bomb calorimeter was used for the determination of the calorific values of the solid biomass residues. The calorific value represents the heating value of the biomass fuels, and it accounts for the amount of calories produced when a unit of any of the biomass fuel is oxidized. A calorific value is measured in MJkg^{-1}. Basically, there are Low Heating Value (LHV) and High Heating Value (HHV) of a combustible fuel. The basic difference between LHV and HHV is that the additional effect of the latent heat of vaporization of water on LHV gives the HHV of the fuel. In a standard context, the determination of the calorific value of a fuel can be achieved either by using ASTM D5865-13 or a bomb calorimeter. In this study, three different agricultural crops were selected with seven total number of residues as shown in Table II. The LHV of the residues which was obtained through experimental procedure was then compared with the range of values in some existing literature as shown in Table II. The LHV of each of the residues was determined experimentally using a bomb calorimeter IKA 2000.

IV. RESULTS AND DISCUSSION

The framework of this research evaluated the electrical potential of the selected crop residues using Eqs. (2) and (3). The estimated quantity of the selected agricultural residues considered in this study is presented in Table III through the use of Eq. (1). The quantity estimated for each of the residues varies significantly in accordance with the production quantity of the crops based on the yield of the crops. The original data for the quantity production of each of the crops was obtained from the Food and Agricultural Organization (FAO) statistics from 2015 to 2021. The physical size of the residue generated from the crop compared with the edible part is another important factor that determines the value of the CRR. The corn stalk has the highest residue production quantity of 8,768,560 tons and then 7,666,500 tons produced by the sorghum stalk. The smallest amount of residue was produced by the husk of wheat due to its small crop production quantity.

The results of the electrical energy evaluations are presented in Figure 4 -11. In Figure 4, the results for the estimation of the electric power potential of corn cob residue is shown based on the available data from 2015-2021. It was observed that the year 2021 shows the highest value of electrical power potential of 2.6 TWh while the year 2019 shows a value of zero indicating that no data was available for the computation. The outbreak of the COVID-19 pandemic restricted the processes of data collection and consequently resulted in a lack of data for the year 2019. The computation of the electrical potential of the agricultural residues was based on multiple factors. The factors are the crop production quantity, crop-to-residue ratio, lower heating value of the residues and the anticipated efficiency of the electric power generator. The sum total of the estimated electrical energy potential of the residues is shown in Figure 11. A close look at Figure 11 revealed that a total potential of approximately 30 TWh of electrical energy with just 40% availability of the residues can be achieved in the country in 2021.

In Figure 5, the estimated electric potential of corn straw residue is presented. It was observed that the highest obtainable potential was in 2021 with a value of 1.24 TWh while 0,93 is the lowest in the year 2015. Compared to what was obtained in Figures 4 and 5, the estimated electric potential of corn stalk residue shown in Figure 6 has greater electrical energy potential throughout the years under investigation than the corn cob and corn straw. The electrical energy potential of the corn stalk is greater than the combined total of both corn cob and straw. In Figures 7 and 8, the estimated electrical energy potential of sorghum straw and stalk residues are presented respectively. In the year 2021, the corresponding electrical energy potentials for the sorghum straw and stalk are 4.82 TWh and 10.11 TWh. The huge difference lies in the fact that the physical size of the stalk is much greater than the straw thereby accounting for a higher CRR of 2.85 for the stalk compared to 1.75 for the straw. Also, in Figures 9 and 10, the estimated electric potential of wheat straw and husk residues are shown respectively. Since the quantity of the residues produced by the husk is higher than the straw, consequently, a higher electrical energy potential of the husk is expected. However, in all the residues under investigation, it was observed that the wheat produced the lowest electrical energy potential considering the integrated factors mentioned earlier as the requirement for electricity generation.

TABLE II LHV OF THE SELECTED CROP RESIDUES

Agricultural crop	Residue Type	LHV ($MJkg^{-1}$)	Range of LHV
Corn	Cob	15.2	12.6–17.4 [21]
	Straw	13.8	12.6–15.6 [21]
	Stalk	14.4	12.6–16.7 [21]
Sorghum	Straw	12.2	12.4 [21]
	Stalk	15.7	15.0–17.0 [21]
Wheat	Straw	16.4	15.6–17.2 [21]
	Husks	14.9	12.9–17.4 [21]

TABLE III ESTIMATED QUANTITY OF THE SELECTED AGRICULTURAL RESIDUES

Year	Corn Cob (T)	Corn Straw (T)	Corn Stalk (T)	Sorghum Straw (T)	Sorghum Stalk (T)	Wheat Straw (T)	Wheat Husk (T)
2015	1526430	801376	6563651	4903518	7985729	31200	6480
2016	1685174	884716.6	7246250	5289253	8613927	31200	6480
2017	1701168	893113.1	7315022	4857300	7910460	43034.16	8937.864
2018	1749464	918468.5	7522695	4760000	7752000	45948.24	9543.096
2019	-	-	-	-	-	-	-
2020	1984000	1041600	8531200	4613000	7512600	28600	5940
2021	2039200	1070580	8768560	4707500	7666500	46800	9720

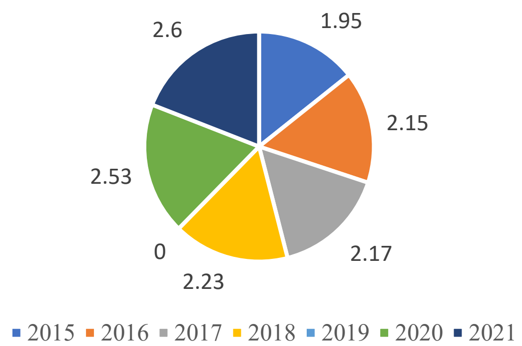

Fig. 4 The estimated electric potential of corn cob residue

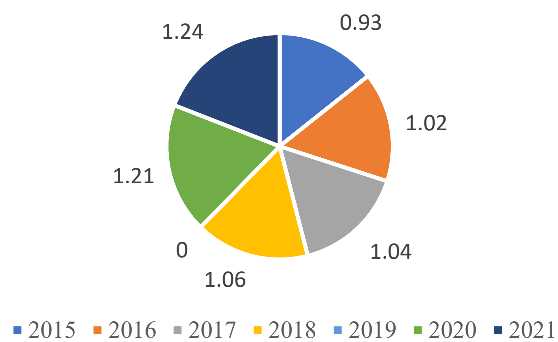

Fig. 5 The estimated electric potential of corn straw residue

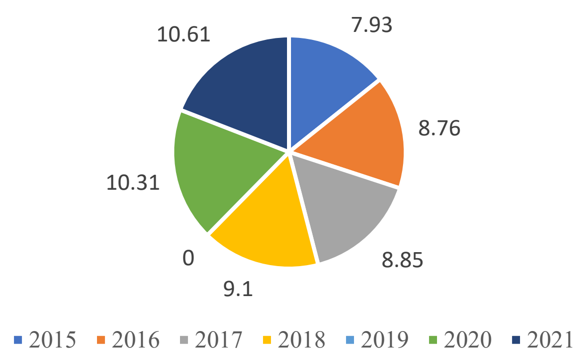

Fig. 6 The estimated electric potential of corn stalk residue

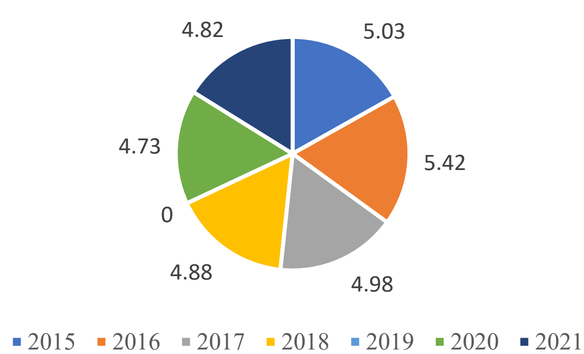

Fig. 7 The estimated electric potential of sorghum straw residue

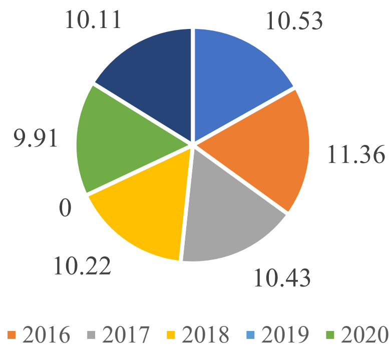

Fig. 8 The estimated electric potential of sorghum stalk residue

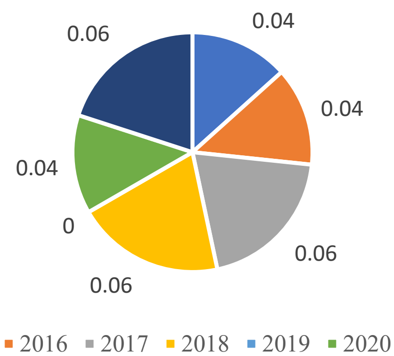

Fig. 9 The estimated electric potential of wheat straw residue

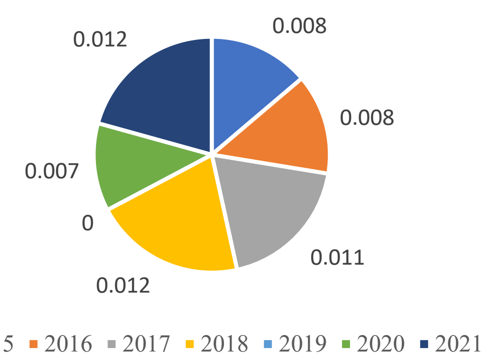

Fig. 10 The estimated electric potential of wheat husk residue

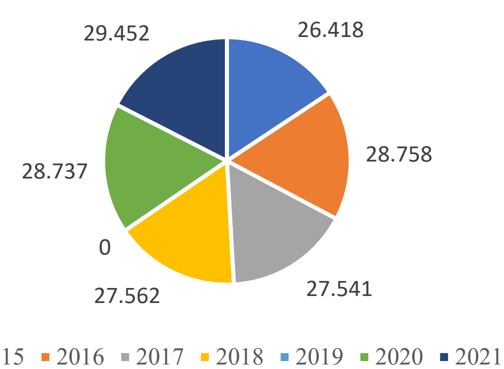

Fig. 11 Total estimated electric potential of all the residues

V. TECHNOLOGICAL ROUTES FOR CONVERSION OF BIOMASS RESIDUES TO ELECTRICITY

Solid biomass residues considered in this study can be converted to energy through direct combustion, gasification and pyrolysis thermochemical processes. In thermochemical conversion, the aggregate bonds in the binding molecules of the solid fuel are broken down to release the energy stored during the photosynthetic process of growing the plant. The technical processes of direct combustion, gasification, anaerobic digestion, and pyrolysis conversion of biomass to power generation have different technological approaches. However, for the conversion of the dry biomass residues to electricity, gasification, and direct combustion are the most appropriate technologies.

A. Gasification Technology

A gasification method can convert solid biodegradable waste into high-value fuel (combustible methane gas) suitable for power generation through an internal combustion engine. It is an environmentally reliable energy generation technique that can be used for the treatment of dry organic waste with low ash content. Gasification is a very promising technological option for the treatment of environmental waste with different particle sizes, moisture content and varying degrees of organically compositional materials. The technological processes involved in biomass gasification for power generation are shown in Figure 12. It is widely recognized that the gasification of biomass has great promise for a more sustainable energy source in the future. Though, just a few economically feasible gasification systems for power generation are currently available in the market, despite major research and demonstration efforts over the last few decades.

In-depth research works have been conducted on gasification-based combined heat and power generation, and several systems have also undergone industrial-scale testing. Many biomass gasification research activities and development over the last few years have emerged from developed and emerging economies around the world. The efforts are focused on production, purification and raising the quality of synthesis gas (syngas) to the natural gas level for power generation. More efforts have also been made toward the production of bio-transport fuel through the gasification of residues from plants to support the sustainable development of the global transportation sector. Due to the global changing economic situation, it may be rational to point out that additional life cycle and techno-economic analyses are required to improve the technical performance of biomass to energy conversion methods. This will be necessary to confront some of the techno-economic barriers of commercial biomass distributed power generation through gasification technologies.

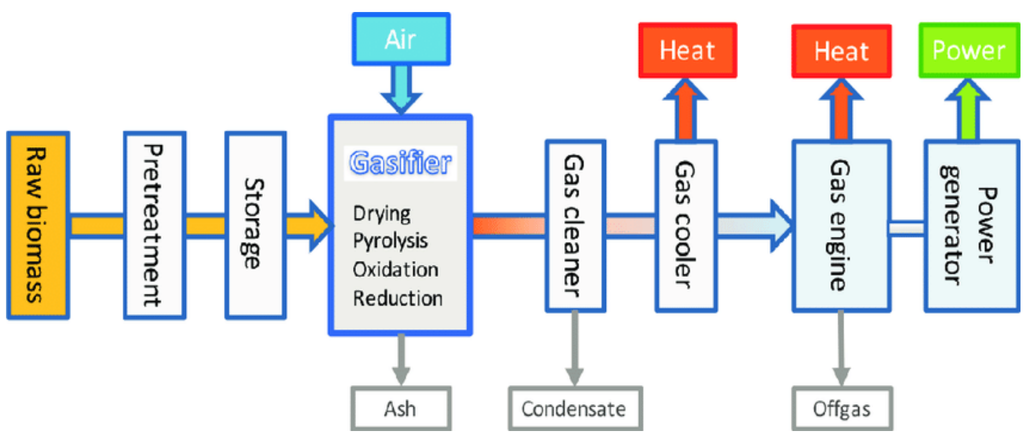

Fig. 12 Flow diagram of power generation from biomass gasification [22]

B. Direct Combustion

Direct combustion of biomass residues has been one of the wastes of energy technologies exploited over the years. The combustion process involves an exothermic chemical reaction driving a mechanical energy-coupled system to generate electricity. The combustion processes of biomass residues shown in Figure 13 have the capability to reduce biodegradable biomass wastes by 80-90% by volume. Traditionally, the utilization of biomass residues in rural areas in developing countries has been by open-air combustion in three-stone cooking stoves which is grossly inefficient and sluggish. Modern combustion technologies involve the application of heat to the residues at high temperatures in a furnace to generate hot gas. The hot gas produced can then be applied to a boiler for the production of steam for running a turbine for power generation. A variety of biomass residues such as crop residues, leaves, forest wood, animal shells, and dried animal wastes can be used for power generation in a combustion facility. From a technical point of view, the combustion of biomass involves a system that functions with low efficiency due to the production and loss of heat energy into the atmosphere.

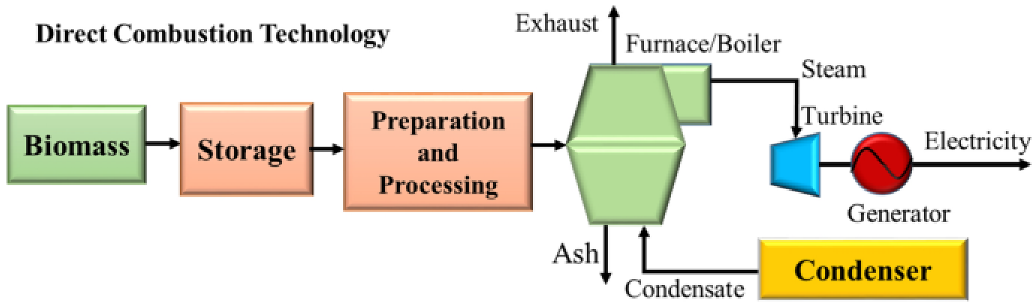

Fig. 13 Stages of biomass combustion for power generation [23]

VI. SWOT ANALYSIS OF THE BIOELECTRICITY PROJECT IN NIGERIA

Presently, Nigeria is far from the expected progress regarding the utilization of biomass for energy applications. A SWOT analysis is a relevant tool in the strategic planning of activities. Therefore, the strengths, weaknesses, opportunities, and threats are analyzed as part of the strategic planning process that will be required for the development of bioenergy projects in the country.

Strengths: The abundance of biomass residues of different kinds in the country is one of the major strengths in any prospective use of solid biomass for bioelectricity in the country. Many research studies have been conducted on the quantification of biomass resource availability. Results obtained so far indicated that the country has huge potential capability for investment in bioenergy due to the availability of multiple types of biowaste materials. Therefore, it is expected that the country can utilize its potential to tap from the available bioenergy resources for job creation and increase income standards for the power sector.

Weaknesses: Nigeria is a developing country with struggling economies. It is thus important to know that the high cost of investment in biomass power generation is a critical challenge to the deployment of bioelectricity projects in the country especially in rural areas. The production of electricity from the combustion of fossil fuels in centralized power plants is economically sustainable compared to the use of decentralized biomass power technologies. This economic constraint may limit the nation's investment capability in bioelectricity due to the capital-intensive nature of the projects. The availability of cheap energy resources from conventional fossil fuel plants could disrupt the quest for bioelectricity development in Nigeria. Besides, the overall electric power efficiencies of bioelectricity technologies are usually below 35% and represent a serious challenge to the development of bioelectricity projects in the country. Nigeria is also lacking in terms of experience personnel in biomass technologies coupled with the mismatch in the location between the biomass feedstock and the demand for power supply.

Opportunities: In Nigeria, the condition of poor rural electrification programs is a very worrisome development. The possibility of using biomass to generate electricity based on decentralized solutions in rural communities is a promising strategy for promoting rural socioeconomic development. The national policy of granting free operational licenses to investors in small-scale renewable energy in Nigeria and the planned tax incentives for companies in Nigeria investing in green energy are two major opportunities to encourage investment in green electricity. The existence of several renewable energy research institutes and private organizations is also a booster to the development of the bioenergy sector in Nigeria. With the promotion of viable policies especially on waste to energy, research activities can be increased to support and boost the market potential of bioenergy in the country. Utilization of policy initiatives in consonance with the expected linkages between the government and investors in bioenergy will guarantee reasonable investment connections and open profitable market access to the investors in bioenergy.

Threats: The majority of renewable energies, including bioenergy, face significant obstacles from uncertain policy and complex institutional systems. Presently, policy attention given to the development of bioenergy in Nigeria is relatively insufficient. Various government agencies in the country and many cross-sector institutions must be allowed to participate in the development of bioenergy policies to inspire trust in investors and project developers. The governments should establish a long-term bioenergy strategy with specific goals of effective coordination. Furthermore, low-level technological readiness is another serious threat to the development of the nation's bioenergy sector. The challenge of low-level technology is impaired by inadequate infrastructure. An increase in technology readiness can hasten commercialization by supporting innovation through policy research, development, and demonstration.

VI. CONCLUSION

It has been observed from the results presented in this study that biomass agricultural residues have the potential to generate electricity in Nigeria. The energy stakeholders in the country need to embark on the feasibility of the various technologies suitable for biomass power generation. Going by the current situation in the country, the application of biomass agricultural residues for power generation has no reasonable attention in the context of renewable energy for sustainable development. The lack of financial commitment towards investment in bioelectricity development in the country is a major constraint. Considering the increasing awareness of the environmental pollution orchestrated by the excessive combustion of fossil fuels, it is desirable for Nigeria to begin the transition to sustainable renewable energy. The current research and development initiatives with respect to bioelectricity programs and investment are highly insufficient.

Therefore, aggressive policy and financial support mechanisms including the required cutting-edge technological sustainability assessment must be established. In addition, prolific life cycle and exergy assessment should be more closely examined for the long-term viability of bioelectricity in support of the nation's growing economy. To encourage investment in the biomass energy generation industry, the technological deficiencies must be addressed from a wider angle. In order to develop technical knowledge based on reliable advanced technology and lower the initial and ongoing costs of biomass energy plants, stakeholders' active participation in the bioenergy program is especially important. It is necessary to intensify biomass research activities being conducted by several institutions and special measures must be taken to lower the expenses associated the overall cost of bioelectricity in the country.

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