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Harnessing bioenergy for sustainable and balanced energy generation in Nigeria

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Abstract

Sustainable energy generation plays a key role in a nation's development. In Nigeria, energy is mainly generated from fossil sources such as natural gas reserves. However, fossil sources pose several environmental and health risks. The use of fossil fuel is characterized by the release of greenhouse gases into the atmosphere, with negative impacts on land and water environments. Furthermore, the increasing human population and increasing scale of industrialization are placing a demand on energy generation in order to remedy the persistent energy shortages currently experienced in the country. In this study, we review alternative platforms for energy generation, with a focus on bioenergy as a dependable option for balancing electricity generation in Nigeria. We highlight the technical processes of bioenergy conversion, the economic impact of bioenergy mixes, and the potential for biogas to complement Nigeria's national grid. Challenges such as inadequate technology, a lack of investment, and policy limitations are considered, along with recommendations for advancing bioenergy adoption. This study concludes that mixing bioenergy into Nigeria's energy system can improve the availability of electricity and reduce dependence on fossil fuels, thereby facilitating a cleaner environment and viable economic growth.

Keywords: *bioenergy, biogas, combined heat and power, electricity*

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1. Introduction

Oil and gas have long been the main sources of energy, revenue, and foreign exchange for Nigeria [1]. However, the advantages do not negate the negative effects of fossil fuel energy. The impact of fossil fuel use is well reported within the Nigerian states. For example, gas flaring and venting are associated with oil production that results in serious environmental concerns [2]. In recent years, there has been a global shift from fossil fuel energy to a sustainable alternative; this shift is also linked to the environmental and health impacts associated with greenhouse gas emissions and depleting fossil fuel reserves [3]. Energy production is a crucial element in spurring economic growth through industrialization, which necessitates a sustainable approach to mitigate the negative impacts of current production [4]. However, Nigeria's energy supply from fossil sources has not been sufficient to cater to the energy needs of her growing population, thereby creating a wide gap between energy demand and supply [5]. Energy is needed for cooking, lighting, electrical appliances, water supply, healthcare, and office spaces, and most citizens now depend on petrol- or diesel-powered generators for electricity [6]. Independent/off-grid electricity generation is twice as expensive as national-grid-supplied energy [7]. Only about 40% of Nigeria's population has access to electricity, with the current electrical system generating an installed capacity of 12,555 MW. Several homes are currently not benefiting from the national grid and rely on unsustainable energy sources for daily activities [8, 9]. In addition to privately owned petrol- or diesel-generating machines, the installation of solar panels for generating electricity is gaining attention [10]. Solar panels capture the sun's energy via solar radiation for electricity generation. Energy derived from renewable sources such as the sun, wind, and biomass are naturally and rapidly replenished. Furthermore, renewable sources do not produce greenhouse gas emissions and are not threatened by finite reserves [11]. Solar energy is presented as a sustainable alternative for salvaging the dilapidating state of Nigeria's energy system. However, significant technological development is needed to overcome the associated strategic and financial challenges [11]. Currently, the financial burden of acquiring a solar system is not affordable for the majority of the population, and there are no government incentives to help low-income families acquire such a system [12]. Furthermore, the materials for installing solar systems, including the battery system, are currently being imported from other countries and subject to international trade agreements and government policies on importation, which could pose a challenge to the use of the corresponding solar systems [13]. Nigeria boasts the presence of diverse raw materials, which could be adopted as resources for the development of alternative energy sources. Harnessing internal resources would not only provide access to

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sustainable energy but create jobs for the growing population and improve the nation's gross domestic product (GDP).

Integrating renewables into the nations' energy mix is a viable option for achieving energy balance. Biomass represents a viable platform for developing sustainable energy. Biomass is a renewable resource and provides the additional benefit of recycling biological waste, such as waste from agricultural farms and household gardens. Harnessing biomass for sustainable energy development has been a subject of research in areas such as biomass pretreatment and bioprospecting for novel hydrolytic enzymes [14, 15]. This review focuses on anaerobic digestion and its contribution in achieving balanced energy generation. Anaerobic digester plants are designed for the anaerobic degradation of organic biomolecules for the generation of biogas and biomethane using microorganisms in the absence of oxygen [16]. This process can be used on a large or small scale to produce energy and manage waste, making it an option for small-scale energy production applications, such as in supporting the energy needs of small and medium enterprises and fulfilling household energy needs. Anaerobic degradation is broadly utilized as a foundation for biochemical energy conversion. This method generates end products such as bioethanol and biogas, which are made up of methane, carbon dioxide, sulfur, and other trace elements. The biogas produced is used in the transport sector as fuel and cooking gas as well as in the electricity sector in the form of biomethane [17]. The digestates are also useful in biofertilizer production. Biomass is a form of carbon source that can serve as an alternative to fossil fuels. Owing to the diverse conversion models, biomass sources account for 14% of the overall energy sources, compared to 5% for other renewables, and they comprised 75% of renewable energy on a global scale in 2012 [18]. Biomass energy has shown potential in efficient energy and electricity generation and is critical to tackling climate change [19]. According to [20], biomass energy accounts for 61% of all the energy provided through renewable sources in Germany, with the prospect of leading to an equivalent reduction in the use of 54 million tons of carbon dioxide. Furthermore, Nigeria's renewable energy and energy policy intends to add 23,000 MW of renewable energy to the existing energy mix [21]. This review highlights and elaborates the potential of harnessing biomolecules from plant biomass for energy and electricity production.

2. Energy use and economic impact

Socioeconomic development in any country is strongly linked to the availability and accessibility of sustainable energy sources, and it is reflected in the measure of energy consumption. Nigeria boasts a growing population (currently over 220 million), with a rapidly expanding economy, which has resulted in a massive increase in the demand for energy [22] in various sectors, such as households, industries, commerce, transport, and agricultural production, constituting a consistent trend. Hence, an increase in energy generation will accommodate the increase in the energy needs of the population. Unlocking and using renewable energy's full potential through its improvement will increase energy production. The inclusion of renewable energy sources in energy systems has been suggested, as it has the potential to reduce greenhouse gases while also improving energy generation. This transition is also beneficial for economic development, as it provides greater access to energy [23]. Electrical power—a form of energy—has been identified as a major limitation to Nigeria's economic growth and greatly influences the distribution of industries in the country [24]. Nigeria has an abundance of the raw materials required to develop enough energy to meet the present and future energy demands; however, it still has limited power available for household and industrial use. A large percentage of citizens (about 95 million citizens) still receive an irregular supply or no power from the national grid, and fuel scarcity/the industrial action of oil workers are recurrent events, demonstrating the nation's local energy challenges. Nigeria produces about 12,000 MW of electricity, with 85% of its electrical production fueled by natural gas. The current production output is below the installed electric production capacity of 12,500 MW. This underutilized production capacity, resulting in a reduced electricity supply, is attributed to operation and transmission constraints and deliberately damaged gas pipelines [7]. Considering the structural challenges hindering electricity generation, transmission, and distribution, as well as their impact on economic development, an alternative sustainable energy source is needed to support Nigeria's energy needs. The federal government of Nigeria has set up a National Renewable Energy Action Plan (NREAP) in order to ensure the provision of grid-connected renewables with a production target of 13,800 MW of electricity by 2030 [25]. The technology for generating solar energy has advanced in recent years, while the direct use of biomass is mostly practiced in rural communities where a national grid supply is mostly inaccessible. The major disadvantage of the latter is its detrimental effect on the ecosystem and soil structure. The direct use of biomass produces large amounts of smoke, which claimed the lives of about 95,000 Nigerians in 2011 [7]. The technology required to convert and advance the utilization of bioenergy is being used in countries such as Germany. Nigeria can purchase and install such technology with the help of trained personnel to improve electricity generation through bioenergy. The scale of bioenergy utilization in electricity generation is low, even though there is potential considering the available materials for production. However, there has been improvement in solar installations across the country. Conversely, **Figure 1** shows a comparison of the utilization of renewable energy from different countries, which indicates that Nigeria has yet to harness its potential in the renewable energy sector. It suggests that Nigeria's renewable sector has yet to develop, and the only country lower in this respect appears to be Ghana.

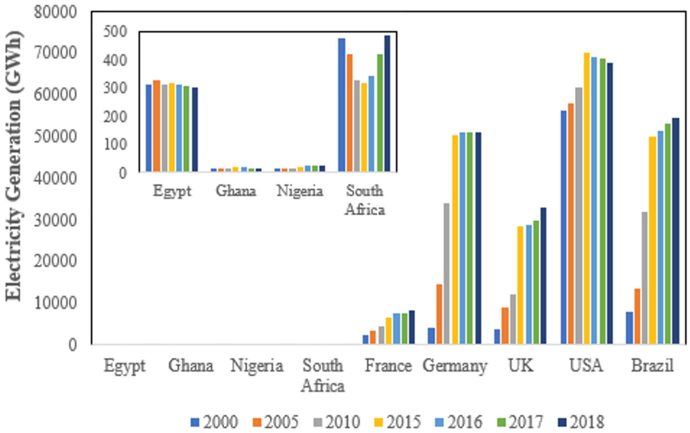

Figure 1 • Electricity generation from different countries. Source: IRENA, 2018 [26].

2.1. Bioenergy conversion system

An increased use of renewable energy has been observed, with biomass making up 10% of the total global energy demand [27]. Biomass energy can be converted into different types of bioenergy that can replace fossil fuels in energy-driven sectors. Furthermore, energy from biomass is flexible because it can be stored and used when needed. This quality is important, especially in comparison to the other, unstable renewables [17]. Generally, the principles and concepts guiding bioenergy production differ in the sense that there are biochemical, physicochemical, and thermochemical conversion processes used for the production of different biomass energy phases, as shown in **Figure 2**. In addition, biochemical conversion involves the use of anaerobic digestion and the fermentation of organic matter into biogas and bioethanol, and physicochemical conversion involves the use of oils extracted from seeds for energy production, like pyrolysis oil, while thermochemical conversion involves the use of solid biomass for energy production, e.g., concerting wood to charcoal. Synthetic natural gas, hydrogenated biofuels, and biomethane can be obtained via advanced processing; therefore, it is possible to use different channels for bioenergy provision. It has been proven that the energy obtained from biomass can be applied in combined heat and power systems, the transport industry, and electricity provision [12]. According to the International Energy Agency [18], biomass energy accounts for 14% of the total primary energy, as opposed to the 5% contributed by other renewable energy sources. Moreover, Germany consumes about 61% biomass energy, and this energy has contributed to an approximate 37.2% reduction in the use of greenhouse gases [20]. The abundance of agricultural biomass in Nigeria can influence energy generation positively, as it is underutilized. Its availability, without being properly channeled to useful ventures, contributes to environmental waste. The anaerobic degradation processes used to generate biogas have long been applied in different countries. The adoption of such processes in Nigeria will aid in the advancement of its energy system. This highlights the importance of agricultural residues to Nigeria's electricity generation system.

2.2. Agro-waste transformation route

Nigeria produces a significant amount of agro-waste after harvest. This agro-waste is left to decay, constituting an environmental hazard because of contaminating the atmosphere with pungent odors. Some of these wastes are renewable energy material because of their bioenergy potential. However, the process of extracting the embedded energy is referred to as anaerobic digestion. This is a variation of a biochemical activity that is exploited for waste management and energy formation. There are four essential steps involved in anaerobic digestion: hydrolysis, acidogenesis, acetogenesis, and methanogenesis. Biochemical activities comprise the degradation of constituents, which converts biomass into smaller molecules. The conclusion of anaerobic degradation leads to the formation of methane, carbon dioxide, etc., which are referred to as biogases [28]. Hydrolysis is essentially the breakdown of biomass in the presence of a catalyst and water. This process allows the biomass to be disintegrated into substrates, which include proteins, carbohydrates, fats, and sugars. However, these products are also further degraded into amino acids, fatty acids, and sugars. This is because there is a need to enter the next stage of breakdown, which is fermentation. The process of fermentation occurs in an acidic pH medium; therefore, the organisms involved in this stage of degradation have the capacity to survive in such an environment. The products of fermentation, which include volatile fatty acids, carbonic acid hydrogen, carbon dioxide, etc., will still need to be broken down further, as the goal is to produce methane. Therefore, acetogenesis, a process in which these organic molecules

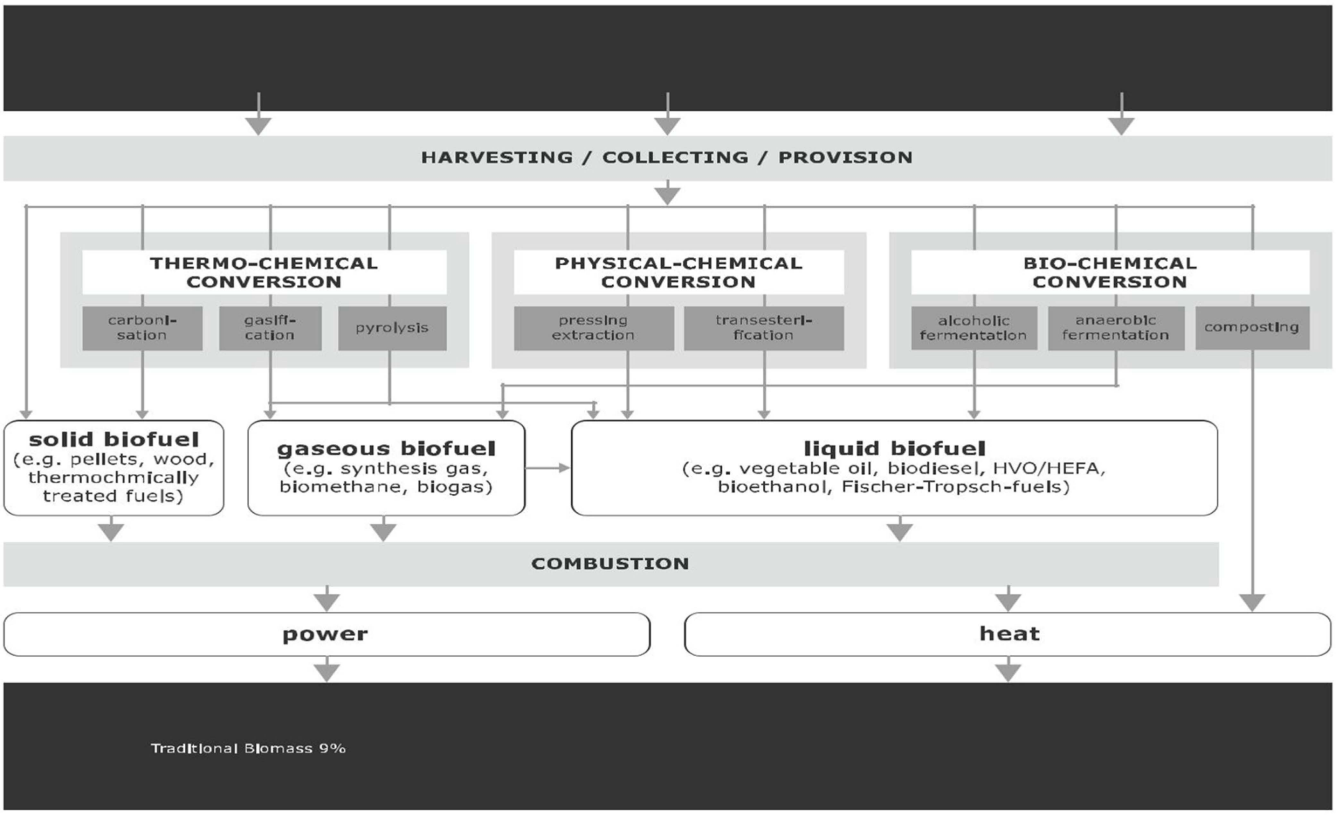

Figure 2 • Biomass energy conversion concepts. Source: IEA, 2013 [18].

form acetic acid, hydrogen, and carbon dioxide via acetoclastic or hydrogen-syntrophic organisms, takes place. Furthermore, these products of acetogenesis are introduced in the methanogenesis stage, where they are converted by methanogenic organisms to form biogas. The intricacies of the formation of biogas have been reported by [19, 29, 30] in relation to the different roles performed by microorganisms and the environment. However, [31] reported that, with the optimization of augmented plant biomass, the possibility of efficient biogas production is dependent on the microbial community and environmental factors. Different microorganisms contribute to various stages of anaerobic digestion. Moreover, biogas produced through anaerobic digestion processes can be used for different applications; for example, biogas is used as transport fuel, injected into the electricity grid, upgraded to biomethane, etc.

2.3. Biogas digesters

Different types of digester plants can be designed, constructed, and used for anaerobic digestion. They can be categorized into two types:

(A) Batch digesters: Here, the substrates are introduced into the digester and allowed to degrade within a specific time frame. The period given for complete degradation is dependent on the characteristics of the substrates involved. Generally, the period is usually within 30–70 days.

(B) Continuously fed digesters: In this case, the digester is constructed to accommodate the continuous loading of the substrates. These substrates are usually introduced to the digester on a daily basis, while the degraded substrates are passed out through an outlet chamber. Therefore, the degradation period is not considered during the use of this bioreactor (**Figure 3**).

However, biogas digesters are not limited to the two aforementioned types. They are also categorized in consideration of the substrate's characteristics. In view of the total solid (TS) characteristics of the substrates, biodigesters are categorized into two types: liquid- and solid-state anaerobic digesters; the former operates with about 15% maximum total solids, while the latter operates with 15% minimum total solids [32]. The liquid-state type is more reliable for substances with high moisture content, such as wastewater [33]. Materials that are watery are suitable for a continuous stirred-tank reactor (CSTRs) due to its capacity for simultaneous operation. The substrates can be fed while the digestate is being removed. This digester can process solid substrates, but it has poor performance for lignocellulose materials due to its capacity to form a detached layer on the liquid. The upflow anaerobic sludge blanket (UASB) reactor, a single-stage reactor, was designed to treat high-rate sewage wastewater [34]. This reactor was developed to abate microbial washout through the separation of the solid retention time (SRT) and hydraulic retention time (HRT). However, it is proficient in processing lignocellulose-rich substrates with less water and energy input for mixing and heat [35]. The plug flow digester is a type of digester that was designed to handle viscous material. The batch digester is also appropriate in the processing of lignocellulose materials. The process requires the digester to be loaded with the substrate and left for a specific period before discharging the digestate. A significant application of this process includes a series of batch digesters with filtration and without a power-driven mixer, which can be utilized for the degradation of single-energy crops [36]. Consequently, digester performance is

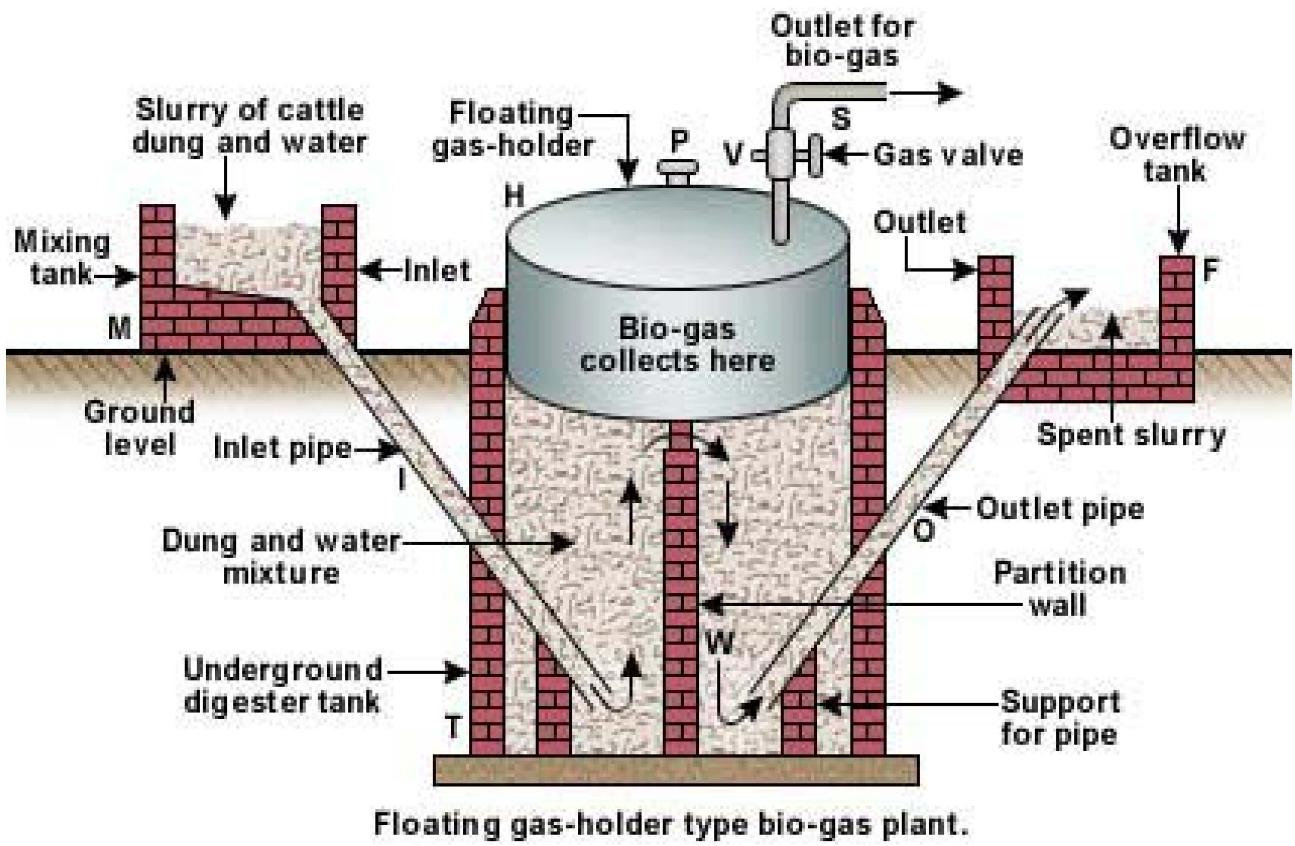

Figure 3 • Floating gas-holder-type biogas digester plant. Reproduced from [37].

unique to the substrates and the design, as the particular design of a digester cannot be applied across different substrates.

3. The impact of bioenergy in balancing electricity generation

Different countries are gradually shifting to renewable energy, of which bioenergy is a component. Biogas is mostly utilized for electricity, heat, and transportation fuel production. Brazil, for example, converts about 85% of its biogas to electricity, and about 55% of the biogas produced in Germany is used for electricity production. In Norway, the biogas produced is mostly utilized as vehicle fuel [38]. In Nigeria, biogas production for injection into the electricity grid is yet to be materialized; nevertheless, the country has immense potential for bioenergy use as the resources are readily available and cheap. As shown in **Figure 4a**, biofuels and waste are utilized for domestic energy production in Nigeria but not channeled into electricity generation, and there has been a continuous increase in the energy generated from biofuels. Therefore, it has become pertinent to include bioenergy in the electricity grid, as the existing scale of electricity production from the grid is inefficient. These gaps can be filled with proper bioenergy production processes. The majority of Nigeria is in dire need of energy, and the inconsistencies in electricity production have influenced the economic output of the country and impacted the populations that require this energy. Therefore, the utilization of bioenergy for the electricity balancing of the grid is of fundamental importance to the country. Although the focal role of bioenergy in electricity balancing is not contentious, there are other renewable energy sources that can compete with bioenergy, such as solar power and hydropower systems. However, their utilization will depend on the needs and demands of local people. Consequently, the present state of bioenergy utilization as a balancing option in the electricity grid in Nigeria has not been fully exploited, probably because of the lack of technological advancements and the training of personnel. According to the [38], about 75% of the electricity consumed in Nigeria is mainly obtained from natural gas, while the remaining 25% is from solar and hydro energy, as presented in **Figure 4b**. As the population has little awareness of these energy processes, there is very little willingness to harness the potential of renewable energy. Nonetheless, with the introduction of government policies,

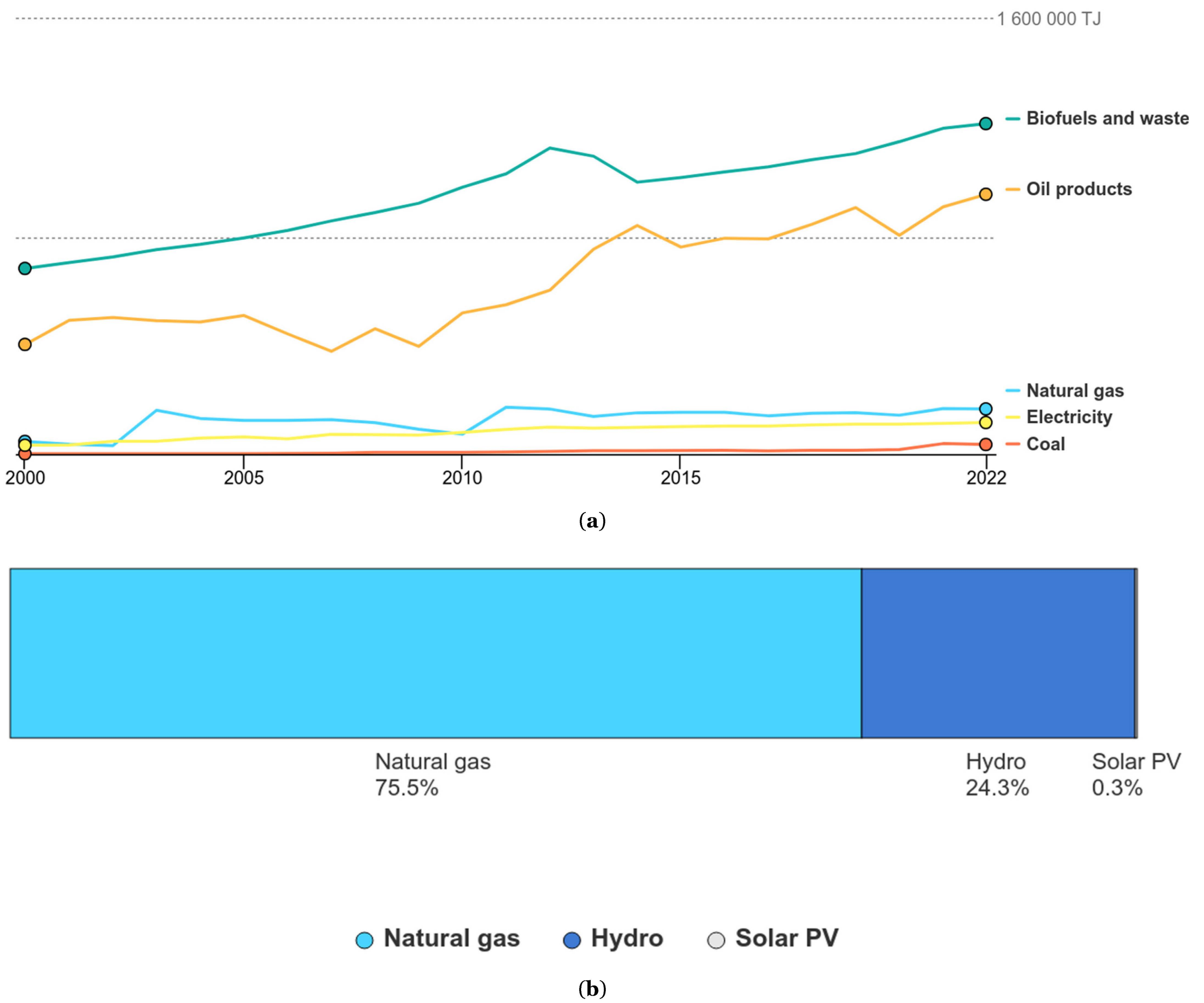

Figure 4 • (**a**) Evolution of total electricity consumption in Nigeria since 2000. (**b**) Electricity generation sources in Nigeria, 2022. Source: IEA, 2022 [38].

incentives, regulations, and interventions to help bioenergy to thrive, the attraction of investment might increase in this sector, as government programs aim to increase awareness and make it easy for businesses to become involved [39]. Moreover, considering the forest plantation distribution of lands per state in Nigeria, there will not be a lack of feedstock for bioenergy use as all the states have the potential to engage in bioenergy production.

4. Biogas conversion pathways

Biogas conversion pathways are processes that illustrate biogas energy utilization systems. The application processes are in accordance with the objectives of their production. However, biogas must be produced before it can be used for appropriate consumption. Dzene et al. [40] highlighted various ways that produced biogas energy can be made available for usage. There are five essential ways this gas can be utilized: heat production, combined heat and power generation, grid injection for heat, grid injection for combined heat and power, and grid injection for transporting fuel. More specifically, the applications can be broken down as follows: a. the use of biogas for heat production; b. the conversion of biogas for combined heat and power generation; c. the use of biogas in natural grid injection for heat production; d. the use of biogas in natural grid injection for combined heat and power generation; and e. the use of biogas in grid injection for the transport sector. Upgrading biogas to biomethane is essential for grid injection and the transportation sector. Consequently, biogas energy can be utilized directly to produce electricity and heat or upgraded to biomethane to be injected into the natural gas grid for storage, and in this form, it can also be used for electricity and heat production.

4.1. Biogas supply based on demand

The model of biogas availability, when required, should be embraced, especially in Nigeria's energy sector. It has been ascertained that biogas can be generated to balance power and cover peak loads in electricity generation. In the case of excess energy production, it can be stored at the production site for a short period of time or upgraded to biomethane to be infused into the natural gas grid; **Figure 5** summarizes this process. This is the concept behind flexibilization. This process drives the maximum utilization of biogas energy for electricity production. Dzene et al. [40] reported that addressing the demand for flexible biogas depends on substrate compositions, feeding rates, and biogas digester plant design. However, a biogas storage system is more suitable for a short period (8 h per day), while a biogas upgrade system applies more to a longer period (72 h) based on cost analysis [41]. The reliability of biological processes should be a priority in any program targeting the flexibilization options, as the biological methods have demonstrated themselves to be dependable and not easily influenced by any rapid changes [42, 43]. Electricity produced from biogas is most often used to augment an existing electricity plan and, as such, is based on the reaction and duration time of the demand. Therefore, rapid, average, and extended periods are considered during operation.

4.1.1. Rapid variability (response time: 15 min maximum; period: up to numerous hours)

This sort of demand is attained through the shutdown of or an extensive reduction in the operational performance of a combined heat and power machine for a brief period, mostly up to one hour but also, in certain circumstances, several hours. Negligible modifications to the operation of an entire plant are required for efficient execution. During this process, control technology is a necessity as a recurrent start-up operation has to be maintained. The desired period for the shutdown depends on the stored gas available. However, due to this change, there is a possibility of nominal load waste. Therefore, a minute overcapacity of the storage system is essential to cushion the effect on the supply.

4.1.2. Average variability (response time: 15 min minimum; period: weekly schedule)

In this case, the distance and the extent of load rotation are greater compared to those for rapid tractability. The modification is initiated within a day or two. According to the situation, further improvement may be required to sustain the demand. Therefore, aside from the overcapacity of gas consumption and an adequate storage system, an enhancement of the appropriate feeding supervision and biological control system is needed. The total installation carried out on site has to correspond to the necessary load requirements. Coherence should exist between installations and the condition for the load variation; the utilization of surplus heat might require an additional installation.

4.1.3. Extended variability (response time: per season; period: months)

In this case, the energy requirement condition is adjusted for the long term. The motives for this process could include seasonal adjustments, such as the consumption of electricity loads from wind and solar power, especially during periods of prolonged adverse

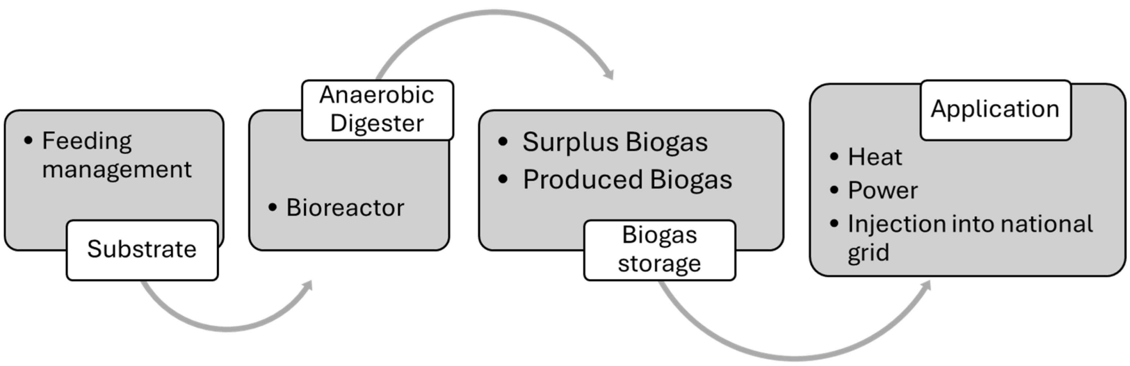

Figure 5 • Process diagram of biogas flexibilization.

weather conditions. The seasonal operations should be reflected in the operational capacity and on-site installations of equipment. However, the reliability of production depends on constant operation, as an immediate adjustment to the operational process could lead to failure. Therefore, the application of this mode is not feasible for increasing the critical industrial load as a quick backup for electricity generation.

4.2. Biogas-based electricity production

There are essentially two ways to use biogas to produce electricity, as depicted in **Figure 6**. A: Electricity can be generated through a combined heat and power engine to produce heat and electricity. B: biogas can be upgraded to biomethane for injection into the natural gas grid to produce electricity from biogas off-site [18]. Jentsch et al. [44] presented the prospect of employing different options in a single plant, which fundamentally depends on the flexibility of the biogas production system. A combined heat and power engine can be built to alternate between two phases during electricity generation. Biogas can be converted to electricity using a combined heat and power engine when electricity production is insufficient, while during periods of excess electricity production, the combined heat and power engine can switch to upgrading biogas in order to inject it into the natural gas grid. This is referred to as 'dynamic biogas upgrading'. This dynamic upgrading process establishes the efficiency of balancing intermittent electricity generation. However, biological methods of biogas production appear to be highly sensitive to changes during the process [41]. The combined heat and power unit of the biological process can take days or weeks to shut down and restart depending on the electricity needs at a given time; its counterpart can be shut down and restarted within minutes. Hence, one limitation of this biological process is that it depends on the type of bioreactor and substrate characteristics. The microorganisms involved in the process must be stable, while minimum feeding and relentless mechanical operation should be regularly verified and maintained to circumvent failure.

4.3. Upgrading biogas for biomethane formation

Biomethane formation is principally achieved through upgrading biogas. The process of upgrading biogas involves eliminating the impurities in the biogas produced so that they can be used in grid injection and the transportation industry, making the product accessible for wider usage. There are essentially two types of biogas-upgrading processes: (a) dynamic biogas upgrading and (b) conventional biogas upgrading. The difference between the two categories is demonstrated in the operational approach used for combined heat and power engines. Jurgusen et al. [45] further stated that during dynamic upgrading, excess electricity produced as a result of a reduced demand is channeled to produce hydrogen, which is used to convert CO_2 obtained from biogas production to synthetic natural gas (SNG). This process is known as methanation. There are two possible ways that the methanation of biogas can be achieved, i.e., (a) methanation in the presence of CO_2 and (b) methanation via CO2 recovered during biogas upgrading. Furthermore, there are two types of methanation: chemical and biological methanation. Chemical methanation is the catalytic conversion of hydrogen and carbon dioxide under higher temperatures and pressures to produce methane and water. This process, known as the Sabatier process, is utilized in the production of synthetic gas (syngas). The hydrogen required for this reaction is obtained from water electrolysis or anaerobic digestion.

$$\mathrm{CO_2 + 4H_2 = CH_4 + 2H_2O}$$

$$\mathrm{2H_2O = 2H_2 + O_2}$$

4.4. Biological methanation

Biological methanation has been suggested as one of the approaches to providing electricity through grid injection. This type of methanation process involves the use of microorganisms engaging in biological processes in an anaerobic digestion system [46]. The microorganisms serve as biocatalysts for the adaptation of hydrogen and carbon dioxide into methane. The equation below depicts the biological methanation process:

$$\mathrm{4H_2 + CO_2 = CH_4 + 2H_2O}$$

Biological methanation microorganisms have a considerable tolerance for impurities, which, in this case, are gases released during the methanation process, e.g., sulfur, ammonia, etc. The microorganism methanation process also occurs within a low temperature range of about 40 °C to 70 °C. Furthermore, biological methanation can be performed in two ways:

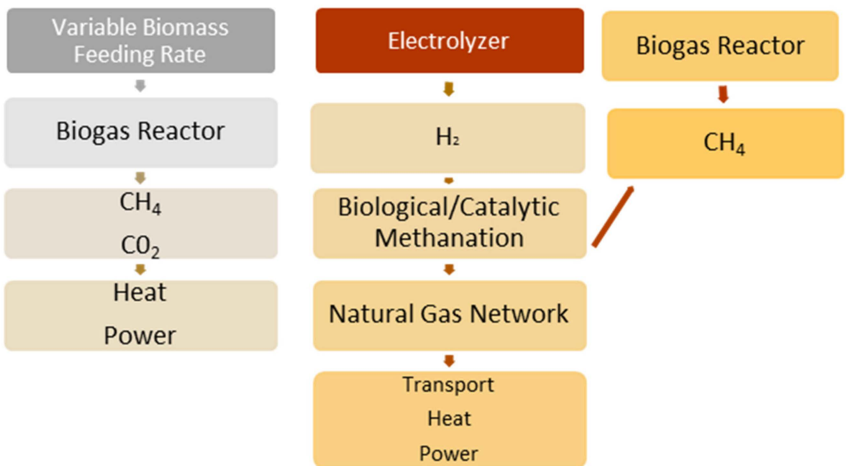

Figure 6 • Pathways for generating electricity through biogas. Source: IEA, 2013 [18].

a. In situ biological methanation

Here, hydrogen is supplied straight to the biogas digester. The digesters of biogas plants can be used for the power-to-gas (PTG) process system. Hydrogen is fed directly to the biogas digester. The carbon dioxide (CO_2) produced during the digestion of the biomass is then converted to methane (CH_4) via an in-situ method, as shown in **Figure 7a**. The biogas produced has a high methane content and calorific value. The degree of CO_2 production determines biogas formation. However, the CO_2 conversion process is challenging, and the methane formation rate is limited. Total conversion of the produced CO_2 is challenging. However, [47] reported on the significance of balance concerning in situ biogas production as a consequence of hydrogen partial pressure, which, in an elevated state (hydrogen injection), destabilizes the system by favoring methanogenic activities while disrupting acetate formation and inhibiting fatty acid oxidation. Furthermore, elevated levels of hydrogen can also stimulate homoacetogenesis, where about 40% of the injected hydrogen is consumed, thereby affecting methane upgrading [48].

b. Ex situ biological methanation in an external reactor

This process introduces the prospect of obtaining CH_4 through pure cultures in an external reactor, as presented in **Figure 7b**. Hydrogen, carbon dioxide, and methanogen (hydrogenotrophic) are required for ex situ biological methanation. The process can proceed without the hydrolysis and acidogenesis stages of anaerobic digestion [49]. Therefore, the efficiency of the system is dependent on the abovementioned constituents. However, the required process conditions and the reactor design must be tailored to fit the desired goal. A corresponding process diagram is shown in **Figure 7b**.

Dzene et al. [40] highlighted the advantages and disadvantages of chemical and biological methanation. a: Chemical methanation is adjustable according to system size, with effortless regulation. However, it requires unusual and costly catalysts, and the gas produced should be of high quality because the catalyzer is affected by low-quality gas. This process requires a high temperature and pressure with low flexibility for the system. This kind of methanation is applied to large, industrial-scale processes. The biological methanation process does not require a high temperature when used for biogas. It involves low pressure, and the priming of the gas is not essential. Additionally, the system is flexible, and it can be used in small-scale digesters. b: The process is not biological, and it is difficult to control, but biological methanation is more appropriate for biogas plants [27]. Research efforts are currently concentrated on the catalysts and extension of biogas-upgrading methods and challenges related to the control of microbiological processes for biological methanation.

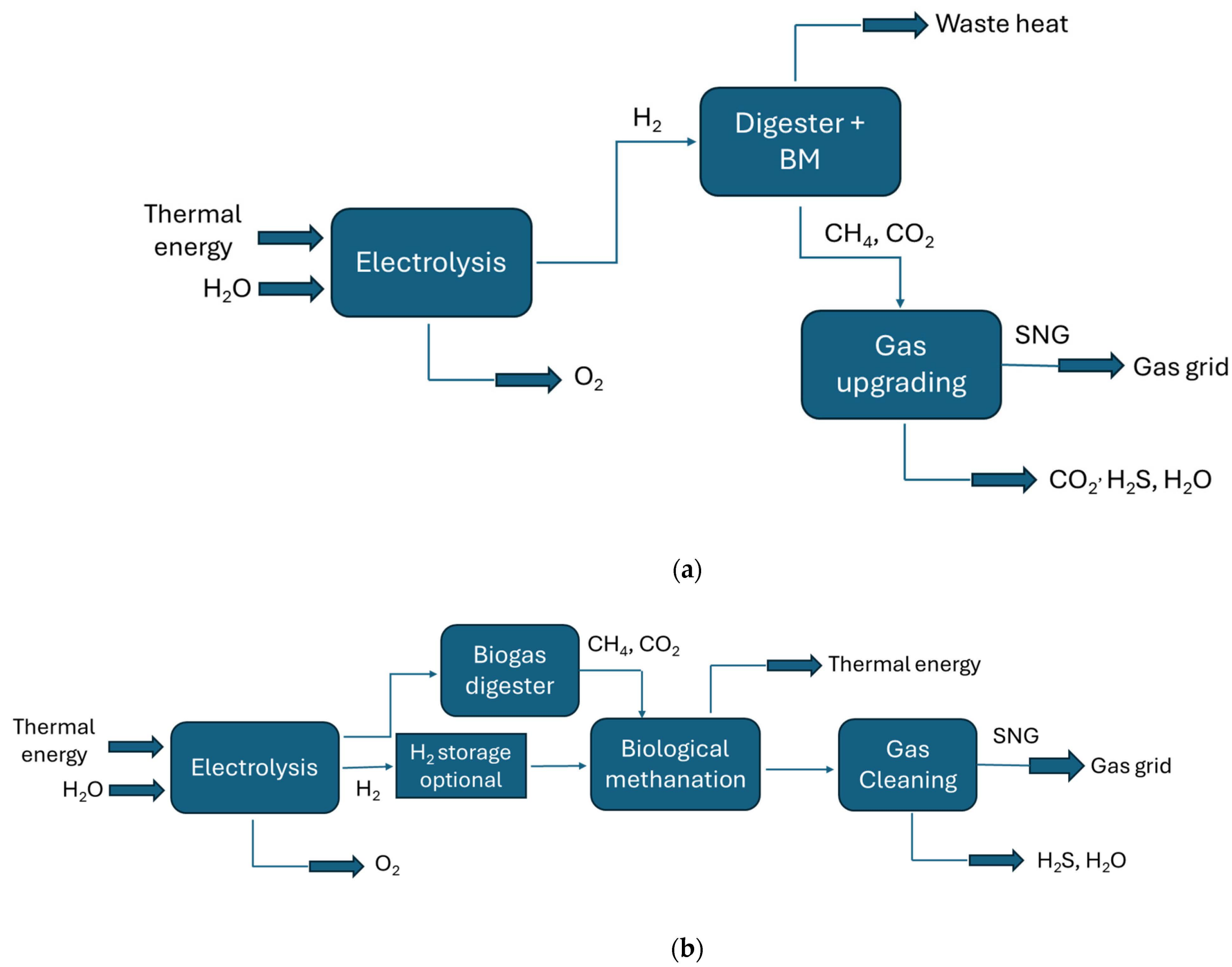

Figure 7 • (**a**) Flowchart for in situ variations in biological methanation. (**b**) Flowchart for ex situ biological methanation. Modified from [27].

4.5. Combined heat and power systems

The option of flexibility in energy provision is mostly limited to a combined heat and power (CHP) unit. The limitations of CHP units are a result of their reaction times. The shutdown of, restart of, or changes to part-load operations can occur within several minutes. The possibility of failure during the reaction time can be reduced by using only part-load operation. However, this flexibility is affected by plant design infrastructure. Normally, during operation, the efficiency of the nominal load is considered normal, but a timeout will require augmentation with an extra energy output. The plant will be more flexible if its capacity is more than the nominal load capacity. Moreover, the upstream equipment also influences the combined heat and power plant's efficiency as it will need to be supplied with gas when required. Additionally, the storage capacity of the substrates, reaction intermediate, and the produced biogas, as well as feed handling, affect the plant's flexibility [50]. The performance of the general operation can be enhanced by the provision of a sufficient storage capacity and the coordinated regulation of gas production, gas storage, and utilization. Grim et al. [42] reported the possible effect of flexibility options through a proper feeding mechanism. However, the use of existing storage facilities aids biogas production in controllable power generation [41]. If this existing storage capacity can provide 8 h of biogas utilization per day, the additional cost of using more advanced design flexibility concepts with pretreatment and biomethanation technology can be eliminated [41]. The sturdiness of the biological process should be considered when the aim of flexibilization is to induce variation in the design of the biogas plant. Grim et al. [42] demonstrated that the biological process can be stabilized and controlled; production is not monumentally affected by immediate changes, as reported by [43]. The biogas utilization demand can be addressed by upgrading the feeding mechanisms in the natural gas grid [50]. There are different ways a plant can achieve flexibility, even though the concept is mostly directed toward electricity generation based on demand. Market demands and grid upgrades must be dealt with together to determine the optimal plant design.

4.6. Future endeavors

Biogas production has been demonstrated to be environmentally friendly. The resources required for the operation of such plants are also available in Nigeria. In light of the need to reduce the use of greenhouse gases to ensure a safe climate, shifting towards green energy must be considered. Nigeria's CO_2 output is significant because of the country's total dependence on fossil fuels, which is also the country's economic and energy mainstay. Therefore, an increase in the pace of the implementation of an already-existing renewable energy policy will be a welcome development.

5. Conclusions

The impacts of alternative energy on Nigeria's energy generation system cannot be over-emphasized. Nigeria has witnessed poor power generation over the years. The increase in the population and the potential of increased industrial development are causes of concern considering the country's poor power generation. Therefore, this study was conducted with the understanding that other sources of energy generation can improve energy generation in Nigeria. Bioenergy was the main focus because there are abundant resources available in Nigeria, especially from the agro sector. This study highlights the technical aspects of biogas production required for use in Nigeria's electricity generation system and to help the country to improve its electricity output. This study shows the possibility of improved power generation in Nigeria through bioenergy utilization. Different renewable energy methods are available in Nigeria. However, biogas production is cheap when considering resource availability. This knowledge will help in the diversification of Nigeria's electricity generation, thereby increasing the availability of electricity to the country's population.

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Conflict of interest

The authors declare no conflicts of interest.

Data availability statement

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References

1. Odularu GO. Crude oil and the Nigerian economic performance. Oil gas business. Geneva: World Organization Centre, William Rappard; 2008 [cited 2025 Feb 22]. Available from: https://www.academia.edu/78120634/Crude_Oil_and_the_Nigerian_Economic_Performance?utm

2. Okoye LU, Adeleye BN, Okoro EE, Okoh JI, Ezu GK, Anyanwu FA. Effect of gas flaring, oil rent and fossil fuel on economic performance: The case of Nigeria. Resour Policy. 2022;77:102677. doi: 10.1016/j.resourpol.2022.102677

3. Candra O, Chammam A, Alvarez JRN, Muda I, Aybar HS. The impact of renewable energy sources on the sustainable development of the economy and greenhouse gas emissions. Sustainability. 2023;15:2104. doi: 10.3390/su15032104

4. Eregha PB, Adeleye BN, Ogunrinola I. Pollutant emissions, energy use and real output in Sub-Saharan Africa (SSA) countries. J Policy Model. 2022;44(1):64–82. doi: 10.1016/j.jpolmod.2021.10.002

5. Chanchangi YN, Adu F, Ghosh A, Sundaram S, Mallick TK. Nigeria's energy review: Focusing on solar energy potential and penetration. Environ Dev Sustain. 2023;25(7):5755–96. doi: 10.1007/s10668-022-02308-4

6. Oyedokun JA, Fasina ET, Adebanji B, AB. Electricity challenges in Nigeria: renewable energy a way forward. Glob J Eng Technol Adv. 2022;11:16–23. doi: 10.30574/gjeta.2022.11.3.0085

7. Edomah N. Economics of energy supply. In: Earth systems and environmental sciences. Amsterdam: Elsevier; 2018. p. 11713–30.

8. Adedeji I, Deveci G, Salman H, Abiola I. The benefits of solar energy on the provision of sustainable affordable housing in Nigeria. J Power Energy Eng. 2023;11(6):1–15. doi: 10.4236/jpee.2023.116001

9. Umar HA, Sulaiman SA, Said MA, Gungor A, Ahmad RK. An overview of biomass conversion technologies in Nigeria. Green Energy Technol. 2021:133–150. doi: 10.1007/978-981-15-9140-2_7

10. Diemuodeke OE, Mulugetta Y, Njoku HI, Briggs TA, Ojapah MM. Solar PV electrification in Nigeria: Current status and affordability analysis. J Power Energy Eng. 2021;9(5):1–25. doi: 10.4236/jpee.2021.95001

11. Agbo EP, Edet CO, Magu TO, Njok AO, Ekpo CM, Louis H. Solar energy: A panacea for the electricity generation crisis in Nigeria. Heliyon. 2021;7(5):e07016. doi: 10.1016/j.heliyon.2021.e07016

12. Ozoegwu CG, Akpan PU. Solar energy policy directions for safer and cleaner development in Nigeria. Energy Policy. 2021;150:112141. doi: 10.1016/j.enpol.2021.112141

13. Abdullahi D, Renukappa S, Suresh S, Oloke D. Barriers for implementing solar energy initiatives in Nigeria: an empirical study. Smart Sustain Built Environ. 2022;11(3):647–60. doi: 10.1108/SASBE-06-2020-0094

14. Madubuike H, Ferry N. Characterisation of a novel acetyl xylan esterase (BaAXE) screened from the gut microbiota of the common black slug (Arion ater). Molecules. 2022;27(9):2999. doi: 10.3390/molecules27092999

15. Madubuike H, Ferry N. Enhanced activity and stability of an acetyl xylan esterase in hydrophilic alcohols through site-directed mutagenesis. Molecules. 2023;28(21):7393. doi: 10.3390/molecules28217393

16. Kothani R, Pandeu AK, Kumar S, Tyagi VV, Tyagi SK. Different aspects of day anaerobic digestion for bio-energy: an overview. Renew Sustain Energy Rev. 2014;39:174–95. doi: 10.1016/j.rser.2014.07.011

17. Thran D, Dotzauer M, Leuz V, Liebetran J, Ortwein A. Flexible bioenergy supply for balancing fluctuating renewables in the heat and power sector: a review of technologies and concepts. Energy Sustain Soc. 2015;5:35. doi: 10.1186/s13705-015-0062-8

18. IEA. World energy outlook. Paris: IEA; 2013 [cited 2025 Feb 9]. Available from: https://www.iea.org/reports/world-energy-outlook-2013

19. Wirth R, Kovace EJ, Maroti G, Bagi Z, Rakhely G, Kovacs K. Characterization of a biogas-producing microbial community using short-read next-generation DNA sequencing. Biotechnol Biofuels. 2012;5(1):41. doi: 10.1186/1754-6834-5-41

20. BMWi. The renewable energy sources act (EGG). Berlin: Federal Ministry of Economic Affairs and Energy; 2014 [cited 2025 Feb 24]. Available from: https://www.bmwk.de/Redaktion/EN/Downloads/renewable-energy-sources-act-eeg-2014.html?utm

21. Okafor CC, Nzekwe CA, Ajaero CC, Ibekwe JC, Otunomo FA. Biomass utilization for energy production in Nigeria: a review. Clean Energy Syst. 2022;3:100043. doi: 10.1016/j.cles.2022.100043

22. Oyedepo SO, Babalola OP, Nwanya SC, Kilanko O, Leramo RO, Aworinde AK, et al. Towards a sustainable electricity supply in Nigeria: The role of decentralized renewable energy system. European journal of sustainable development research. 2018;2(4):40. doi: 10.20897/ejosdr/3908

23. Advisory Group on Energy and Climate Change (AGECC). Energy for a sustainable future. Summary report and recommendations. New York: The Secretary-General's Advisory Group on Energy and Climate Change; 2010 [cited 2019 Feb 24]. Available from: https://www.un.org/millenniumgoals/pdf/AGECCsummaryreport[1].pdf?utm

24. Adeshina MA, Ogunleye AM, Suleiman HO, Yakub AO, Same NN, Suleiman ZA, et al. From potential to power: advancing Nigeria's energy sector through renewable integration and policy reform. Sustainability. 2024;16:8803. doi: 10.3390/su16208803

25. Okoro PN, Chong K, Röder M. Enabling modern bioenergy deployment in Nigeria to support industry and local communities. Biomass Bioenergy. 2024;190:107403. doi: 10.1016/j.biombioe.2024.107403

26. IRENA. Renewable energy statistics. Abu Dhabi: The International Renewable Energy Agency; 2018 [cited 2025 Feb 8]. Available from: https://www.irena.org/publications/2018/jul/renewable-Energy-Statistics-2018

27. Götz M, McDaniel Koch A, Graf F. State of the art and perspectives of CO_2 methanation process concepts for power-to-gas applications. Proceedings of the International Gas Union Research Conference; 2014 Sep 17–19; Copenhagen, Denmark; 2024.

28. Christy EM, Sampson NM, Edson LM, Anthony IO, Golden M, Michael S. Microbial anaerobic digestion as an approach to the decontamination of animal waste in pollution control and generation of renewable energy. Int J Environ Res Public Health. 2013;10(9):4390–417. doi: 10.3390/ijerph10094390

29. Bauer C, Korthals M, Gronanuer A, Lebhn M. Methanogens in biogas production from renewable resources: a novel molecular population analysis approach. Water Sci Technol. 2008;58(7):1433–9. doi: 10.2166/wst.2008.514

30. Westerholm M, Leven L, Schnurer A. Bioaugmentation of syntrophic acetate-oxidizing culture in biogas reactors exposed to increasing levels of ammonia. Appl Environ Microbiol. 2012;78(21):7619–25. doi: 10.1128/aem.01637-12

31. Ugwu TN, Nwachukwu AA, Ogbulie TE, Anyalogbu EA. Effective optimization of bacterial and alkaline augmented plants substrate on biogas yield using operational conditions. Green Energy Environ Technol. 2022;0:1–18. doi: 10.5772/geet.12

32. Brown D, Shi J, Li Y. Comparison of solid-state to liquid anaerobic digestion of lignocellulosic feedstocks for biogas production. Bioresour Technol. 2012;124:379–86. doi: 10.1016/j.biortech.2012.08.051

33. Sawadeenaturant C, Surendra KC, Takara D, Oechsner H, Kharal SK. Anaerobic digestion of lignocellulosic biomass: challenges and opportunities. Bioresource Technol. 2015;178:178–86. doi: 10.1016/j.biortech.2014.09.103

34. Chong S, Sen TK, Kayaa P, Ang HM. The performance enhancement of up-flow anaerobic sludge blanket (UASB) reactors for domestic sludge treatment: a state of art review. Water Res. 2012;46(11):3434–70. doi: 10.1016/j.watres.2012.03.066

35. Li T, Park ST, Zhu J. Solid-state anaerobic digestion for methane production from organic waste. Renew Sustain Energy Rev. 2011;15(1):821–6. doi: 10.1016/j.rser.2010.07.042

36. Weiland P. Biogas production: current state and perspectives. Appl Microbiol Biotechnol. 2010;85(4):849–60. doi: 10.1007/s00253-009-2246-7

37. Absar A. Biogas potential in Pakistan. Bangalore: Institute of Information Technology; 2012 [cited 2025 Feb 23]. Available from: https://www.researchgate.net/publication/275645496_Biogas_potential_in_Pakistan

38. IEA. Nigeria energy outlook. Paris: IEA; 2022 [cited 2024 Feb 12]. Available from: https://www.iea.org/articles/nigeria-energy-outlook?utm

39. Adewale A. Challenges and prospects of renewable energy in Nigeria: a case of bioethanol and biodiesel production. Energy Rep. 2020;6:77–88. doi: 10.1016/j.egyr.2019.12.002

40. Dzene I, Romagnohi F. Assessment of the potential for balancing wind power supply with plants in Latvia energy. Procedia. 2015;72:250–5. doi: 10.1016/j.egypro.2015.06.036

41. Hahn H, Krautkremer B, Hartmann K, Wachendorf M. Concepts for a demand-driven biogas supply for flexible power generation. Renew Sustain Energy Rev. 2014;29:383–93. doi: 10.1016/j.rser.2013.08.085

42. Grim J, Nollson D, Hasson PA, Nordberg A. Demand-oriented power production from biogas: modeling and simulation under Swedish conditions. Energy Fuels. 2015;29:4066–75. doi: 10.1021/ef502778u

43. Lv Z, Leite AF, Harms H, Richow HH, Iebetrau J, Nikolaunsz M. Influence of substrate feeding regime on methanogenic activity in biogas reactors approached by molecular and stable isotope methods. Anaerobic. 2014;29:91–9. doi: 10.1016/j.anaerobe.2013.11.005

44. Jentsch M, Trost T, Stumer M. Optimal use of power to gas energy storage systems in a 55% renewable energy scenario. Energy Procedia. 2014;46:254–61. doi: 10.1016/j.egypro.2014.01.180

45. Jurgusen L, Ehimen EA, Born J, HohnNuelson JB. Utilization of simple electricity from wind power for dynamic biogas upgrading: northern case study. Biomass Bioenergy. 2014;66:126–32. doi: 10.1016/j.biombioe.2014.02.032

46. REN21. Renewable 2013 global status report. Paris: REN21 Secretariat; 2013 [cited 2025 Feb 26]. Available from: https://www.ren21.net/wp-content/uploads/2019/05/GSR2013_Full-Report_English.pdf

47. Voelklein MA, Davis R, Murphy JD. Biological methanation: Strategies for in-situ and ex-situ upgrading in anaerobic digestion. Appl Energy. 2019;235:1061–71. doi: 10.1016/j.apenergy.2018.11.006

48. Angelidaki I, Treu L, Tsapekos P, Luo G, Campanaro S, Wenzel H, et al. Biogas upgrading and utilization: current status and perspectives. Biotechnol Adv. 2018;36:452–66. doi: 10.1016/j.biotechadv.2018.01.011

49. Lecker B, Illi L, Lemmer A, Oechsner H. Biological hydrogen methanation—a review. Bioresour Technol. 2017;245:1220–8. doi: 10.1016/j.biortech.2017.08.176

50. Szarka N, Schlowin F, Trommler M, Fabian JH, Eichhorn M, Otwein A, et al. A novel role for bioenergy, a flexible demand-oriented power supply energy. Energy. 2013;6:18–26. doi: 10.1016/j.energy.2012.12.053