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CONVERSION OF AGRICULTURAL BIOMASS CORN RESIDUES: IMPACT ON POWER GENERATION AND SUSTAINABLE EMISSIONS REDUCTION IN NIGERIA

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ABSTRACT

Nigeria is presently drifting towards making an ambitious commitment to renewable energy development. Small scale solar energy is currently being harnessed for rural electrification in Nigeria but the use of biomass especially agricultural residues for power generation is largely neglected. Therefore, in this paper, the assessment of the potential of three corn (maize) residues for power generation is conducted for the geo-political zones in the country. Different corn residues (stalk, cob, and straw) were processed into dried samples with particles diameter of 0.35-0.42 mm and used experimentally in IKA C2000 bomb calorimeter for the determination of lower heating values. Crop-to-residue ratios of the selected residues were also determined using standard laboratory analysis while a mathematical computational method was used for the estimation of the potential bioenergy of the residues. A total of 145.2 PJ (40.3 TWh) of the potential bioenergy estimated from the residues is equal to approximately one-half of the total electricity consumption of 26.26 TWh in the country in 2016. The energy potential also represents 4,604 MW of electricity and the current national electric power generating capacity fluctuates between 4000-5000 MW. A total of 9416991 Gg of emissions that could be saved using the residues for power generation was also calculated for all the geopolitical zones. Findings revealed that the bioenergy potential of 4,604 MW estimated from the selected corn residues can produce a substantial amount of the national electricity demand. The estimated emissions potential is mainly from carbon dioxide (CO_2), carbon monoxide (CO) and methane (CH_4) known for their high level of anthropogenic environmental pollution.

Keywords: cob, straw, stalk, bioenergy, emission, renewable energy, Nigeria.

1. INTRODUCTION

Biomass is a derivative of biodegradable material from plants and animals [1] for sustainable power generation. Williams *et al*. [2] described the lignocellulosic biomass obtained from agricultural plant residues as environmentally friendly source of domestic fuel for power generation and production of bio-chemicals. The potential of biomass application for energy generation and emission reduction have been studied in many recent literatures [3-5]. Biomass feedstock are in different categories such as animal wastes, waste water, algae, woody energy plants, food wastes, wood processing wastes and agricultural post-harvest residues. In rural areas of many developing countries especially in Sub-Saharan Africa (SSA), solid agricultural biomass wastes are typically burnt in open air three stone stoves for cooking and heating but such practice has enormous consequences for the environment. However, agricultural post-harvest crop residues such as stalks, husks, shells, leaves, cobs, straws and stubbles are good sources of onsite rural power generation in modern bioenergy power systems. Agricultural residues are usually harvested alongside their respective crops and they can be source of income opportunity for farmers when they are sold to local power industries.

In many developing countries, extension of centralize electricity grid to off-grid rural communities are confronted with some stimulating economic constrictions. On this account, there are growing pursuits for autonomous renewable power generation in off-grid locations. Apart from solar, wind and hydropower systems that have been used for small scale power generation in isolated off-grid communities, biomasses especially from agricultural residues also holds their prominence. Unlike other renewable sources of energy that intermittently dependent on prevailing weather conditions, application of biomass for power generation enjoys the benefit of controllability and availability. Utilization of biomass for power generation is well fitted into the concept of emerging global decarbonisation agenda by means of integrated distributed renewable energy technologies shown in Figure-1.

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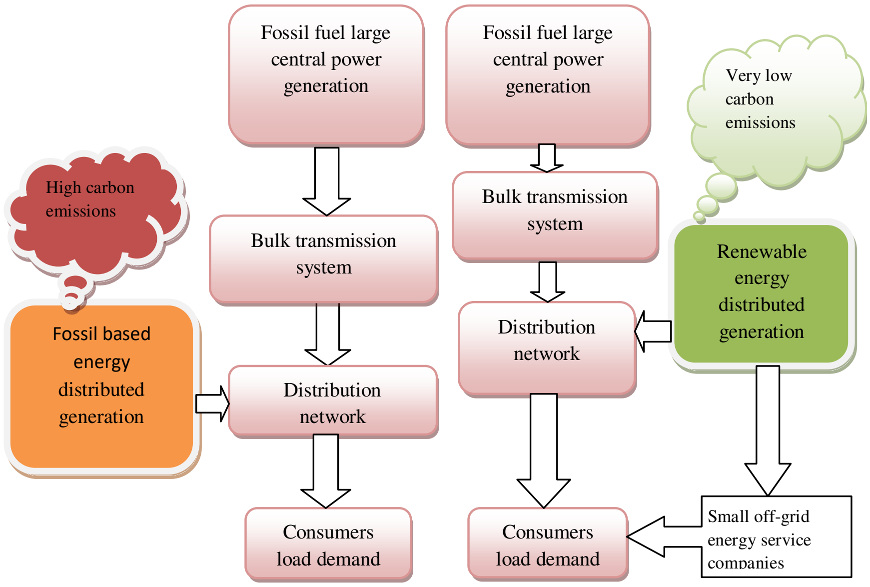

Figure-1. Comparative analysis between present and emerging electric power architecture.

Currently, there are multidimensional approaches towards reducing the level of unsafe emissions into the atmosphere due to the growing issues of global warming consequences. The present schemes of the global energy supply primarily hinge on fossil fuel technologies [6] characterize by emissions of anthropogenic Greenhouse Gases (GHGs). Destructive emissions from fossil fuelled power technologies into the atmosphere are largely sulphur oxides (SO_X), nitrogen oxides (NO_X), aldehydes ($CH_3CH_2CH_2CHO$), methane (CH_4), carbon monoxide (CO), carbon dioxide (CO_2) and ash particulate substances with detrimental effects on living creatures and the natural ecosystem. In the agenda of emerging power system technologies, distributed generation based on low carbon renewable energy portfolio is strongly advocated. Bioenergy is characteristically a low environmental impact renewable energy with potential to meet a realistic percentage of global energy demand [7-8]. Consequently, in this study, the potential of energy recovery from agricultural corn residues in Nigeria is presented. The analysis explicitly concentrates on the assessment of biomass residues for power generation and their sustainable impact on emission savings.

2. MATERIALS AND METHODS

2.1 Geographical description of the case study area

Nigeria is located on the Gulf of Guinea along the coast of West Africa. The country has 36 administrative states excluding the Federal Capital Territory (FCT) located at the centre. The country is divided into six geopolitical zones: North-east, North-west, North-central, South-east, South-west and South-south as shown in Figure-2. The country has about 70% of the total land mass of approximately 92.4 million hectares dedicated for agricultural production [9] thereby signifying a huge potential of agricultural biomass production [10].

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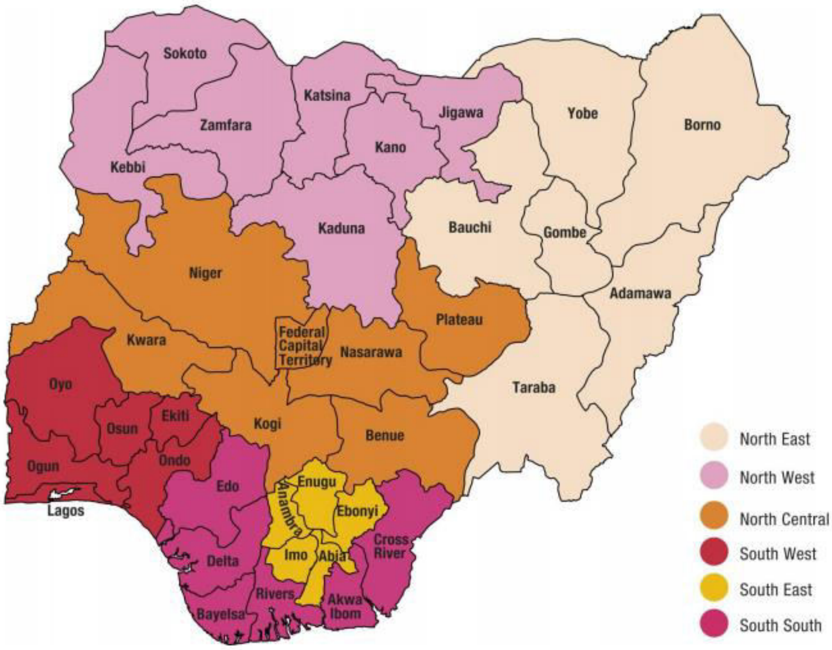

Figure-2. Map of Nigeria showing the geopolitical zones in the country.

2.2 Selection of Biomass Agricultural Residues

Agricultural activities in the country is largely in line with rainfall distribution. Corn also known as maize is the largest cereal crop grown in Nigeria as shown in Figure-3 [11]. In Africa, Nigeria is the largest producer of corn with South Africa occupying the second position. In SSA, corn is one of the important cereal crops for domestic consumption. Residues generated from corn are potential feedstock for utilization in biomass power plants. Like rice husk, corn residues can be used for power generation either in biomass gasifier or a combustion system. Properly dry corn residues are suitable fuels for production of bioenergy. Biomass residues can be dried naturally or artificially for energy production. There are many technologies in existence for drying biomass such as rotary and screw dryer [12]. Where the technologies are unavailable, biomass residues can be dried passively by the use of sun. Passive drying of residues is the cheapest form but the slowest means of drying biomass. The use of rotary and screw dryer for drying biomass requires additional cost input as well as increasing embedded energy. The essence of using dry biomass for power generation is to increase the energy content of the biomass because an efficient energy generation can only be achieved on very low moisture content.

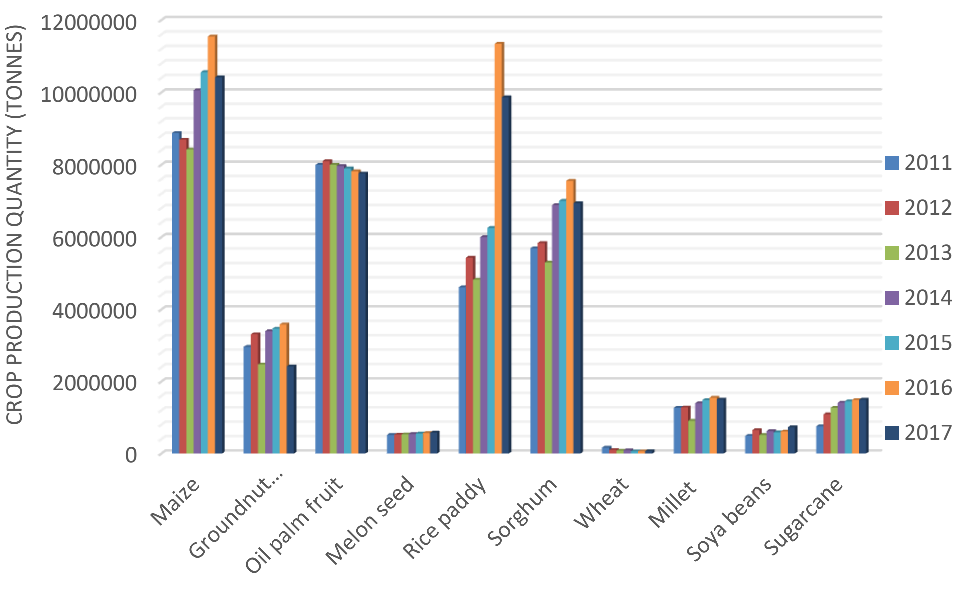

Figure-3. Major Agricultural crop production in Nigeria (2011-2017).

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2.3 Estimation of bioenergy potential of the corn residues

In Figure-4, the selected residue samples used in this study are shown. Of the three corn residues, corn cob is widely being used for heat and electricity across different parts of the world. It is for the reason that it has no direct consequence on the degradation of soil fertility. Excessive removal of corn stalk has notable long-term effects on the productivity of soil quality due to leaching. Corn stalk is essentially a field based agricultural biomass residue because it remains in the farm after harvesting the crop. However, corn cob and straws are by products of post-harvest processing. Despite the requirement to replenish the soil in some situations, a fraction of crop residue can sustainably be made available for energy production. Some dry bioenergy corn residues (cob, straw and stalk) can be converted into electrical energy using different technologies such as direct combustion, gasification, co-firing and pyrolysis.

(a) Corn cob (b) Corn straw (c) Corn stalk

Figure-4. Corn biomass residue samples.

To produce electricity from a bioenergy dry residue feedstock, the lower heating value of the residue and the quantity of net biomass yield are important variables. In this study, the lower heating values of the residues based on dry matter were determined experimentally using IKA C2000 Bomb calorimeter shown in Figure-5. Dried samples of the residues with particle diameter of 0.35-0.42 mm were utilized as feedstock materials in the Bomb calorimeter. The lower heating value (LHV) of a biomass residue is the representation of the recoverable energy content measured in $MJ/kg$when the residue is burnt in air. The calorific values determined for LHV_{cob},LHV_{straw} and LHV_{stalk} are 15.7MJ/kg, 12.2MJ/kg and 15.3MJ/kg respectively.The estimation for the energy generation, E_g is calculated using the Eq. (1):

$$E_g = \sum_{j}^{crop} P_{qj} \times P_{rr,k} \times \Gamma_{ak} \times LHV_{kj} \qquad (1)$$

P_{qj} is the total production quantity of the j crop under consideration and the values are presented in Table-1 using the year 2017 crop production statistical data of the Federal Ministry of Agriculture. $P_{rr,k}$ is the product-to-residue ratio and they were determined independently for the three residues based on the average of three selected varieties of corn (flint, dent and pod) residues. Theoretically, the available quantity of an agricultural residue of a crop can be calculated from the crop using the factor of product-to-residue ratio [13-15]. Γ_{ak} denotes the percentage availability factor of residue for power generation. Since the competitive use of crop residues could potentially affect the available quantity of residue for production of energy, therefore the value of $\Gamma_{ak} = 50\%$ was assumed in this study. The $P_{rr,k}$ is determined using the Eq. (2):

$$P_{rr,k} = \frac{W_{RS}}{W_{CS}} \qquad (2)$$

W_{RS} = weight of residue sample
W_{CS} = weight of the food crop sample.

Figure-5. IKA C2000 Bomb calorimeter.

2.4 Estimation of emission inventories from burning the corn residues

This section provides estimation for emissions from burning the corn residues. Burning of crop residues after harvest is a common practice in Nigeria but inappropriately, it is one of the main sources of air quality deterioration due to emissions of GHGs. The inventory of

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major emissions from the corn residues were estimated based on Eq. 3.

$$E_{pol.} = TM_{CRB} \times EF_{Pol.} \quad (3)$$

Where:
$E_{pol.}$ = emission of pollutant (Gg/yr); TM_{CRB} = Total mass of residue burnt (Gg/yr) and $EF_{Pol.}$ = emission factor for pollutant (gkg^{-1}).

The total mass of residues burnt (TM_{CRB}) in the fields or used for cooking was computed using Eq. 4 as applied by Street *et al.* [16]:

$$\mathrm{TM_{CRB}} = \sum_{j}^{crop} \mathrm{P_{qj}} \times \mathrm{P_{rr,k}} \times \mathrm{DM_{CR}} \times \mathrm{Ƌ_{MRB}} \times \mathrm{E_B} \quad (4)$$

Where DM_{CR} = dry matter to crop ratio, E_B = burning efficiency and $Ƌ_{MRB}$ = percentage of dry matter residue burnt in the field (%). The coefficients for the computation of emission inventory of the crop residues are presented in Table-1.

Table-1. Coefficients of emission inventory of the crop residues.

Parameters for emission inventory calculation	Index value
Dry matter to crop ratio, DM_{CR}	0.88 [17]
Percentage of dry matter residue burnt in the field, $Ƌ_{MRB}$	0.25[18]
Burning efficiency, E_B	0.92[19]
Emission factors (gkg^{-1})	
carbon dioxide (CO_2)	2327.14[20]
carbon monoxide (CO)	80.3[21]
Methane (CH_4)	3.4[21]
Nitrogen oxides (NOx)	3.7[21]
Nitrous oxide (N_2O)	0.07[22]
Ammonia (NH_3)	1.6[21]
Sulphur dioxide (SO_2)	0.44[23]
Non-methane volatile organic compounds (NMVOC)	4.4[21]
Particulate matter (PM_{10})	4.26[21]
Particulate matter ($PM_{2.5}$)	4.13[21]
Elemental carbon (EC)	0.95[20]
Organic carbon (OC)	2.25[20]

3. RESULTS

3.1 Availability of the selected biomass residues and estimation of potential bioenergy

The obtained product to residue ratio of the stalk residue ($P_{rr,stalk}$) is 1.48. The value is obviously in the rage of 1.5 that was reported in literature [24-26]. The slight difference might be due to variation in the yield of the crop in different countries. For corn straw residue ($P_{rr,straw}$), a value of 0.21 was obtained while 0.20 was presented by [27] and $P_{rr,cob}$ = 0.3 was obtained in this study while 0.29 was reported in the research conducted by [27-28]. The main reason for determining the values of the product to residue ratios in this study is due to the fact that the values are subject to changes from country to country or one region to another. Some factors such as weather condition, moisture content and crop yield could constitute to the variation in the values obtained. These values presented for P_{rr} were used to evaluate the theoretical potential of the three biomass residues shown in Table-2.

Table-2. Corn production quantity and theoretical potential of the corn residues.

Geopolitical zone	Corn production quantity [29] (tonnes)	Theoretical potential of straw residue (Gg)	Theoretical potential of cob residue (Gg)	Theoretical potential of stalk residue (Gg)
Northeast				
Adamawa	291,160	61.1	84.4	430.9
Bauchi	277,360	58.2	80.4	410.5
Borno	783,890	164.6	227.3	1160.2
Gombe	299,600	62.9	86.9	443.4
Taraba	651,710	136.9	189.0	964.5
Yobe	107,480	22.6	31.2	159.1
Northwest				
Jigawa	95,170	20.0	28.0	141.0
Kaduna	1,202,880	25.3	35.0	1780.3
Kano	236,960	50.0	69.0	350.7
Katsina	271,150	57.0	79.0	401.3
Kebbi	123,600	26.0	36.0	183.0
Sokoto	104,460	22.0	30.3	155.0
Zafara	147,220	31.0	43.0	218.0
Northcentral				
Benue	253,840	53.3	73.6	375.7
Kogi	397,780	83.5	115.4	588.7
Kwara	200,290	42.1	58.1	296.4
Nasarawa	210,110	44.1	61.0	311.0
Niger	500,570	10.5	145.2	741.0
Plateau	502,290	10.5	145.7	743.4
*FCT	93,380	19.6	27.1	138.2
Southeast				
Abia	216,650	45.5	62.8	32.2
Anambra	158,120	33.2	45.9	23.4
Ebonyi	129,380	27.2	37.5	191.5
Enugu	197,590	41.5	57.3	292.4
Imo	277,040	58.2	80.3	410.0
Southwest				
Ekiti	210,530	44.2	61.1	311.6
Lagos	89,990	19.0	26.1	133.2
Ondo	305,190	64.1	88.5	451.7
Ogun	191,110	40.1	55.4	282.8
Osun	172,710	36.3	50.1	255.6
Oyo	429,080	90.1	124.4	635.0
South-south				
AkwaIbom	172,270	36.2	50.0	255.0
Bayelsa	99,450	20.9	28.8	147.2
Cross River	208,130	43.7	60.4	308.0
Rivers	209,260	44.0	60.7	310.0
Edo	192,150	40.4	55.7	284.3
Delta	269,430	56.6	78.1	399.0

The results estimated for the potential bioenergy of the residues are shown is Figure-6. In the Northeast geopolitical zone, a total of 36.1 PJ of potential bioenergy was estimated from the residues. Borno exhibits the highest potential bioenergy in the region followed by Taraba while the least potential is exhibited by Yobe. As a matter of fact, agricultural policy interventions is given more priorities in the northern parts of the country. More recently, there is significant increase in the population engaged in farming in the entire northern Nigeria. Despite this, more efforts are still needed to increase productivity to achieve self-sufficiency in food production in the country. This can be accomplished through the use of improved technologies. As for Taraba with a potential bioenergy of 10 PJ, the state is famously known for its activeness in agricultural activities. The potential bioenergy of Borno and Taraba combine together put up nearly 60% potential of the North-eastern region. The total bioenergy potential of 36.1 PJ estimated for the region has equivalent amount of electricity of 1,445 MW.

In the north-western geopolitical zones, results obtained placed Kaduna on a conspicuous lead among others with a potential nearly equivalent to the average of the total of 28.5 PJ for the entire region. In a very recent effort, the Kaduna State Commercial Agriculture Development Project (CADP) with the support of financial grants from World Bank has strengthen empowerment of local farmers in the state. The World Bank assisted agricultural project was initiated with the objective to transform agricultural production in the state especially in the local areas where commercial farming can be achieved. Although, the anticipated target of the project has not been achieved in totality but the positive impact thus clarifies the leading status of the state in production of corn in the whole of the country. The total theoretical bioenergy potential calculated based on the 0.5 availability factor of the residues in the sub-region has equivalent estimated power potential of about 904 MW. In the North-central Nigeria, the states of Plateau, Niger and Kogi show up the potential of 7.5 PJ, 7.4 PJ and 5.9 PJ respectively. Plateau and Niger are very close in rank with a difference of just 0.1 PJ. FCT which shows the least potential of 1.4 PJ is treated as part of the north-central geopolitical zone for ease of analysis. This value of 1.4 PJ is the same for Jigawa in the north-west geopolitical zone while Lagos in the southwest recorded the overall lowest potential of 1.3 PJ. The state of Oyo (6.4 PJ) leads in the southwest, Imo (4.1 PJ) in the southeast while Delta is ahead of others in the South-south geopolitical zone with an estimated value of 4.0 PJ.

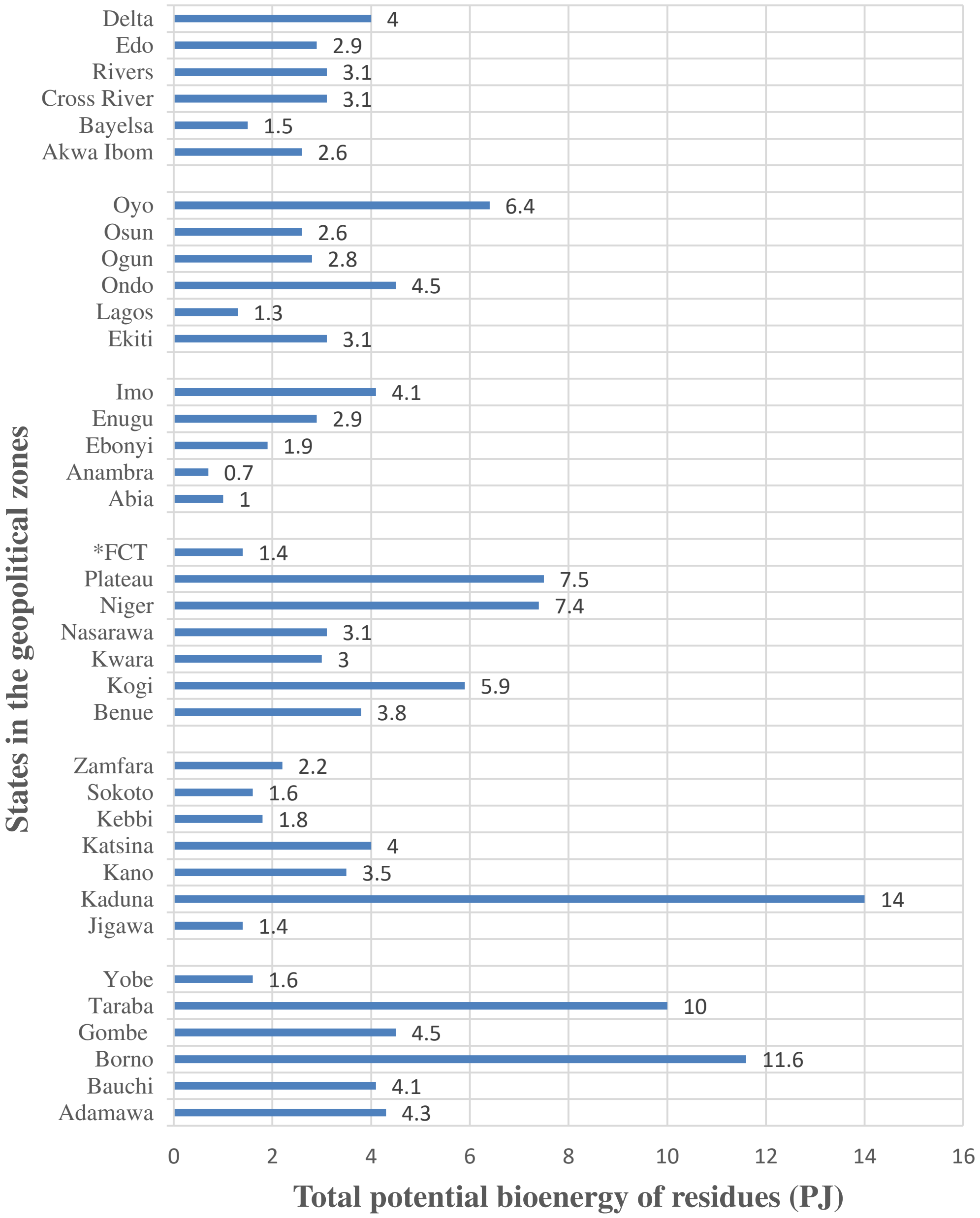

Figure-6. Theoretical potential bioenergy of corn residues in the geopolitical zones.

3.2 Emission inventories from open burning of corn residues

Burning of crop residues in an open air is one of the key sources of emission of air pollutants. Particulate matters, methane, sulphur dioxide, nitrogen oxides, carbon monoxide, black carbon and volatile organic compounds have notable undesirable effects on the occurrences of climate change condition, poor atmospheric air quality [30-33] and destruction of human and animal health [34-35]. Statistics on emissions related to burning of crop residues in Nigeria is highly connected with large information constraints and uncertainties. This is very obvious considering the fact that there is unavailability of nation-wise specific GHG emission factors for agricultural activities in the country. The quantity of different kind of pollutants associated with open air burning of corn residues are evaluated and presented in Figure-7.

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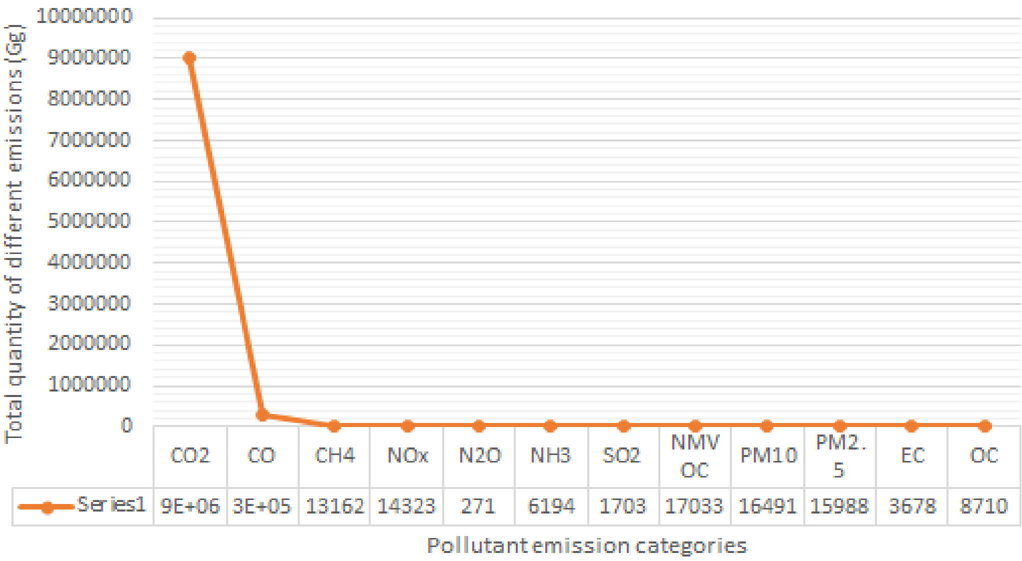

Figure-7. Estimated total quantity of different emission in open air burning of the residues.

It is clearly shown in the figure that open burning of the corn residues contributes more of CO_2 with an estimated potential of 95% of the total emissions. The CO component of the total emissions calculated contributes just 3.3% while the CH_4 fraction represents 0.14%. However, characteristically, CH_4 is well known for its higher heat trapping potential in the atmosphere compare to CO_2 but it has diminutive life span. Besides, the rest of other pollutants also contribute to the total emissions but in a smaller percentage. It is important to note that this analysis is carried out on a single crop but when a range of crops are considered, the contribution to emissions by burning different crops will vary significantly with respect to their emission factors. Crop production quantity and the percentage of dry matter residue burnt in the fields are also important contributing factors to the quantity of emissions produced when agricultural residues are burnt in open air.

The results presented in Figure-8 highlighted the total quantity of pollutant emissions across all the geopolitical zones. The total estimated emissions for the geopolitical zones are 2350567 Gg, 1861557 Gg, 2010841 Gg, 708454.3 Gg, 1363487 Gg and 1122084 Gg for Northeast (NE), Northwest (NW), Northcentral (NW), Southeast (SE), Southwest (SW) and South-south (SS) respectively. These indicated that a total of 9416991 Gg of emissions from different pollutants could be saved using the residues for power generation. The 0.5 availability factor of residues assumed to be burnt is based on the fact that there are many common practices of burning crop residues in Nigeria especially for cooking, heating and land preparation for sowing crops or other farming activities. Burning of crop residues in opening air is persistence in Nigeria and many other part of the world, despite its unsafe and deteriorated magnitudes for air quality, ecosystem, and the global climate. The NE geopolitical zone contributes the largest GHG emission while NC occupy the second largest value. The SE shows the least contribution among the geopolitical zones. In general, open burning of corn residues contributes a very large GHG emissions to the evolving activities of global warming potential (GWP) with local, regional and global effects. From human health perspective, some particulate matters coarse and fine particles could cause cardiovascular infections and faster aging of the lungs due to long term exposure. To modulate the impact of pollutants orchestrating from opening burning of crop residues, farmers are to be educated through awareness raising campaigns on the modern alternative means of utilizing the residues especially for power generation.

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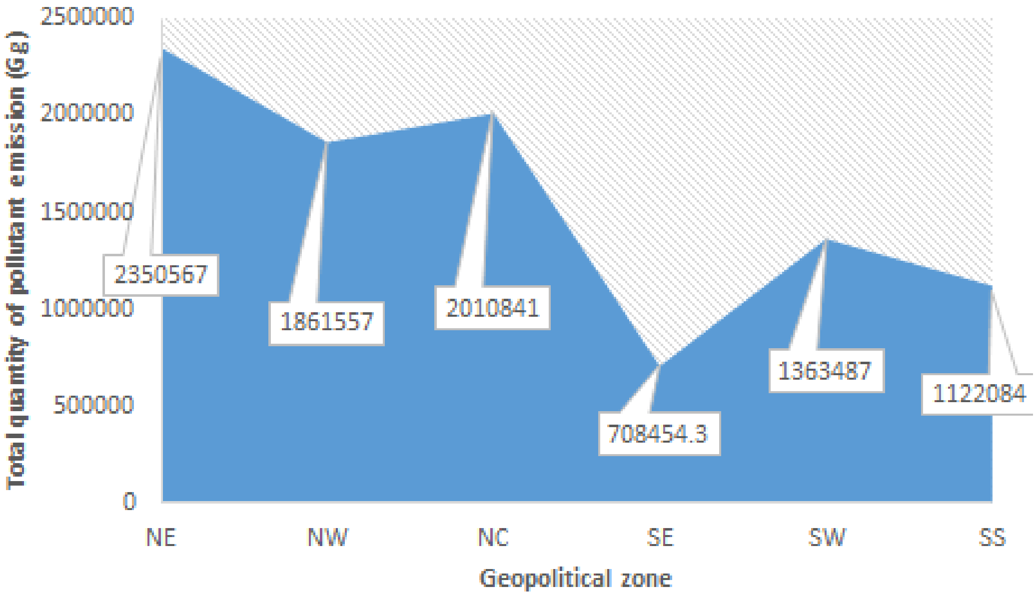

Figure-8. Total quantity of pollutant emissions by geopolitical zones.

4. DISCUSSIONS

From the general results presented, the three geopolitical zones in the northern part of the country have a remarkable total potential bioenergy of 96.7 PJ which represents approximately 67% of the estimated potential bioenergy of the total residues in the country. This can be attributed to recent improvement in the agricultural value chain especially in production of cereal crop in the northern part of the country. In the southern axis, the southwest geopolitical zone exhibits the second highest estimated potential of 20.7 PJ followed by 17.2 PJ for the south-south geopolitical zone. The south-eastern geopolitical zone has the overall least total potential bioenergy of 10.6 PJ in all the five states in the region. The nationwide impressive total of 145.2 PJ of the potential bioenergy as estimated base on the 0.5 availability factor of the residues is equivalent to 40.3 TWh of electrical energy. According to International Energy Agency [36] (IEA), in 2016, the total electricity consumption in the country is 26.26 TWh indicating that the estimated value of 40.3 TWh of energy shows a great potential in Nigeria. Likewise, given that 145.2 PJ is also equivalent to 4,604 MW of electricity whereas the current national electricity generation capacity fluctuates between 4000 MW to 5000 MW is an indication that biomass corn residues for power generation represents a promising renewable energy for the country. Therefore, there is possibility that if 50% of the available biomass corn residues in the country is properly exploited for power generation, a substantial amount of the national electricity demand can be met.

5. CONCLUSIONS

More than half of the population of people in Nigeria live in rural areas without access to electricity. Undoubtedly, electricity infrastructural system is one of the indispensable lifetime supporting amenities. In rural areas of the country, burning of agricultural residues from forest and crop residues for heating and cooking is a common practice. Expected connections of rural areas to the national grid have not yield to noticeable results for the fact that rural electrification in the country is still below 10%. Therefore, production of off-grid electricity by the use of bioenergy technologies could be a viable alternative. As a result, the promising potential of the biomass crop residues for power generation presented in this study could provide an alternative solution to the current constricted scenario of rural electrification in the country. Conclusively, the utilization of the biomass crop residues for power generation in the country will give rise to sustainable development in addition to reduction of environmental emissions.

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