# JOURNAL OF ENERGY POLICY, RESEARCH AND DEVELOPMENT (JEPRD)




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# EDITORIAL

The Energy Commission of Nigeria (ECN) was established by Act 62 of 1979 and its subsequent amendments with the responsibility for the strategic planning and coordination of national policies in the field of energy in all its ramifications. In doing so the Commission, inter alia, is serves as a centre for gathering and dissemination of information relating to national policy in the field of energy development; collate, analyze and publish information relating to the field of energy from all sources; and makes recommendations for the exploitation of new sources of energy to the Government. Accordingly, the Energy Commission of Nigeria publishes JOURNAL OF ENERGY POLICY, RESEARCH AND DEVELOPMENT (JEPRD), in order to accomplish its mandate.

JEPRD serves as the vehicle for the dissemination of research and developmental efforts and policies on energy in Nigeria as well as from other parts of the world deemed relevant to Nigeria's energy development. The Journal is published bi-annually with the main objective of bringing together research findings and policies strategies in all aspects of energy and also to serve as a forum for energy experts to provide, receive and exchange information to foster the growth and better utilization of energy in all its ramifications.

This second issue has seven articles featuring various aspects in the field of energy. The first paper is from Etiosa Uyigue et al, on a study conducted to determine the electrical energy consumption of selected end-use appliances in residential houses in Nigeria. The paper concluded that the average annual electricity consumption in Nigeria households is much higher than those in European countries where a similar study was done.

The second paper is by M.B. Shitta et al, in which an experiment that compared the performance of Light Emitting Diodes (LEDs) with Compact Fluorescent Lamps (CFLs) to ascertain the energy efficiency of the lighting types. As reported.  The third paper is also from M.B. Shitta et al. which reports on the savings made, when compact fluorescent lamps were deployed within the functions rooms of University of Lagos Guest Houses and Conference Centre.

The fourth paper by Bijaya Pokharel and O. Ojo, proposed the use of Static Synchronous Compensator (STATCOM) as a voltage regulating device at the point of common coupling to minimize terminal voltage fluctuation of wind turbine systems operating at maximum power point tracking mode (MPPT) during varying wind speeds. The fifth paper is a comparative investigation of African mesquite (*Prosopis Africana*) seed oil as a biodiesel and edible oil by J.S. Ibrahim et al. The sixth paper by O.A. Babatunde et al, the performance of Mobile Phone batteries used in Nigeria and brought out the need for standardization.  The seventh is a paper by Dr (Mrs) Roseline Kela et al, that highlighted the various current R&D activities, pilot projects and challenges in the area of efficient cook stoves development in Nigeria.

The Commission is now committed to timely publication of the journal. In no time, transactions of the journal will fully be on-line. You are, therefore, encouraged to continue to submit your articles for possible publication.

**Engr. Professor E. J. Bala, *FNSE, FAEng.***
Editor-in-Chief

# A SURVEY OF HOUSEHOLDS ELECTRICITY CONSUMPTION OF END-USE APPLIANCES IN NIGERIA

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**ABSTRACT**

A study was conducted to determine the electrical energy consumption of selected end-use appliances in residential houses in Nigeria. The end-use monitoring study was undertaken in the Federal Capital Territory, Abuja to assess the current level of energy efficiency of lighting appliances, refrigerators and air conditioners. A total of 35 households were monitored. The households were selected at random based on their income status. Data logger devices such as serial watt meters, *Multivoies* (watt meter with six pliers), lamp meters and temperature sensors were used to measure energy consumptions and energy related parameters for a period of 30 day from each household. Data obtained showed that electricity supply was available for 63% of the monitoring period and power outage accounts for 37% of the period. A total of 51% of the houses had air conditioners installed in them with an average power consumption of 1387kWh/annum. A total of 37% of the houses had fridge-freezers cooling systems with an average energy consumption of 698kWh/annum. Deep freezers were found in 46% of the households; the average energy consumption of deep freezers was 756kWh/annum. The average annual consumption of fridges was 420kWh/annum. The study revealed that power supply to the houses was unstable. Air conditioners were the most used appliances in most of the houses monitored and had the highest annual consumption. The average annual electricity consumption in Nigeria households is much higher than those in European countries where a similar study was conducted.

## INTRODUCTION

With a population of well over 160 million people, only about 40% of Nigerians have access to electricity. In places where there is access to electricity (mainly in the urban areas), consumers of electricity suffer from frequent power outages which last for several hours. The survey conducted in three large cities in Nigeria – Abuja, Lagos and Benin City[1] revealed that over 80% of those interviewed do not get electricity supply for up to 24 hours a day as shown in Fig. 1. The grid-generated electricity is inadequate for the population; as at August 2012, the peak generation was 4,477.7 MW[2]. The inadequate and unstable supply of electricity in Nigeria have forced a large portion of the industry, businesses and households to rely on diesel and petrol generators as primary or back-up source of electricity. Moreover, a large part of the energy generated is wasted from the use of inefficient appliances and wasteful human behaviour.

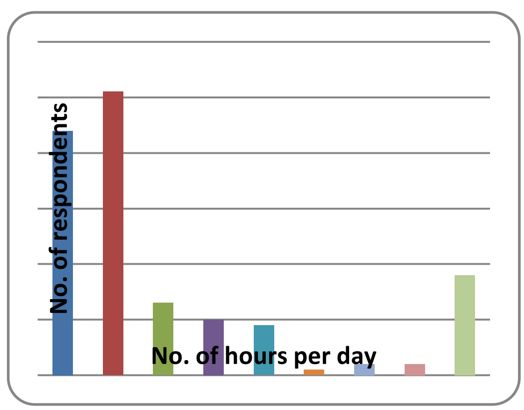



*Fig. 1: The number of hours respondents get electricity per day [1]*

Wielet al [3] reported that energy consumption contributes to about 25% to 30% of energy-related $CO_2$ emission, accounting for 26% of all anthropogenic $CO_2$ emission and 14% of global net contribution to climate change from greenhouse gases. Similarly, Price et al[4] reported that the use of energy in human activities related to buildings, including the use of appliances, equipment and lighting accounts for 42% of total energy consumption (including the use of biomass) and 36% of total energy related $CO_2$ emissions. The study further reported that the industrialized countries consume half of this energy, while the remainder is consumed by the rest of the world. CLASP[5] asserted that improving energy efficiency in the residential, commercial and building sectors will help to save money, reduce pollution and improve the indoor environment of homes and productivity in commercial buildings.

Promoting energy efficiency best practices is particularly relevant for the Nigeria power sector. This has the potential to reduce electricity demand and free more power which can be made available for more Nigerians. With support of the UNDP and the Global Environment Facility, the Energy Commission of Nigeria (ECN) and the National Centre for Energy Efficiency and Conservation (NCEEC) inaugurated a programme[6] to promote energy efficiency best practices in Nigeria. Part of the objectives of the Programme was to put in place a minimum energy performance standards (MEPS) for end-use appliances and introduce energy labels. Before MEPS are developed, it is imperative to understand the base line energy consumption and the level of efficiency of existing appliances. MEPS are mandatory standards and are done in a manner that they balance technical possibility with economic viability and the competitive forces within a particular market.

The objective of the study was to assess the current level of energy efficiency of selected appliances (lighting, refrigerators and air conditioners) used in Nigeria. The study also monitored the total household electricity usage. This paper therefore will give the preliminary report of the end-use energy monitoring study which was conducted in the six geopolitical zones of Nigeria. It will also share the progress made so far as well as share the success stories and lessons learnt. The study is on-going, thus the paper will present the report of the study that was conducted in the Federal Capital Territory, Abuja.(Fig. 2)the report of the study that was conducted in the Federal Capital Territory, Abuja. (Fig. 2)

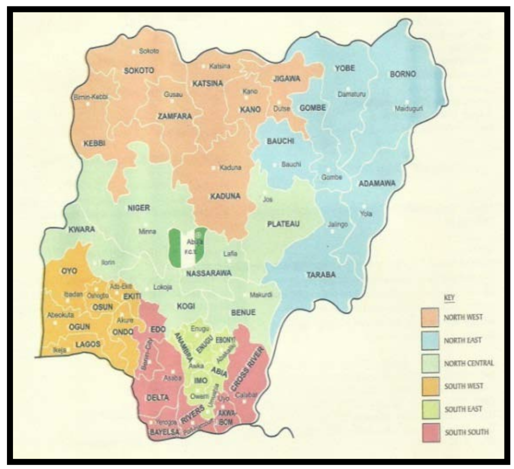



*Fig. 2: Map of Nigeria showing the six geopolical zones and the Federal Capital Territory, Abuja*

**METHODOLOGY**

Energy data werecollectedfrom Abuja, the Federal Capital Territory of Nigeria. A total of 35 householdsweremonitored during the study. The criteria for choosinghouseholdsinclude the size of the family and the socio-economic status such as the income level. The Study Team collected data using different electronic data logger devices for a period of 30 daysfrom each house. Data logger devices are smalldevicesused to measureatregularinterval the electricconsumption of different appliances. Threedifferent data loggerdeviceswereused for monitoring during the study. Theyinclude*Serial Wattmeter,* which was designed to measure the active energy and voltage for single-phase appliances with power level lower than 2.6 kW.

The devicewas placed between the standard socket-outlet (design to accommodate voltage from 0-250 V) and the plug of the appliance to be measured. The serial wattmeter is entirely autonomous and can be left to monitor anyappliance for several months according to the frequency of the selected data memory - memory can record data for up to 13 months. At the end of the measurement period, the data recorded were read using the Oscar software which transferredthe data to a computer for analysis. One serial watt meterwas used per appliance. The serial wattmeterswere used to collect data from refrigerators and some lighting appliances.

Multivoies Meteris a device designed for the measurement of a large number of channels of power consumption and energies from electrical switch boxes. It includes a din rail mounted concentrator to measure voltages and supplied power to the system, and several modules equipped with current sensors. The memory of the Multivoies can collect data for up to 4 months. If recording is required for more than 4 months, the device can be reset to collect more data. The Multivoies system can interface with Personal Data Assistant (PDA) using infrared communication or low power radio (Bluetooth). The Multivoies meter helped to collect the total consumption from the household, energy consumption from air conditioners and lighting equipment that were not connected to wall socket. The average voltage per ten minutes was recorded with the multivoie system to detect the periods with and without power supply.

Electronic thermometers were installed in all the houses monitored to provide information on the temperature changes during the time of measurement. The thermometer is an autonomous electronic data logger of reduced size provided with temperature sensor. It takes regular measurements and stores at interval between each measurement. The thermometer has a very broad range of measurements (-50°C to 120°C).The data were stored in a non volatile memory of strong capacity (64kb) allowing a recording going up to 65,000 measurements (1 byte per data, for an autonomy of approximately 1 year and 3 months for recordings with the step of 10 minutes).

There were several challenges encountered during the entire monitoring period. The electrical connections in many of the houses that were selected to collect data were faulty; there were cases where the neutral terminal of some houses had a measureable amount of voltage. Where such anomalies existed, the data logger devices could not be used. This problem resulted in lengthening the time to collect data as the Project Team spent more time to look for houses where the electrical connection were properly done. Furthermore, the illegal practice of bypassing meters was found in some of the houses that were selected for the study. In such houses, it was difficult to use the data logger devices especially the Multivoies Meter. Many of the data logger devices were damaged during the monitoring period. Several reasons might have been responsible for this; voltage fluctuation and the use of generators during the period of power outage.

There were many cases of errors between the configuration, installation and the dismantling of data logger devices. Hence, about 20% of the data logger devices were unusable. Moreover, the distribution boards found in many of the houses were complex. There were no labels on the different circuits in the distribution board; as a result, the Project Team had to check manually all fuses to trace the line to any appliance. In some cases it was quite difficult to fully identify all appliances connected to a specific electrical circuit. Finally, there was the problems due to security, religious and traditional practices. In many of the houses, the Project Team was not given full access to every part of the house during installation of the data logger devices and as a result, it was difficult to fully measure the consumption of all the appliances. The power outages had influence on the report when calculating the average annual consumption of an appliance that is switched off for half of the time because there was no power supply will certainly consume less energy as the appliance with a stable electricity supply.

## RESULT OF STUDY

The study revealed that the power supply to the houses was unstable, thus they do not receive continuous supply of electricity. Fig 3 shows the percentage of power access and power outage. On the average, electricity supply was available for 63% of the monitoring period and power outages accounted for 37% of the period.

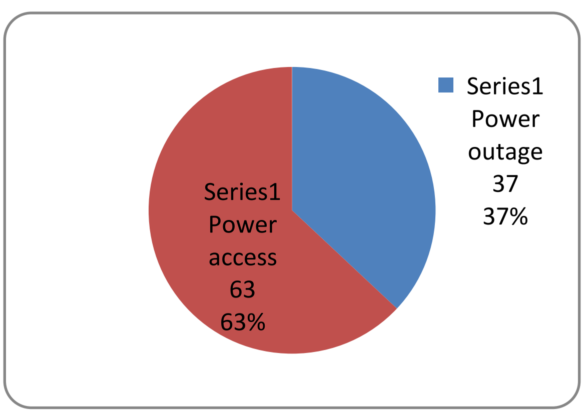
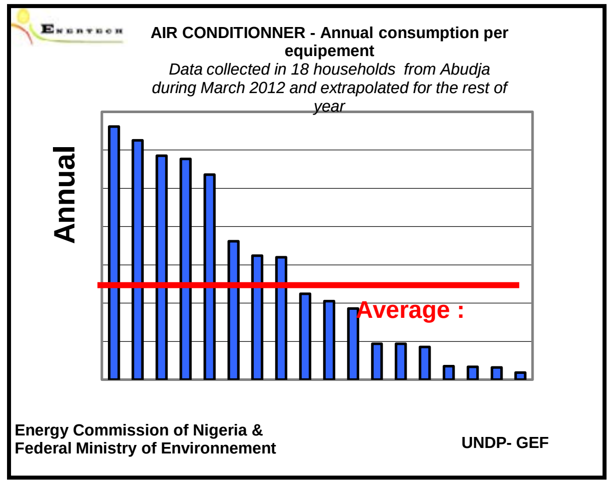



Fig. 3: Power access and power outage in Abuja

51% of the households in Abuja had air conditioners installed in them. Fig. 4 shows the highest energy consuming air conditioner was 3307 kWh/annum while the lowest was approximately 92 kWh/annum which give anaverage of 1387 kWh/annum.

*Fig 4: Annual consumption of air conditioners monitored in Abuja*




Many of the houses monitored have one or more of the following appliances – fridge-Freezer (having both a fridge and freezer compartment), Fridge (only fridge compartment) and freezer (having only freezer compartment). A total of 37% of the households had fridge-freezer cooling systems. The average annual consumption for fridge-freezer was 698 KWh/annum; the highest consumption was 1,230 KWh/annum while the lowest was 427 KWh/annum. (Fig. 5)

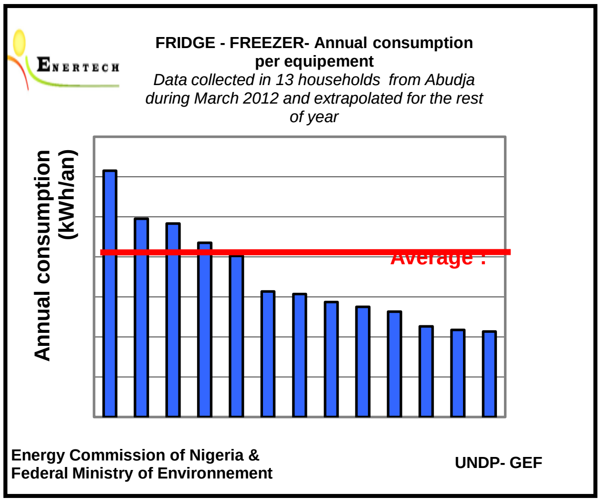



*Fig. 5: Annual consumption of fridge-freezer monitored in Abuja*

Freezers (popularly called deep freezers) were found in 45% of the households. The average annual consumption for freezers was 756 KWh/annum, the highest consumption was approximately1318 KWh/annum, while the lowest was 212.50 KWh/annum. (Fig. 6)

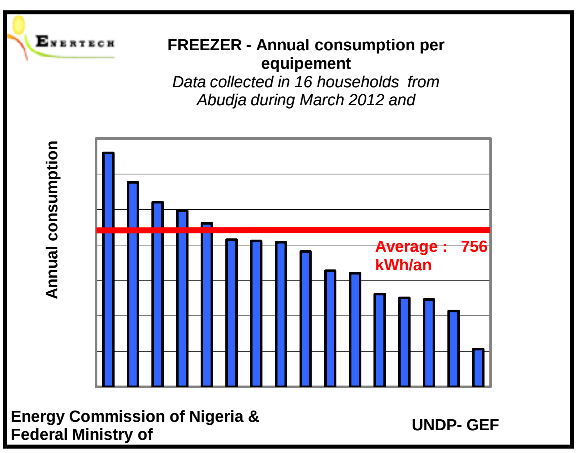



*Fig. 6: Annual consumption of freezers monitored in Abuja*

Sixteen (16) fridges were monitored during the study and the average annual consumption was 420 KWh/annum; the highest reading was 941 KWh/annum and the lowest was 125 KWh/annum. (Fig. 7)

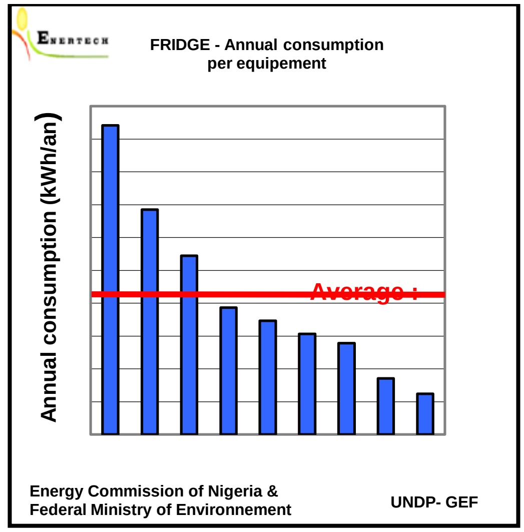



*Fig 7: Annual consumption of fridges monitor in Abuja, Nigeria*

## DISCUSSION

The study in the Nigeria Federal Capital Territory revealed that the energy consumption of appliances is very high compared to countries where energy efficiency measures have been put in place. Similar studies have been carried out in many countries in Europe. These countries include France, Sweden and England. Compared to these countries in Europe, the average annual consumption of fridges, fridge-freezers and freezers in Nigeria is the highest. The lowest consumption of energy was recorded in England.

| | **Annual consumption per equipment (kWh/an)** | | |
|---|---|---|---|
| **Country** | **Fridge** | **Fridge-freezer** | **Freezer** |
| **FRANCE 2007** | 253 | 460 | 556 |
| **SWEDEN 2007** | 225 | 469 | 470 |
| **ENGLAND 2011** | 162 | 427 | 344.5 |
| **NIGERIA 2012** | **420** | **698** | **756** |

*Table 1: Average annual consumption for Nigeria and European countries*

Table 1 also revealed that the average annual consumption for cool appliances in European countries decreases with time. From the study conducted in France in 2007, the average annual consumption of fridge, fridge-freezer and freezer was 253, 460 and 556 Kwh/annum respectively. The study conducted in England in 2011 (about four years after the study in France) reveal a considerable fall in the annual energy consumption of domestic cold appliances. This may be as a result of several energy efficiency measures such as standard and label which have been introduced in many European countries. From the study in France and the study in England, there was 36%, 7% and 38% decrease in average annual consumption for fridges, fridge-freezer and freezer respectively.

The preliminary study in Abuja,Nigeria compared to the study in England revealed that the average annual consumption recorded in the current study are significantly higher than that recorded in England. For instance, the study revealed that the average annual energy consumption for fridge, fridge-freezer and freezer for Nigeria was 61%, 39% and 54% respectively higher compared to England. This calls for the need to embark on energy efficiency programmes in Nigeria. This further justifies the objective of the on-going Nigeria Energy Efficiency Programme, on the need to introduce measures to promote energy efficiency in end-use appliances.

## CONCLUSION

When compared to other countries where similar studies have been done, the average annual energy consumption of cold appliances in Nigeria is the highest. This implies that the energy efficiency of cold appliances inNigeria is low compared to those of these countries. The results of this study further justify the need to put in place energy efficiency measures to reduce electricity demand of the end users. The use of regulatory instruments such as mandatory minimum energy performance standards (MEPS) can help to improve the energy efficiency of cold appliances. Since MEPS have to be developed empirically, the result from this study will provide the required information to the relevant agent of government to set up the appropriate energy performance benchmark suitable for cold appliances in the Nigeria market.

## APPRECIATION

The authors of this paper extend their gratitude to the Global Environment Facility (GEF) and the UNDP Nigeria Country Office for providing the financial support to embark on this study. The technical support of the Energy Commission of Nigeria and the National Centre for Energy Efficiency and Conservation is highly appreciated.

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# EXPERIMENTAL COMPARISON OF LIGHTING PERFORMANCE OF LED WITH CFL

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## ABSTRACT

Lighting has been identified as one of the areas where energy conservation can be achieved in the shortest possible time, when the right technology is deployed. This experiment compares the performance of Light Emitting Diodes (LEDs) with Compact Fluorescent Lamps (CFLs) to ascertain the energy efficiency of the lighting types. Five distinct brands of 3 W LED were purchased from the market, with the brand comprising a set of five (5) lamps each. With the aid of a light meter, the Illumination of the lamps was measured at the manufacturer's rated operating voltage to obtain the luminous efficacy of the lamps. The luminous efficacy of 5 W and 8 W compact fluorescent lamps (CFLs) and LEDs were compared at the same operating voltage to ascertain the best performance. The efficacy of the LED lamp was observed to be higher when compared to that of the CFLs under test. In the analysis that followed, a typical household which deployed ten (10) lamps each of LEDs, CFLs, and incandescent lamps revealed that, although the initial cost of purchasing LED was higher, the energy saving was quite significant when compared to CFLs and incandescent bulbs. It is concluded that if energy efficiency is considered a priority when lighting systems are being deployed in buildings, LED provides the technology that can help achieve the desired performance even though the initial cost of purchase is higher.

***Keywords**:Luminous Efficacy, Light Emitting Diodes, Energy Efficiency and Conservation, Compact Fluorescent Lamp*

## 1.0 INTRODUCTION

Light is a form of electromagnetic radiation. It is similar in nature and behaviour to radio waves at one end of the frequency spectrum and X-rays at the other. Light is reflected from a polished surface at the same angle that strikes it [1]. Light source can be measured in terms of its Luminous intensity measured in candela (cd); Luminous flux (lm) is the measure of the visible light energy emitted. The luminance of a lamp is the visible light emitted per square meter. A Light Emitting Diode (LED) is a solid state device which is highly energy-efficient and very reliable source of luminosity [2].A single LED is a DC low-voltage solid state device and cannot be directly operated on standard high-voltage AC power without circuitry to convert the voltage applied and the current flow through the lamp. In principle a series diode and resistor could be used to control the voltage polarity and to limit the current, but this would be very inefficient since most of the applied power would be dissipated by the resistor.

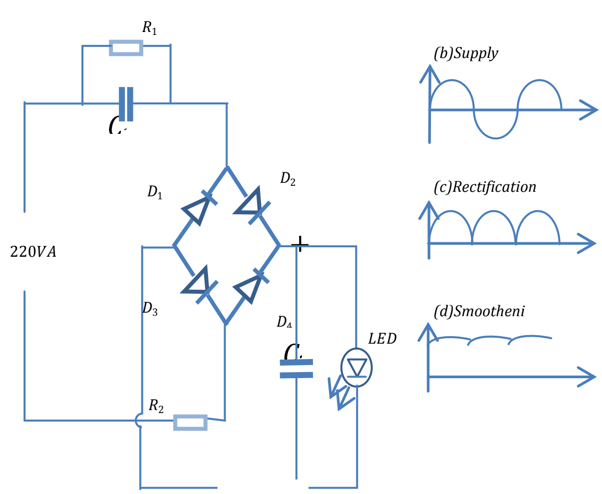
A series string of LEDs would minimize dropped-voltage losses, but one LED failure would extinguish the whole string.Paralleled strings increase reliability by providing redundancy. In practice, three or more strings are usually used [3]. To be useful in providing illumination, a number of LEDs must be placed close together (cluster) in a lamp to combine their illuminating effects, because when using the colour-mixing method, a uniform colour distribution can be difficult to achieve.While the arrangement of white LEDs is not critical for colour balance,it provides illumination through a combination of semiconductor chips which serve as light generators and phosphors acting as light converters. When first developed, LEDs were limited to single device use in applications such as instrument panels, electronics, pen lights and, more recently, strings of indoor and outdoor Christmas lights. This is in contrast to evacuated bulbs used in incandescent lamps and low-pressure gas tubes in fluorescent lamps [4].

Manufacturers have expanded the application of LEDs by clustering several small devices. The first clustered LEDs were used for battery powered items such as flashlights and headlamps. Today, LED lamps are made using as many as 180 LEDs per cluster, and encased in diffuser lenses which spread the light in wider beams. They are now available with standard bases which fit common household light fixtures; LEDs are the next generation in home lighting [5]. However, the contribution of Compact Fluorescent Lamps (CFLs) for efficient lighting and energy savings cannot be ignored. Several studies have reported the energy saving potentials of Compact Fluorescent Lamps (CFLs) [6, 7]. Although CFLs have been in the forefront in the drive towards energy efficiency and conservation, particularly in lighting applications with derivable benefits noticeable in residential and commercial buildings [8], more savings can be achieved when LEDs are used in place of CFL. Many advantages have been attributed to the use of LED lamps such as very low power consumption, and high efficiency (124lm/W), among others [9-11]

However, there are challenges associated with the adoption and use of LED technology, which includes ascertaining the claims of the performance and the operating characteristics quoted by some manufacturers. Moreover majority of LEDs in Nigerian appliance market are devoid of proper ratings and labels hence the motivation for this work. There is growing customer concern about the reliability of the lamps and their ability to withstand erratic voltages from the country's electricity supply grid.

The main objective of this study is to test the characteristics of LEDs and compare their luminous efficacy with CFLs as claimed by manufacturers within the same operating voltages so as to determine their performance. It is expected that this work adduce reasons why consumers should prefer Light Emitting Diode (LEDs) Lamps and provide them with the right information required to make informed decisions when purchasing lamps from the open market.

Fig.1 is the circuit diagram of the LED lamp under test.It comprises of the supply voltage (Fig. 1b), a rectifier (Fig. 1c), the smoothing capacitor (Fig. 1d) and thin film resistors.




1.aCircuit diagram of the LED lamp

Fig. 1: Circuitry of the LED

$V_s$ = supply voltage = 220Vac

$V_L$ = LED voltage (3V)

I = 20mA

Number of LEDs = 28

Total voltage of the 28 LEDs connected in series gives

28 x 3V = 84.0Vdc

The current flowing through the LED at maximum light output is 20mA

Hence, the power consumed P = IV

= 20 x $10^{-3}$ A x 84V = 1.68W

## 2.0 METHODOLOGY

This study was conducted by carrying out a survey on the various brands of lamps available in the Nigerian market. Majority of lamps predominantly found in the market are Incandescent lamps, Compact Fluorescent Lamps (CFLs), Rechargeable (DC and AC) lamps, Fluorescent tubes, Filament and Light Emitting Diode (LED) Short and long type. Out of the lamps available in the market, a sample of five different brands of LEDs were purchased, with each brand comprising a set of ten (10), which is the required minimum number that meets test criteria in accordance with the IEC 60969 standard laboratory procedure for testing lamps.

The luminosity of the different brands was tested based on the operating conditions stated on the brand's label.Each lamp by brand type was tested by varying the voltage at step intervals of 10V beginning from 210V to 250V, for all the brands and the behavior of the LEDs under the range of varied voltage input was logged directly on the computer by the light meter and observed on the computer monitor. Data for all the lamps were collated and the average value of the luminosity at each voltage step for a given brand was taken at particular voltages. The various lamps tested were compared in terms of their efficacy within the varied voltage range selected for the experiment to ascertain the claims by the selected lamp's manufacturers, Table 1 is the technical data of the lamps.

Table 1. Technical Data of the lamps

| Lamp Type | Watt (W) | Operating Voltage/ Frequency (V/Hz) | Socket Type | Lifetime-Hours (H) | No. of LEDs | Luminous Efficacy (Lm/W) |
|---|---|---|---|---|---|---|
| LED | 3 | AC 220 – 240V/50Hz | E27 | Not indicated | 28 | 35 |
| LED | 3 | AC 220 – 240V/50Hz | E27 | Not indicated | 28 | 35 |
| LED | 1 | AC 220V/50 Hz | E27 | 80,000 | 20 | 35 |
| LED | 1 | AC 220V/50 Hz | GU10 | 80,000 | 14 | 35 |
| LED | 1.02 | AC 220/50 Hz | B22 | Nil | 16 | 35 |
| CFL | 5 | AC 220-250/50Hz | E27 | 10,000 | NA | 35 |
| CFL | 8 | AC 220-250/50Hz | E27 | 10,000 | NA | 35 |

## 2.1 EXPERIMENTAL APPARATUS/EQUIPMENT

The specifications of the measuring instruments used are:

**LIGHT METER**

- A 3 to 4 digit display with a high speed 40 segment bar graph
- Light sensor of 115×80×20mm
- Lead length on light sensor: 150cm
- Measuring levels for Lux range from: 0Lux – 400Lux, 400Lux – 4kLux,

4kLux – 40kLux and 40kLux to 400kLux

- Accuracy: ±3% rdg ±0.5% f.s. (<10,000Lux) and ±4% rdg ±10d. (>10,000Lux)
- Sampling rate of 1.5 times per second
- Analysis software

**ENERGY METER**

- A digital display screen
- Maximum Load of 13A, 3120W
- Measurable current of 0.02A to 13A and
- Wattage of 5W – 3588W

**COMPUTER**

- HP ProBook
- Windows XP Professional

## 2.2 EXPERIMENTAL SETUP

The experimental setup is shown in Fig. 2. The variac is used to vary the input voltage through the range of 210V to 250V. Measurement of the luminosity of the LEDs are performed inside a testing cubicle (63.5×63.5×127.0cm) with the interior painted black to prevent reflection of light from the walls of the box. This ensured that the light incident on the light meter was obtained directly from the lamp. An ATP Light meter was used to measure the luminosity per square metre at a distance of about 1.2m from the lamp. The luminosity was measured and logged directly by the computer.

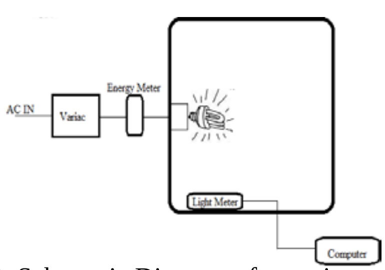



Fig. 2: Schematic Diagram of experimental setup (Adopted from [6])

Fig. 3 is the validation set up for the experiment carried out using the setup in Fig. 2. Standard procedure for testing lamps which starts with 100h controlled aging time was employed, after which the lamps were transferred to the sphere in Fig. 3. The lamps were powered while in the sphere and allowed to stabilise for 20 minutes before the test was carried out.

Fig. 3: YF-1000 lamp Testing Analysis Machine at National Centre for Energy Efficiency and Conservation (NCEEC)

## 3.0 RESULTS AND DISCUSSION

Fig.4 is the comparison of the three different lamps considered at their manufacturer stated operating voltages. At 200 V, 3W rated specimen A LED had the least efficacy compared to 3W rated specimen B LED which was better than the 8W CFL at the same operating voltage of 220V.It can be seen clearly from the chart that specimen B LED had the highest efficacy at the same operating voltage of 200V. When the voltage was varied to 230 V, Specimen B LED slightly increased in terms of its efficacy but remained higher than the CFL and specimen A LED.

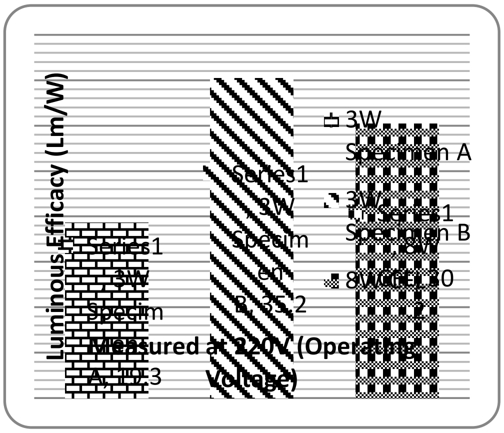



Fig. 4: Luminous Efficacy comparison of LED Specimen A, LED Specimen B and 8W CFL

According to the manufacturer's information on Table 1, the operating voltage of specimens A and B, lies between 220V and 240V while that of the CFL lies between 220V and 250V. 240V, is the stated upper limit of the LED's operating voltage. The efficacy of specimen B LED dipped a little compared to CFL but rose higher than specimen A LED at the same operating voltage.

Fig.5is the comparison of the efficacy of the best performed 3Wrated specimen B LED with 5W CFL at the same operating voltage. The 3W specimen B LED outshone the 5W CFL in terms of efficacy which is the parameter the manufacturers claimed to be the same as stated on their packs.

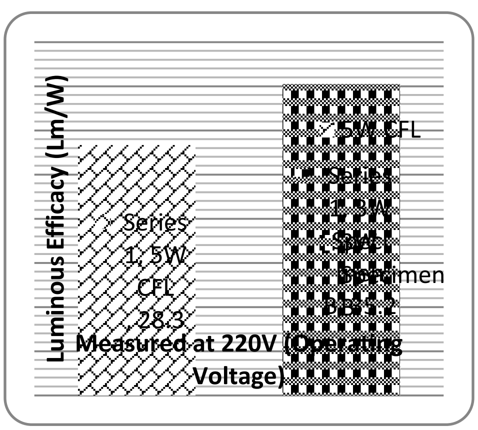



Fig. 5: Luminous Efficacy Comparison of the best performed LED and CFL of 5W.

The best among the tested lamps was the 3W specimen B LED Fig. 6. This was compared with two CFLs of 5W and 8W in terms of efficacy at the same operating voltage. It was found that the LED's efficacy at the manufacturer's stated operating voltage was better than to the two CFLs.

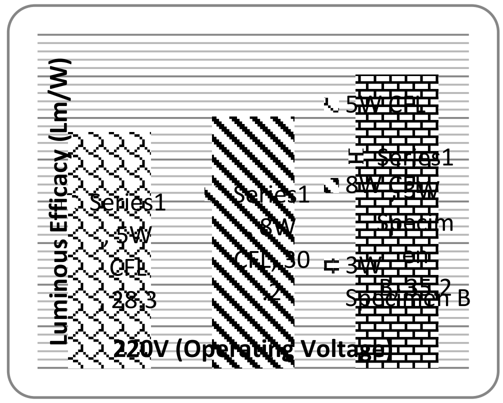



Fig. 6: Luminous Efficay Comparison of the best performed LED with CFL of 5W and CFL 8W

## 4.0 COMPARISON OF OPERATING COSTSOF LED, CFL AND INCANDESCENT LAMPS

Initial installation cost may be high for LED lighting solutions compared to incandescent and CFL solutions. But initial cost does not account for the total cost of owning, operating, and maintaining a lighting system. Because of their long useful life, LED lighting fixtures avoid the maintenance and materials costs, which multiple replacements of incandescent lamps require over tens of thousands of hours of operation. Since LEDs consume far less energy, the annual power costs can be reduced by up to 80%.The total cost of LED lighting systems, therefore, can be significantly lower than conventional systems. In fact, payback on LED lighting solutions can often be realized within three years of installation.

Table 2 considers a typical household which deploys 10 lamps each of 3W LED, 8W CFL, and 60W Incandescent. The assumption made is that the utility company charge ₦12.50/kWh and the lamps are run for 8hrs daily in a year. Although the initial cost of purchasing and installing LEDs may be high, the savings is quite much when compared to Incandescent and CFL. It can be seen from the table, that the difference in terms of energy cost per annum is much. Between LEDs and CFLs, there is a difference of ₦ 1,825 and between the LED and Incandescent is ₦20, 805. This implies that over time, the LED running cost will remain low as shown in Fig 7.

Table 2: The Energy Cost Comparison between LED, CFL and Incandescent Lamps for a Typical Household

| Comparison | 3W LED | 8W CFL | 60W Incan-descent |
|---|---|---|---|
| Unit cost x 10 Lamps | ₦ 8,000 | ₦ 5,000 | ₦ 500 |
| Lamp Life (Rated) | 80,000 hrs (3,333 days or 9 years) | 10,000 hrs (1667 day or 5years) | 1000hrs (167 days) |
| Annual Energy Cost | ₦1095 | ₦ 2,920 | ₦ 21,900 |

Fig. 7, shows the running cost of operating LED, CFL and Incandescent bulbs deployed in an average apartment containing 10 lamps each of the LED, CFL and Incandescent over time (Days). It can be seen that the cost of running Incandescent bulbs kept increasing over time. Based on estimate, the LED will pay-back by the end of three (3) years from installation.

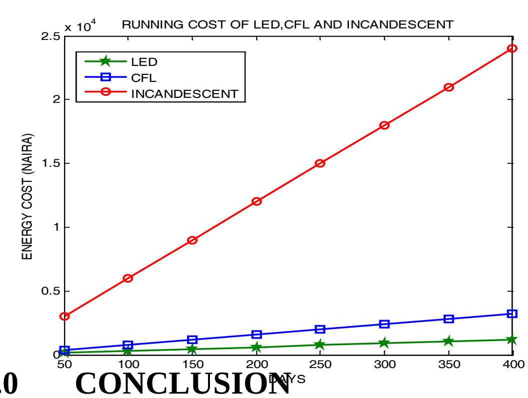



Fig. 7: Running Cost of LED, CFL and Incandescent

## 5.0 CONCLUSION

Most of the manufacturers of LED lamps claim 80,000 hourslife time. Having carried out test on some parameters for all the LED samples the averages for the measurement were taken. This was used to compare the lamps at their manufacturers stated operating voltages. It is clear that the LED lamps perform very well in terms of efficacy within the stated operating voltages when compared to the CFLs and incandescent bulbs tested. Further attempt to compare the efficacy of LED beyond the upper limit of the stated operating voltage with CFL was made but the result showed that above LED's operating voltages, its performance dipped. The result apparently indicates that 3W rated LED, in terms of its efficacy out performed CFLs within their stated operating voltages.

The analysis made when 10 lamps each of LED, CFL and Incandescent lamps were deployed in a typical apartment given approximately the same illumination when measured, and operated for equal number of hours and assuming a utility charge of ₦12.50/kWh, at the end of one (1) year. The cost of running CFL was found to be ₦2, 920, that of Incandescent bulb₦21,900 and LED₦1,095. The figures showed marked difference in terms of cost of running Incandescent lamps and CFLs.

With advancement in solid state electronics and semi-conductor technology, the pace of technological development of LEDs is fast and as research is being conducted into the use of better materials, the reliability and performance of LEDs will continue to improvewith respect to other lighting types. As more people embrace the technology to satisfy their lighting requirements, the cost of purchasing and deploying LED lamps will reduce significantly. It can be said that LED is the next generation lighting that can replace CFL in terms of energy efficiency. This is apparent in the results obtained and it is strongly recommended if energy efficiency is a priority.


## ACKNOWLEDGEMENT

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# IMPROVEMENT OF BUILDING ENERGY PERFORMANCE AND HUMAN OCCUPANT COMFORT THROUGH ENERGY EFFICIENCY MEASURES

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## ABSTRACT

The reduction of energy consumption in buildings through the adoption and implementation of energy efficiency and conservation measures has been identified to reduce energy cost, mitigate climate change, increase energy accessibility, improve occupancy comfort and achieve sustainable development. This paper reports the savings made when compact fluorescent lamps are deployed within the functions room of University of Lagos Guest Houses and Conference Centre. The total cooling load of the functions room before the installation was 27.63 kW, requiring four units of 7 kW free blow stand-alone air-conditioners to cool. On a 4 to 5 ratio; for each 100W incandescent lamp, 5 CFLs of 8 W were replaced. 100 W incandescent lamps were each replaced with 8 W compact fluorescent lamps. After the replacement, the cooling load reduced to 18.77 kW and the number of air conditioners required reduced to two (2) units of 7 kW free blow stand-alone air conditioners, which translates to a saving of 18%. A proposal to totally replace all the incandescent lamps with the required quantity of energy efficient lamps is also made. When the proposal is implemented, 32% saving can be realised from the total initial load; and this load will require three 7 kW free blow stand-alone air conditioners of any brand. The study recommends that energy-efficient technologies are necessary for new, existing buildings and refurbishment projects, since this will help reduce energy consumption, improve building energy performance and human occupant comfort.

***Keywords**: Building Energy Performance; Lighting; Cooling Load; Occupancy Comfort; Compact Fluorescent Lamps; Energy Efficiency*

## 1.0 INTRODUCTION

A building provides spaces and generally has an environment that is conditioned from that of its surroundings to suit particular purposes. Buildings therefore includes a physical enclosure with some means for creating a comfortable internal environment for human habitation and are used to provide microclimate for human existence and space for all human activities [1, 2].

There is a strong relationship between a building's interior and corresponding energy performance, reason being that most of the energy consumed in the interior environment is expanded to ensure occupants' comfort especially in environment and lighting. The major factor in building design is human comfort. Temperature and humidity have large impact on the body's heat transfer and are largely responsible for human comfort [3]. Other factors include building surface colour and texture, face temperature, transmissivity, characteristics of the sun or night sky, human body (surface area exposed and colour or texture of clothing) and energy consuming equipment or devices within the building space. The physiology of human beings as warm-blooded mammals requires the internal body temperature to be maintained within very close limits (between 36$^o$C and 38$^o$C, the normal temperature being 37$^o$C). Falling below 30$^o$C and rising above 41$^o$C, death is imminent. Considering that humans live in environments where the external temperature varies between -40°C to over 50°C, this is quite a demanding requirement and is achieved with a number of mechanisms.Heat is released into the body by all metabolic processes including nutrition, respiration and movement to mention a few. In order to maintain a balanced temperature, the body must therefore find ways to lose heat at the same rate at which heat is being produced by these processes [4].

The four basic mechanisms by which the body exchanges heat with its environment are evaporation, convection, conduction and radiation. Evaporation and convection are mechanisms of heat loss from the body. Radiation and conduction can result in either heat gain or heat loss depending on the temperature of body relative to its surroundings [5].

One major energy-consuming appliance that contributes to space heating is lighting. Maintaining sufficient lighting levels in a sustainable manner is necessary for the productive operation of a building and improvement of occupant performance. Lighting need is important to energy analysis for two main reasons.Lights consume energy and in general lights produce heat [6]. Over the years, more priority is being given to building aesthetics while energy demand continues to receive little or no attention during building design and construction.This trend continues to hold notwithstanding increase in population which results in high energy consumption. To minimize energy consumption in buildings, architects and builders ought to pay attention to the lighting requirements of buildingswith building designs made to allow for as much natural lighting as possible, so that building occupants can depend less on artificial lighting. Presently, artificial lighting contributes significantly to high energy consumption in most buildings. In most developed countries for instance, where energy data is taken seriously such as United States, a report by the Energy Information Administration shows that buildings account for 37% of the energy use in the country. Of this amount, 53% is consumed by residential buildings.In most advanced countries, building account for about 40% of total energy use [7]. Lighting accounts for 8.8% of the total capacity consumed in residential [8] and 23% in commercial buildings [9].

With increase in global population, energy use in buildings has become a growing concern. This is because increase in population results in increasing demand for more houses and office accommodation. This in turn increases building service demand such as air conditioning, lighting, computers and other electrical and electronic appliances. All of these contribute to the building energy demand. Energy consumption in buildings accounts for a significant percentage of total world energy consumption, with values that range from 40% in Europe and USA [10, 11] to 30% in some Mediterranean countries [12,13, 14]. Buildings are responsible for at least 40% of energy use in most countries. The absolute figure is rising fast as construction booms, especially in developing countries (U.S Congress, Office of Technology Assessment, building Energy Efficiency, OTA-E-518). However, increase in energy usage, though desirable, has its implications on humans, the environment, economy and even the energy supply system [15].

Against this backdrop, it is imperative that measures are taken to reduce energy demand in buildings and also ensure that human comfort is given very high priority. In designing buildings, energy conservation can be prioritized by introducing proper energy management and control measures especially at the architectural design stage of building creation [16].Also energy efficient technologies can be incorporated and

alternative energy sources integrated into building architecture so as to provide buildings with a diversified energy mix and generate energy enough to meet occupants' needs with any excess fed back into an intelligent grid infrastructure [17].
Efficiency in building involves reduced energy consumption for acceptable levels of comfort, air quality and other occupancy requirement. Energy efficiency in buildings provides a wide range of societal benefits including significant consumer cost savings, reduced energy demand and improved electric system reliability.

This study provides an energy management solution to energy waste and building-occupant discomfort observed within the functions room of University of Lagos Guest Houses and Conference Centre. The lighting need within this room was initially met using 108 units of 100 W incandescent bulbs resulting in energy waste since this lighting type is found to be highly inefficient in energy conversion. However, there are more efficient lighting types (Compact Fluorescent Lamps and LEDs) that couldbe deployed to illuminate the interior spaceeven better yet save energy. This problem is not only peculiar to the functions room being discussed as similar observation is found to exist in many building types such as eventcenters and shopping malls across the country.

The purpose of this work is to determine the energy need, calculate the cooling load inside the functions room over specified period of time and size the HVAC equipment needed when all the light bulbs are incandescent type andenergy-saving alternative. The next stepis to compare the use of inefficient light bulbs (incandescent bulbs) and energy saving lamps (compact fluorescent lamps) on both the cooling requirements and human-occupancy comfort. These quantifications will aid architects, builders and engineers in making appropriate building design decision by adopting energy efficiency measures that seek to provide comfortable indoor conditions for building occupants.

## 2.0 METHODOLOGY

The entrance of air into the space under consideration is primarily through the door and air conditioning system installed, as all other openings such as windows have been sealed. This room initially designed for 40-capacity has over the years become overstretched as it now accommodates more occupants than its initial design capacity.

Prior to a lighting retrofit exercise conducted by the National Centre for Energy Efficiency and Conservation (NCEEC), the University functions room under consideration had a total of 108 units of 100W incandescent bulbs of different colours (yellow – in majority, blue and red making up the remaining) installed. As part of the implementation of energy efficiency measures and contribution to the reduction in energy consumption, attendant pollution and heat, the Centre replaced 60 units of these inefficient bulbs each with 8W rated energy saving lamps.

Based on the retrofit, the paper examines the reduction in cooling load within this space and its influence on human-occupant comfort, energy demand, cost and the environment. This helps demonstrate a practical consequence of installing and using typical lighting application within a space.

### 2.1 COOLING LOAD ESTIMATION

The various methods for estimating cooling load include thetransfer function methods, cooling load temperature differential/cooling load factors and total equivalent temperature differential/time-averaging methods [18].

In this paper, the cooling load temperature differential/cooling load factors (CLTD/CLF) method as described in the ASHRAE [19]was considered. This method though not optimum will yield the most conservative results based on the peak values to be used in sizing equipment.

The cooling load compares the sensible and latent heat required to maintain human comfort in a space with incandescent bulbs and energy efficient lamps. Information on location, site and weather data, internal design information and operating schedules were obtained.

The total building cooling load consists of heat transferred through the building envelope (walls, roof, floor, windows, doors etc.) and heat generated by occupants, equipment and lights. Ashrae [19], Urban [20] and Bansal [21] published the heat output of human bodies for various activities as shown in Table 1. The table consists of sensible heat gain with effect on the dry bulb temperature and latent heat gain with effect on the moisture content. The manner in which heat enters into this space includes:

1. Solar radiation through transparent surfacessuch as windows
2. Heat conduction through exterior walls androofs
3. Heat conduction through interior partitions,ceilings and floors
4. Heat generated within the space by occupants, lights, appliances, equipment and processes
5. Loads as a result of ventilation andinfiltration of outdoor air
6. Other miscellaneous heat gains

## 2.2 ASSUMPTIONS

1. Weather conditions are selected from a long-term statistical database. The conditions do not represent any actual year, but are representative of the location of the room. ASHRAE has tabulated such data.
2. The solar loads on the functions room are assumed to be those that would occur on a clear day in the month chosen for the calculations.
3. The building occupancy is assumed to be at full design capacity.
4. All equipment and appliances used in the room (except lightings) are considered to be operating at a reasonably representative capacity and are assumed the same for all the conditions under consideration.
5. Lights and appliances are assumed to be operating as expected for a typical day of design occupancy.
6. Latent as well as sensible loads are considered.
7. Heat flow is analysed assuming dynamic conditions, which means that heat storage in building envelope and interior materials is considered.
8. The latent heat gain is assumed to become cooling load instantly, whereas the sensible heat gain is partially delayed depending on the characteristics of the conditioned space. According to the ASHRAE regulations, the sensible heat gain from people is assumed 30% convection (instant cooling load) and 70% radiative (delayed portion).

**9.** The energy analysis program compares the total energy use in a certain period with various alternatives (in lighting use) in order to determine the optimum one.

Table 1: Heat production rate in a human body

| Activities | Rate of heat production (W) | (W/m$^2$) |
|---|---|---|
| **Sleeping** | 60 | 35 |
| **Resting** | 80 | 45 |
| **Sitting, Normal office work** | 100 | 55 |
| **Typing** | 150 | 85 |
| **Slow walking (3km/h)** | 200 | 110 |
| **Fast walking (6km/h)** | 250 | 140 |
| **Hard working (filing, cutting, digging, etc** | More than 300 | More than 170 |

Source: [21]

### 2.2.2 HEAT GAIN

The heat (sensible and latent) gain is computed according to information available in literature. The heat gain in this functions room is computed from roof, walls, solar load through glass, infiltration air, ventilation air, air supply, internal loads (thermal energy generated, internal loads from equipment, people and lights) and 5% of heat was added to the total sensible and latent heat as safety factor [19,20] . Table 1 and Table 2 show the heat output of human bodies for various activities.

Table 2: Rate of Heat Gain from Occupants at various activities (at indoor air temperature of 25.5$^{o}$C)

| Latent heat (W) | | | | |
|---|---|---|---|---|
| Seated at rest | 115 | 100 | 60 | 40 |
| Seated, very light work, writing | 140 | 120 | 65 | 55 |
| Seated, eating | 150 | 170 | 75 | 95 |
| Seated, light work, typing | 185 | 150 | 75 | 75 |
| Standing. Light work or | 235 | 185 | 90 | 95 |
| walking Slowly | 255 | 230 | 100 | 130 |
| Light bench work | 305 | 305 | 100 | 180 |
| Light machine work, walking 1.34m/s | 400 | 375 | 120 | 255 |
| Moderate dancing | 470 | 470 | 165 | 300 |
| Heavy work, lifting, Athletics | 585 | 520 | 185 | 340 |

Source: [25]

On the electrical lighting load, which is the obvious load consideration in this paper, the amount of electricity $Q_c$ required for a light source to illuminate a given area is computed using equation 1

$$\frac{Q_c}{A} = \frac{E_{v,min}\ (lm/m^2)}{\varepsilon_{source}\ \ (lm/W)} \qquad (1)$$

This equation assumes that all light emitted from the source travels in equal amounts in the direction of the surface to be illuminated. Table 3 and Table 4 show the luminous efficacy of different light bulbs minimum luminous intensity for common environments respectively.

Table3: Luminous efficacy of select light sources

| Fixture Type | Luminous Efficacy $\varepsilon$ $(lm/W)$ | Overall Lighting Efficiency, $\eta$ (%) |
|---|---|---|
| **Candle flame** | 0.3 | 0.05 |
| **Halogen** | 12 | 1.8 |
| **Incandescent** | 17 | 2.5 |
| **White LED bulb** | 34 | 5.0 |
| **Compact fluorescent** | 63 | 9.2 |
| **Tube fluorescent** | 88 | 13.0 |
| **High pressure sodium** | 130 | 19.0 |

Source [20]

Table 4: Minimum luminous intensity for common environments

| Environment/ Activity | Minimum lighting $E_{v,min}$ $(lux)$ |
|---|---|
| **Storage** | 0 to 150 |
| **Residential living room** | 50 |
| **Kitchen** | 300 |
| **Office** | 400 to 500 |
| **Television studio** | 1000 |
| **Detailed work** | 1000 to 1500 |

Source [20]

Equation 1 is applied to the space under consideration with minimum luminous intensity of 450 lux, as in Table 4 to obtain the capacity and quantity of light bulb needed for both incandescent and compact fluorescent lamps (CFLs).

Supposing a light source shines towards a flat 1 m x 1 m square in this room:
The capacity of incandescent bulb required on this 1 m x 1 m square surface, is obtained as

$$\frac{Q_c}{A} = \frac{450(lm/m^2)}{17\ (lm/W)} \approx 26.5W/m^2$$

From Table 4 it is found that 26.5 W of electricity is required to illuminate the area to the proper level instead of the 100 W incandescent bulb installed. Since this room comprises many 1 m x 1 m squares, (with an area of $161m^2$), then each square requires this amount of electricity. Overall, this functions room will require a total power demand (lighting) of 4266.5 W when the 26.5 W incandescent bulbs are installed. With this result, the standard size of incandescent lamps available in the market that would have been installed is shown in Table 5.

Table 5 shows the quantity of standard size incandescent lamps needed in the functions room.

| Capacity (W) | Quantity |
|---|---|
| **25** | ≈170 units |
| **40** | ≈107 units |
| **60** | ≈71 units |
| **100** | ≈43 units |

The number of lighting point required to achieve the intended power demand is obtained by using equation 2

$$Number\ Incadescent\ lamp\ required =$$

$$\frac{Total\ \ Power\ \ Demand\ \ (wit\,h\ inc\,andescent\ \ lamp\,)W}{Lamp\ \ Capacity\ \ (W)per\ \ unit} \quad (2)$$

Similarly, applying equation 1 theory to capacity and quantity of compact fluorescent (energy saving) bulbs to be used in this space,

$$\frac{Q_c}{A} = \frac{450(lm/m^2)}{63\ (lm/W)} = 7.14\ W/m^2 \approx 8\ W/m^2$$

Then, a total power demand of 1149.54 W of the 7.14 W CFLs is required to make the lighting conditions in the room energy efficient with improved human comfort. With the various standard sizes of CFLs in the market, Table 6 shows the quantity of energy saving lamps required to be installed in the functions room with improvement in level of human comfort.

The heat gain considers the situation when all the light bulbs are incandescent type and energy saving type.

### 2.2.3 OPERATING/INPUT PARAMETERS

The operating parameters used in the course of the calculations are as follows:

- **i.** Location: Akoka, Yaba, Lagos, Nigeria
- **ii.** Type of Building: A functions room within University of Lagos Guest Houses and Conference Centre
- **iii.** Floor area: 11.5 m x 14 m = 161 $m^2$
- **iv.** Floor height = 4 m
- **v.** Window area = 0.75 $m^2$
- **vi.** Number of windows: 6
- **vii.** Wall: Material: Wall number. U value = 0.630 $W/m^{2\,0}C$
- **viii.** Roof: MaterialU value = 0.693 $W/m^{2\,0}C$
- **ix.** Windows: U value = 6.2 $W/m^{20}C$
- **x.** Occupancy: 60 persons
- **xi.** Working: time of use of the space is 10 hrs
- **xii.** Location: Latitude of the Guest House is $6^0$ 30’
- **xiii.** Outdoor design dry-bulb: $35^0C$
- **xiv.** Outdoor design wet-bulb: $18^0C$
- **xv.** Indoor design dry-bulb: $25^0C$
- **xvi.** DailyRange: $10^0C$
- **xvii.** Relative humidity: 50%
- **xviii.** Wind velocity: 2m/s
- **xix.** Occupancy hours for people from 8 A.M. to 6 P.M. (10hrs)
- **xx.** Light remains on from 8 A.M. to 6 P.M.
- **xxi.** Total power demand of the 100 W incandescent bulbs: 9180 W
- **xxii.** Total power demand of the equal number of 8 W Compact Fluorescent Lamps: 734.4 W
- **xxiii.** Total power demand of the mixture of the 100 W and 8 W lamps currently in use: 4488 W
- **xxiv.** Total wattage of all the appliances within the space: No appliance
- **xxv.** Roof number one (check Table 31t page 28-42 and U value for the roof from ASHRAE 2007 handbook).
- **xxvi.** Wall number four (4) (check Table 31t page 28-42 and U value for the wall from ASHRAE 2007 handbook).
- **xxvii.** Values of Cooling Load Temperature Difference (CLTD) for roof taken from Table 30, page 28-42 of ASHRAE 2007 handbook.
- **xxviii.** Values of Cooling Load Temperature Difference (CLTD) for wall taken from Table 32, page 28-45 of ASHRAE 2007 handbook.
- **xxix.** Values of Cooling Load Temperature Difference (CLTD) for glass taken from Table 34, page 28-49 of ASHRAE 2007 handbook.

**xxx.** Values of Shading Coefficient (SC) are taken from Table 11, page 29-25 of ASHRAE 2007 handbook.

**xxxi.** Values of Solar Cooling Load (SCL) are taken from Table 36, page 28.50, zone Type C of ASHRAE 2007 handbook.

**xxxii.** Values of Cooling Load Factor (CLF) for lighting are taken from Table 37 based on 10hours in space, page 28.51, zone Type C of ASHRAE 2007 handbook.

**xxxiii.** Rates of Sensible Heat Gain (SHG) and Latent Heat from people are taken from Table 3, page 28.8 of ASHRAE 2007 handbook.

## 3.0 RESULTS AND DISCUSSION

The results as shown in Table 7 gives the heat gain in the functions room under the three different conditions;

Table 7 shows the heat gain by the room before retrofitting i.e. incandescent lamps only, with this condition, a total load of **23.23 kW** is needed to be cooled, for human comfort. The table also shows the total load after replacing all of the incandescent lamps with compact fluorescent lamps (CFLs). It is apparent that savings of **9 kW** is made after the exercise.

Table 7. Heat gain from the functions room at the three different conditions

| | Heat gain by the functions room before replacement of lamps | Heat gain by the functions after replacement of lamps |
|---|---|---|
| LOAD SOURCE | WATT (W) | WATT (W) |
| Lights | 9180 | 734.4 |
| People | 9078 | 9078 |
| Ventilation | 3865.656 | 3865.656 |
| **Sub Total Load** | **22123.6566** | **13,678.056** |
| Safety Factor* (5% of Sub Total Load) | 1106.1828 | 683.9028 |
| **Total Load** | **23229.8394** | **14361.9588** |

Fig. 1 shows the cooling load by the various sources of heat considered in the functions room under the conditions of heat gain from the building with all incandescent lamp and with all energy saving lamps. The lighting source accounts for 39.52% of the cooling load considered when all the incandescent are in place.

The savings achieved with the implementation of energy efficiency measures (the energy saving retrofitting) in this functions room is obvious in Fig.1.

Total retrofitting of incandescent lamps with energy saving lamps offer a saving of **8,867.88 W** in the cooling load. This shows a saving of 62%.

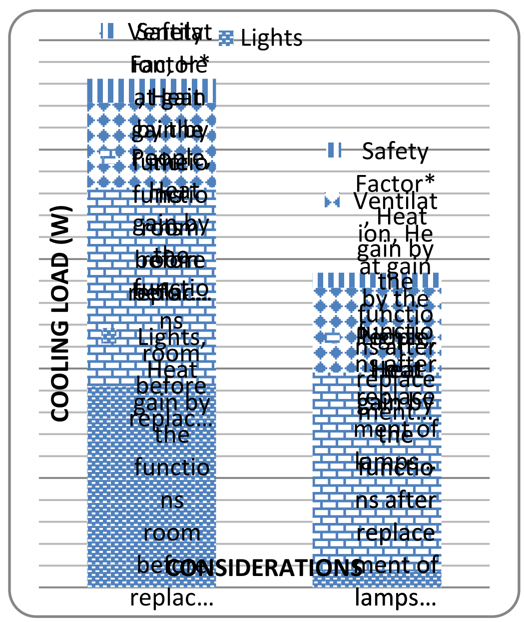


Figure 1: The graph of the Cooling Loads resulting from the two conditions

The numbers of standard size of air conditioning Units of 7 kW capacity required in the functions room under the two conditions are presented in Table 8.

Similar studies [22] on an overview of compact fluorescent lamp retrofitting and Abolarin et al [23] on energy (lighting) savings in students' hostels, also concluded that savings are achievable when inefficient light bulbs are retrofitted with energy efficient ones. This energy efficiency implementation results in a friendly environment as reported in [24] that over 45% of pollutant emission is prevented from the atmosphere.

Table 8. Quantity of ACs required for installation under the three conditions

| Conditions | Cooling Load (W) | Quantity of ACS |
|---|---|---|
| **Heat gain by the functions room before replacement of lamps** | **23229.839** | ≈4 units |
| **Heat gain by the functions after replacement of lamps** | **14,361.958** | ≈2 units |

## 4.0 CONCLUSION

This study shows that energy efficient technologies when deployed in buildings will help cut down on building energy use and improve human-occupancy comfort. In this paper, selected cooling load of the room was calculated with a focus on replacing the inefficient lightings with efficient ones. Cooling load of the room under consideration amount to **23.23 kW**, this requires four (4) units of 7 kW free blow stand-alone air conditioners. When all the incandescent lamps are replaced, the load reduced to **14.36 kW**, this required two (2) units 7 kW free blow stand-alone air conditioners to condition the room, instead of the initial four 7 kW air conditioner before the exercise. From this retrofitting exercise, a saving of 9 kW is achieved from the total cooling load demand of the functions room. This automatically reduced the number of air conditioners from four (4) to two (2). This analysis clearly shows that a 34.41% savings is achievable from lighting alone. This study, therefore, recommends that energy efficiency technologies should be adopted right from the design stage to reduce the energy demand of buildings.


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# Point of Common Coupling Voltage Control of a DFIG Wind Turbine Connected to Weak Grid

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## ABSTRACT

DFIG wind turbine system is the most popular wind power generator in current market. Even though the active and reactive power output of DFIG can be controlled independently, the active power output of those wind turbines varies with wind speed. The converters in DFIG have limited capacity as a result it cannot supply usually required reactive power hence the terminal voltage of the wind turbine system connected to weak distribution grid fluctuates. So voltage regulation device is required for safe operation of power grid. This paper proposes the use of Static Synchronous Compensator (STATCOM) as a voltage regulating device at the point of common coupling to minimize terminal voltage fluctuation of the wind turbine system operating at maximum power point tracking mode (MPPT) during varying wind speed. The control scheme for DFIG wind turbine system and STATCOM is systematically developed and the effectiveness of the proposed system is verified by simulating in MATLAB/Simulinksoftware.

**Keywords:** DFIG wind turbine system, STATCOM, Voltage Regulation, Voltage Fluctuation, MPPT

## 1. INTRODUCTION

Wind power is the most reliable and developed renewable energy source over past decades. The increased awareness of people towards renewable energy, support from governmental institution and rapid advancement in power electronics industry, which is the core of wind power system, are the most contributing factors for the development of wind power systems. Hence the share of wind power with respect to total installed power capacity is increasing. With the increased penetration level of wind power in power system, additional services, such as voltage control provided by the wind turbines, become more important [1]. Most utility companies want wind turbine generator systems to behave analogous to conventional synchronous generators in terms of supplying active and reactive powers [2]. Unfortunately, most wind farms are usually located at remote places, driven by wind and weather patterns with little up-front analysis performed regarding the existing power grid in that location and such locations tend to be weaker points in the distribution system. So they require extra reactive power compensation devices for connecting wind farms to the grid [3].

Variable speed wind turbines generators utilizing doubly fed induction generators (DFIGs) are most popular in the wind power industry especially for multimegawatt wind turbine generators [2]. DFIG is a wound-rotor induction generator which is connected to the grid at the stator terminals, as well as at the rotor mains via a partially rated variable frequency ac/dc/ac converter (VFC), which only needs to handle a fraction (25 –30 %) of the total power to accomplish full control of the generator. The functional principle of this variable speed generator is the combination of DFIG and four-quadrant ac/dc/ac VFC equipped with IGBTs. The ac/dc/ac converter system consists of a rotor-side converter (RSC) and a grid-side converter (GSC) connected back-to-back by a dc-link capacitor. The beauty of DFIG is its efficient power conversion capability at variable wind speed with low price because of partial size rated converter.

Although wind turbines with DFIG are able to control active and reactive power independently, the reactive power capability of those generators is subject to several limitations resulting from the voltage, current, and speed, which change with the operating point [2]. The aerodynamic aspects of the wind turbines create terminal voltage fluctuation in wind turbine [4]. Since the DFIG has power electronic converters with limited capacity, it cannot supply usually demanded reactive power on a continuous basis. If the wind farm is far from the point of common coupling (PCC), then there will be more loss if reactive power is generated from DFIG.

In [4] and [5], STATCOM is proposed to minimize voltage fluctuation in DFIG system. In [6], reactive power compensation using STATCOM is proposed for improving fault ride-through capability and transient voltage stability in DFIG system. Although external hardware increases the cost of overall system, STATCOM can be used to provide reactive power in already installed DFIG system that has voltage regulation problem.

Hence in this paper, use of STATCOM connected at the PCC with the weak distribution grid to regulate the voltage so that connected load to the system always gets required power with regulated voltage during varying wind speed is investigated. DFIG wind turbine system operating in maximum power point tracking mode (MPPT) and blade pitch control (power regulation) mode is modeled. Vector control approach is used for the electrical power output control from DFIG. A STATCOM is designed to regulate voltage at the PCC with the weak distribution grid so that connected load to the system always gets required power with regulated voltage during varying wind speed in the wind generation system.

The remainder of the paper is organized as follows. Section II describes about variable speed wind turbine modeling and control. Section III discusses about DFIG control scheme. Section IV introduces the STATCOM modeling and controller design whereas section V briefly shows the studied system. Section VI shows the results obtained using MATLAB/Simulink and finally section VII concludes the paper.

## 2. WIND TURBINE MODELING AND CONTROL

The turbine is the prime mover of Wind Energy Conversion System (WECS) that enables the conversion of kinetic energy of wind $E_w$ into mechanical power $P_m$ and eventually into electricity.

$$P_m = \frac{\partial E_w}{\partial t}\ C_p = \frac{1}{2} \rho\ A V_w^{\ 3}\ C_p \quad (1)$$

where $V_w$ is the wind speed at the center of the rotor (m/sec), $\rho$ is the air density (kg/m$^3$), $A$ is the frontal area of the wind turbine (m$^2$); R being the rotor radius. $C_p$ is the performance coefficient which in turn depends upon turbine characteristics (blade pitch angle β and tip speed ratio (TSR)) that is responsible for the losses in the energy conversion process. The numerical approximation of $C_p$ used in this study is [7]:

$$C_p(\lambda,\beta)=0.5176\left(\frac{116}{\lambda_i}-0.4\beta-5\right)e^{-21/\lambda_i}+0.0068\lambda \quad (2)$$

where the TSR $\lambda$ and $\lambda_i = f(\lambda,\beta)$ are given by-

$$\lambda=\frac{\omega_t R}{V_w} \text{ and } \frac{1}{\lambda_i}=\frac{1}{\lambda+0.08\beta}-\frac{0.035}{\beta^3+1} \quad (3)$$

where $\omega_t$ is the turbine speed and R is the blade radius of the wind turbine. The plot of $C_p$ Vs $\lambda$ at various values of β is shown in Fig. 1.

## 2.1 MAXIMUM POWER POINT TRACKING MODE

From the plot shown in Fig. 1, we can state that-

For β= 0 degree, $\lambda_{opt}=8.1$ and $C_{p\_\max}=0.48$

Now the rotor mechanical torque extracted from the wind that in turn drives wind generator is: $T_t=\frac{P_m}{\omega_t}$

Now from equations (1) and (3),

$$T_t=\frac{1}{2\omega_t}\rho A V_w^{\,3} C_p=\frac{R}{2\lambda}\rho A V_w^{\,2} C_p \quad (4)$$

From equation (4) if we are able to run the wind generator that corresponds to wind speed $V_w$ in such a way that wind turbine will be operating in maximum power point (as shown in Fig. 2) then we can extract maximum available power from the available wind speed via wind turbine.

## 2.2 Blade Pitch Control Mode

Pitch angle control is the most common means for adjusting the aerodynamic torque of the wind turbine when wind speed is above rated speed. In high speed operation, generator power begins to exceed its rated power so the pitch control will be activated which pitches the wind turbine blades by angle β so as to extract less mechanical power (as shown in Fig.1. when β increases, $C_p$ decreases means $P_m$ decreases) from wind. In this study the combined turbine speed and turbine mechanical power is chosen as the controlling variables for pitch control as shown in Fig. 4. The proportional and integral gains of the pitch controller are specified by the manufacturer.

Two distinct operating modes of DFIG wind turbines at different wind speed is clearly shown in Fig. 3.

# 3. DFIG MODELLING AND CONTROL

The dynamics of DFIG is represented by a fourth-order state space model using the synchronously rotating reference frame (qd-frame) as follows [8]:

(where $p=\frac{d}{dt}$ throughout the paper)

$$V_{qs}=r_s I_{qs}+\omega\lambda_{ds}+p\lambda_{qs} \quad (5)$$

$$V_{ds}=r_s I_{ds}-\omega\lambda_{qs}+p\lambda_{ds} \quad (6)$$

$$V_{qr}=r_r I_{qr}+(\omega-\omega_r)\lambda_{dr}+p\lambda_{qr} \quad (7)$$

$$V_{dr}=r_r I_{dr}-(\omega-\omega_r)\lambda_{qr}+p\lambda_{dr} \quad (8)$$

where $V_{qs}$, $V_{ds}$, $V_{qr}$, $V_{dr}$ are the q and d-axis stator and rotor voltages; $I_{qs}$, $I_{ds}$, $I_{qr}$, $I_{dr}$ are the q and d-axis stator and rotor currents; $\lambda_{qs}$, $\lambda_{ds}$, $\lambda_{qr}$, $\lambda_{dr}$ are the q and d-axis stator and rotor fluxes; $\omega$ is the angular velocity of the synchronously rotating reference frame; $\omega_r$ is the rotor angular velocity and $r_s$ and $r_r$ are the stator and rotor resistances. The flux linkage equations are given as:

$$\lambda_{qs} = L_s I_{qs} + L_m I_{qr} \quad (9)$$
$$\lambda_{ds} = L_s I_{ds} + L_m I_{dr} \quad (10)$$
$$\lambda_{qr} = L_m I_{qs} + L_r I_{qr} \quad (11)$$
$$\lambda_{dr} = L_m I_{ds} + L_r I_{dr} \quad (12)$$

where $L_s$, $L_r$ and $L_m$ are the stator, rotor and mutual inductances respectively with $L_s = L_{ls} + L_m$ and $L_r = L_{lr} + L_m$ : $L_{ls}$ being the self inductance of stator and $L_{lr}$ being the self inductance of rotor.

All the equations above are induction motor equations, if induction motor acts as generator then current direction will be opposite. Assuming negligible power losses in stator and rotor resistances, the active and reactive powers are given as:

$$P_s = -\frac{3}{2}\left[V_{qs} I_{qs} + V_{ds} I_{ds}\right] \quad (13)$$

$$Q_s = -\frac{3}{2}\left[V_{qs} I_{ds} - V_{ds} I_{qs}\right] \quad (14)$$

$$P_r = -\frac{3}{2}\left[V_{qr} I_{qr} + V_{dr} I_{dr}\right] \quad (15)$$

$$Q_r = -\frac{3}{2}\left[V_{qr} I_{dr} - V_{dr} I_{qr}\right] \quad (16)$$

The total active and reactive power generated by DFIG is:

$$P_{Total} = P_s + P_r \text{ and } Q_{Total} = Q_s + Q_r$$

If $P_{Total}$ and $Q_{Total}$ both are positive; DFIG is supplying power to the power grid, else it is drawing power from the grid. The rotor speed dynamics of the DFIG is given as:

$$p\omega_r = \frac{P}{2J}(T_m - T_e - C_f \omega_r) \quad (17)$$

where P is number of poles of the machine, $C_f$ is friction coefficient, J is inertia of the rotor, $T_m$ is the mechanical torque generated by wind turbine and $T_e$ is the electromagnetic torque generated by the machine which is given as:

$$T_e = \frac{3}{2}\left[\lambda_{qs} I_{ds} - \lambda_{ds} I_{qs}\right] \quad (18)$$

where positive (negative) values of $T_e$ means DFIG works as a generator (motor).

Electrical control of DFIG is achieved by controlling the RSC and GSC. The control objective of RSC is to regulate the stator side active power $P_s$ (or rotor speed $\omega_r$) and the reactive power $Q_s$ independently. Similarly the control objective of GSC is to maintain constant dc-link voltage and to control reactive power injected by GSC to the grid regardless of magnitude and direction of rotor power [9].

### *3.1 Control of the RSC*

Fig. 5 shows the general vector control scheme of the RSC in which independent control of $P_s$ and $Q_s$ is achieved by controlling rotor current. Aligning the d-axis of reference frame along the stator flux linkage vector then $\lambda_{qs} = 0$ and $\lambda_{ds} = \lambda_s$. Substituting $\lambda_{qs} = 0$ in (18) and (9) and solving we get,

$$T_e = -\frac{3P}{4}\frac{L_m}{L_s}\lambda_{ds} i_{qr} \quad (19)$$

From (17) and (19):

$$i_{qr} = \left(\frac{2J}{P}p\omega_r - T_m\right)\frac{4}{3P}\frac{L_s}{L_m \lambda_{ds}} \quad (20)$$

Equation (20) gives the rotor speed dynamics for designing speed control. Similarly substituting $\lambda_{qs} = 0$ and solving (9), (10) and (14) gives:

$$i_{dr} = \frac{\lambda_{ds}}{L_m} - \frac{2}{3}\frac{L_s Q_s^*}{L_m V_{qs}} \quad (21)$$

where $Q_s^*$ is the desired reactive power that stator supplies to the grid. Equation (21) gives the stator reactive power control equation. Now substituting values of $\lambda_{dr}$ and $\lambda_{qr}$ given by (11) and (12) into (7) and (8) and during steady state and further simplification yields,

$$V_{qr} = r_r i_{qr} + \sigma L_r p i_{qr} + \omega_{so}\left(\frac{L_m}{L_s}\lambda_{ds} + \sigma L_r i_{dr}\right) \quad (22)$$

$$V_{dr} = r_r i_{dr} + \sigma L_r p i_{dr} - \omega_{so}\sigma L_r i_{qr} \quad (23)$$

where $\omega_{so} = (\omega - \omega_r)$ and $\sigma = 1 - \frac{L_m^{\ 2}}{L_s L_r}$.

Equation (22) and (23) gives the inner current control loop for the RSC control.

### *3.2 Control of the GSC*

Fig. 6 shows the general vector control scheme of the GSC where control of dc-link voltage $V_{dc}$ and reactive power exchange between GSC and power grid is achieved by controlling current in synchronously reference frame [8].

Aligning the stator voltage vector along q-axis of reference frame then $V_{ds} = 0$ and $V_{qs} = V_s$. Now dc voltage dynamics in dc-link is given by,

$$C\ pV_{dc} = I_o + \frac{3}{4}\left(M_{df} i_{df} + M_{qf} i_{qf}\right) \quad (24)$$

where $C$ is the dc-link capacitance, $I_o$ is the dc current from RSC towards GSC and $M_{df}$ and $M_{qf}$ are q and d-axis modulation indexes of GSC respectively. Since $V_{ds} = 0$, assuming $V_{ds} \approx V_{df}$ and $V_{qs} \approx V_{qf}$ so, $M_{df} \approx 0$. Hence equation (24) will be:

$$i_{qf} = \frac{4}{3}\frac{1}{M_{qf}}\left(C\ pV_{dc} - I_o\right) \quad (25)$$

Similarly, the GSC supplied reactive power is controlled using d-axis current given by following relation.

$$i_{df} = \frac{2}{3}\frac{Q_f^*}{V_{qf}} \quad (26)$$

where $Q_f^*$ is the desired reactive power to be supplied to the grid via GSC. Again using KVL across the RL filter gives:

$$V_{qf} = r_f i_{qf} + L_f p i_{qf} + \omega_s L_f i_{df} + V_{qs} \quad (27)$$

$$V_{df} = r_f i_{df} + L_f p i_{df} - \omega_s L_f i_{qf} \quad (28)$$

Equation (27) and (28) gives the inner current control loop for the GSC control.

## STATCOM MODELLING ANDONTROLLER DESIGN

STATCOMis modelled as a PWM converter comprising of IGBT with a dc-link capacitor and a coupling transformer connected in shunt to the distribution network through a coupling transformer as shown in Fig. 7. The objective of STATCOM is to regulate the voltage magnitude swiftly at the PCC bus within a desired range by exchanging the reactive power with the distribution system. At the same time the converter in STATCOM should maintain constant dc-link voltage. A filter capacitor $C_m$ is also connected in shunt to the same bus for mitigating harmonics.

Dynamic equations of the STATCOM converter in qd reference frame:

$$V_{q1} = r_s I_{q1} + L_s p I_{q1} + \omega L_s I_{d1} + V_{q2} = M_{q1}\frac{V_{dc}}{2} \quad (29)$$

$$V_{d1} = r_s I_{d1} + L_s p I_{d1} - \omega L_s I_{q1} + V_{d2} = M_{d1}\frac{V_{dc}}{2} \quad (30)$$

where $V_{q1}$, $V_{d1}$, $V_{q2}$, $V_{d2}$ are the q and d-axis converter output voltages and PCC bus voltages respectively, $I_{q1}$, $I_{d1}$ are the q and d-axis converter output currents, $r_s$ and $L_s$ are line resistance and inductance respectively, $M_{q1}$ and $M_{d1}$ are q and d-axis modulation indexes of the converter respectively, $V_{dc}$ is the dc-link voltage and $\omega$ is the angular velocity of the synchronously rotating reference frame.

Again in the converter, dc voltage dynamics in dc-link is given by:

$$C_{dc} pV_{dc} = -\frac{3}{4}(M_{q1}I_{q1} + M_{d1}I_{d1}) \qquad (31)$$

The voltage magnitude ($V_m$) at PCC is given as.

$$V_m^2 = V_{q2}^2 + V_{d2}^2 \qquad (32)$$

Differentiating (32) w.r.t. time,

$$pV_m^2 = 2V_{q2}\, pV_{q2} + 2V_{d2}\, pV_{d2} \qquad (33)$$

Equation (33) gives the square of voltage magnitude dynamics at PCC. Then the voltage magnitude will be: $V_m = \left|\sqrt{V_m^2}\right|$.

***DC-voltage control:***

Equation (31) can be rewritten as:

$$-\frac{4}{3}C_{dc} pV_{dc} = (M_{q1}I_{q1} + M_{d1}I_{d1}) = \sigma_{dc} = k_{dc}(V_{dc}^* - V_{dc}) \, (34)$$

where $k_{dc}$ is the PI controller for dc-voltage control given as:

$k_{dc} = \left(k_{Pdc} + \frac{k_{Idc}}{s}\right)$. Then equation (34) will be:

$$\frac{4}{3}C_{dc} pV_{dc} = \left(k_{Pdc} + \frac{k_{Idc}}{s}\right)V_{dc}^* - \left(k_{Pdc} + \frac{k_{Idc}}{s}\right)V_{dc}$$

$$\Rightarrow \frac{V_{dc}}{V_{dc}^*} = \frac{\frac{3}{4C_{dc}}\left(sk_{Pdc} + k_{Idc}\right)}{s^2 + s\frac{3k_{Pdc}}{4C_{dc}} + \frac{3k_{Idc}}{4C_{dc}}} \qquad (35)$$

Comparing denominator of (34) with Butterworth second order polynomial i.e. $s^2 + \sqrt{2}\omega_{0dc}s + \omega_{0dc}^2$,

$$k_{Pdc} = \frac{4}{3}\sqrt{2}\omega_{0dc}C_{dc} \;\; and \;\; k_{Idc} = \frac{4}{3}C_{dc}\omega_{0dc}{}^2$$

where $\omega_{0dc}$ is the bandwidth of the DC-voltage controller, which depends upon the design value.

***Voltage magnitude control:***

From Fig. 7, the dynamic voltage equations at PCC can be written as:

$$C_m \; pV_{q2} = I_{q1} - I_{q2} - C_m\omega V_{d2} \qquad (36)$$

$$C_m \; pV_{d2} = I_{d1} - I_{d2} + C_m\omega V_{q2} \qquad (37)$$

Substituting (36) and (37) into (33) gives:

$$\frac{C_m}{2} pV_m^2 = V_{q2}\left(I_{q1} - I_{q2}\right) + V_{d2}\left(I_{d1} - I_{d2}\right) = \sigma_m = k_m(V_m^{2*} - V_m^2) \, (38)$$

where $k_m = \left(k_{Pm} + \frac{k_{\mathrm{Im}}}{s}\right)$ is the PI controller for voltage magnitude control. Then equation (38) can be written as:

$$C_m pV_m^2 = \left(k_{Pm} + \frac{k_{\mathrm{Im}}}{s}\right)V_m^{2*} - \left(k_{Pm} + \frac{k_{\mathrm{Im}}}{s}\right)V_m^2 \quad (39)$$

$$\frac{V_m^2}{V_m^{2^*}} = \frac{\frac{2}{C_m}\left(sk_{Pm} + k_{\text{Im}}\right)}{s^2 + s\frac{2k_{Pm}}{C_m} + \frac{2k_{\text{Im}}}{C_m}} \quad (40)$$

Comparing denominator of (40) with Butterworth second order polynomial, we get:

$$k_{Pm} = \sqrt{2}\omega_{0m}\frac{C_m}{2} \;\; and \;\; k_{\text{Im}} = \frac{C_m}{2}\omega_{0m}^{\;\;2}$$

where $\omega_{0m}$ is the bandwidth of the voltage controller, which depends upon the design value.

***Inner current control:***

If we assume:

$$r_s I_{q1} + L_s pI_{q1} = K_{1q}(I^*{}_{q1} - I_{q1}) = \sigma_{1q} \quad (41)$$

$$r_s I_{d1} + L_s pI_{d1} = K_{1d}(I^*{}_{d1} - I_{d1}) = \sigma_{1d} \quad (42)$$

Then equation (29) and (30) can be written as:

$$M_{q1} = (\sigma_{1q} + \omega L_s I_{d1} + V_{q2})\frac{2}{V_{dc}} \quad (43)$$

$$M_{d1} = (\sigma_{1d} - \omega L_s I_{q1} + V_{d2})\frac{2}{V_{dc}} \quad (44)$$

Equation (43) and (44) gives modulation indexes which are the output of the converter. And $K_{1q}$ and $K_{1d}$ are PI current controllers for q and d axis currents respectively, where:

$$K_{1q} = K_{1d} = \left(k_{P1} + \frac{k_{I1}}{s}\right) \quad (45)$$

Combining equations (41) and (45) gives:

$$\left(r_s + sL_s\right)I_{q1} = \left(k_{P1} + \frac{k_{I1}}{s}\right)I_{q1}^{\;*} - \left(k_{P1} + \frac{k_{I1}}{s}\right)I_{q1}$$

$$\Rightarrow \frac{I_{q1}}{I_{q1}^{\;*}} = \frac{\frac{1}{L_s}\left(sk_{P1} + k_{I1}\right)}{s^2 + s\frac{1}{L_s}(r_s + k_{P1}) + \frac{1}{L_s}k_{I1}} \quad (46)$$

Comparing denominator of (46) with Butterworth second order polynomial,

$$k_{P1} = \sqrt{2}\omega_{0c}L_s - r_s \;\; and \;\; k_{I1} = L_s\omega_{0c}^{\;\;2}$$

where $\omega_{0c}$ is the bandwidth of the current controller, which depends upon the design value. Bandwidth of the controller depends upon the switching frequency at which converter is operating. If $\omega_{sw} = 2 * \prod * f_{sw}$ is the switching frequency then, for this design, current controllers and voltage controllers bandwidth is taken as:

$$\omega_{oc} = \frac{1}{10}\omega_{sw} \text{ and } \omega_{om} = \omega_{odc} = \frac{1}{10}\omega_{oc}.$$

## 4. TEST SYSTEM

Fig. 8 demonstrates the single line diagram of the test system. A 1.5 MW DFIG wind turbine system is connected to the distribution network at PCC bus where a STATCOM is connected to regulate the voltage. Three different types of loads, a linear RL load, a constant load (P, Q) and a nonlinear load ($P_{non}$, $Q_{non}$) are also connected in shunt to the same PCC bus. The DFIG wind turbine system is always generating its optimum reactive power (0.4 Mvar, closely equal to 30% of total power rating of DFIG. The distribution network is modeled as weak ( $X / R = 5$ ). The wind speed in the wind turbine varies and so does the power output from wind turbine system. The connected electrical load remains constant during the entire study period. When the wind speed is low (above cut-in speed but below rated speed), at that time DFIG turbine will be operating in MPPT mode and at higher wind speed (above rated speed but below cut-out speed), DFIG turbine will operate in power regulation mode so it will generated the rated power. When the overall system does not have enough power (at low wind speed), the STATCOM supplies the extra reactive power required regulating the voltage at PCC within normal range $(\pm 10\%)$.

The dynamic equations of the system are shown below. For the RL loads, voltage equation is:

$$V_{PCC} = r_L I_L + L_L pI_L + \omega L_L I_L \quad (47)$$

where $r_L$ and $L_L$ is the resistance and inductance of RL load.

The capacitor voltage equation is:

$$C_m \; pV_{PCC} = I_s + I_w - I_g - I_L - I_{LL} - I_{nL} \quad (48)$$

where $C_m$ is the filter capacitor, $I_s$ and $I_w$ are the current supplied by STATCOM and DFIG wind turbine system respectively and $I_g$, $I_L$, $I_{LL}$ and $I_{nL}$ are current drawn by distribution grid, RL load, linear load and non-linear load respectively.

Non-linear load representation:

$$P_{non} = P_o \left( \frac{V_m}{V_{rated}} \right)^3 \left( \frac{f_m}{f_{rated}} \right)^3 \quad (49)$$

$$Q_{non} = Q_o \left( \frac{V_m}{V_{rated}} \right)^3 \left( \frac{f_m}{f_{rated}} \right)^3 \quad (50)$$

where $P_o$ and $Q_o$ are base active and reactive powers of non-linear loads respectively. $V_m$ and $f_m$ are local voltage magnitude and frequency respectively. $V_{rated}$ and $f_{rated}$ are nominal voltage magnitude and frequency of the distribution system respectively.

Constant load current equations:

$$I_{qLL} = \frac{2}{3} \frac{PV_{qPCC} - QV_{dPCC}}{V_{qPCC}^2 + V_{dPCC}^2} \quad (51)$$

$$I_{dLL} = \frac{2}{3} \frac{PV_{dPCC} + QV_{qPCC}}{V_{qPCC}^2 + V_{dPCC}^2} \quad (52)$$

Non-linear load current equations:

$$I_{qnL} = \frac{2}{3} \frac{P_{non}V_{qPCC} - Q_{non}V_{dPCC}}{V_{qPCC}^2 + V_{dPCC}^2} \quad (53)$$

$$I_{dnL} = \frac{2}{3} \frac{P_{non}V_{dPCC} + Q_{non}V_{qPCC}}{V_{qPCC}^2 + V_{dPCC}^2} \quad (54)$$

## 5. SIMULATION RESULTS

Simulation studies are carried out for a 1.5 MW DFIG wind turbine system to verify the effectiveness of proposed voltage regulation scheme using STATCOM at PCC under varying wind speed. The DFIG wind turbine is connected to distribution grid with 690 V (l-l). The distribution grid is model as weak grid. Overall system is simulated in MATLAB/Simulink. Table I shows the DFIG wind turbine parameters [7] and [10], Table II shows the STATCOM and the system parameters used for simulation study.

Fig. 9 shows the wind speed profile of DFIG wind turbine system. The wind speed varies in a range of $\pm 4$ m/s around its mean value of 12 m/s. The variation of wind speed causes fluctuations in electrical power output (active power) from wind generator as shown in Fig. 14. But the connected load in the system will remain constant; as a result there will be voltage fluctuation (as shown in Fig. 11) in the distribution system if there is no additional reactive power compensation device; because the distribution network is modelled as weak as a result cannot provide demanded extra reactive power.

When a STATCOM is connected at the PCC as shown in Fig. 8, then as soon as wind speed is low, it supplies extra reactive power required (shown in Fig. 13) to the distribution grid to maintain voltage magnitude at PCC within nominal range shown in Fig. 10. The positive (negative) active/reactive power supplied to the grid as shown in Fig. 15 means grid is receiving (supplying) power. As depicted clearly in Fig. 15, the weak distribution grid cannot supply additional reactive power when system needs it at lower wind speed.

## 6. CONCLUSION

In the DFIG wind turbine system operating in maximum power point operation mode connected to weak distribution grid, terminal voltage fluctuates with fluctuation in wind speed if there is no additional reactive power compensation device. This fluctuation is more significant in lower wind speed. This paper proposes a STATCOM to be connected at PCC in distribution grid for voltage regulation purpose. Simulation results have shown that fast voltage regulation of the overall grid can be achieved by connecting STATCOM at PCC during varying wind speed.

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# Comparative Investigation of Prosopis Africana Seed Oil as a Biodiesel and Edible Oil

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## ABSTRACT

The global and urgent need for alternative and renewable energies to fossil fuels has necessitated this study. The use of African Mesquite (*Prosopis Africana*) seed oil as biodiesel and edible oil was investigated. The seed was subjected to soxhlet extraction using petroleum ether (60 – 80$^{o}$C) as a solvent and mechanical expression to extract its oil. The oil yields of 18% and 23.6% were obtained respectively from the two processes. The clear, golden-yellow and transparent liquid (oil extract) was subjected to chemo-physical and thermal analysis to ascertain its composition in the raw state. A stimulated distillation using a GC-MS analyzer gave a 95% stable yield of diesel at the temperature range of 325 – 330$^{o}$C. The products were made up of alkanes, alkenes, aromatics and carboxylic acids members ranging from 10 to 20. The distillation curve displays the trend of yields with temperature. The fatty acid profile from the GC-MS analyzer showed that the oil has 63% linolenic acid with 0.08% free fatty acids. From the results, the oil favourably compares with NAFDAC's specifications for edible oils and also presents great potentials for biodiesel when transesterified or thermally cracked. Based on the oil composition and prospects for biodiesel, an ASTM distillation apparatus was used to thermally pyrolyze it to produce biodiesel.

**Keywords:** biodiesel, *prosopisafricana*, comparative investigation, chemo-physical properties, analysis, edible oil.

## INTRODUCTION

There is currently an increased global demand for alternatives to fossil fuels and hence researchers have seen the dire need and the urgency to plunge into action. This is as a result of the incessant increase in the prices of fossil fuels; petrol diesel and other fractions. They are no doubt non-renewable; the sources of fossil fuels are diminishing and the surging demand for energy has been on the increase since the nineteenth century. The supply however depends on the availability and the acceptability of fuels and how easily they can be delivered. Equally, the exhaust gases (flue) or products of combustion from diesel combustion engines continually pollute the environment, its environmental impacts on lives of communities, vegetation and aquatic lives also contribute in misbalancing the ecosystem.

Biodiesel as a renewable source of energy is non-toxic, biodegradable and available to be implemented immediately and currently the best substitute for diesel today. Biodiesel is a name used to describe a clean burning alternative fuel, produced from domestic, renewable resources [1].

Based on these facts, African Mesquite (Prosopisafricana) oil, its biodiesel and blends were produced and comparatively analyzed for their physio-chemical properties viz a viz; acid value, relative density, carbon residue content, water content (crackle test), kinematic viscousity, flash point, cloud point, ash content, pour point, cetane number, calorific value, engine performance test, combustibility test and so on.

Prosopis oil seeds are in abundance in the savannah and sub-savannah regions of the world and in Nigeria, have not been effectively utilized except as food condiment or seasoning around the Benue, Kogi, South-eastern areas, outside which, they are left out unutilized. Mindful of other production processes, the biodiesel was produced thermally at appropriate temperature(s) and will be used to substitute the transesterified biodiesel and petroleum diesel as alternative energy resource after comparison with the standard Automotive Grade Oil (AGO).

Also, the bond structure/stability of the samples in relation to diesel was monitored using a Fourier Transform Infrared (FTIR) Spectrophotometer.

The results obtained were compared with the standard fossil fuel diesel – Automotive Grade Oil (AGO) using ASTM, IP, AOAC and NAFDAC standards. The suitability of the oil, its biodiesel, the blends and the new method of production will be brought to limelight. Based on the findings of this research work, due recommendations will be proffered on the possibility of enlisting prosopis seed oil as a potential biodiesel in the biodiesel diary after those of jatropha, canola, soybeans and so on; its blends at different ratios with petrol-diesel for use in diesel engines, and establishing another method for producing biodiesel viz a viz, thermal conversion or pyrolysis also called depolymerization method at different temperatures. Ideally, biodiesel could be produced solely from vegetable oils that provide all the needed constituents. This will make the biodiesel industry completely independent from fossil-based resources and the biodiesel will be truly a bio-based product, which in turn will further increase the energy security of our country and enhance the environmental benefits of biodiesel and prepare ground for the emergence of bio-refinery in Nigeria.

When the diesel engine was invented, vegetable oils were used as the first liquid fuel after coal dust. (www.biodiesel.org). However, their use was abandoned when comparatively inexpensive petroleum-based fuels became available.

The petroleum-based fuels, besides offering an economic advantage were free from so many of the problems which have been with the use of vegetable oils as fuels. The problems associated with the use of vegetable oils are injector fouling; ring sticking and varnish build up on the cylinder walls. These problems could be attributed to the high viscousity of vegetable oils and to the reactivity of the polyunsaturated fatty acids components of the triglycerides. Researches have shown that viscousity and other attendant problems can be overcome by different reactions to form biodiesel. These include: transesterification process, thermal cracking/pyrolysis, micro emulsification, and algae production to form fuels which are called biodiesel.

Although biodiesel may seem like a recent innovation, it was first used over a century ago. (Fangruiand Milford, 1999).Dr. Rudolf Diesel, the inventor of diesel engine, designed it to run on coal dust suspended in water, heavy mineral oil, and vegetable oils. When Dr. Diesel demonstrated his engine at the World Exhibition in Paris in 1900, it was running on 100% peanut oil [2].

Through its economic interest, there is no doubt that fossil fuels play a vital role in the generation of energy to drive automobiles and mechanics but recent informed survey has indicated that at the present rate of energy consumption, since the fossil oil is the major source of energy, there is continued decline in the quantity of crude petroleum which serves as a source for diesel oil production. Moreover, the rate of replacement is not commensurate to the rate of consumption. For instance, at the end of 1986, there was sufficient oil remaining to last 34 years, natural gas for some 58 years, and coal, 219 years in Nigeria [3].

Nigeria's contribution to biodiesel production has just begun with researches at top gear towards its eventual kick-off. At present, the emphasis is on Biofuel/bioethanol production with the federal government's establishment of its plants and ethanol crop plantations across the country. This research work is one of such.

**Materials and Methods**

50kg of African mesquite seeds and 5 litres of automotive grade oil (AGO) used as standard and for blends were purchased from Modern Market in Makurdi, Benue State and Conoil Filling Station in Effurun, Delta State respectively.

ASTM standard methods for distillation of petroleum products D86-82 was used to thermally decompose the vegetable oil. ASTM standard distillation equipment AE 133-78 was used with minor modifications. A sample of AGO was obtained from Conoil Filling Station, Effurun, DeltaState. The prosopis seeds were sent for bulk soxhlet extractor using petroleum ether (60-80$^{o}$C) as solvent to the Biochemistry department of the University of Nigeria, Nsukka, Nigeria. For mechanical extraction, it was carried out at a local oil mill in Makurdi. In addition to chromatographic and mass spectrometric analysis of the distillates and blends, samples of oil were comparatively and chemo-physically analyzed at the petroleum/chemical laboratory of Light-House Petroleum Engineering Services Company, a leading analytical laboratory in Nigeria and Petroleum Training Institute (PTI), both in Effurun, Delta State of Nigeria. Engine performance test using diesel test engine was conducted at the Mechanical Engineering department workshop of Federal University of Agriculture (UNIAGRIC), Makurdi, Nigeria.

The prosopis seeds having hard cotyledonious shell were crushed (dehuled and dehuled), milled and ground to coarse powder. They were sieved to remove shells and inner transparent membranes and dried for two to three days before being ready for extraction. For the mechanical press, after crushing and ground, they were toasted and poured into the oil expeller for extraction.

American Oil Analytical Chemists (AOAC) official methods 981:11 for oils and fats for preparation of samples were employed (Firestone and Yurawecz, 2006). This was done by using clear sediment free-liquid sample of oil after extraction, direct and inverting the container several times.

Three samples of the seeds were prepared for the percentage oil yield determination:

**(1)** Pre-treated samples (P1): Heated/boiled for about five hours, manually dehuled dried and ground to powder.

**(2)** Untreated samples (P2): crushed, sieved and ground to powder.

**(3)** Fermented samples (*gbaye*) (P3): Heated/boiled for five hours, dehuled and fermented and ground to powder: the sample is odourous.

Weight of initial mass of sample (10g) was determined before solvent extraction using hexane and petroleum ether. Weight of oil after concentration and drying was determined and the percentage calculation with respect to the initial weight of 10g was determined to give the percentage oil yields of each sample.

2.5 litres x 5 bottles of petroleum ether (60 – 80$^{o}$C) were used to extract oils from the 50kg of prosopis seeds using bulk soxhlet extractor, 2 - 4 litres by volume. The following methods were used for the chemo-physical analysis: Flash point, (ASTM D 92/93 Method); Moisture content/volatile matter, (ASTM 4377 Method); pour point,

$$\% \, H_2O \text{ content} = \frac{w_1 - w_2}{w_1} \times 100\% \quad (1)$$

(ASTM D 97 Method); Cloud point, Carbon residue, (ASTM D 189 Method);

$$\% \text{ Carbon content} = \frac{w_2}{w_2 - w_1} \times 100\% \quad (2)$$

$w_2$ = weight of crucible + oil,

$w_1$ = weight of crucible + residue.

Kinematic viscousity, (ASTM D 445); density/specific gravity, (ASTM D 4052/ISO-AOAC Methods);

Kinematic viscousity, V = C x t (3)

C = Tube calibration constant

T = Average flow time.

$$D_T \text{ (g/mL)} = \frac{w - w_1}{v_T} \quad (4)$$

Where w and $w_1$ = weight (g) of Pycnometer empty and filled with test sample; $v_T$ = volume of Pycnometer (mL) at temperature, T (20$^{o}$C)

To calculate specific gravity$_{20}{}^{o}{}_{C}$ of sample at temperature,

$$\text{Specific gravity @ } 20^{o}\text{C} = \frac{D_{20}}{d_{H_2OT}} \quad (5)$$

Index of refraction, (AOAC Official Method 921.08);

$$R = R^1 + K\,(T^1 - T) \quad (6)$$

[4], JAOAC, 1986). Melting and boiling point, (AOAC Official Method 920.157) (Lewkowitsch, 1921, JAOAC, 1986). Iodine value, (IUPAC-AOCS-AOAC Method); Fatty acid profile (FFA),

$$\text{Acid value} = \frac{titre(ml)x(5.01)}{weight \triangleright of \triangleright sample} \quad (7)$$

The FFA figure is usually calculated as oleic acid (1ml of 0.1M NaOH = 0.0282g oleic acid) in which case, the acid value = 2 x FFA. For most oils, acidity begins to be noticeable to the palate when the FFA calculated as oleic acid is about 0.5 -1.5% [5]. Calorific value, (bomb calorimetry); Saponification value,

$$\text{Saponification value} = \frac{(b - a)x(28.05)}{wt(g)ofsample}$$

(8)

Peroxide value/stability, multiply the values obtained by 2 = mEq/kg of peroxide oxygen of sample (ml M per kg) (Onwuka, 2005). Trace metals, (AAS/Spectroil Method) [6]. Stimulated distillation, (ASTM 86); and FTIR, and ASTM standard methods for Cetane number index, (ASTM D613); distillation (ASTM D86); viscosity, (ASTM D445); density, (ASTM D4052); chromatography of fatty acid and sulphur content, (ASTM D4294) of petroleum fuels. Pyrolysis experiments were carried out at temperatures ranging from 350 to 400C using the ASTM bench home-made 5 L stainless still batch distillation unit. The vegetable oil (500ml) was introduced into the pyrolysis reactor and then heated by an external electric resistance. Using an in-tank method of petroleum blending, the biodiesel (pyrolyzate) obtained after chemo-physical screening were blended with AGO earlier obtained from Conoil Filling Station at different proportions. They include, B10, B20, B30, B40, B50, B60, B70, B80 and B90. B100 represents 100% pyrolyzate (biodiesel). The blends were centrifuged for homogeneity before proceeding with fuel analysis using ASTM standards.

Engine performance testwas carried out by testing the biodiesel in a four-cylinder, 30 hp Kubota engine (V1305) on a dynamometer. The speed was varied by ramping up and then back down again to eliminate hysteresis in the measurements. Torque, power, and airflow were recorded for each speed increment.

The consumption tests were done by filling the fuel tank with the test fuel then weighing it with a digital scale accurate to 1 gram.

## RESULTS AND DISCUSSION

The percentage oil yield of *Prosopisafricana*seed is in the range of 18 to 24%, with the treated seeds presenting the highest yield. The yield from the fermented seeds which is used as food condiment was quite low but promissory. The yields from using petroleum ether were higher than the yields from hexane. See Tables 1 and 2.

**Table 1: Percentage Oil yield using Petroleum Ether as a solvent**

| Sample | Initial weight of sample (g) | Weight of flask (g) | Weight flask + oil (g) | % Oil Content |
|---|---|---|---|---|
| P1 | 10 | 95.91 | 98.27 | 23.6 |
| P2 | 10 | 95.91 | 98.03 | 21.2 |
| P3 | 10 | 95.91 | 97.71 | 18 |

P1 - Pre-treated Prosopis seeds sample, P2 - Untreated Prosopis seeds sample, P3 - Fermented Prosopis (*gbaye*) sample.

**Table 2: Percentage Oil yield using Hexane as a solvent**

| Sample | Initial weight of sample (g) | Weight of flask (g) | Weight of flask + oil (g) | % Oil Content |
|---|---|---|---|---|
| P1 | 10 | 95.91 | 98.11 | 22.0 |
| P2 | 10 | 95.91 | 97.99 | 20.8 |
| P3 | 10 | 95.91 | 97.55 | 16.4 |

In describing the chemo-physical properties of *prosopisafricana*, Table 3 gives a clear picture. Density, which with some conversions gives the specific gravity falls within the permissible limit of the ASTM, ISO and API specification which ranges from 0.875 to 0.95 kg/m$^3$ (Kinast, 2003, Knothe*et al*, 2006). The flash and pour points of 113$^o$C and -13 respectively as obtainable with other vegetable oils are above the minimum recommendation of ASTM which is 100$^o$C making the oil and its biodiesel flammably safe for handling and haulage. The kinematic viscousity is expected high (12.16 cSt) quite above specification for biodiesel (1.9 – 6.5 cSt). The viscousity of vegetable oils is usually high and that is the major challenge for biodiesel production. But it is expected that when converted to biodiesel, the specification would have been met and indeed Table 6 justifies this claim. The biodiesel and their blends fell comfortably within specification. That is the breakthrough! Other parameters in Table 1 present prosopis oil as a potential biodiesel material and edible oil within ASTM and NAFDAC’s specifications. The free fatty acid content is quite minimal and overall, there is no significant toxic trace element(s) contained in the oil. The heating value is quite promissory with low moisture content.

Table 4 is the fatty acid profile of the oil; percentage saturated which is predominantly linolenic and oleic acids are high enough for biodiesel for high cetane numbers whether estimated or calculated. The unsaturated free fatty acid is very low and commendable (Kinast, 2003).

**Table 3: Physico-chemical properties of prosopis oil**

| S/N | Test | Unit | Result |
|---|---|---|---|
| **1** | Density @ 20$^{o}$C | Kg/m$^{3}$ | 0.925 |
| **2.** | Refractive Index 40$^{o}$C | N/A | 1.447 |
| **3.** | Saponification Valu | mg KOH/g | 190 |
| **4.** | Iodine value (wijis) | g/100g | 11 |
| **5.** | Peroxide Value | Meq/kg | 6 |
| **6.** | Free Fatty Acid | % | 0.08 |
| **7.** | Kinematic Viscous @ 40$^{o}$C | cSt | 12.16 |
| **8.** | Iron Content | mg/kg | 1.37 |
| **9.** | Copper Content | mg/kg | 0.03 |
| **10.** | Sulphur Content | mg/kg | < 0.05 |
| **11.** | Flash Point | $^{o}$C | 113 |
| **12.** | Pour Point | $^{o}$C | -13 |
| **13.** | Cloud Point | $^{o}$C | |
| **14.** | Moisture Content | Mass % | 0.04 |
| **15.** | Carbon Residue | Mass % | 0.13 |
| 16. | Melting Point | $^{o}$C | 18 |
| 17. | Heating Value | kJ/kg | 43,729 |
| 18. | Total Acid | mg/kg | 7.14 |
| 19. | Ash Content | % | 0.008 |

**Table 4: Fatty Acid profile**

| Fatty Acid | Saturated (%) | Unsaturate (%) |
|---|---|---|
| Lauric (C-12) | 0.5 | - |
| Palmitic (C-16) | 4.5 | - |
| Oleic (C18) | 29 | 0.08 |
| Linoleic (C 18: 2) | 63 | - |
| **Total** | **98** | **0.08** |

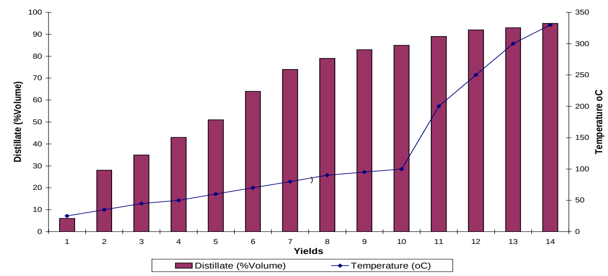


**Fig. 1: Distillation Curve of Prosopis Oil**

Fig. 1 presents the stimulated distillation curve of prosopis oil with temperature using GC analyzer. The curve lines position the highest yield in volume of diesel thermally produced when prosopis was pyrolyzed. At temperature of 325 – 400$^{o}$C, the distillates were obtained with the action of sodium hydroxide as a catalyst to yield the polar and non polar components. The non-polar component which is our biodiesel contains alkanes, alkenes, aromatics and carboxylic acids members ranging from 10 to 20.

Table 6 is the comparative analysis of prosopis biodiesel, AGO and AGO blends of prosopis. The table speaks for itself. Prosopis biodiesel favourably compares with AGO if not better. Biodiesels have low acid contents, sulphur content, carbon residue/ash content, somewhat higher heating values, less prone to the formation of polyaromatichydrocarbons (PAHs) and pollutants [7]. These are clearly shown in the Table 6.

## Conclusion

The comparative investigation of African Mesquite (*Prosopis Africana*) seed oil presents the facts that the savannah and sub savannah perennial tree plant presents great potential for edible oil and biodiesel. Although the nutrient value was not ascertained as it bothers beyond the scope of this work, the chemo-physical properties clearly highlights its edibility according to NAFDAC.s specification for edible oils and can well be enlisted as one of such. The Biodiesel potential which is the main thrust of this paper cannot be underestimated as this work x-rays. Also the possibility of thermal conversion process/pyrolysis also called depolymerisation as a biodiesel production option is however brought to limelight. Several of such works highlighting thermal conversion process have been noted (Dunn, 1999; Schwab *et al*, 1988). The products were made up of alkanes, alkenes, aromatics and carboxylic acids members ranging from 10 to 20 at the temperature range of 300 - 400$^{o}$C. The distillation curve displays the trend of yields with temperature. Overall, the oil favourably compares with NAFDAC's specifications for edible oils and also presents great potentials for biodiesel when transesterified or thermally cracked.

**Table 6: Comparative Analysis of *Prosopis Africana* Oil, its biodiesel, biodiesel-AGO blends and Diesel (AGO)**

| Sample | Density @ 20°C | Calorific value (kj/kg) | Total Acid (mg/g) | Carbon Residue % Wt | $H_2O$ Content % Wt | Flash Point °C | Viscousity @ 40°C cSt | Ash Content % | Pour Point °C |
|---|---|---|---|---|---|---|---|---|---|
| Diesel (AGO) | 0.8701 | 44,938 | 0.23 | 0.17 | 0.03 | 120 | 2.00 | 0.006 | |
| PO | 0.925 | 43,729 | 7.14 | 0.13 | 0.04 | 113 | 12.16 | 0.008 | -13 |
| B100 | 0.9104 | 44,147 | 4.25 | 0.12 | 0.03 | 94 | 2.65 | 0.005 | -15 |
| B90 | 0.9064 | 44,357 | 6.30 | 0.28 | 0.025 | 97 | 2.69 | 0.005 | -14 |
| B80 | 0.9023 | 44357 | 6.13 | 0.25 | 0.035 | 99 | 2.52 | 0.005 | -13 |
| B70 | 0.8983 | 44,543 | 5.25 | 0.25 | 0.03 | 102 | 2.46 | 0.005 | -13 |
| B60 | 0.8943 | 44,543 | 4.55 | 0.23 | 0.03 | 104 | 2.39 | 0.0045 | -13 |
| B50 | 0.8903 | 44,543 | 3.36 | 0.19 | 0.03 | 107 | 2.33 | 0.004 | -13 |
| B40 | 0.8862 | 44,543 | 5.22 | 0.18 | 0.03 | 109 | 2.26 | 0.005 | -13 |
| B30 | 0.8822 | 44,752 | 6.02 | 0.094 | 0.03 | 112 | 2.20 | 0.005 | -12.5 |
| B20 | 0.8782 | 44,752 | 5.40 | 0.08 | 0.03 | 115 | 2.13 | 0.005 | -12 |
| B10 | 0.8741 | 44,938 | 5.60 | 0.078 | 0.03 | 117 | 2.07 | 0.006 | -12 |

PO-Prosopis Oil, B100-100% prosopis biodiesel (pyrolyzate), B90-90%prosopis, biodiesel + 10% AGO, B80-80% prosopis biodiesel + 20% AGO, B70-70% prosopis biodiesel + 30% AGO, B60-60% prosopis biodiesel + 40% AGO, B50-50% prosopis biodiesel + 50% AGO, B40-40% prosopis biodiesel + 60 % AGO, B30-30% prosopis biodiesel + 70 % AGO, B20-20% prosopis biodiesel + 80 % AGO,
B10- 10% prosopis biodiesel + 90 % AGO

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# PERFORMANCE TESTING OF MOBILE PHONE BATTERIES

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## ABSTRACT

This paper reports the performance of mobile phone batteries. The performance tests carried out include determination of the battery capacity (Ampere-hour rating), measurement of the battery's talk time, self-discharge test and ohm test. These tests were carried out using Cadex C8000, an advanced programmable battery testing system. Results show that the battery type (whether it's a battery that came along with newly purchased mobile phone or a replacement battery) had significant effect on the battery's actual Ampere-hour capacity and talk time. Therefore, it is concluded that batteries which came along with newly purchased mobile phones perform better than replacement batteries obtained from mobile phone accessory shops. This confirms the claim of consumers on the underperformance of replacement batteries; consequently, there is need for standards for mobile phone batteries imported into the Nigerian market.

Keywords: Mobile phone, Battery capacity, Talk time, Battery performance.

## 1.0 INTRODUCTION

Cell phone is also known as mobile phone.The name indicates that the phone does not have to be stationed in one location. These phones operate without a cord of the necessity of a home base. It is easy to be carried by the user and isused to make and receive calls among many other applications [1]. Mobile phones are equipped with a wide range of applications for work, play and for communicating with smart networks. The use of mobile phones has now been integrated into human lives; it has become a general populace item that cannot be done without. The continuous use of a mobile phone has been made possible by the components integrated into the device such as resistors, capacitors, diodes, inductors, transistors, integrated circuit (IC) and battery, to mention but a few. The battery in a mobile phone servesas an energy storage device.

The tremendousincrease in the applications running on mobile phones means more energy is required from the energy storage device (battery).The increase of mobile phone users and usage has sprung replacement parts manufacturers and retail shops, most especially for the battery, which is a frequently failed part. As different companies manufacture batteries, there are bound to be differences in the batteries'quality and reliability in terms of meeting the need for powering the device, as may be claimed by those manufacturers. A challenge of meeting the need of users has been observed to lead to an individual having more than one battery for a mobile phone [2]. As a new mobile phone comes with at least one battery, replacement batteries are also available in the market for phones whose batteries are no longer good. The replacement batteries are not necessarily manufactured by the mobile phones' manufacturers and their economic values are not the same, as the replacement batteries are also of different prices. The choice of purchase is a function of users' financial buoyancy and usage experience.

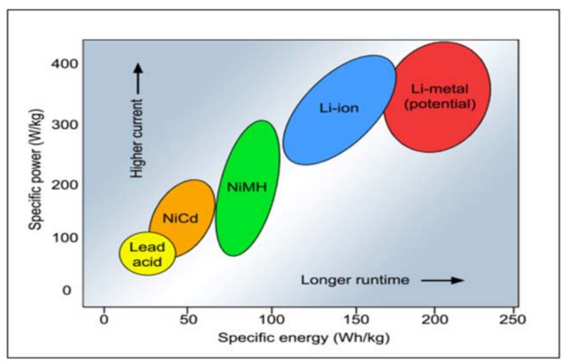
Improper disposal of batteries cause harm to the environment and the health of the consumers. Although Li-Ion batteries which are used in modern mobile phones are free of heavy metals (lithium has a low atomic number), lithium's high degree of chemical activity can create environmental problems. When exposed to water, which is present in most landfills, the metal can burn, causing underground fires that are difficult to extinguish. Landfill is not sustainable; dumping mobile phone batteries creates long term pollution risk to the environment. Since hundreds of millions of mobile phones batteries and their replacements are in use in Nigeria, there is a high risk of hazard caused to the health of the consumers and the environment if the batteries are improperly disposed.Therefore, this study focuses on testing the performance of mobile phone batteries; comparing the manufacturers' specifications with results obtained. This will help to identify batteries that do not meet up with specifications, thus controlling the influx of substandard batteries in the country. This results in better performance of the batteries and consequently, customers' satisfaction. It guarantees that Nigerians purchase durable batteries which have the performance stated in their labels.Also, itminimizes the adverse environmental effects of disposing the batteries.

## 1.0 THEORY

A battery stores electrical energy and delivers it through an electro-chemical reaction. A battery is made up of electro-chemical cells. An electrochemical cell consists of a cathode and an anode which areseparated by an electrolyte. Electric current is created as a result of the flow of electrons from the anode to the cathode. Primary cells (or batteries) are used once and discarded while secondary cells (or batteries) are rechargeable and can be used several times.

The major types of rechargeable batteries include: Lead Acid, Nickel Cadmium (NiCd), Nickel Metal Hydride (NiMH) and Lithium Ion (Li-Ion). Lithium-Ion batteries are the most advanced and most expensive batteries used in mobile phones today. They are commonly used in mobile phones because they have excellent power/weight ratio, longer talk time and do not experience "memory effect". Memory effect is a condition whereby rechargeable batteries lose their maximum energy capacity if they are not allowed to deeply discharge before being recharged.

Fig. 1 illustrates the energy and power densities of lead acid, nickel-cadmium (NiCd), nickel-metal-hydride (NiMH) and the Li-ion family (Li-ion).Specific energy is the capacity a battery can hold in watt-hours per kilogram (Wh/kg); specific power is the battery's ability to deliver power in watts per kilogram (W/kg) [3].




(Source:http://batteryuniversity.com/learn/article/global_battery_markets)

Figure 1: Specific energy and specific power of rechargeable batteries

## 2.1 LITHIUMION BATTERY TECHNOLOGY

Pioneer work with the lithium battery began in 1912 under G.N. Lewis but it was not until the early 1970s when the first non-rechargeable lithium batteries became commercially available. Lithium is the lightest ofh all metals, has the greatest electrochemical potential and provides the largest energy density for weight. Attempts to develop rechargeable lithium batteries failed due to safety problems. Because of the inherent instability of lithium metal, especially during charging, research shifted to a non-metallic lithium battery using lithium ions. Although slightly lower in energy density than lithium metal, lithium-ion is safe, provided certain precautions are met when charging and discharging. In 1991, the Sony Corporation commercialized the first lithium-ion battery. Other manufacturers followed suit [4].

Rechargeable lithium batteries involve a reversible insertion/extraction of lithium ions (guest species) into/from a host matrix (electrode material), called lithium insertion compound, during the discharge/charge process. The lithium insertion/extraction process occurring with a flow of ions through the electrolyte is accompanied by the reduction/oxidation reaction of the host matrix combined with a flow of electrons through the external circuit. The name of lithium-ion battery is usually determined by cathode material, for example, lithium iron phosphate, and lithium cobalt battery [5]. The principle behind the chemical reaction in the lithium ion battery is one where the lithium in the positive electrode lithium cobalt oxide material is ionized during charge, and moves from layer to layer in the negative electrode. During discharge, the ions move to the positive electrode and return to the original compound. The chemical reactions for charge and discharge are as shown in equations 1, 2 and 3[6]:

Positive electrode

$$LiCoO_2 \underset{\text{Discharge}}{\overset{\text{Charge}}{\rightleftarrows}} Li_{1-x}CoO_2 + xLi^+ + xe^- \qquad (1)$$

Negative electrode

$$C + xLi^+ + xe^- \underset{\text{Discharge}}{\overset{\text{Charge}}{\rightleftarrows}} CLi_x \qquad (2)$$

Battery as a whole

$$LiCoO_2 + C \underset{\text{Discharge}}{\overset{\text{Charge}}{\rightleftarrows}} Li_{1-x}CoO_2 + CLi_x \quad (3)$$

## 3.0 METHODOLOGY

### 3.1 EQUIPMENT USED

Cadex C8000, which is an advanced programmable battery testing system was used to measure the performances of the mobile phone batteries.The Cadex C8000 battery testing system is equipped with digital drivers to handle batteries from 50mAh to 100Ah [7].

### 3.2 BATTERY TESTING

Seven mobile phone batteries were subjected to performance tests. Batteries A1, A2 and A3 were batteries used in Nokia mobile phones; batteries B1 and B2 were used in Samsung mobile phones while batteries C1 and C2 were used in Techno mobile phones. A1, B1 and C1werebatteries that came along with newly purchased mobiles while A2, A3, B2 and C2 were replacement batteries for the phones. Battery A3 was purchased at twice theprice of Battery A2.All the batteries were new batteries. Listed in table 1 are the batteries' specifications:

Table1: Specifications of the batteries tested

| BATTERY | A | | | B | | C | |
|---|---|---|---|---|---|---|---|
| | A1 | A2 | A3 | B1 | B2 | C1 | C2 |
| Model | BL-5CB | BL-5C | BL-5C | AK | AK | BL-6GT | BL-6 GT |
| Battery Chemistry | Li-Ion | Li-Ion | Li-Ion | Li-Ion | Li-Ion | Li-Ion | Li-Ion |
| Ah Rating | 800 mAh | 1020 mAh | 1020m | 800m | 800 mAh | 1800m | 1800m Ah |
| Voltage Rati | 3.7V | 3.7V | 3.7 V | 3.7V | 3.7V | 3.7V | 3.7V |
| Energy Ratin | 3.0 Wh | 3.8 Wh | 3.8 Wh | 2.96W | 2.96 Wh | 6.66' Wh | 6.66 Wh |
| Country Manufacture | Country | Count | Count | Count | Count | Countr | - |

The batteries were subjected to performance tests to ascertain their practical performances as compared to their specifications. Cadex C8000, an advanced programmable battery testing system was used to measure the performances of the mobile phone batteries. The tests conducted include [7]:

i. **Determination of the battery capacity (Ah rating).**The batteries were discharged to obtain the first capacity; then they were charged and discharged to determine the second capacity (the first capacity is the capacity after the first discharge while the second capacity is the capacity after the second discharge). The charge and discharge cycle was repeated until the difference between capacities from one cycle and the next was less than 5%.

ii. **Measurement of the battery's talk time:** Simulated GSM or CDMA discharge pulse was used to determine the battery's talk time. The batteries were charged,and then discharged using the GSM or CDMA discharge pulse.

iii. **Self-Discharge Test**: Self-discharge testidentifies the self-discharge or the amount of charge a battery loses if it is left alone for a period of time. The standard time was 24 hours. The batteries were charged and discharged to obtain their capacities (first capacity). The batteries were then charged and left for a 24-hour rest period;during this time, the batteries lost energy through self-discharge. Then, the batteries were discharged to determine their capacities (second capacity). The difference between the second and first capacity is the self-discharge rate.

iv. **Ohm Test**: The ohm test measures the resistance of the battery which is an estimate of the battery capability to handle load.

## 3.3 STATISTICAL ANALYSIS

The tests results were analysed using one-way ANOVA to determine if the battery type (either battery that came along with newly purchased mobile phone or replacement battery) had significant effect on the test results. SPSS software was used for the analysis.

## 4.0 RESULTSAND DISCUSSION

### 4.1 Determination of thebattery capacity (Ah rating)

Table 2 shows the measured capacities of the batteries while tables 3 and 4 show the statistical analysis of the results.

There was a statistically significant difference between groups as determined by one-way ANOVA ($F(2,4) = 153.176$, $p = .000$). This shows that the battery type(whether it's a battery that came along with newly purchased mobile phone or a replacement battery) had significant effect on the actual Ah capacity of the battery. The actual Ah capacities of the batteries that came along with newly purchased mobile phones were between 95-100% of their specifications while the replacement batteries showed poor results. However, battery A3 which was purchased at twice the price of battery A2 showed better result (89% of the manufacturer's specified value) when compared to battery A2.

Moreover, table 2 also shows that the capacities of the batteries after their first discharge were low. This is because lithium-based battery chemistries should not be stored at full charge state so as to minimize age-related capacity loss. Hence, new batteries should be charged to full capacity before use. Also, lithium-based battery chemistries should not be stored at too low state-of-charge so as to keep the battery in operating condition and allow self-discharge.

Table 2: Capacities of the batteries

| BATTERY | A | | | B | | C | |
|---|---|---|---|---|---|---|---|
| | A1 | A2 | A3 | B1 | B2 | C1 | C2 |
| Ah Rating Specification (mAh) | 800 | 1020 | 1020 | 800 | 800 | 1800 | 1800 |
| 1st *Capacity* (%) | 40 | 3 | 53 | 55 | 3 | 53 | 1 |
| 2nd Capacity (%) | 100 | 17 | 93 | 97 | 17 | 96 | 3 |
| Final Capacity (%) | 100 | 18 | 89 | 97 | 17 | 95 | 3 |
| Actual Ah Capacity Available (mAh) | 800 | 183.6 | 907.8 | 776 | 136 | 1710 | 54 |

Table 3: Descriptives Table (Battery Capacity)

| | Sum Squares | df | Mean Square | F | Sig. |
|---|---|---|---|---|---|
| Between Groups | .381 | 2 | .190 | .571 | .605 |
| Within Groups | 1.33 | 4 | .333 | | |
| Total | 1.71 | 6 | | | |

Table 4: ANOVA Table (Battery Capacity)

| 95% Confidence Interval for Mean | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| Battery | N | Mean | Std. I | Std. Error | Lowe Boun | Uppe Boun | Min | Max |
| A1-C1 | 3 | 97.333 | 2.516 | 1.452 | 91.08 | 103.5 | 95.0 | 100.00 |
| A2-C2 | 3 | 12.666 | 8.386 | 4.841 | -8.16 | 33.49 | 3.00 | 18.00 |
| A3 | 1 | 89.000 | . | . | . | . | 89.0 | 89.00 |
| Total | 7 | 59.857 | 44.52 | 16.83 | 18.67 | 101.0 | 3.00 | 100.00 |

| | Sum of Squares | df | Mean Square | F | Sig. |
|---|---|---|---|---|---|
| Between Groups | 11743.524 | 2 | 5871.762 | 153.17 | .000 |
| Within Groups | 153.333 | 4 | 38.333 | | |
| Total | 11896.857 | 6 | | | |

## 4.2 Measurement of the battery's talk time

Table 5 shows the battery talk time results while table 6 is the output of the ANOVA analysis. Statistically significant difference between groups was found for the GSM and CDMA tests (GSM: $F(2,4) = 203.949$, $p = .000$; CDMA: $F(2,4) = 171.914$, $p = .000$). This shows that the battery type had significant effect on the battery talk time.

From Table 5, battery A1's talk time seemed lower than that of battery A3 because battery A1 had a lower Ah rating (800mAh) compared to battery A3 (1020mAh). Also, battery A3 which was purchased at twice the price of battery A2 showed better results when compared to battery A2.

Talk time can differ because they are dependent on the mobile phone battery, mobile phone, mobile phone features, service provider, network conditions, strength of network signals, etc.

Table 5: Battery talk time

| BATTERY | | A | | | B | | C | |
|---|---|---|---|---|---|---|---|---|
| | | A1 | A2 | A3 | B1 | B2 | C1 | C2 |
| GSM | Capacity (%) | 98 | 25 | 98 | 97 | 24 | 94 | 13 |
| | Talk time (mins) | 11 | 34 | 136 | 11 | 29.5 | 227 | 32.5 |
| CDMA | Capacity (%) | 10 | 27 | 100 | 98 | 22 | 94 | 13 |
| | Talk time (mins) | 12 | 43 | 159 | 12 | 28.5 | 269 | 39.5 |

Table 6: ANOVA Table (Battery talk time)

| | | Sum of Squares | df | Mean Square | F | Sig. |
|---|---|---|---|---|---|---|
| GSM | Between Groups | 9925.524 | 2 | 4962.762 | 203.949 | .000 |
| | Within Groups | 97.333 | 4 | 24.333 | | |
| | Total | 10022.857 | 6 | | | |
| CDMA | Between Groups | 10257.524 | 2 | 5128.762 | 171.914 | .000 |

| | | | |
|---|---|---|---|
| Within Groups | 119.333 | 4 | 29.833 |
| Total | 10376.857 | 6 | |

### 4.3 Self-Discharge Test

Table 7 shows the self-dischargetest results. From table 8, the battery type didn'thave any significant effect on the self-discharge of the battery ($p > 0.05$).According to Cadex[8], self-discharge increases with age, cycling and elevated temperature. A battery should be discarded if the self-discharge reaches 30 percent in 24 hours.

Table 7: Self-discharge test results

| BATTERY | A | | | B | | C | |
|---|---|---|---|---|---|---|---|
| | A1 | A2 | A3 | B1 | B2 | C1 | C2 |
| *Ah Rating Specification (mAh)* | *800* | *1020* | *1020* | *800* | *800* | *180* | *1800* |
| *1st Capacity (%)* | *99* | *23* | *94* | *97* | *19* | *95* | *3* |
| 2nd Capacity (%) | 99 | 22 | 93 | 96 | 18 | 95 | 3 |
| Capacity loss | 0 | 1 | 1 | 1 | 1 | 0 | 0 |
| Ah Capacity Loss (mAh) | 0 | 10.2 | 10.2 | 8 | 8 | 0 | 0 |

Table 8: ANOVA Table (Self-Discharge Test)

### 4.4 Ohm Test

Table 9 shows the self-discharge test results while table 10 shows the ANOVA analysis results. From table 10, the battery type didn'thave any significant effect on the resistance of the battery ($p > 0.05$).

Table 9: Resistances of the batteries

| BATTERY | A | | | B | | C | |
|---|---|---|---|---|---|---|---|
| | A1 | A2 | A3 | B1 | B2 | C1 | C2 |
| Resistance (mOhm) | 144.40 | 222.40 | 155.70 | 218.00 | 218.30 | 141.30 | 220.00 |

Table 10: ANOVA Table (Ohm Test)

| | Sum of Squares | df | Mean Squa | F | Sig. |
|---|---|---|---|---|---|
| Between Groups | 5369.882 | 2 | 2684.941 | 2.842 | .171 |
| Within Groups | 3778.307 | 4 | 944.577 | | |
| Total | 9148.189 | 6 | | | |

## 5.0 CONCLUSION

Batteries A1, B1& C1 which came along with newly purchased mobile phones had better performance results than replacement batteries A2, A3, B2 & C2, and they conformed to their stated manufacturer's specifications to a large extent. This verifies some users' complaints about their dissatisfaction with the performances of replacement batteries when compared to the batteries that come along with newly purchased mobile phones.Moreover, cost is a major factor, as Battery A3 which was a replacement battery bought at twice the price of Battery A2 performed betterthan Battery A2.

Hence, there is need to set up standards for mobile phone battery and create policy framework to regulate imported mobile phone batteries. This ensures better performance of mobile phone batteries, value for the money spent to purchase the batteries and reduction of the adverse environmental effects associated with the disposal of these batteries.

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# CURRENT STATUS OF RESEARCH AND DEVELOPMENT ACTIVITIES ON EFFICIENT COOKSTOVES IN NIGERIA

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## ABSTRACT

Fuelwood and charcoal constitute about 60% of total primary energy consumption in Nigeria. To procure fuelwood, many hectares of forest are continuously lost thereby aggravating desert encroachment in some parts of the country. Despite the attendant environmental and health implications, merchandising in fuelwood and charcoal has emerged as one of the most lucrative businesses in the country due to the unending demand, the available option to reverse the ugly trend is a two-prong approach of reducing fuelwood consumption rate through the promotion of efficient cookstoves and systematic phasing out the use of fuelwood for cooking. Several research and development (R&D) aimed at achieving these two options are on-going at different institutions across the country. Consequently, proto-types have been developed and were found to be more efficient than the existing traditional means of fuelwood use in Nigeria. This paper highlights the current R&D activities, pilot projects and challenges in the area of efficient cookstoves development in Nigeria.

Key words: current status; research and development; cookstoves, fuelwood, charcoal

## 1.0 INTRODUCTION

Energy is the mainstay of Nigeria's economic growth and development. It plays a significant role in the nation's international diplomacy, serves as a tradable commodity for earning the national income which is used to support government development programmes. It also serves as an input into the production of goods and services in the nation's industry, transport, agriculture, health and education sectors, as well as an instrument for politics, security and diplomacy [1]. Energy consumption in Nigeria is categorized based on the end-users into three groups, the residential, commercial and industrial sectors. Whilst most of the households in the urban and semi urban areas have access to modern energy supply, majority of the rural areas depends mainly on fuelwood for both domestic and commercial energy needs [2]. According to Udo*et al*, [3], in most countries, the industrial sector constitutes the largest consumers of energy followed by residential and then commercial sectors. In Nigeria, however, it has been established that residential sector consumes the highest amount of energy among the other sectors [1]. Nigeria has one of the lowest net electricity generation per capita rates in the world. Electricity generation falls short of demand, resulting in load shedding, blackouts, and a reliance on private generators [2].

Roughly 20 million households in Nigeria cook with fuelwood[4]. Nigeria has been documented to have one of the largest and most sophisticated fuelwood markets in the world, delivering firewood from dry savannah-land clearings to a network of urban retail outlets [4]. However, very few efficient improved cookstoves are available to Nigerian consumers making the country among those with the high number of deaths resulting from smoke fuels with estimated 95,000 Nigerians dying annually from problems arising from toxic smoke from rudimentary cook-stoves [4].

It is reported that as at 1981, Nigeria had 13,071,464 hectares of forest distributed across different parts of the country [5]. In the process of procuring fuelwood, however, many hectares of forest and natural vegetation in Nigeria are lost, thereby aggravating desert encroachment in some areas. Accordingly, fuelwood and charcoal are found to constitute about 40 % of total primary energy consumption in Nigeria. The annual national demand is estimated to be 39 million tonnes out of which about 95% is consumed in the household for cooking and cottage industrial activities such as processing cassava, and oil seeds, which are closely related to household activities [5]. The pattern of fuelwood and charcoal consumption for the period 1981 – 2006 is shown in tables 1 and 2.

The nature of fuelwood utilization for energy production in Nigeria is also a cause of concern. Most of the stoves being used are archaic; they produce excessive smoke and have high thermal inefficiency thereby consuming much more fuelwood than necessary for a particular activity. The inefficient stoves also cause devastating damage to the general health of the users and others within the immediate environment made up of mostly women and children.

In an effort to reduce the negative impact of the fuelwood utilization, Nigerian researchers have identified a two-prong approach of reducing fuelwood consumption rate through the promotion of efficient cookstoves and systematic phasing out the use of fuelwood for energy. Consequently, research and academic institutions in Nigeria have launched several R&D programmes that have developed various types of efficient cookstoves that have proven to be more efficient than the traditional stoves.

This paper discusses the current status of the R&D activities for the production of efficient cookstoves in Nigeria, the identified challenges of the activities and recommendations for improvement.

## 2.0 CONVENTIONAL COOKSTOVES IN NIGERIA

Despite the difficulties of procuring fuelwood and the attendant loss of resources, the present mode of fuelwood utilization in Nigeria is grossly inefficient. The fuelwood cooking is mainly done through the traditional 3-stone stove (as shown in figs 1 & 2) and other similar inefficient means leading to severe waste of energy and attendant health problems owing to excessive smoke. In an effort to reduce the waste and minimize the associated problems, researchers in Nigeria have developed various types of efficient wood-burning and charcoal stoves to replace the inefficient stoves.

*Fig. 1: Locally fabricated open-stoves*

*Fig. 2: Inefficient fuelwood stoves*

## 3.0 THE CURRENT STATUS OF RESEARCH AND DEVELOPMENT IN ENERGY EFFICIENT COOK STOVES IN NIGERIA

Nigerian researchers have developed various types of efficient fuelwoodcookstoves that have proven to be more efficient than the traditional stoves. The efficient fuelwoodcookstoves uses less quantity of fuelwood and possesses higher thermal efficiency than the traditional stoves.

The energy efficient cook stoves include but not limited to the solar cook stoves, biogas cook stoves, improved wood stoves, improved sawdust stoves, improved coal and/or charcoal stoves, briquette stoves, improved kerosene stoves and low power consuming electric stoves.

### 3.1 RESEARCH AND DEVELOPMENT IN SOLAR COOK STOVES

Research and development (R&D) activities in solar thermal for household cooking and heating have been recorded by the research centres of Energy Commission of Nigeria, the academia as well as private institutions in Nigeria.

Nigeria lies in the tropics and is endowed with abundant sunshine all the year round. The daily average sunshine hour in the southern region is about 8 hours during dry season and about 4 hours during the rainy season. While greater values of daily sunshine hours are obtainable in the northern region of the country, with an average of about 10 hours during dry season and 6 hours during the rainy Season [6].

Nigeria has been graded by the Solar Cookers International (SCI) as the 5$^{th}$ out of the 25 countries with greatest potential benefits from solar cooking (Table. 3). The heat energy produced by the sun is enormous and can go beyond 1000 W/m$^2$ [7] which corresponds to half the power of an electric kettle. It only takes 10 – 15 minutes to boil water on a solar cooker, and it's free, as long as the sun shines.

Some Nigerian institutions and research centres have conducted a number of research and development activities in different types of solar cookers. As part of the R & D efforts in solar cooking in Nigeria, Dahiru et al [8] reported the performance of a concentrating solar energy cooker with mirrors glued on the inside wall of the parabolic concentrator (Fig.2) as reflective material with reflectivity of over 80%. The cooker was evaluated by undertaking water boiling and rice cooking tests. The results obtained were compared to those obtained using a traditional fuelwood stove; the solar cooker was found to have boiled the water and cooked rice at the rates of 3.7g/min and 1.66g/min respectively with 41% efficiency.

Bello *et al*, [9] reports the performance and of a Solar Box Cooker at Ilorin. The results of the investigation illustrated that a maximum temperature of 88$^0$C was attained for the water boiling tests and suggest that the constructed solar cooker would take between one-and-half hours and two-and half hours to cook such commonly eaten foods like egg and rice in this tropical station. The average collector efficiency of the solar box cooker has been estimated to be about 47.56%.

*Figure 2:* **Parabolic Solar Cooker**

In June 2010, the students of the Department of physics and Industrial Physics at Evan Enwerem University in Owerri, Nigeria designed a parabolic solar cookers andsolar box cookers.

*Figure 3:* **Box type solar cookers**

### 3.2 RESEARCH AND DEVELOPMENT IN BIOMASS COOKSTOVES

There is a huge potential for the use of biomass as an energy source in Nigeria. Biomass refers to energy derivable from sources of plant origin such as trees, grasses, agricultural crops and their derivatives, as well as animal wastes [1]. As an energy source, biomass may be employed as solid fuel, or transformed by means of diversified technologies to liquid or gaseous state for the production of electric power, heat or fuel for motive power. Biomass resources are regarded as renewable as they are naturally occurring and when appropriately administered, may be harnessed without significant depletion.

Fuelwood and charcoal use by the households are by far the largest single demand on forests and woodlands. The commonly used medium of consumption is the traditional three-stone stove with efficiencies as low as 15% or even less Figs. 1 & 2). While it would be difficult, if not impossible to immediately stop the use of fuelwood for cooking in Nigeria, efficient wood-burning and charcoal stoves could be deployed as short term measures with to reduce the amount trees that are felled to supply fuelwood. The potentials of fuel wood and other biomass are summarized in Table 2.

Many versions of efficient wood-burning and charcoal stoves have been developed by research centres of the ECN. They are in form of Clay-based, metallic, or insulated cook stoves of various sizes that conserve the amount of fuelwood consumed by up to 50%. They lead to faster cooking and with the attachment of chimneys, they allow for organized exit of smoke which consequently reduces smoke inhalation. (Figs. 5 – 11).


*Fig. 5:* Double-pot improved stove by SERC, Sokoto

*Fig. 6:* Clay-based improved stove by SERC, Sokoto

*Fig. 7:* Clay based and Saw dust Stoves by SERC, Sokoto


*Fig. 8:* Double & single -pot energy saving stove by SERC, Sokoto

*Fig. 9:* **One-pot improved stoves by SERC**

*Fig. 10:* **Metal Efficient Stove by NCERD, Nsukka**

*Fig. 11:* **Metal Efficient Stove by NCERD, Nsukka**

## 3.3 RESEARCH AND DEVELOPMENT IN ELECTRIC STOVES IN NIGERIA

Locally fabricated electric cook stoves are found in Nigeria, they are mostly used by households and in students' hostels in the universities, colleges and polytechnics. They are highly inefficient in terms of electric power consumptions but they are fast in cooking and time saving in action because they produce very high heat energy sufficient enough to cook beans in less than an hour. As part of their power consumption characteristics, they are mostly associated with causing power break down in the cut out and distribution boxes of the users connections.

## 3.4 RESEARCH AND DEVELOPMENT IN BIOGAS STOVES IN NIGERIA

Biogas digesters, which are capable of producing biogas that could be used for domestic and industrial uses, have also been developed by many researchers in Nigeria. In Nigeria, the various research centres of Energy Commission of Nigeria and other institutions have developed pilot biogas plants that were found to be viable for domestic gas supply. in different locations across the country. Some of the projects are shown in Figs. 12, 13 & 14

*Fig. 12, 13 & 14:* **Biogas Digester Pilot Plant and portable floating type developed by NCERD, Nsukka and SERC Sokoto respectively**

## 4.0 CHALLENGES OF RESEARCH AND DEVELOPMENT IN NIGERIA

In Nigeria, research and development is faced with numerous challenges which if overcome, will make the research and developmentatmosphere more conducive, attractive and will bring in more professionals to the lifeline. Some of the challenges of research and developmentin Nigeria include:

1. Infrastructural Constraints: Although Nigeria is the world 9th largest country with proven results of natural gas; there are presently insufficient infrastructures to deploy the gas to the general populace for cooking.

2. Technological Constraints: Even though the products of the research and development activities are proven to be more efficient than the traditional stoves, their efficiencies are still low when compared to those produced in the developed countries, e.g. Save 80 fuelwood stove that saves up to 80% of fuelwood used for cooking.

## 6.0 CONCLUSION

Households are the leading Nigerian energy consuming sector, and most of these energies are being wasted unnecessarily in cooking, heating and other domestic activities. Whilst the current research and development activities have assisted in reducing the impact, but a lot more has to be done especially in the areas of funding to support the on-going energy saving campaigns in Nigeria's household sector. Some of the recommended strategies to be adopted are as follows:

1. Capacity Development: Development of training programmes and technical courses in entrepreneurship and managerial skills for researchers;
2. The existing Research and Development centres and technology development institutions should be adequately strengthened in terms of tools and equipment to ensure expertise in the area of improved cook stoves;

3 There are limited public funds available for the deployment and continuous improvement of R&D results. Also, the level of private sector participation in the R&D in Nigeria is almost zero.

4. There is inadequate public awareness on energy efficiency technologies and their benefits, both economically and environmentally in the country. This makes it difficult for the people to procure more efficient devices which could be more expensive at the initial stage but saves a lot in operational cost.

5. Preparation of standards and codes of practices, maintenance manuals, life cycle costing and cost- benefit analyses. There is need for the Standards Organisation of Nigeria to develop a relevant standard for the different types of cook stoves developed or imported into the country. Priority should be given to the area of energy efficiency and conservation during the drafting or the said standards.

Table 1: Energy Consumption by Sector – Fuelwood ('000 tonnes)

| Year | Manufacturing | Household | Services | Total |
|---|---|---|---|---|
| 1981 | 602.60 | 11449.32 | 5498.38 | 17550.29 |
| 1982 | 702.27 | 13343.08 | 5502.16 | 19547.51 |
| 1983 | 807.12 | 15335.36 | 5629.53 | 21772.02 |
| 1984 | 903.90 | 17174.02 | 6171.76 | 24249.67 |
| 1985 | 1054.33 | 20032.27 | 5922.69 | 27009.29 |
| 1986 | 1216.83 | 23119.71 | 5746.40 | 30082.94 |
| 1987 | 1401.33 | 26625.30 | 5479.75 | 33506.38 |
| 1988 | 1616.84 | 30720.02 | 4982.54 | 37319.41 |
| 1989 | 1850.27 | 35155.09 | 4561.00 | 41566.36 |
| 1990 | 2024.13 | 38458.50 | 5813.97 | 46296.61 |
| 1991 | 2296.61 | 43635.61 | 5632.94 | 51565.16 |
| 1992 | 2599.60 | 49392.48 | 5441.20 | 57433.28 |
| 1993 | 2935.49 | 55774.30 | 5259.39 | 63969.18 |
| 1994 | 3302.34 | 62744.43 | 5202.11 | 71248.88 |
| 1995 | 3711.54 | 70519.23 | 5126.23 | 79357.00 |
| 1996 | 4167.96 | 79191.18 | 5024.87 | 88384.00 |
| 1997 | 4677.84 | 88878.88 | 4885.38 | 98442.10 |
| 1998 | 5247.46 | 99701.69 | 4695.66 | 109644.81 |
| 1999 | 5879.00 | 111701.08 | 4542.31 | 122122.39 |
| 2000 | 6579.85 | 125017.11 | 4422.96 | 136019.92 |
| 2001 | 7366.72 | 139967.67 | 4164.60 | 151498.98 |
| 2002 | 8253.05 | 156807.98 | 3678.54 | 168739.57 |
| 2003 | 9216.45 | 175112.64 | 3613.03 | 187942.13 |
| 2004 | 10325.81 | 196190.33 | 2813.81 | 209329.95 |
| 2005 | 11530.95 | 219088.01 | 2532.74 | 233151.69 |
| 2006 | 12872.22 | 244572.21 | 2239.92 | 259684.36 |

Source: Nigerian Energy Balance, Energy Commission of Nigeria 2011

Table 2: Energy Consumption by Sector – Charcoal ('000 tonnes)

| Year | Manu-facturing | Household | Services | Total |
|---|---|---|---|---|
| 1981 | 8.57 | 2.90 | 136.98 | 148.45 |
| 1982 | 9.68 | 6.63 | 149.53 | 165.84 |
| 1983 | 6.83 | 32.28 | 146.15 | 185.27 |
| 1984 | 6.06 | 67.59 | 133.31 | 206.97 |
| 1985 | 7.27 | 85.03 | 138.92 | 231.21 |
| 1986 | 6.99 | 108.13 | 143.18 | 258.30 |
| 1987 | 7.34 | 131.07 | 150.15 | 288.55 |
| 1988 | 8.28 | 148.94 | 165.13 | 322.36 |
| 1989 | 8.42 | 171.31 | 180.39 | 360.12 |
| 1990 | 6.79 | 254.00 | 141.51 | 402.30 |
| 1991 | 7.43 | 295.94 | 146.06 | 449.43 |
| 1992 | 7.10 | 343.77 | 151.21 | 502.08 |
| 1993 | 6.83 | 397.62 | 156.44 | 560.89 |
| 1994 | 6.74 | 461.70 | 158.16 | 626.60 |
| 1995 | 6.39 | 533.11 | 160.50 | 700.00 |
| 1996 | 6.45 | 611.81 | 163.74 | 782.00 |
| 1997 | 6.47 | 698.72 | 168.41 | 873.61 |
| 1998 | 6.03 | 794.70 | 175.22 | 975.94 |
| 1999 | 6.23 | 902.90 | 181.13 | 1090.27 |
| 2000 | 6.45 | 1025.51 | 186.02 | 1217.98 |
| 2001 | 6.90 | 1156.20 | 197.56 | 1360.66 |
| 2002 | 7.60 | 1288.79 | 223.67 | 1520.05 |
| 2003 | 8.03 | 1462.37 | 227.72 | 1698.12 |
| 2004 | 8.98 | 1595.66 | 292.40 | 1897.04 |
| 2005 | 9.84 | 1784.57 | 324.85 | 2119.26 |
| 2006 | 10.77 | 1989.44 | 367.32 | 2367.52 |

Source: Nigerian Energy Balance, Energy Commission of Nigeria 2011

Table 3: 25 Countries with the Greatest Potential Benefits from Solar Cookers in Descending Order

| COUNTRY | POSITION | Annual Insulation 2=best 1=good (NASA) | % forest/ wood-lands (UNFAO data) | Est. fuel scarcity 2 = >1/2 pop., 1=< 1/2 pop. (SCI est.) | Est. population 2020 (in millions) (UN data | Est. % pop. with Both sun & fuel scarcity | Est. no. of people with both sun & fuel scarcity 2020 (in millions |
|---|---|---|---|---|---|---|---|
| India | 1st | 1.2 | 21 | 2 | 1312 | 12 | 154.3 |
| China | 2nd | 1 | 16 | 2 | 1402 | 7 | 98.1 |
| Pakistan | 3rd | 1.5 | 4 | 2 | 227 | 20 | 45.2 |
| Ethiopia | 4th | 1.5 | 5 | 2 | 105 | 23 | 24.2 |
| **Nigeria** | **5th** | **0.5** | **19** | **1** | **177** | **7** | **12.4** |
| South Africa | 6th | 2 | 7 | 1 | 44 | 20 | 11.0 |
| Brazil | 7th | 0.75 | 67 | 1 | 210 | 4 | 8.4 |
| Uganda | 8th | 1 | 26 | 2 | 47 | 16 | 7.5 |
| Tanzania | 9th | 1 | 45 | 1 | 50 | 15 | |
| Afghanistan | 10th | 1 | 2 | 2 | 40 | 17 | |
| Sudan | 11th | 2 | 30 | 1 | 93 | 15 | |
| Nepal | 12th | 1 | 33 | 2 | 35 | 17 | |
| Kenya | 13th | 1 | 32 | 1 | 39 | 15 | |
| Somalia | 14th | 2 | 13 | 2 | 18 | 27 | |
| Niger | 15th | 2 | 2 | 1 | 22 | 22 | |
| Mozambique | 16th | 2 | 40 | 1 | 24 | 16 | |
| Burkina Faso | 17th | 0.5 | 27 | 1 | 21 | 16 | |
| Haiti | 18th | 2 | 6 | 2 | 10 | 31 | |
| Madagascar | 19th | 1 | 22 | 1 | 27 | 11 | |
| Malawi | 20th | 1 | 34 | 2 | 17 | 16 | |
| Zimbabwe | 21st | 2 | 58 | 2 | 13 | 20 | |
| Sri Lanka | 22nd | 1 | 35 | 1 | 21 | 11 | |
| Eretria | 23rd | 2 | 14 | 2 | 7 | 27 | |
| Dominican Republic | 24th | 2 | 28 | 1.5 | 11 | 15 | 1.7 |
| Zambia | 25th | 1 | 54 | 1 | 14 | 8 | 1.1 |

Source: Solar Cookers International (SCI), 2004

Table 1: Renewable Energy Sources and Capacities In Nigeria

| ENERGY SOURCE | CAPACITY |
|---|---|
| Large Hydro | 11,250MW |
| Small Hydro | 3500MW |
| Fuel Wood | 13,071,464 hectares (forest land 1981) |
| Animal Waste | 61 million tonnes / yr |
| Crop Residue | 83 million tonnes /yr |
| Solar Radiation | 3.5 – 7.0 KWh/M$^2$-day |
| Wind | 2-4 m/s (annual average) |

Source:Renewable Energy Masterplan, Energy Commission of Nigeria 2012

Table 3 Products of Research and Development on Energy Efficient Cookstoves in Nigerian Institution

| S/N | RESEARCH INSTITUTES/ CENTRES | TYPE OF EFFICIENT COOKSTOVE | YR OF DEVT | PERFORMANCE (% efficiency) |
|---|---|---|---|---|
| 1 | **Sokoto Energy Research Centre (SERC) Usmanu DanFodiyo University, Sokoto, Nigeria** | Single and double box type solar cookers | 2006 | 47.56 |
| | | Parabolic solar Cooker | 2006 | 41 |
| | | Clay based Improved woodstove | 2003 | 25 |
| | | Biogas Digesters | 1998 | 40 |
| 2 | **National Center f Energy Research and Devt NCREI University of Nigeria, Nsukka** | Metal based Efficient woodstove | 2011 | 50 |
| | | Charcoal stove | 2005 | 30 |
| | | Sawdust Stove | 2005 | 30 |
| | | Biogas Digesters | 2001 | 40 |
| 3 | **Developmental Associations for Renewable Energ (DARE) Kaduna Nigeria (CDM project)** | Stainless Steel Efficient Woodstove (Save 80: Developed in Germany, assembled in Nigeria) | 2010 | 80 |

Source: Compendium of Research and Development Result, Energy Commission of Nigeria 2011

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