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Appraisal of the Economic Geology of Nigerian Coal Resources

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Abstract
The coal deposits discovered so far in Nigeria are located mainly in the Lower, Middle and Upper Benue Trough. The coal deposits of the Anambra Basin in the Lower Benue Trough, located in southeastern Nigeria contain the largest and most economically viable coal resources. In the Lower Benue Trough, lignite and sub-bituminous coals occur within the Mamu Formation (Middle Campanian – Late Maastrichtian). High-volatile bituminous coals are found within the Awgu Formation (Middle Turonian – Early Santonian) in the Middle Benue Trough while the Upper Benue Trough contains lignites and sub-bituminous coals in the Gombe Sandstone Formation (Early Campanian – Late Maastrichtian). On the economic geology, the sub-bituminous coals in the Lower and Upper Benue Trough are best for combustion, power generation and chemical production and better for liquefaction while the high-volatile bituminous coals in the Middle Benue Trough, besides its best for liquefaction, are the most suitable as raw material for coke making in steel manufacture.
Keywords: Nigerian Coal, Benue Trough, Sub-bituminous, Bituminous, Coking.

1.0 Introduction

Nigeria is endowed with a large coal deposits most of which are reported to be within the Benue Trough (Carter *et al.,* 1963 and Obaje *et al.,* 1994). The Benue Trough of Nigeria which is subdivided into Lower, Middle and Upper portions contains a thick folded sedimentary pile ranging in age from Albian to Recent (Kogbe, 1976; Petters, 1982, and Ojoh, 1992). Anambra Basin in the Lower Benue Trough is a major coal producing basin in Nigeria where intensive exploration and exploitation activities have been on since 1916 owing to the discovery of commercial coal in Udi near Enugu in 1909 by the Mineral Survey of Sothern Nigeria (Famuboni, 1996). Coal was discovered in the Mamu Formation (formerly called the 'Lower Coal Measures') of the Anambra Sedimentary Basin of south-eastern Nigeria (Simpson, 1954). De-Swardt and Casey (1963) later reported the occurrence of coals in the Nsukka Formation (formerly called the 'Upper Coal Measures'), located 4 miles north of Okaba town. Lignites and sub-bituminous coals are distributed within the coal measures of the Maastrichtian Mamu and Nsukka Formations in the Lower Benue Trough (Akande *et al.,* 1992a).

The Nigerian coals are sub-bituminous (black coals) of Campanian – Maastrichtian age, and lignites (brown coals) of Tertiary age. However, the Obi-Lafia coal deposit in the Middle Benue Trough is geologically, the oldest coal deposit in Nigeria so far discovered. This deposit is believed to be Turonian – Coniacian in age (Obaje and Hamza, 2000). The Obi-Lafia coal deposit has been described as coking coal by the Nigerian Steel Development Authority (NSDA) now National Steel Raw Materials Exploration Agency (NSRMEA) which carried out detailed investigation of the deposit some decades after it had been reported by the Geological Survey.

Coal mining commenced in Nigeria in 1916 at Enugu in a drift mine. But total dependence on oil and oil-derived foreign exchange in planning the nation's economy resulted in the relegation of coal to the background.

Prior to the discovery of oil at Oloibiri in Bayelsa State in 1956, coal played a significant role in Nigeria's economic development. Coal was mainly utilized by the Nigerian Railway Corporation (NRC) to operate its locomotives, by the Electric Corporation of Nigeria (ECN) later National Electric Power Authority (NEPA) now Power Holding Company of Nigerian (PHCN) for the generation of electricity; and by the Nigerian Cement Company (NIGERCEM) at Nkalagu for firing its kilns.

However, coal production has steadily declined in the last few decades due to the loss of two of its traditional customers, who switched from coal to diesel, natural gas and hydro resources for the generation of electricity and for transportation services.

As a result of a major linkage between energy resources, national development and economic growth, coal industry is recovering world-wide and Nigeria is not left out.

Economically coal has many uses. This paper attempts to appraise the economic significance of Nigerian coal resources.

2.0 Geological Setting

The geology and stratigraphic descriptions of sediments in the Benue Trough of Nigeria have been generally discussed and widely reviewed by many authors (Carter *et al.,* 1963; Reyment, 1965; Petters, 1982; Offodile, 1976; Benkhell, 1989; Obaje *et al.,* 1994; Omada and Ike, 1996; Obaje, 2009). Although minor lignites and sub-bituminous coal deposits have been reported from the Sokoto Basin northwestern Nigeria (Kogbe, 1976), the

Mid – Niger (Bida) Basin (Adeleye, 1976) and the Dahomey Embayment (Reyment, 1965), the major coal resources of Nigeria occur within the Benue Trough (Figure 1).

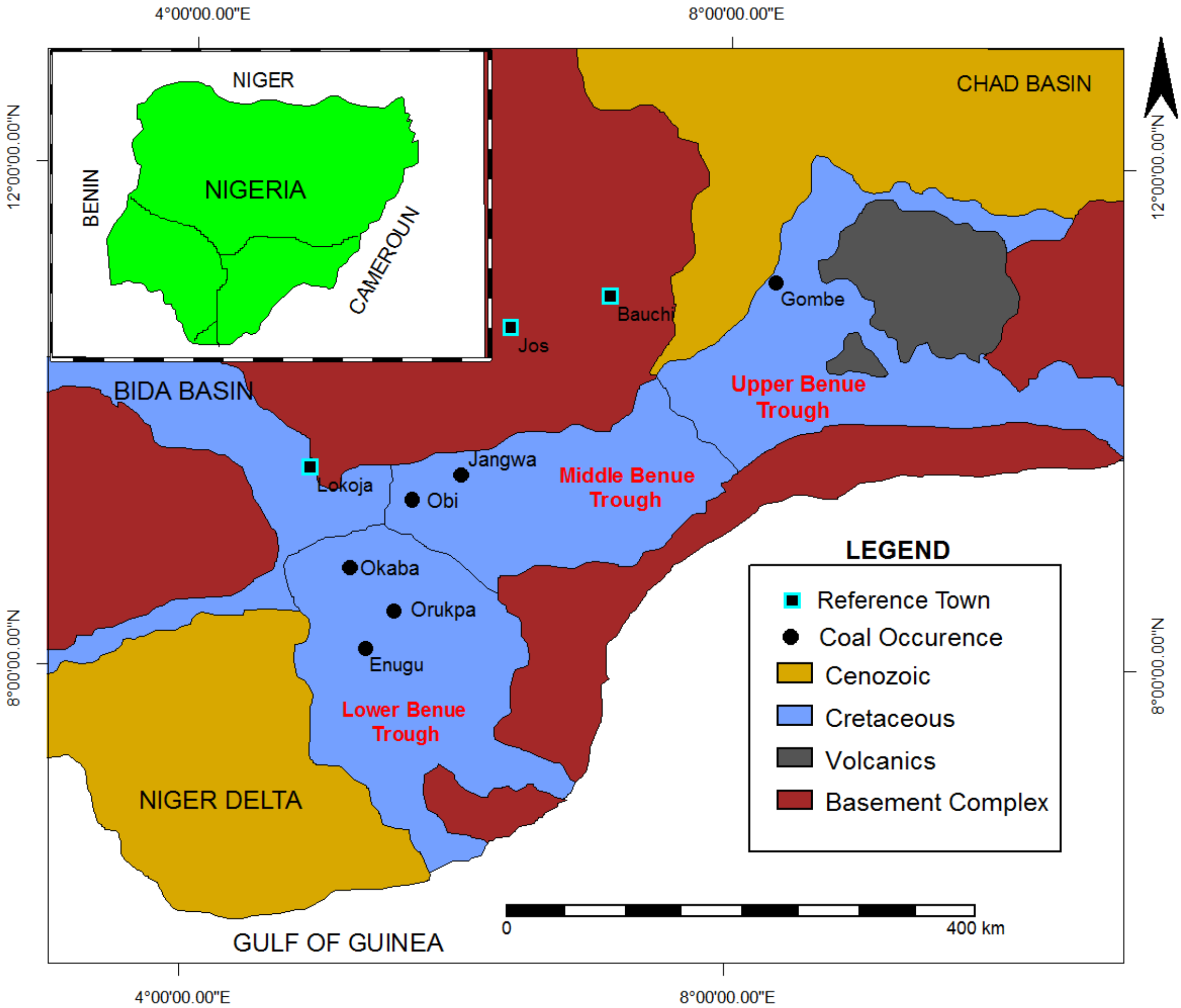

Figure 1. Location of major coal occurrences in the Benue Trough of Nigeria (modified from Obaje *et al*., 1998).
Lignites and sub-bituminous coals are distributed within the coal measures of the Maastrichtian Mamu and Nsukka Formations in the Lower Benue Trough (Akande *et al.,* 1992a) and in the Campanian – Maastrichtian Gombe Sandstone Formation in the Upper Benue Trough (Figure 2). The coals in the Lower Benue outcrop mainly in Enugu area where four mines: Iva Valley, Onyeama, Okpara and Ribadu are being worked by the Nigerian Coal Corporation. Other mines that are being worked in this area include those at Okaba and Orukpa within the Mamu Formation. In the Upper Benue, laterally extensive beds (about 2m thick) of lignites and sub-bituminous coals outcrop along the bank of River Kolmani in Gombe town and along a stream channel behind the village of Hamman Gari about 20km from Gombe on the Gombe – Yola road. Borehole occurrences of coal seams within the Gombe Sandstone have also been reported by De-Swardt and Casey (1963) and Carter *et al* (1963). Not much follow-up studies have been carried out on these coals and consequently they are presently not being worked.

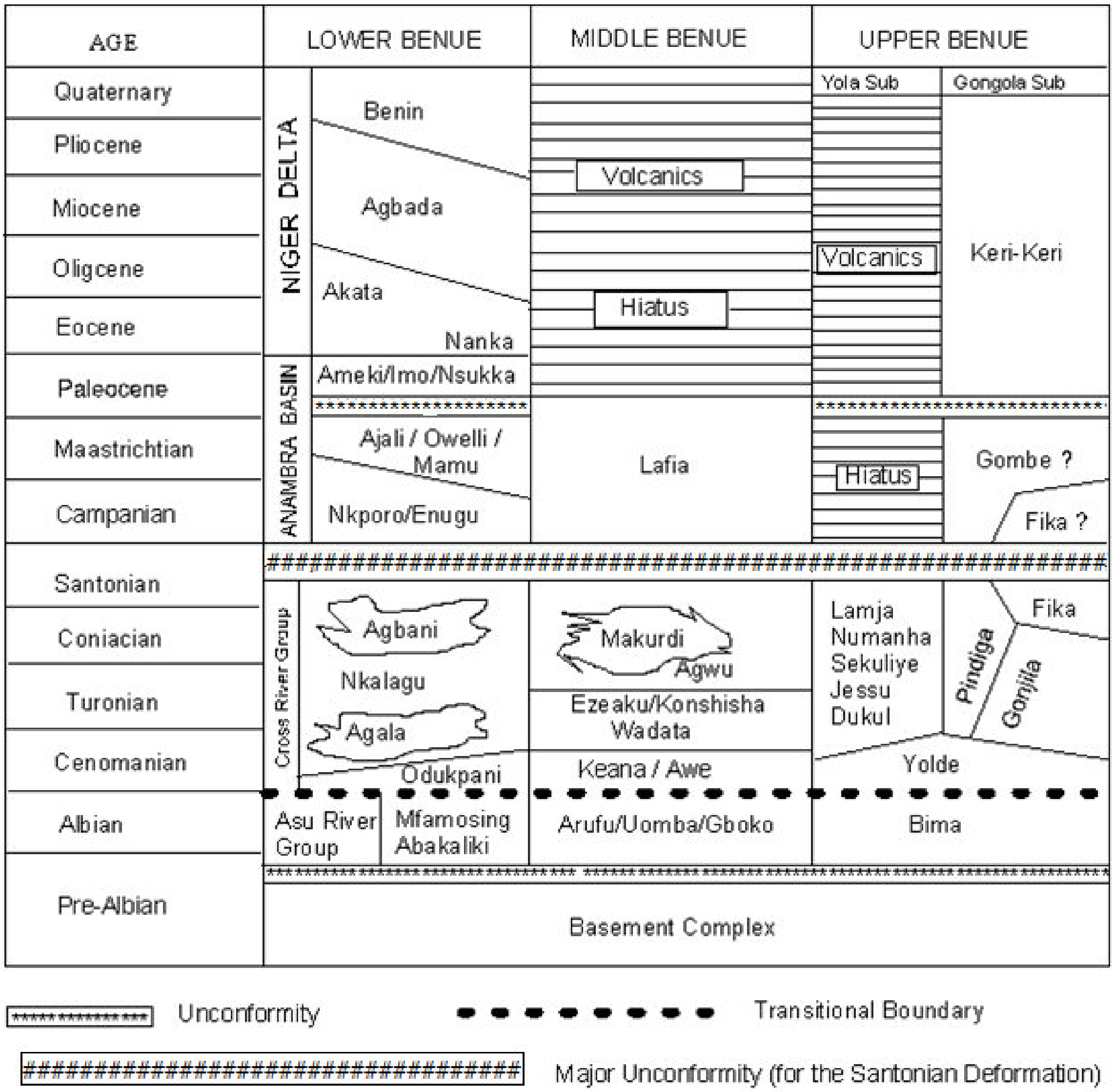

Figure 2. Stratigraphic successions in the Benue Trough of Nigeria (modified from Obaje, 2009).

The entire coal deposits in the Middle Benue Trough are within the Turonian – Santonian Awgu Formation. Outcrops of high-volatile bituminous coals occur along the bank of River Dep, 500m behind the village of Jangwa. Coal seams of between 1 to 5m thick have been encountered in many of the boreholes drilled by the National Steel Raw Material Exploration Agency (NSRMEA). Whose cores are stockpiled at the Obi camp of the Agency. The Obi camp is about 32km southeast of the town of Lafia in Nasarawa State.

3.0 Coal Formation

The Nigerian coal sequence represents a two phase system, with partial repletion of the coal sequence. The series begins with the typical transgressive period connected with a slight subsidence, whereby a broad shallow sea was formed. During this time the sediments of the Enugu Shale were deposited. In the central part of the basin the subsidence terminated, the shallow basin was largely silted up and an extensive swamp area was developed, a condition favourable for the abundant growth and accumulation of vegetation. The inception of the regressive coal forming periods was marked by fluctuations between marine and non-marine conditions. The lower part of the Mamu Formation contains occasional marine intercalations.

The Ajali Sandstone conformably overlies the Mamu Formation, and attains an average thickness of about 150m. It is essentially a friable coarse-grained white sandstone. The water supply boreholes that are located on the Udi Plateau provide detailed information on the lithologic succession of the sandstone formation. The Formation consists of gravelly and coarse sandstone within the upper horizons, and grades into medium fine-grained sandstone at greater depths. Clay and coal units occur towards the bottom of the groundwater boreholes, probably indicating the transition zone between the Ajali Sandstone and the coal-bearing Mamu Formation. The sandstone sequence is covered by a thick mantle of red earth.

4.0 Physical and Chemical Characteristics

The coals of south-eastern Nigeria are black to brownish-black and have dark brown streak. The coals fracture at right angles to the bedding. The coals are mostly dull, though thin bands and lenses of vitrain, with brilliant conchoidal fracture are usually present. The average width of these bands is from 1 to 2mm, but in some areas, notably at Orukpa, thicker bands may occur. Some specimens of coal have the dull, lusterless appearance of durain. In the Ogboyaga area, this type is more abundant. Most of the coal fracture rather irregularly along the bedding planes and produce a dull grey molted surface on which fragmentary plant remains can be recognized. Marcasite is sometimes present and forms a thin coating on the cleat.

The chemical analyses of Enugu, Orukpa and Okaba coals have shown that moisture of the Nigerian coals is low when compared with most low-rank coals. The volatile content is high. There is a definite increase in the percentage of volatile, from south to north. On an ash-free, dry basis, the volatile content of No 3 seam, Enugu, varies from 42% to 50% while that of Ogboyaga ranges from 47% to 57%. The high volatile content is a reflection of the exceptionally large proportion of hydrogen in the Nigerian coals. As in other low-to medium-rank coals of this type, the nitrogen content is high; sulphur is low but increases in coals of the Nsukka Formation. Sulphur is commonly present in most Nigerian coals in the form of pyrite and marcasite. The ash content varies between 5% and 20%. The high melting point of the ash prevents clinkering.

The calorific value of an air dried sample of Nigerian coal is usually between 7,000 and 8,000 kca/kg. In conjunction with the high volatile content, this places the coal in groups A and B of the sub-bituminous class of the American Society of Testing Material (ASTM). Most of the Nigerian coals are of medium quality and non-coking. The Obi-Lafia coal is coking but the coal has high sulphur and ash content and would require considerable washing before coking.

The Nigerian coal is rich in resins and waxes and is of potential interest as a source of chemicals and also for utilization in the manufacture of plastics. It gives a gas of high calorific value and exceptional yields of tars and oils, both in the high and low temperature carbonization processes. It is a good producer-gas fuel and suitable for complete gasification by oxygen-enriched steam blast processes. The Nigerian coals can be used for the production of benzene, chloroform, coal tar and also for the production of gas.

5.0 Coal Occurrences in Nigeria

Apart from sparsely reported occurrences of lignites and minor sub-bituminous coals in the Sokoto Basin (Kogbe, 1976), in the Mid-Niger Basin (Adeleye, 1976) and in the Dahomey Embayment (Reyment, 1965), all the coal deposits of Nigeria occur in the Benue Trough (Figure 1). Mineable coal deposits in Nigeria occur at Enugu, Okaba, Ogboyaga, Orukpa, Obi-Lafia, Gombe and Chikila (Obaje, 2009).

There is a reported occurrence of coal seams in Ezimo, Enugu State; Iyoko River, east of Ukana and Egodo River near Okpatu both in Benue State. There is a main coal seam in Inyi area, Enugu State. Inyi coal deposit is the only deposit that occurred in the Upper Coal Measures in Nigeria other deposits occurred in the Lower Coal Measures. It is thinner and poorer in quality than that of the Lower Measures.

Other areas where coal outcrops in Nigeria include: Jamata in Kogi State, occurring as thin seams in Patti Formation of Maastrichtian-Campanian age. Coal seams of about 1.7m were also discovered near Doho in Gombe area of Gombe State. They occur in Kerri-Kerri Formation of Paleocene age. Several coal outcrops of about 2 – 4.6m thick have been reported from Garin Maiganga, south of Gombe. National Steel Raw Materials Exploration Agency (NSRMEA) has been exploring for coal in that area. This coal belongs to the Gombe sandstone of Cretaceous age.

A coal seam is exposed for a distance of 4.8km near Okuluku village, a few kilometres south of Odokpono, Kogi State. In one section the coal is 1.2m thick but all the other exposures are less than 1.07m. This also applies to the coals found around Dekina in Kogi State. The coal seams which occur near Afikpo, Imo State, in sediments older than the Lower Coal Measures have been examined, but proved to be patchy and unworkable. Coal seams have been discovered at Afuze, near Auchi in Edo State, and at Ute near Owo in Ondo State, but they are very thin and it is unlikely that economic deposits will be found further to the west. Thin, unworkable seams of poor quality are also known to occur around Lamja in Adamawa State.

A large coal reserve probably in excess of 1,000 million tonnes is also believed to occur within the Mamu Formation at depth of over 600m in Amansiodo area of Enugu State. Thin coal seams have also been discovered at Gindi – Akunti, Plateau State and at Janata – Koji area of Kwara State.

6.0 Economic Geology

6.1 Combustion

The calorific value of an air dried sample of Nigerian coal is usually between 7,000 and 8,000 kca/kg (Orajaka *et al.,* 1990). Mackowsky (1982) in his work found out that the calorific value of Onyeama, Orukpa, Okaba and Gombe coals ranges between 7,000 – 8,000 kcal/kg, while that of the Obi/Lafia coal ranges between 7,500 – 8,500 kcal/kg. These are high and optimum calorific values for combustion. It can be used as a domestic fuel. It gives a gas of high calorific value and produces exceptional yields during low-temperature carbonization processes.

The combustibility, grindability, calorific values and ash properties are genetically linked to one another and they all depend on the coal rank and maceral composition (Mackowsky, 1982). And based on combustion properties (calorific value, grindability and ash properties) the most optimum coals for combustion are those from the upper part of the Onyeama mine, lower part of the Orukpa mine, Okaba whole mine and the sub-bituminous series of the Gombe coal deposits.

6.2 Gasification

Coal-based vapor fuels are produced through the process of gasification. Gasification may be accomplished either at the site of the coalmine or in processing plants. In processing plants, the coal is heated in the presence of steam and oxygen to produce synthesis gas, a mixture of carbon monoxide, hydrogen, and methane. This synthesis gas (syngas) can then be converted into transportation fuels like gasoline and diesel through the Fischer – Tropsch process. Currently, this technology is being used by the SASOL Chemical Company of South Africa to make gasoline from coal and natural gas. Alternatively, the hydrogen obtained from gasification can be used for various purposes such as powering a hydrogen economy, making ammonia, or upgrading fossil fuels.

On-site gasification is accomplished by controlled, incomplete burning of an underground coal bed while adding air and steam. To do this, workers ignite the coal bed, pump air and steam underground into the burning coal, and then pump the resulting gases from the ground. Once the gases are withdrawn, they may be burned to produce heat or generate electricity. Or they may be used in synthetic gases to produce chemicals or to help create liquid fuels.

In these regards, Enugu, Orukpa and Okaba coals in the Lower Benue Trough are optimum for gasification while the high-volatile bituminous coals in the Middle Benue Trough (Obi/Lafia coals) are sub-optimum for this purpose.

6.3 Liquefaction

Liquefaction processes convert coal into a liquid fuel that has a composition similar to that of crude petroleum. Coal can be liquefied either by direct or indirect processes. However, because coal is a hydrogen-deficient hydrocarbon, any process used to convert coal to liquid or other alternative fuels must add hydrogen. Four general methods are used for liquefaction: (1) pyrolysis and hydrocarbonization, in which coal is heated in the absence of air or in a stream of hydrogen; (2) solvent extraction, in which coal hydrocarbons are selectively dissolved and hydrogen is added to produce the desired liquids; (3) catalytic liquefaction, in which hydrogenation takes place in the presence of a catalyst; and (4) indirect liquefaction, in which carbon monoxide and hydrogen are combined in the presence of a catalyst.

Alternatively, coal can be converted into a gas first, and then into a liquid, by using the Fischer – Tropsch process. In the Bergius process, coal is liquefied by mixing it with hydrogen gas and heating the system (hydrogenation). This process was used by Germany during World War I and World War II and has been explored by SASOL Chemical Company in South Africa.

The effectiveness of coal conversion depends on the total reactive macerals of low- to medium-ranking coals. Whitehurst *et al.* (1980) show that optimum conversion of coal to oil and gas can be achieved by using high-volatile bituminous coals through a process enhanced by introducing hydrogen donor solvents, e.g. 40% tetralin. In the diagram published by Davis *et al.* (1976), the optimum conversion field corresponds to high-volatile bituminous coals with a total amount of reactive macerals exceeding 70%. In these regards, the high-volatile Obi/Lafia bituminous coal in the Middle Benue Trough is the best suited for liquefaction while the Onyeama coal in the Lower Benue Trough is better for this purpose. Although Orukpa and Gombe coals in the Lower and Upper Benue Trough respectively have adequate proportions of total reactive macerals, they are lower in rank for optimum liquefaction. The Okaba coal is low in rank and has too much inertinite macerals, making it unsuitable for liquefaction (Obaje *et al.,* 1994).

6.4 Coke Manufacture

Coal is used by the steel industry, mostly for the manufacture of coke (coking coal) for metallurgical processes such as iron and steel manufacture. Coke is made out of coal and the quality of the coal determines to a large extent the quality of the resulting coke. More than 90% of the coke consumed in the steel industry is used in the blast furnace while a small quantity is used in the in the foundry processing of metals (Gransden *et al.,* 1991). In the blast furnace, coke is used in the reduction of iron ore and as a source of process heat. It provides the energy to produce iron by burning to form carbon dioxide at the "tuyeres" of the blast furnace.

The blast furnace process of making iron and steel employs coke (the solid product from coal carbonization) as a major raw material. But not all coals can yield the type of coke (metallurgical coke) that can be utilized in a blast furnace. Nigerian coals are generally non-coking (except Obi/Lafia coal) and hence the cokes derived therefore are not directly utilizable in blast furnaces. The high-volatile bituminous coals in the Middle Benue Trough Obi/Lafia coal specifically are most suitable raw material for coke making in steel manufacture. Enugu coal however, blended with Obi/Lafia coal and imported high grade coals could be useful in this respect.

6.5 Electric Power Generation

When burned in a furnace with a boiler, coal generates energy in the form of heat. In a power plant that uses coal as fuel, this heat converts water into steam, which is pressurized to spin the shaft of a turbine. This spinning shaft drives a generator that converts the mechanical energy of the rotation into electric power.

The National Electric Power Authority (NEPA) now Power Holding Company of Nigeria (PHCN) had operated coal-fired power stations at Ijora (Lagos State) and Oji River (Enugu State). The thermal station at Egbin (Lagos State) is supplemented by the electricity generated from the Kainji Lake, to meet the national peak demand. Sub-bituminous coals in the Lower and Upper Benue Trough are best for power generation.

6.6 Industrial Uses

The Nigerian coal is rich in resins and waxes and is of potential interest as a source of chemicals and also for utilization in the manufacture of plastics (Fatoye *et al.,* 2012). It gives a gas of high calorific value and exceptional yields of tars and oils, both in the high and low temperature carbonization processes. The Nigerian coals can be used for the production of benzene, chloroform and coal tar. Sub-bituminous coals in the Lower and Upper Benue Trough are best for chemical production.

7.0 Conclusion

Nigeria has abundant coal deposits that could be exploited to diversify the nation's economy. Nigerian coal include lignites, sub-bituminous coal and bituminous coal and are all found within the Benue Trough of Nigeria. The coal deposits of the Anambra Basin in the Lower Benue Trough, located in southeastern Nigeria contain the largest and most economically viable coal resources. Although minor lignites and sub-bituminous coal deposits have been reported from Sokoto Basin, Mid-Niger (Bida) Basin and the Dahomey Embayment (Reyment, 1965). The only bituminous coal (Obi/Lafia coal) discovered so far in Nigeria occur in the Middle Benue Trough while sub-bituminous coals are confined mostly to Lower and Upper Benue Trough. The sub-bituminous coals in the Lower and Upper portions of the Trough could be exploited for export to where they are put to use as sources of energy, in combustible engines and in industrial furnaces, as well as in liquefaction process plants where they could be converted to liquid hydrocarbons. The high-volatile bituminous coals in the Middle Benue Trough on their part could constitute the bulk of the raw material for coke making consumable in the blast furnace of the Ajaokuta Steel Project.

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