World Journal of Advanced Research and Reviews
eISSN: 2581-9615 CODEN (USA): WJARAI
Cross Ref DOI: 10.30574/wjarr
Journal homepage: https://wjarr.com/

(Review Article)

Biomass-to-power: Opportunities and challenges for Nigeria

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World Journal of Advanced Research and Reviews, 2023, 20(02), 001–023

Publication history: Received on 10 September 2023; revised on 30 October 2023; accepted on 01 November 2023

Article DOI: https://doi.org/10.30574/wjarr.2023.20.2.2214

Abstract

Power is needed for the growth and development of any country. The Nigerian power sector continues to face tremendous challenges, especially in the areas of power generation and sustainability in the electricity value chain. Successive governments have carried out several reforms, but these problems persist. The major causes are tied to the lack of diversity in the country's energy mix and over-dependence on non-renewable fossil fuels for power generation. With Nigeria's growing power demand and the Federal Government's commitment to renewable energy for reduced carbon emission, the potential of biomass in power generation can no longer be overlooked. Biomass is a renewable resource that is abundant in supply in Nigeria. Biomass resources can be obtained from multiple sources and has very low net carbon emission. Its immediate addition to Nigeria's energy mix would aid the country in meeting its 2030 goal of increasing renewable power generation by 45% and reducing greenhouse emissions by 20%. This paper therefore studies the history of power generation in Nigeria and the challenges encountered so far. It then looks at biomass resources availability in the country, their viability as feedstocks for power generation, and biomass-to-power conversion processes. The challenges of this alternative power solution are identified and recommendations given. If these can be implemented, the biomass-to-power solution can significantly address the issues of low power generation and carbon emission. It would help improve energy security, environmental sustainability, circular economy, and economic opportunities for those in the biomass and power supply chain in Nigeria.

Keywords: Biomass; Bioenergy; Biomass-to-power; Sustainable Power Generation; Renewable Energy; Nigeria.

1. Introduction

Energy is an essential tool for nation-building. Various aspects of a country's economic, social, and political development are invariably tied to the amount of energy available to the country [1]. The higher the energy access a country has, the faster the rate of development. On the contrary, deficits in a country's energy supply lead to lower standards of living, economic decline, poor healthcare delivery, and poverty [2]. Every country depends on energy to keep up with the ongoing race for development happening simultaneously around the world [3].

Humans, from their early years, have constantly devised means to generate and use energy for various purposes in their societies. Wood, a form of biomass, has been used since antiquity for cooking, heating, as a light source, for signals and communication, and other purposes [4]. Hydroenergy (used in water wheels) was used in ancient Mesopotamia, Greece, and other parts of Southern Europe for grinding and milling. As the years rolled by, hydroenergy was harnessed for power generation through the application of hydropower turbines. Fossils have also aided in the development of human society since their discovery. Currently, fossil fuels account for 85% of the world's energy supply [5]. Coal played a very important role during the Industrial Revolution and was used extensively for production processes, transportation, and heating [6]. Crude oil is currently widely used and has taken the place of coal on the scale of importance. Globally, crude oil makes up about 37% of energy production worldwide [7]. Natural gas is also widely used for heating, power

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generation, etc. Mankind has further discovered other energy sources which include but are not limited to solar, tidal, geothermal, nuclear, and wind energies.

With such diverse energy sources, it is generally expected that global energy demands would be met, and thus electric power generation would be evenly distributed around the world. But this is far from the reality. A good percentage of the world's population still live without electricity and consume traditional energy sources (biomass) in a way that is harmful to them and the environment [8]. Before 2009, Osaghae [9] estimated that 1.6 billion people (around one-fourth of the world's population) lacked access to electricity and depended on other sources of energy. But recently, this number has reduced thanks to intentional actions by various governments around the world. As of November 2022, the number of persons without electricity access was estimated at 770 million [10]. Most of these people live in high energy deficit third world countries where constant power remains elusive, especially in rural areas. Almost 50% of those without electricity live on the African continent [2]. However, the demand for steady power supply is on the rise in Africa largely due to population rise [11], increase in urbanization [4], economic growth [5], industrialization [12], lifestyle adjustments amongst other factors. Provision of uninterrupted power supply remains a major goal for many governments on the continent. Successive administrations have made this area their key action point as they look forward to upgrading the poor population to modern energy consumption [8].

Aside from power generation and constant supply, sustainability is now a key issue. Many countries, governments, and organizations around the world are devising means to meet power needs through renewable means. This is in response to the United Nations Sustainable Development Goals (SDG) program Goal 7 which emphasizes the need for clean, affordable, and modern energy for all by 2030 [13]. The goal is to ensure energy security, achieve low carbon dioxide emissions, and make lasting economic impacts [14]. It has been established that fossil fuels and other forms of non-renewable energy are the prime causes of environmental pollution [15]. They release high levels of harmful oxides and other Greenhouse gases (GHGs) leading to the depletion of the ozone layer, global warming, acid rain, and other menaces [3]. In addition to the potential to cause harm to humans and the environment, they are also finite and can be used up sometime in the future [16]. Renewable energy (also called alternative energy) on the other hand, is sustainable, clean, and abundant [14]. Renewable energy sources are biomass, geothermal heat, Ocean and tidal, wind, and solar. Though they are most preferred, some of these energy sources also have their limitations. For example, while wind and solar energies can produce a good amount of energy, both are volatile because they depend on the weather and seasons for optimal production [17]. This is one area where biomass has a comparative advantage over other renewable energy sources and is the major reason for the recent heightened interest in biomass-produced electricity or biomass-to-power.

Biomass is an abundant natural resource that is broadly distributed worldwide. However, its inherent potential as an energy source for modern use is often overlooked in many countries [18]. Biomass refers to renewable organic materials that are produced directly or indirectly by living organisms through metabolism [19]. Sources of biomass include agricultural resources and residues, forest resources, and wastes such as food wastes, industrial wastes, animal wastes, and municipal solid wastes (MSW) [20]. Aside from being an energy source, it also serves as a raw material for many industrial processes [15]. In most developing countries, especially those in Africa, it remains the most used energy source [21]. For instance, biomass accounts for 87% of annual energy usage in Nigeria [4], 87% in Burkina Faso, 91% in Burundi, 85% in Niger and Madagascar, 90% in Central African Republic and so on [9]. Some properties of biomass that make it desirable are its abundance in supply, the multiplicity of sources, a wide range of applications, and low net carbon production, amongst others [22]. Since biomass has many desirable properties and is abundant in supply, it is generally touted to be the energy source for the future, one with the potential to replace fossil fuels. Power-generating plants that utilize biomass as their primary (and sometimes only source of energy) are springing up in many parts of the world today. For instance, biomass-powered plants produced about 43.8 TWh of electricity in Germany in 2016 accounting for 23% of renewable energy production in the country [17]. Aside from Germany, the USA, Japan, and Brazil, 58 more countries are producing electricity from biomass [23] with more to join soon. Many technical analyses have shown that biomass-to-power generating plants have better overall environmental benefits compared to fossil-powered plants [24]. This is because the carbon dioxide produced during power generation is used up again by the biomass crop during their growth [23]. Also, biomass plants are highly reliable in that they can operate continuously without dependence on weather or temperature and the power they produce is of great quality [22].

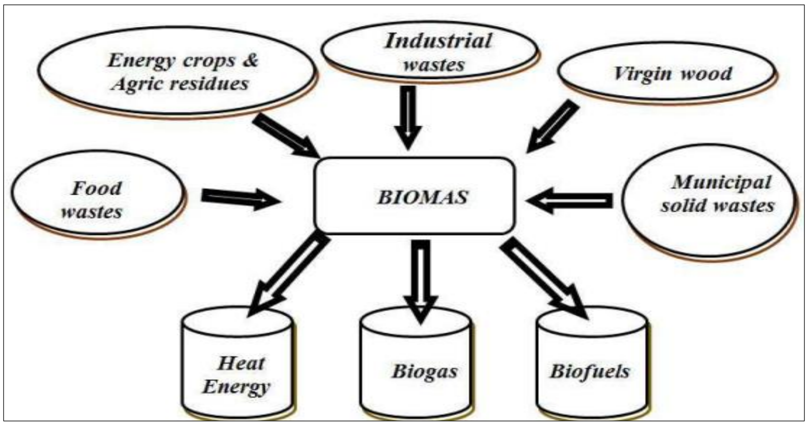

Figure 1 Sources and products from biomass [12, 25].

Nigeria is Africa's giant and continues to experience increasing power demand. Despite being a major producer and exporter of crude oil, Nigeria still suffers epileptic power supply leading to lower industrial and commercial activities in many parts of the country [21]. These harm mass productivity in the country. According to The Council of Renewable Energy of Nigeria, an estimated 126 billion naira is lost yearly due to power interruptions [11]. Jekayinfa et al [14] assert that there is a strong relationship between power availability and socioeconomic development. Nigeria's current power generation is not enough for her population [26]. Her electricity consumption per capita is around 156 kWh [5]. The country's electricity principally comes from two sources: fossil-powered plants (>80%) and hydropower plants [12]. The unfavorable power supply situation in Nigeria mostly results from the high energy demand in the country (due to a high population) and lack of diversity in the energy mix [15]. To correct this anomaly, the Federal and State Governments in Nigeria have synergized efforts to improve the electricity situation in the country. The government of Nigeria's current goal in the power sector is laid out in four plans: an additional 30,000 MW installed on-grid capacity expansion, 45% electricity generation from renewable sources, and 90% nationwide electrification by 2030, total electrification of the country by 2040, and 20% reduction in greenhouse gases (GHGs) emission by 2030 [27]. The country also wishes to attain carbon neutrality by 2060. Nigeria's commitment to the ideals of renewable electricity generation is not unconnected to the fact that it currently sits at the 38th place globally in terms of carbon dioxide emissions [13]. To help the country achieve both goals of improved electricity generation and environmental protection, integration of renewables into Nigeria's energy mix has become a necessity and biomass is being considered because of its inherent desirable properties.

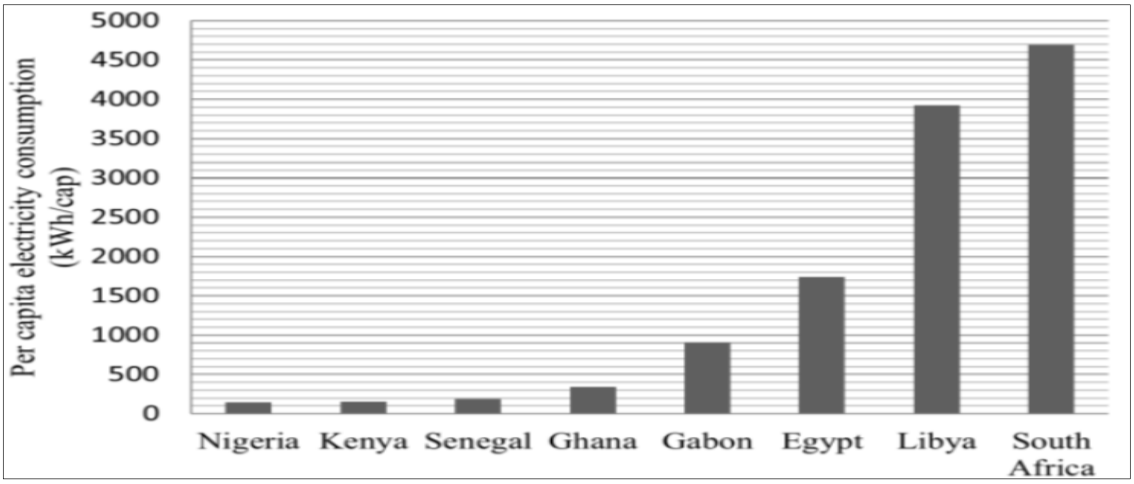

Figure 2 Electricity consumption per capita of some African Countries [12].

This paper therefore assesses the viability of the biomass-to-power solution in Nigeria. It takes a holistic look at Nigeria's power sector, its history, current stage of development, and future projections. It also considers Nigeria's plans and policies for renewable electricity production through biomass to meet her local needs and environmental safety standards. A variety of biomass-to-electricity conversion processes are shown herein, and their attendant process designs and schematic diagrams. Also, this work highlights inherent challenges with the introduction of biomass-to-power plants in Nigeria, proffers solutions, and clearly states the roles of the government and private sector in Nigeria in the realization of this alternative power solution. The main goal of this work is to promote the effective use of the abundant biomass resources in Nigeria to meet her power demands, champion the course of circular economy in the power sector, and ensure environmental sustainability as enshrined in Goals 7 and 13 of the UN Sustainable Development Goals (SDGs).

2. Power Generation and supply in Nigeria

2.1. Country Profile

Nigeria is a Federal Democratic Republic located in West Africa on the Gulf of Guinea. A well-known country in the sub-Saharan region, the country borders the Atlantic Ocean to the South, Benin Republic to the West, the Republic of Cameroun and the Republic of Chad to the East, and Niger Republic to the North. Due to her land mass, she has expansive borders with her neighbors thus allowing for inter-country movement and trade. Nigeria's total area is 923,768 km2 with land mass and water bodies constituting 98.6% and 1.4% respectively [2]. Approximately 74.5 million hectares out of the total land mass is fit for agriculture [28]. Out of this, 37.3% is arable land, permanent meadows, and pastures, about 9.5% is forested, while an estimated 3.3% is permanently cropped [29]. The availability of fertile land for agriculture makes lots of Nigerians venture into agriculture (most subsistent) thus producing a lot of biomass resources.

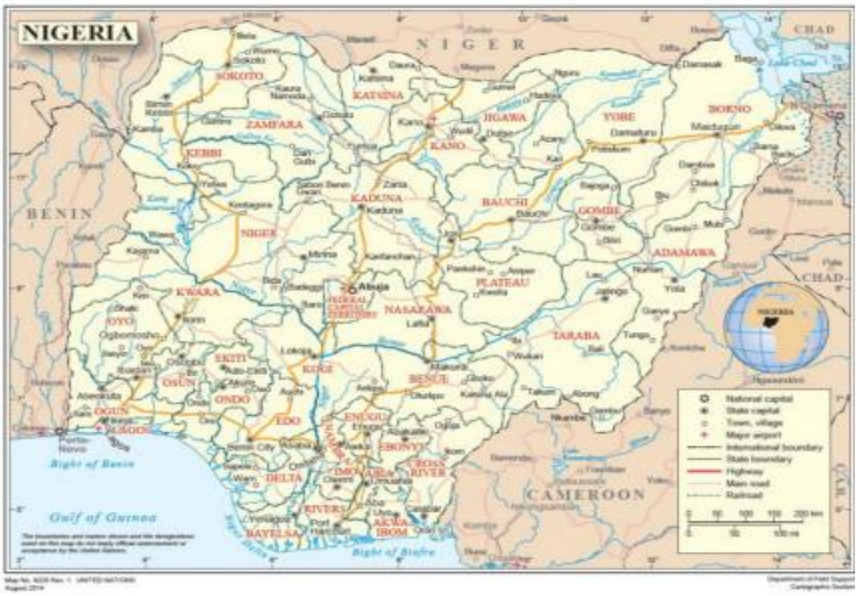

Figure 3 A map of the Federal Republic of Nigeria [14].

Nigeria is the most populous country in Africa with an estimated population of over 200 million people who speak over 500 languages [20]. This high population gives her a population density of about 21.04 persons/km2 [30]. At an annual growth rate of 2.5% [27], the population density is projected to increase yearly. Nigeria is typically a developing country. An estimated 48% of the country's population lives in rural areas while more than 60% of its people live below the poverty line [28]. But despite this, there are increased industrial and commercial in the country, especially around key cities like Lagos, Abuja, Kano, Kaduna, Port Harcourt, Nnewi, Aba, Agbara, and Onitsha. There are also lots of mining activities for solid minerals in the northern parts and crude oil exploration and production in the Niger Delta region of southern Nigeria. Nigeria has a large economy which is powered mostly by crude oil export [20]. It is the sixth-largest producer of crude oil and along with Libya, houses two-third of Africa's crude oil reserve [11]. It is also a growing gas powerhouse with the huge discovery of gas reserves in the South-Eastern and South-Southern parts running into several trillion cubic feet (tcf) [12, 16]. Furthermore, Nigeria is rich in other mineral resources like limestone, gold, coal, iron ore, gypsum, etc.

Table 1 Nigeria's available Energy Resources [12].

Resource		Reserves (natural units)	Production level (natural units)	Utilization (natural units)
Crude oil		36.22 billion barrels	2.06 million bpd	445,000 bpd
Natural gas		187 trillion SCF	7.1 billion SCF/day	3.4 billion SCF/day
Coal and lignite		2.734 billion tonnes	Insignificant	Insignificant
Tar sands		31 billion barrels of oil equivalent	0	0
Large hydropower		11,250 MW	1,938 MW (167.4 million MWh/day)	167.4 million MWh/day
Small hydropower		3,500 MW	30 MW (2.6 million MWh/day)	2.6 million MWh/day
Solar radiation		3.5 – 7.0 kWh/m^2/day	excess of 240 kWp of solar PV or 0.01 million MWh/day	excess of 0.01 million MWh/day solar PV
Wind		2 – 9 m/s at 10 m height	-	-
Biomass	Fuelwood	11 million hectares of forest and woodland	0.12 million tonnes/day	0.12 million tonnes/day
	Animal waste	245 million assorted animals in 2001	0.781 million tonnes of waste/day in 2001	not available
	Energy crops and agric. residues	72 million hectares of agric. land and all waste lands	excess of 0.256 million tonnes of assorted crops residues/ day in 1996	not available

Nigeria remains one of the largest economies on the African continent [27]. This is one major reason she continually attracts huge foreign direct investments (FDIs). Nigeria's huge population leads to a large market which in turn leads to increased industrial, commercial, and domestic activities. This makes the country's power demand higher than many countries in Africa [2]. Power demand is on a steady increase in Nigeria and may continue to do so in the future. Oyedepo [11] estimated Nigeria's power demand to multiply by 7.5 between 2010 and 2030. Despite the increasing demand, Nigeria remains a low energy-consuming country when compared to many nations [16]. The gross power deficit in Nigeria affects its economy in many ways [30].

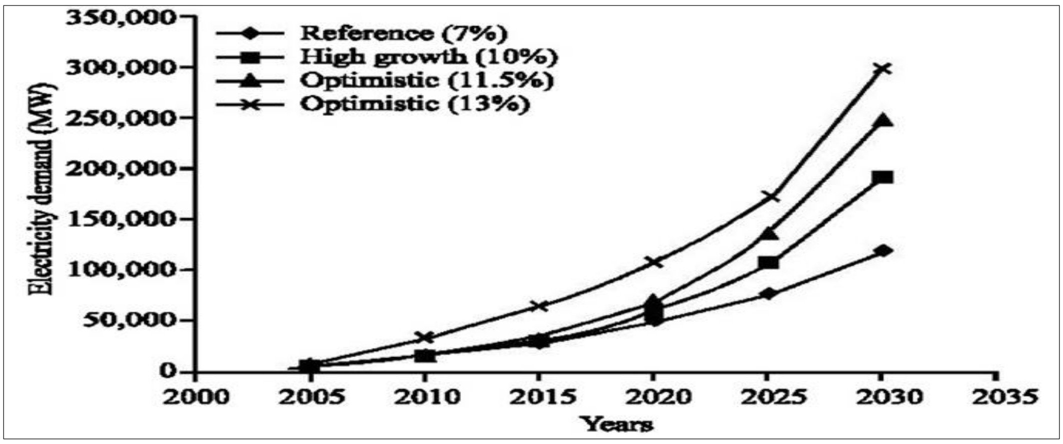

Figure 4 Projected 35-year Power Demand (2000-2030) [11].

2.2. History of Power Generation in Nigeria

The history of power generation in Nigeria can be traced to the colonial era. Nigeria was originally a British Protectorate and as such, the colonial powers were responsible for the country's administration before independence. The British administration at the time needed power for the smooth running of administrative operations in the country. In 1886, 2 power-generating sets (generating approximately 60kW) were installed in the Colony of Lagos [31]. Then, the colonial government built the first power generation station (a 20MW station) at Ijora, Lagos in 1896 [32]. Subsequently, the Nigerian Electricity Supply Company (NESCO), a utility company, started operations in the Jos Plateau region in 1929 by generating and transmitting about 25MW of power [33].

The major change happened in the sector when the Electricity Corporation of Nigeria (ECN) was established in 1951 and vested with the responsibility of generating and transmitting power across Nigeria [34]. The body went on to install two coal-powered turbines in the towns of Oji and Ojora to serve the coal mining sites of Enugu and the colonial office in Lagos [32]. The Niger Dams Authority (NDA), which was principally in charge of developing and maintaining dams, was later established in 1962. The authority developed the 320 MW Kainji Hydropower Plant in 1969 and sold the generated power to the ECN for transmission and distribution [31]. The National Military Government of General Yakubu Gowon noticed that some roles of both organizations overlapped and in 1972, merged both bodies into a single entity called the National Electric Power Authority (NEPA) giving it the sole oversight and responsibility of power generation, transmission, and distribution in Nigeria [35].

During the regime of former President Olusegun Obasanjo, the National Integrated Power Project (NIPP) was launched to address the power shortage in Nigeria and make use of the excess gas flared in gas-producing states in the country [35]. A total of 10 NIPP plants are in operation today and they are managed by the Niger Delta Power Holding Company Plc [2]. President Obasanjo also signed the Electric Power Sector Reform Act (EPSRA) into law in 2005 thus unbundling the National Electric Power Authority (NEPA) into the Power Holding Company of Nigeria (PHCN) which was to be a temporary vehicle for the deregulation and privatization of the power sector [31]. This reform was done to improve the efficiency of power supply across the country. The PHCN was broken down into 6 generation companies (GenCos), 1 transmission company (The Transmission Company of Nigeria, TCN), and 11 distribution companies (DisCos) [34]. It also saw the creation of the Rural Electrification Agency [2]. The GenCos are to generate power for the Transmission Company of Nigeria (TCN) which transmits the power to DisCos for distribution to the end users. The complete privatization of the various successor companies of PHCN was completed under the regime of President Goodluck Jonathan and the body ceased to exist by September 30, 2013. President Jonathan's administration also established the Nigerian Bulk Electricity Plc (NBET) on July 29, 2010 [2]. NBET is to be the pool manager of electricity generated in Nigeria. They buy power from Generation Companies (Gencos) and Independent Power Producers (IPPs) through Power Purchase Agreements (PPAs) and sell to Distribution Companies (Discos).

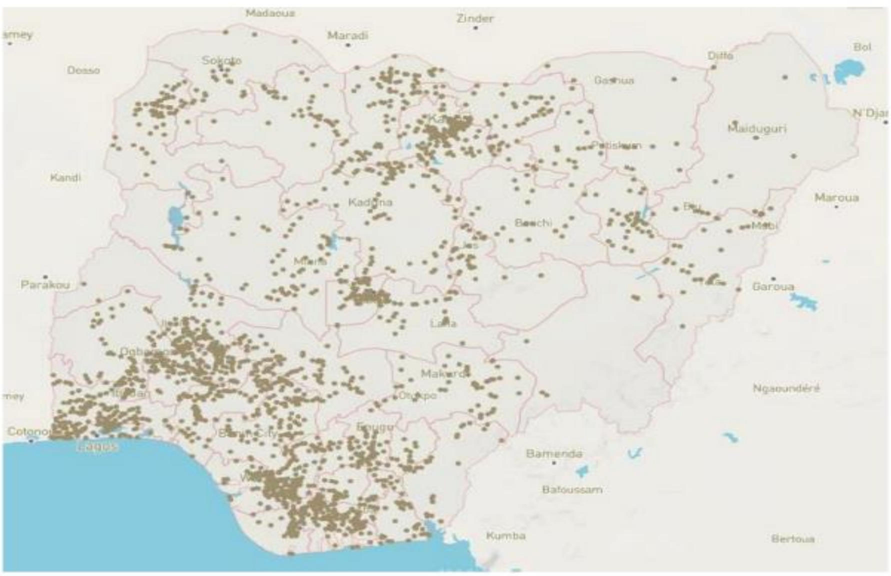

Figure 5 On-grid electricity spread in Nigeria [14]

Power sector reforms were also carried out by the administration of former President Muhammad Buhari. On March 17, 2023, he signed a constitutional amendment for Nigerian States to independently license, generate, transmit, and distribute electric power [36]. President Bola Tinubu also signed the Electoral Act 2023 into law wherein provisions were made for businesses and individuals without license (but with undertaking) to generate power no greater than 1 MW aggregate at a site and/or distribute power not greater than 100 kW aggregate at a location. The 2023 law also lays great emphasis on renewable energy production as it mandates the Nigerian Electricity Regulatory Commission (NERC) to only issue licenses to generation companies (GenCos) with plans to meet Nigeria's renewable energy regulations. Since then, state governments have sought investors and private entities to come develop captive power solutions and Independent Power Plants in their domains to serve the capital, businesses and local communities. Independent power plants that exist across the country include 642MW Afam VI Power Plant, 450MW Azura Power Plant, 480MW Okpai Power Plant, 141MW Geometric Power Aba IPP, 191MW (later upgraded to 685MW in 2015) Ibom Power Plant, 10MW Alausa Power Plant, and many more which are still upcoming. These IPP solutions have added their quota in boosting power access in Nigeria but more still needs to be done.

2.3. Power Generation and Supply Chain in Nigeria

Most plants in Nigeria operate on the Open Cycle generation system [32]. Power in Nigeria is mostly generated at a voltage range of 11.5-16KV and then stepped up to 330KV by a step-up transformer at the power station for onward transmission to transmission substations [33]. The Transmission Company of Nigeria (TCN) is solely responsible for transmission and does so using alternating current (AC) through transmission towers [35]. TCN's transmission network consists of 330KV lines (5,000 km), 132KV lines (6,000 km), and 330/132KV substations (23) [11], The essence of transmitting power at such high voltage is to ensure it can travel long distances with minimal or no power losses [34]. At the transmission substations (mostly away from industrial and residential centers), the voltage is dropped to 132KV and sent to DisCo's primary substations. It is at these primary substations that the voltage is dropped to 33KV for distribution to several injection substations. At the injection substations, the DisCos could further step down the voltage to 11KV using 33KV/11KV transformers. The power can then be distributed using the 11KV feeder lines. Power distribution is also done using 33KV lines in certain instances. For residential areas, the 11KV voltage is stepped down to between 220-240V consumption capacity using secondary transformers located nearby. However, power could be distributed to heavy industries, factories, airports, and large commercial buildings at 11KV or even 33KV and stepped down using various 33KV/415V and 11KV/415V transformers.

For independent Power Producers (IPPs) and captive power solutions, the use of the Transmission Company of Nigeria (TCN) is greatly reduced. In the case of embedded power generation, a distribution network is needed thereby eliminating the need for transmission [35]. A case study is Elektron Energy Limited, a company building Nigeria's first truly embedded power solution with the Victoria Island Independent Power project in partnership with Eko Electricity Distribution Plc (EKEDP) [37]. The IPPs may also build their distribution networks and install ring main units (RMUs). However, for power generation from (1MW and above), transmission, distribution (100KW and above), and energy trading, such independent power producers must obtain an operating license from the Nigerian Electricity Regulatory Commission (NERC) [33].

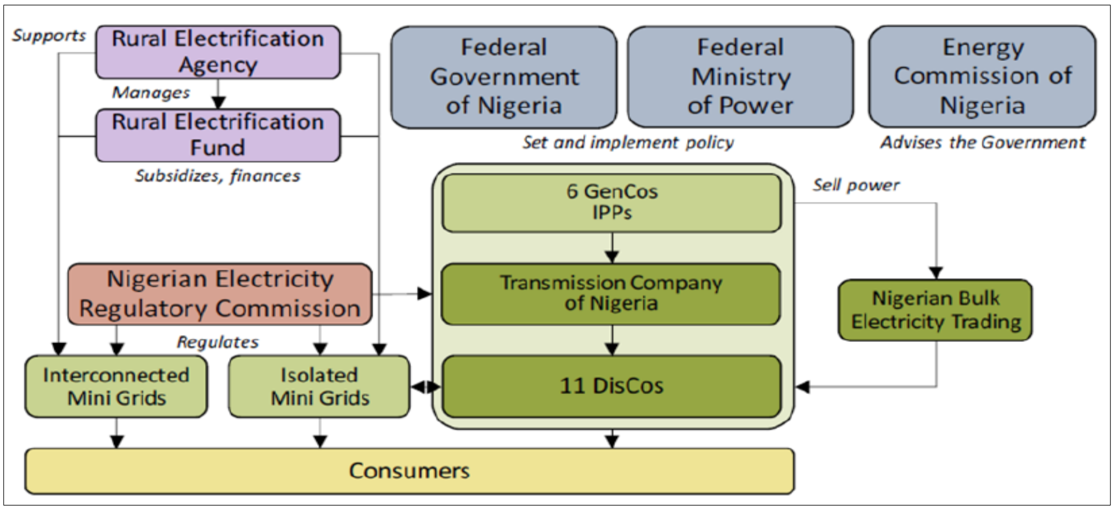

Figure 6 The Nigerian Power Sector and key stakeholders [35]

2.4. Current Challenges in Power Generation and Supply in Nigeria

Nigeria is yet to get it right when it comes to power generation and supply. The low generation, supply, and consumption are affecting the country in various areas. The weakened industrial sector in the country is a direct consequence of epileptic power supply in the country [28]. Despite the efforts of the Federal Government of Nigeria to remedy the situation, some challenges remain some of which are given below:

- Inadequate generation to meet current power needs [33].
- Use of worn-out generation turbines and constant breakdown of machinery and equipment [38].
- Growing population and the corresponding increase in power demand [16].
- Lack of State Governments' participation in the power sector [35].
- Stalled generation due to water management and gas supply issues [27].
- Lack of variety in the energy mix [33].
- Poor access to finance by Independent Power Producers (IPP) companies for off-grid power projects [27].
- High power losses (technical and commercial) in transmission and distribution [35].
- Use of outdated transmission and distribution equipment in some parts of the country [27].
- Insufficient power distribution infrastructure by Distribution Companies (Discos) [35].
- Vandalization and theft of generation, transmission, and distribution equipment [2].
- Inefficacy of the Rural Electrification Agenda [35].

The Federal Government of Nigeria is making conscious efforts to surmount these challenges. Private sector participation is generally sought after at the moment [13]. The government is trying to woo local and foreign investors into the sector. Another conscious effort is the diversification of energy resources for power generation. The Central Government seeks to incorporate renewables into Nigeria's energy mix. Hopefully, these efforts will start yielding possible results in the nearest future.

3. Biomass as an alternative for Power Generation in Nigeria

The major resources used in power generation in Nigeria are natural gas and water [15]. Due to unstable supply, many Nigerians have resorted to mini generators to power their homes. Larger businesses and industries generate their power for daily operations using heavy-duty power generators [13]. This makes Nigeria rank high as the world's largest importer of generators (gasoline and diesel-powered) [5]. The greater effect is on businesses and commercial activities in the country. Incessant power outages and the increasing running cost for these generators are among the chief reasons why some companies leave Nigeria [20]. Other issues resulting from the use of large numbers of generators are the release of carbon monoxide (CO) and other poisonous gases and solids into the atmosphere and noise pollution prevalent in industrial and commercial clusters in many cities in Nigeria.

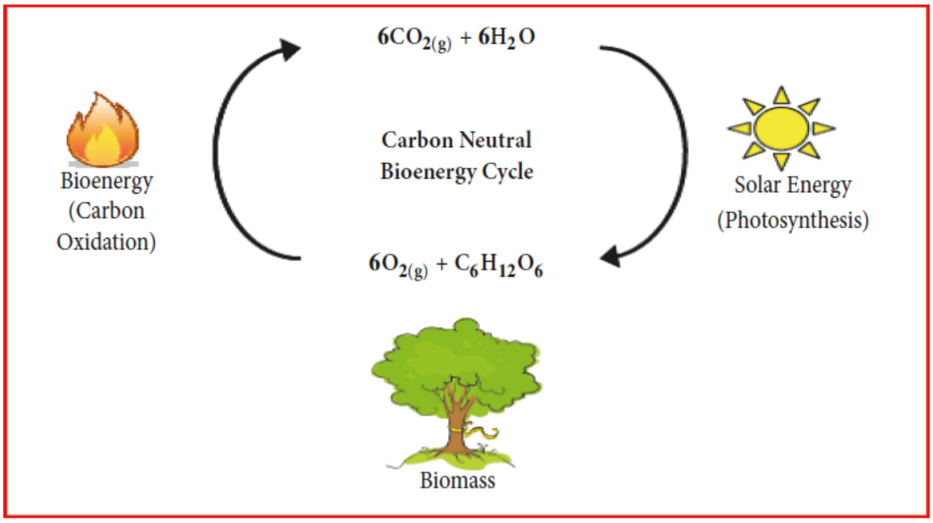

Figure 7 Biomass ensures a balanced carbon cycle [16].

The finite nature of petroleum resources is another major issue Nigeria should start considering biomass as an alternative [3]. If new petroleum reserves are not discovered, the current oil reserves will be depleted in about 50 years and gas reserves in 115 years [16]. Biomass, on the other hand, is readily available and renewable. The organic molecules in biomass having chemical energy can be converted to thermal, mechanical, and/or electrical energy when harnessed.

Incorporating biomass into Nigeria's energy mix would also improve the socioeconomic development of Nigeria [13]. It would create jobs for many in the agricultural and waste management sectors. It would also improve the green and circular economy in Nigeria and help achieve the Kyoto Protocol by reducing the emission of greenhouse gases from fossil fuels [26]. The use of waste components and biomass residues can take care of the high amount of waste generated in the country [5]. In recognition of the immense contribution biomass could have on Nigeria's generation capacity and environmental sustainability, the Federal Ministry of Environment, in collaboration with the United Nations Development Programme (UNDP), included biomass resources in the Renewable Energy Master Plan (REMP) and aims to implement it to the fullest [33]. The REMP program, launched in 2006, aims to boost the integration of renewable energy into Nigeria's energy mix.

Table 2 Renewable Energy Master Plan (REMP) and targeted generation from renewable energy sources [12, 33].

Energy Resource	2010 (MW)	2015 (MW)	2030 (MW)
Large hydro	1,930	5,930	48,000
Small hydro	100	734	19,000
Solar PV	5	120	500
Solar Thermal	0	1	5
Biomass	0	100	800
Wind	1	20	40
Total RE	2,036	6,905	68,345
Total Energy Resources	16,000	30,000	192,000
Percentage of RE (%)	13	23	36

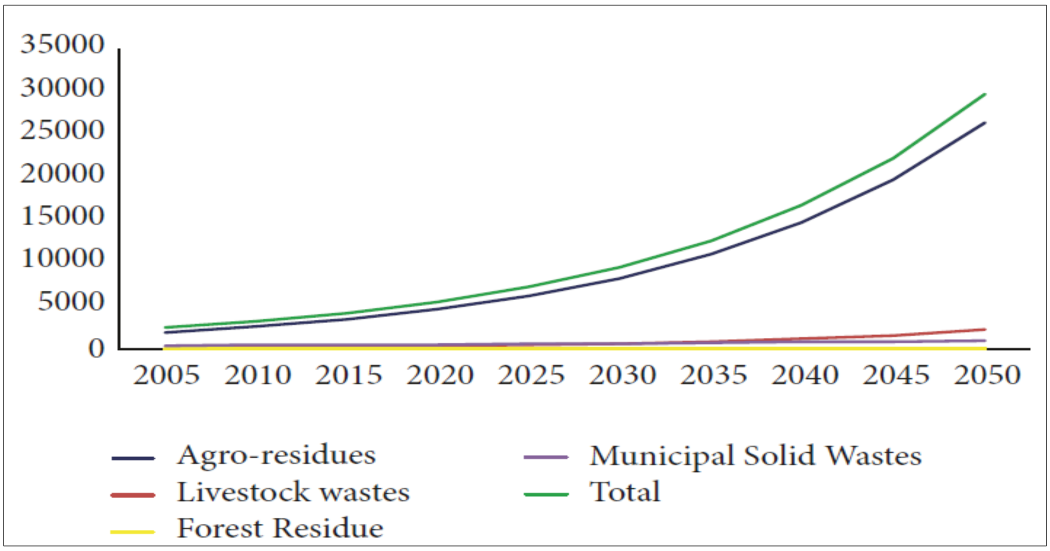

Figure 8 Energy potential per annum of available biomass resources in Nigeria [16].

3.1. Availability and Energy Potential of Biomass Resources in Nigeria

Biomass is abundant in supply across the 6 geo-political zones in Nigeria. Almost 70% of Nigerians use biomass for cooking and other daily activities [2]. The country produces an estimated 144 million tons of biomass annually [29]. In Friday and Oyekale [21], it was reported that the available biomass resources in Nigeria exceed 200 billion kg with a greater majority coming from charcoal and woody fuel. Jekayinfa et al. [14] report that more than 2.3 EJ of energy can currently be harnessed from Nigeria's biomass resources. Ojolo et al. [1] give a more specific figure and pegs the total energy potential of biomass in Nigeria to be about 5.5EJ as of 2020 with the possibility of increasing to 29.8EJ by 2050. While biomass resources might not be able to cover all of Nigeria's power needs [5], it is more than enough to meet the country's traditional energy needs and can complement modern energy applications [11]. If properly harnessed, the biomass resources in Nigeria can contribute a great deal to power generation in Nigeria.

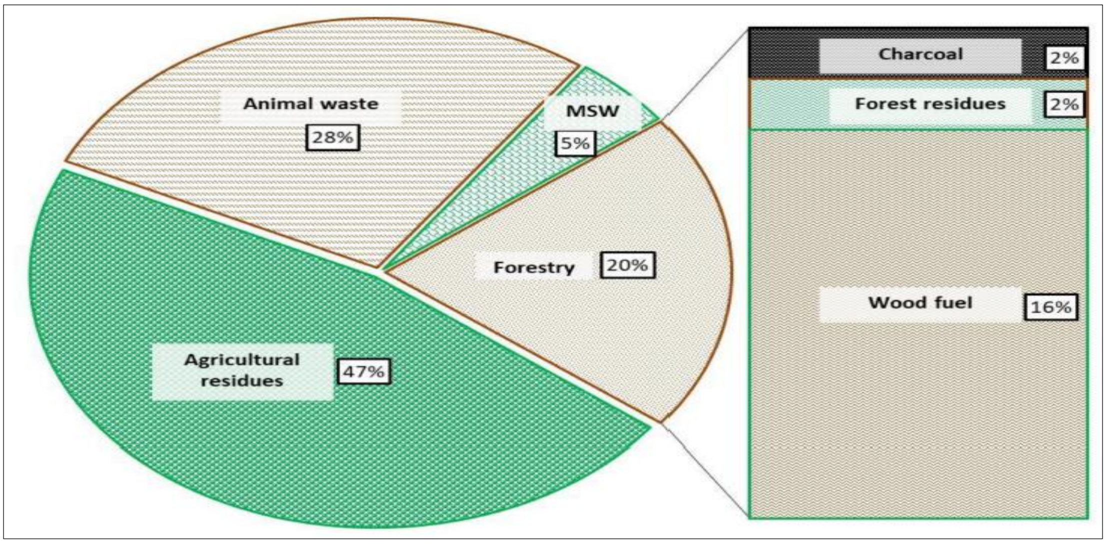

Figure 9 Contributions to Nigeria's biomass resource pool [14]

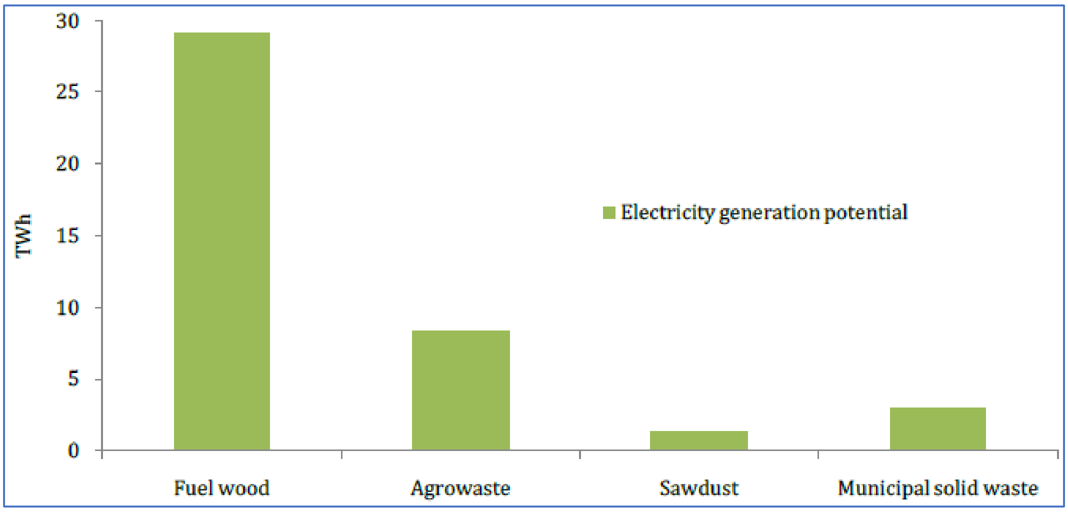

Figure 10 Electricity generation potential of some Biomass resources in Nigeria [20].

Biomass resources in Nigeria are nominally grouped into agricultural biomass (energy crops, perennial crops, etc.), agricultural residues, forest residues, and municipal solid wastes [1]. They occur naturally in solid, liquid, and gaseous forms [2]. Friday and Oyekale [21] report that biomass in solid form is the most abundant and commonly used in the country. But the ones in liquid and gaseous forms that exist are also useful. The highest contributor to the biomass resource pool in Nigeria is agricultural biomass and residues [1]. It was reported by Emberga et al. [39] that Nigeria produces 227,500 tonnes of animal waste daily which could result in the daily production of 6.8 million m^3 (cubic meters) of biogas. Oluoti et al. [20] state that wood waste produced in Nigeria was about 5.2 million tonnes per annum out of which sawdust accounts for roughly 1.8 million tonnes per annum. The theoretical yield of forest residues in Nigeria is estimated at 8.7 Mtoe [5]. Crop residues in Nigeria could produce 13 Mtoe of biogas and 8 Mtoe of ethanol annually [15]. Also, about 20kg of municipal solid waste (MSW) is reportedly generated in the country daily [11]. These municipal solid wastes, when harnessed properly, could contribute between 6 to 52% of the current power supply in Nigeria [5].

Table 3 Biogas production potential from waste materials in Nigeria [26].

Organic Wastes	Amounts in Units (millions)	Total Biomass generated (millions per tons year-1)	Estimated biogas potential (billion m3 year-1)
Urban solid waste		39.1	33,150
Crop remnants		83	117,000
Human faeces	130	52	65,910
Slaughterhouse remnant		83.3	103,350
Poultry droppings	112.9	32.6	64,350
Pig excrement	9.6	15.3	21,450
Sheep and goat excreta	100.9	39.6	62,790
Cattle excreta	21	197.6	142,350
Aggregate	25.53	15.65	610,350

Table 4 Energy crops production data in Nigeria [28, 40].

Resources	Production Area (10^6 ha)	Total Production (10^6 MT)	State with Highest Production	Production Capacity (10^3 MT)
Cowpea	2.860	3.368	Benue	0.428
Cassava	3.482	4.2533	Benue	3.792
Maize	4.149	7.677	Kaduna	0.436
Cotton	0.399	0.602	Zamfara	0.155
Soybeans	0.291	0.356	Benue	0.079
Groundnut	2.785	3.799	Niger	0.547
Sorghum	4.960	7.141	Kano	0.746
Millet	4.364	5.171	Sokoto	0.714
Rice	2.433	4.473	Kaduna	0.732

Table 5 Average annual production of crop residues in Nigeria [12].

Crop	Residue type	Residue amount (Gigagrams, Gg)	Energy (PetaJoules, PJ)
Maize	Stalks	5,938.01	69.83
	Cob	1,473.70	17.33
Cassava	Stalks	1,052.54	12.38
	Peelings	7,716.56	90.74
Rice	Straw	2,918.50	34.32
	Husk	806.37	9.48
Groundnut	Straw	1,369.25	16.10

	Husk	1,038.14	12.20
Yam	Peelings	6,372.83	74.93
Sorghum	Straw	5,304.86	62.39
Millet	Straw	4,571.40	53.76
Groundnut	Straw	1,369.25	16.10
Total		39,931.41	469.56

Biomass resources differ in their energy potential just as they do in their sources [41]. Studies have been carried out by various researchers on the potential energy each biomass resource can yield on its own [21]. This is a very important detail as it helps to characterize biomass resources and ascertain which to incorporate into the energy.

Table 6 Biomass Energy Potential in Nigeria in [41].

Biomass resource	**Quantity (billion kg/year)**	**Estimated energy potential (PJ/year)**
Crop residues	153.76	2,033.85
Perennial crop residues	2.35	28.88
Forest residues	19	362.95
Municipal solid wastes	4.51	21.36
Animal wastes	17.69	106.39
Human wastes	2.87	28.83
Overall total	200.18	2,582.26 (61.67 Mtoe)

3.2. Biomass Conversion to Electric Power

Biomass conversion technologies refer to the processes that valorize biomass into useful products. Biomass-to-power conversion generates electric power using biomass as the primary, and at most times, only feed stock. A series of technologies exist while research is still ongoing to develop new and more efficient technologies. In selecting the best biomass-to-power technology to use at a particular location or situation, some factors such as biomass fuel available and energy potential, amount of power to be generated, and cost amongst others.

It is common for many biomass-to-power plants to pre-treat biomass feedstock to obtain optimum yield [44]. Biomass pre-treatment often removes impurities from biomass feedstock, increases the recovery energy from each batch, and ensures process equipment durability by reducing their workload. Common pre-treatment methods are chipping, pelleting, briquetting, milling, torrefaction, distillation, hydrolysis, and solubilization, amongst others [43].

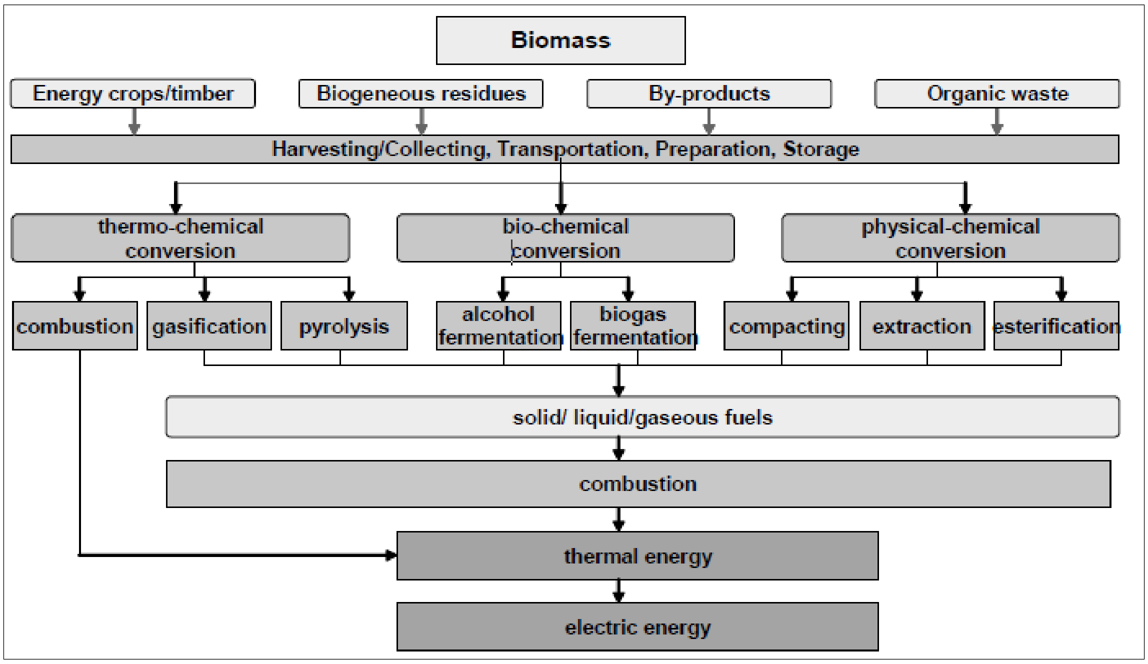

Figure 11 Biomass-to-power conversion processes [42].

3.2.1. Direct Combustion

In this conversion technology, biomass is burned directly in the air to convert the inherent chemical energy into thermal energy (heat). Aside from heat generation, carbon dioxide (CO_2) and water are also produced [23]. The produced heat and hot flue gas pass the thermal energy over to process water producing steam to turn turbines and ultimately generating electric power.

This is the most common biomass-to-power technology used in many parts of the world [21] and it is also the oldest among biomass conversion technologies [42]. It is commonly preferred because of its simplicity and the range of biomass resources that can be used [29]. However, it is amongst the least efficient technologies [23]. Direct combustion is mainly of three types: fixed bed combustion, fluidized bed combustion, and dust combustion but all follow the same general principle [44].

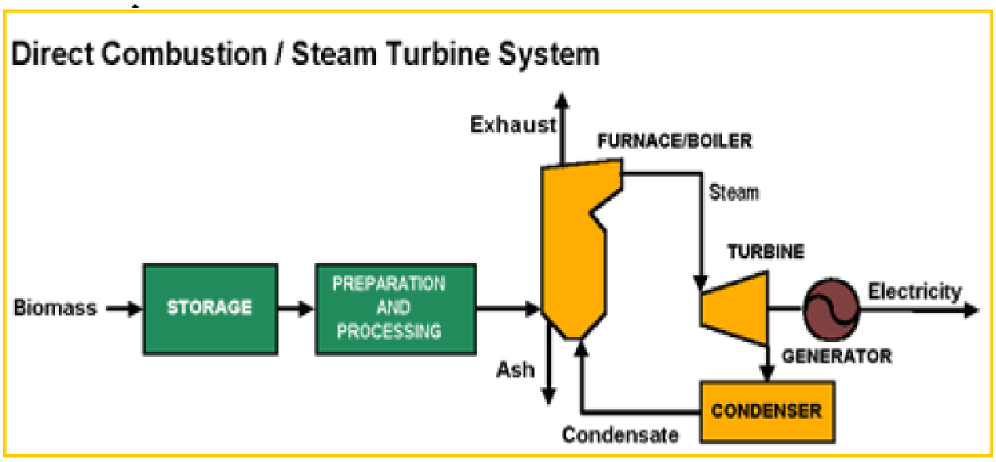

Figure 12 Direct combustion of biomass to generate power [19, 45].

3.2.2. Mixed-Fired Combustion

Mixed-fired combustion technology employs biomass and other fuel sources for the combustion process. The fuel mix then gives the needed thermal energy for the power generation process. In this technology, biomass could be the primary or secondary fuel [19]. But in existing mixed-fired plants, coal is the primary fuel, and biomass is used as a secondary fuel accounting for about 3-5% of composition by mass [44].

Mixed-fired technology can be grouped into three types: direct mix-fired technology, indirect mix-fired technology, and parallel mix-fired technology. The only difference between the three is how the biomass is introduced into the fuel mix.

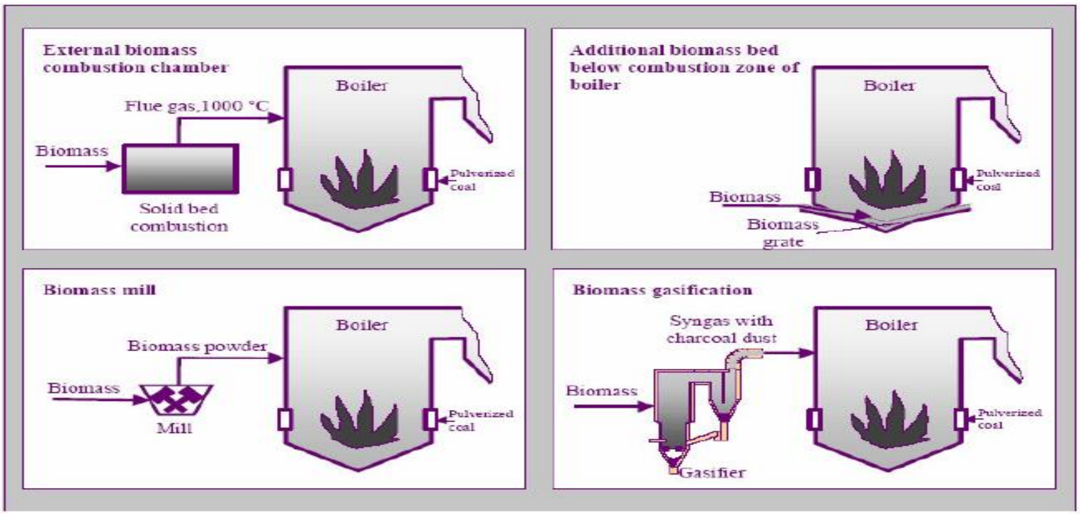

Figure 13 Mixed-firing process with pulverized coal and biomass [44].

3.2.3. Gasification

Gasification refers to the use of gasification agents (air and/or steam) for oxidization of biomass feedstock at temperatures between 800 – 900⁰C to produce combustible gases [29]. The gases produced, called synthetic or syn gas, are of low calorific value (about 4 – 6 MJ) and contain methane (2 – 3%), carbon monoxide (18 – 20%), hydrogen (18 – 20%), carbon dioxide (8 – 10%), and traces of nitrogen, steam, and other hydrocarbons [15, 28]. The produced syn gas can is then used as fuel to drive turbines for power generation. It could also be used in the production of chemicals [29]. The gasification agent, reactor type, and operating pressure affect the efficiency of this conversion process [19].

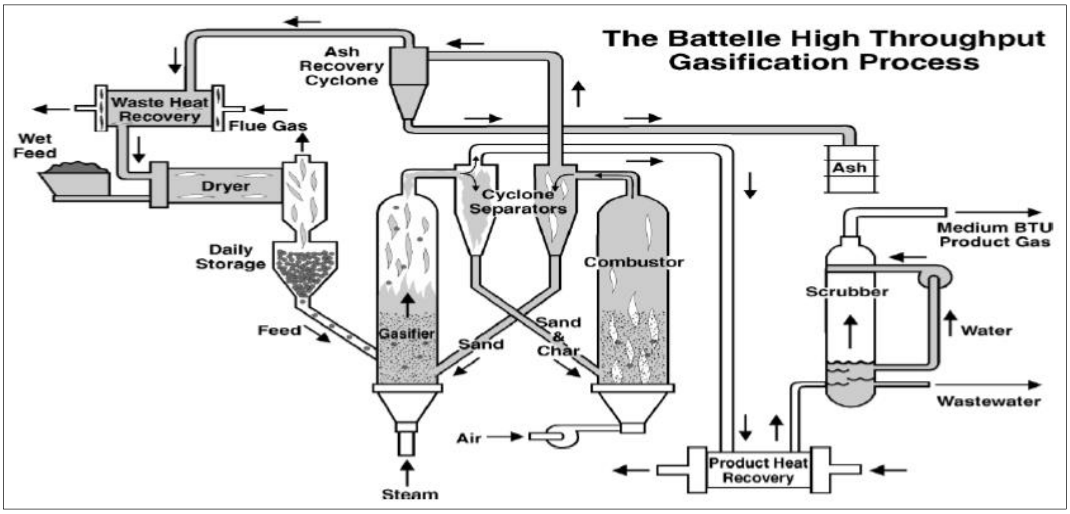

Figure 15 A model Battelle gasification system [19, 45].

Biomass gasification is carried out using a gasification medium, the gasifier. The main types of gasifiers are updraft gasifiers, downdraft gasifiers, crossdraft gasifiers, and fluidized beds [20]. The major determinants of the type of gasifier to be used in biomass-to-power applications are the properties of the biomass feedstock, the amount of power to be produced, and the operating conditions.

3.2.4. Pyrolysis

This is simply the thermal conversion of biomass into combustible gases, solid char, and liquid fuel at a temperature of about 500^{0}C in the absence of steam and air [23]. Pyrolysis can be catalytic or non-catalytic depending on the feedstock involved. For woody biomass, non-catalytic is mostly used while catalytic pyrolysis is mostly used for plastic wastes. The combustible gases produced during pyrolysis can be used to supplement power generation. However, pyrolysis is mostly done for the liquid fuel produced during the process. This fuel called pyrolysis oil, also known as bio-oil or bio-crude, can be upgraded and used in turbines and diesel engines for power generation and can serve as transport fuel [45].

Table 7 Operating conditions for the various kinds of pyrolysis [19].

Parameters	Conventional Pyrolysis	Fast Pyrolysis	Flash Pyrolysis
Pyrolytic Temperature (K)	550 – 900	850 – 1250	1050 – 1300
Heat rate (K/s)	0.01 – 1	10 – 200	>1000
Particle Size (mm)	5 – 50	<1	<0.2
Solid residence time (sec)	300 – 3600	0.5 – 10	<0.5

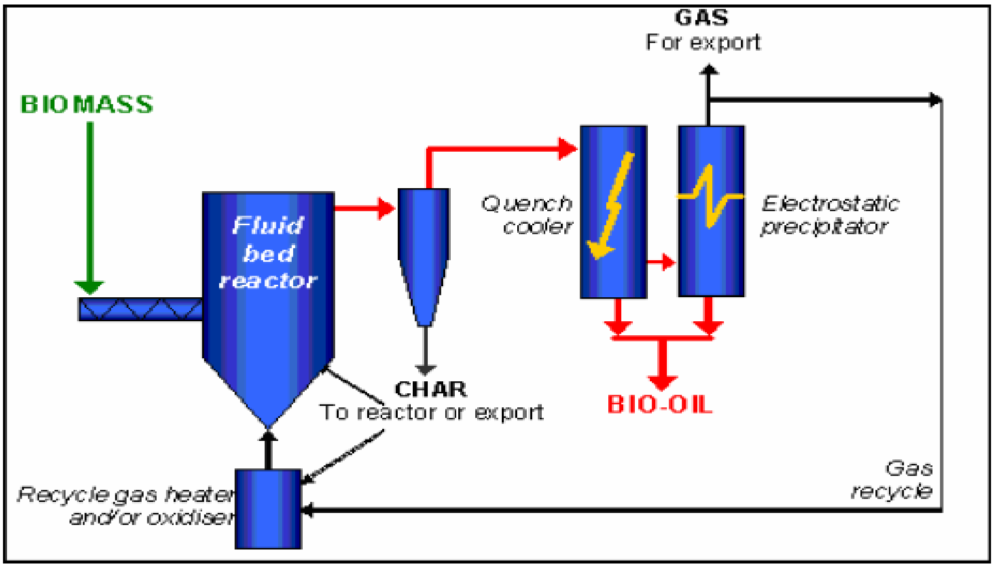

Figure 16 Biomass pyrolysis for gas and bio-oil production useful for power generation [44].

3.2.5. Anaerobic Digestion (Biogas Production)

Anaerobic digestion is the biochemical process of converting biomass into biogas in the absence of oxygen leaving behind a residue called digestate. The biogas produced consists mainly of biomethane, carbon dioxide (CO_2), and about 1% of other gases such as ammonia (NH_3) and hydrogen sulfide (H_2S) [29]. The produced biogas is burned to produce energy to drive turbines and gas engines for power generation while the digestate is used for enriching the soil.

Moisture-rich biomass resources are usually used in this process because they aid microbes in the biodegradation of the feedstock [40]. The Biomethane Potential (BMP) of the biomass resource is considered when choosing a feedstock. The Biomethane Potential (BMP) is the amount of biomethane that can be produced in an ideal situation where there is no digestate production. To obtain more calorific value and increased efficiency in engines and turbines, the generated biogas is cleaned and upgraded [28].

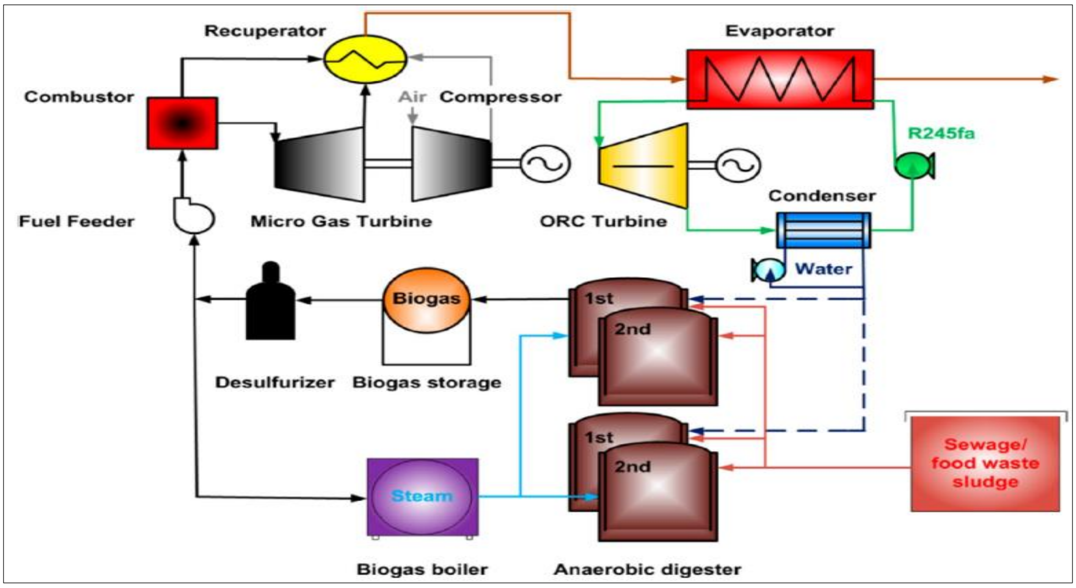

Figure 17 Power generation from biomass using anaerobic digestion technology [46].

3.2.6. Fermentation (Bioethanol Production)

Fermentation, much like anaerobic digestion, is produced from the action of enzymes on biomass and waste feedstock [3]. Bioethanol is commonly used as a transport fuel but can also be used as a feedstock for power generation. The fuel is burned in a boiler to produce heat and steam. It is this steam that turns turbines and engines for power generation.

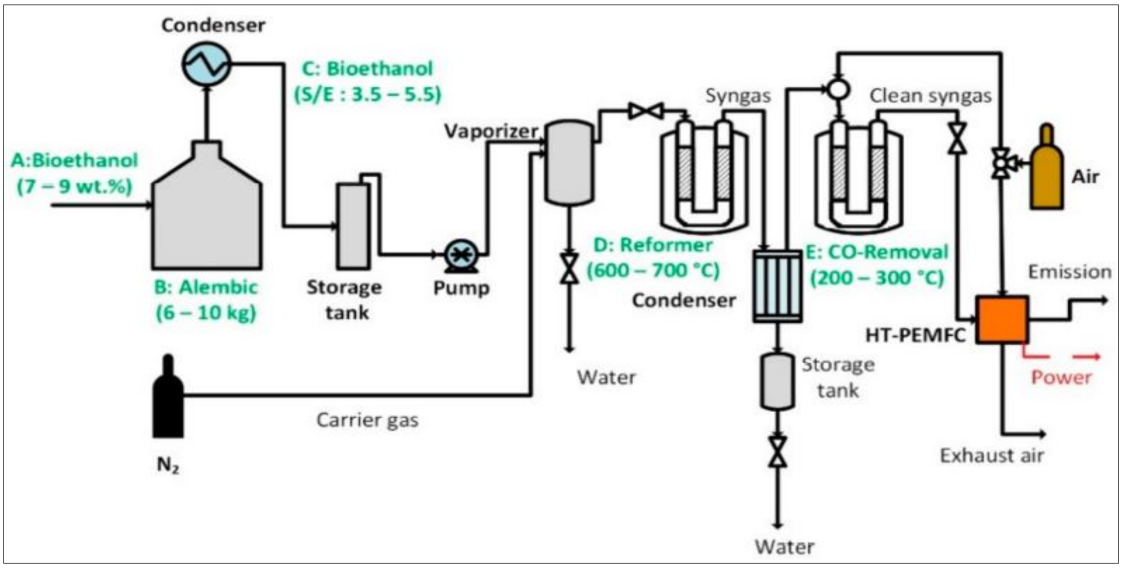

Figure 18 Power generation from bioethanol [47].

4. Opportunities and market for Biomass-to-power solution in Nigeria

4.1. Transmission Connection and Embedded Generation

Biomass power plants can contribute to Nigeria's national grid system and improve general availability nationwide through connected transmission. Such plants could produce and evacuate power to the grid using existing transmission infrastructure owned by the Transmission Company of Nigeria (TCN), the only body in Nigeria saddled with that responsibility. TCN would then transmit to distribution companies (DisCos) for forward distribution to final consumers.

Alternatively, the plants can serve local 11KV and 33KV lines directly removing the need for transmission through embedded generation. Embedded generation is a viable power production opportunity in Nigeria [35]. Once the quality of the generated power is affirmed by the distribution company, the distribution could take place immediately.

4.2. Micro- and Mini-Grid Systems for Local Communities, Markets, and Small Commercial Centers

There have been several suggestions by various researchers on the need for Nigeria to develop more micro- and mini-grid systems [27]. Micro- and mini-grid systems are sets of small power consumption networks that are connected to the larger national grid but are also able to generate and distribute power independently [35]. Although the terms "micro-grid system" and "mini-grid system" are often used interchangeably, the main difference between the two lies in the size of the network and sometimes in the reliability of the system.

There are numerous benefits of having these systems in place in Nigeria. The independence of micro- and mini-grid systems makes them highly efficient and easy to manage [27]. They can aid in delivering power in the event of a national blackout so those connected to the systems would not be affected. Biomass-to-power plants can be incorporated into micro- and mini-grid systems even as the only power source, especially in places where biomass resources are abundant.

4.3. Captive Power Solutions for Heavy, Medium and Small-scale Industries

For constant power supply to aid smooth operations, many industries are going off the national grid and employing captive power solutions. Captive power solutions are power generated and consumed by the same organization [35]. This is common amongst many heavy industries in Nigeria such as oil refineries, crude oil exploration sites, cement plants, and others. However, it remains a huge opportunity in Nigeria. Biomass-to-power plants can serve in this regard and constantly supply industries with power as long as the feedstocks are readily available. A model 60MW biomass-to-power plant can generate about 3,500 jobs across the whole industrial and captive power chain [16].

4.4. Rural Electrification Projects

Biomass-to-power plants can aid in the electrification of rural communities. The Nigerian Government, in a bid to increase energy access to rural and unserviced communities, set up the Rural Electrification Agency (REA) in 2006 [33]. However, REA uses solar energy for most of its projects. It is time to incorporate biomass into the rural energy generation mix for sustainability and efficiency.

5. Challenging Factors mitigating Biomass-to-power Solution in Nigeria

5.1. Cost

Cost is among the main limiting factors in building and operating biomass-to-power plants in Nigeria. Capital investment costs for biomass plants can be quite expensive [5]. Although fossil-power plants are also not cheap, they are more financially viable when compared to biomass-to-power plants, especially for large-scale power generation [44]. The major contributor to the high cost of implementing biomass-to-power plants results from the logistics of sourcing and supplying the needed amount of biomass fuel to keep the plant running. A lot of investment is needed for land and energy crop cultivation [28]. If raw materials can't be sourced locally, transportation costs to convey raw biomass fuel from other parts of the country to the plant can be very high [23]. These all raise the cost of power generation through biomass and ultimately affect the selling price of power generated. Okafor et al. [5] state that raw materials constitute between 60 – 70% of production costs in bioenergy facilities.

In a country like Nigeria where energy prices are regulated by government institutions such as NERC, it would be quite a task for potential investors for biomass-to-power plants. Sobamowo and Ojolo [16] estimated the energy cost of power from gasification at $0.5775 per kWh which is about thrice the electricity tariff set by NERC. The costs of other technologies seem to be higher. Capital energy costs from direct combustion and pyrolysis are about $1.9–2.9/kW and $3.5–4.5/kW respectively. The Nigerian populace can't pay this high because of the economic situation in the country. Hence, biomass-to-power plants can be set up for the major goal of environmental protection [33].

5.2. Inadequate Information on Available Biomass Resources

Nigeria still has lots of biomass and waste resources not properly accounted for [29]. The data collection and reportage system have a great influence on investment decisions by local and foreign investors [5]. Available biomass, waste, and biodegradable resources are not properly reported in the country [26]. Data has a say on the choice of conversion technology and reactor type needed for such technology [30]. While some data may exist in Nigeria, they do not give comprehensive information to guide decision making such as residue estimation, biomass composition, and bioenergy potential [15]. If the government of Nigeria, through the Federal Ministries of Agriculture and Environment, could set up bodies to provide complete and comprehensive data on biomass resources in Nigeria, it could help in the implementation of biomass-to-power plants.

5.3. Poor Waste Management and Energy Recovery

It is important to note that waste collection and management in Nigeria is not as advanced as those of western nations [26]. Waste management is mostly handled by government agencies in many parts of the country aside from Lagos and a few other states that allow private sector participation. Only about 41% of generated waste in the country is collected [5]. The impact of this poor collection, sorting, and management of generated wastes which should have served as good biomass feedstock for power plants, is further environmental pollution [14]. Agricultural and forest residues, municipal solid wastes (MSWs), food wastes and others mostly end up in dumpsites and landfills without any energy recovery plan.

Most waste management agencies in Nigeria have not yet subscribed to the waste-to-energy philosophy and are more concerned about waste disposal. For instance, it was recorded that solid wastes in Nigeria emitted about 491,000 tons of methane in 2015 and could rise to 670,000 tons in 2030 with the potential to generate around 4.74 × 109 kWh by 2030 [5]. If conscious efforts are made to enhance waste collection and energy recovery from wastes in Nigeria, it would aid in biomass-to-power technology adoption and reduce harmful emissions.

5.4. Subsistence Agriculture

Nigeria is still a developing country where most farmers engage in subsistence agriculture to provide food for themselves and their immediate families. Only a few farmers engage in the production of energy crops. Energy crops are plants that are cultivated for their inherent energy potential [29]. Some of the common energy crops in Nigeria are Jatropha, poplar, and eucalyptus [28]. Other well-cultivated energy crops are sorghum, cassava, maize, oil palm, green coffee, sugarcane, cotton lint, millet, and soybean amongst others [29]. Some of these crops, like the Jatropha, are inedible while others also serve as food to humans and/or animals breeding conflicts about whether to grow them for food or energy [5]. As it stands today, preference is mostly given to crops grown for food rather than energy applications [15]. Thus, not all energy crops produced can be used in energy applications [14].

Large-scale cultivation of energy crops is instrumental in improving the availability of biomass resources for biomass-to-power applications. It is capital-intensive and requires expansive land and labor to cultivate and harvest [23]. Other infrastructure and facilities such as irrigation, appropriate fertilizers, and transport facilities must also be available [40]. This often results in some tussle between cultivating energy crops or food crops with the existing resources [19]. Nigerian farmers need to be enlightened and funded to incorporate the farming of energy crops. Despite all the challenges, the cultivation of energy crops increased continually from 2004 to 2013 and continues to rise annually [29].

5.5. Technical Limitations

Biomass-to-power, just like any other biomass conversion and valorization technologies, is a highly technical process. The unit operations in biorefinery and biomass conversion are more complex when compared to oil refineries [5]. The technicality of biomass-to-power has a high impact on power generation, overall efficiency, and profitability of the plants. There is then a need for professionals with requisite skills to build and man the plants. Specialized skills are required for energy recovery optimization, equipment and plant design, and plant operations. Unfortunately, Nigeria does not have it for now [45]. This has hampered the development and commercialization of biomass-to-power solutions and bioenergy applications in general [5, 16].

5.6. Lack of Sufficient Government Support

Despite its support and plans for adding renewable energy sources to Nigeria's energy mix, the Federal Government of Nigeria has not done much in terms of biomass for power generation. The government does not grant financial incentives to prospective investors in biomass-to-power solutions which would have made it attractive. The financial resources reserved for renewable power production are far insignificant when compared to those set aside for fossil power solutions [39]. Also, little or nothing is done about the mass sensitization of the populace on Nigeria's biomass resources and their potential to generate power.

6. Promoting Biomass-to-power solution in Nigeria

6.1. Policy Formulation and Implementation

Biomass-to-power is yet to be implemented in any part of Nigeria despite being in use in many countries across the globe. The Federal Government of Nigeria has a large role to play in seeing the realization of this renewable energy solution. The implementation and sustainability of biomass-to-power solutions in Nigeria would depend largely on government policies [14]. Chanchangi et al. [2] noted that there are no import waivers for players in the power sector. If the government can propose financial inducements, tax rebates, and investment protection, amongst others, for prospective investors, many would grab the opportunity to be part of this energy revolution. These policies would see to the rapid adoption of biomass-to-power and other renewable energy solutions in Nigeria [39].

Another part the government needs to improve on is policy implementation. Some renewable energy policies such as the National Renewable Energy and Energy Efficiency Policy (NREEEP) and National Energy Policy (NEP) created to boost the introduction of renewable energy into Nigeria's power sector, are yet to be fully implemented [14]. The recent Electricity Act 2023 signed into law by President Bola Tinubu holds great promise for the biomass-to-power solution. In the new law, generation companies are to introduce a component of renewable energy in their energy mix. Nigerian Electricity Regulatory Commission (NERC) would also not license any new company until they show proof of producing power from renewable sources. If the government, through NERC, the regulatory body, sees through the implementation of this new law and other favorable policies, legislation, and regulations in Nigeria, it would be easier to implement biomass-to-power in Nigeria.

6.2. Funding Support

Funding remains a very big factor in implementing biomass-to-power solutions in Nigeria. Prospective investors might not have all the funds to build and operate these plants, source raw materials, or upscale their generation capacity. If the government can make funding available through bodies such as the Central Bank of Nigeria (CBN), the Bank of Industry (BOI), and other special interventional renewable energy funds.

Private institutions like commercial banks, venture capitalists, and private equity financing firms can invest and support startups seeking to enter this clean energy business. Most of these private organizations fund businesses that are sustainable and eco-friendly. Biomass-to-power solutions should be considered if a good business model is developed.

6.3. Research, Training and Development

Nigeria has a lot of work to do in this regard. The processes involved in biomass-to-power conversion require the use of specialized equipment. Most of the process equipment are not manufactured in Nigeria and only but few persons in the country can fully operate them [48]. This can be remedied by indigenous manpower development. Key technical and managerial skills needed for renewable energy development should be identified [39]. With this, research and development centers for biomass-to-power solutions can be set up by government agencies such as the Ministries of Power and the Environment in conjunction with key local and international renewable energy players. This would see to the rapid implementation of biomass-to-power in Nigeria and the overall shift to renewable power generation.

6.4. Marketing and Promotion

Massive sensitization needs to be done if this renewable power solution is to be implemented in Nigeria. There is a need to identify stakeholders in the biomass-to-power value chain. These stakeholders are the farmers engaged in energy crop production, waste management agencies, and processing firms, and others involved in biomass feedstock production. Others are generation companies (GenCos), Independent Power Producers (IPPs), Distribution Companies (DisCos), the Nigerian Electricity Regulatory Commission (NERC), Nigerian Electricity Supply Industry (NESI), the Rural Electrification Agency (REA), Energy Commission of Nigeria (ECN), the Ministries of Power, the Environment and Agriculture, the Central Bank of Nigeria (CBN), commercial banks, equity financers, venture capitalists, and prospective private investors. The last set of stakeholders is the public who would be consuming the power generated from biomass-to-power solutions.

Upon identification, the next step is to engage these stakeholders through local and international conferences, symposia, media briefings, mass sensitization, etc. The main goal here is to enlighten and promote the biomass-to-power solution as efficient and sustainable. With critical interest and inherent challenges stalling its implementation this solution can be identified and discussed to see a way out. It could further lead to Public-Private partnerships (PPPs). The government of Nigeria can set up a body to see to the marketing and promotion of biomass-generated power implementation in Nigeria.

7. Conclusion

Nigeria's demand for quality and steady power continues to rise due to its ever-rising population, cultural changes, and increase in economic activities. Despite having abundant energy resources, the country remains energy-poor. Nigeria's current power generation is insufficient to serve her energy needs leading to low electricity consumption per capita, individual importation and use of multiple diesel and gasoline-powered generating sets, noise pollution, and uncontrolled emissions of greenhouse gases (GHGs). The greater part of Nigeria's power generation comes from fossil fuels which are not renewable and further add to the pollution problem. This paper therefore considered the viability of Nigeria's biomass resources as a worthy power generation alternative. The available biomass resources in Nigeria were assessed and their potential for power generation was discussed. It was shown that although biomass alone could not solve Nigeria's power needs, there are enough biomass resources to add to Nigeria's energy mix and support other traditional energy demands. The various biomass-to-power conversion technologies were identified as combustion, mixed-firing, gasification, pyrolysis, anaerobic digestion, and fermentation. The mitigating factors to the biomass-to-power solution in Nigeria were identified as cost and funding, inadequate information on available resources, unfavorable government policies and support, and technical limitations, amongst others. These can be surmounted by government action in policy formulation and implementation, credit access for prospective investors, investment in research, training, and development, and good promotion of the solution. This work shows that if the biomass resources in Nigeria can be properly harnessed, the biomass-to-power solution can be used for embedded generation, captive power solutions, mini-grids, and rural electrification which could increase power availability and electricity access, lessen the burden on the national grid, and increase Nigeria's carbon credit by reducing greenhouse carbon emissions due to biomass' balanced carbon emission structure.

Compliance with ethical standards

Acknowledgements

The author wishes to express his profound gratitude to his professors and academic mentors. Engr. Prof. Madueke S. Nwakaudu, Engr. Modestus O. Anusi, Engr. Dr. Innocent S. Ike, Engr. Anyadike Nkwocha, Engr. Ogbonna Nkuzinna, and all academic and non-academic staff of the Department of Chemical Engineering, Federal University of Technology, P.M.B, 1526, Owerri, Nigeria.

The author also thanks the management and entire staff of Elektron Energy. Mr. Omotola Talabi, Mr. Deen Solebo, Mr. Jide Onakoya, Engr. Gbenga Ajumo, Engr. Oladipo Ogunniyi, Mr. Oluwadamilola Abolarinwa, Engr. Alexander Nelson, Engr. Obed Okoeguale, Engr. Damilola Alli, and every member in the team working to make the goal of renewable and affordable energy accessible to all.

Disclosure of Conflict of interest

The author declares that there is no conflict of interests.

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