Acoustic Energy Harvesting in Nigeria: Prospects, Technical Problems and Socio-Economic Obstacles

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Author's contribution

The sole author designed, analysed, interpreted and prepared the manuscript.

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ABSTRACT

Aims: To investigate the prospects or potentials of acoustic energy harvesting in Nigeria as well as highlight technical problems and socio-economic obstacles.

Study Design: The study re-examined existing data, noise levels and noise power, from road traffic, aircraft, industrial/occupational, outdoor and indoor noise sources. Noise levels and noise power obtained from recent measurements of such noise sources were also examined and analyzed. The data were compared with values from noise sources used for electricity in other countries of the world. Technical problems and socio-economic obstacles have been highlighted.

Place and Duration of Study: The study was carried out in Abakaliki, Ebonyi State, Nigeria. The duration was one year: April, 2019 and April, 2020.

Methodology: Wide range noise level measurements, analysis and re-examination of existing data on road traffic, aircraft, industrial/occupational, outdoor and indoor noise were conducted, in line with the objectives of the study, in cities, industries as well as homes with different noise features. Measurements were carried out using sound level meter, SLM, (Bruel and Kjaer 2203) with $\frac{1}{2}$ – octave band filter and SLM, EXTECH 407750 with RS232, sound level recorder (B & K 7005), and noise level (statistical) analyzer (B & K 2121) to obtain noise levels and indices. Also, noise power was subsequently obtained for each of the various noise levels and indices.

Results: Maximum noise levels, $L_{max.}$; noise power, $W_{max.}$; octave band pressure levels, BPLs; and other indices for the different noise sources were determined. $L_{max.}$ and W_{max} for aircraft were as

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high as 116 dB and 0.4 W, respectively, while those for industry and road traffic ranged from 104.0 dB-131.0 dB and 67.5 dB-85.6 dB corresponding to 0.025 W-12.59 W and 0.0000056 W-0.00036 W, respectively. Spectral power of road traffic noise varied between 5.17×10^{-5} W and 9.69×10^{-3} W. Outdoor and household noise sources had L_{max}. of up to 48.5 dB and 88.0 dB, that is, 0.000000071 W and 0.00063 W, for quiet and noisy periods, respectively. It was observed that road traffic noise has the highest potential for acoustic energy harvesting in Nigeria being reasonably steady over time, especially, on intra-city roads. Availability of tricycles/motorcycles in abundance and frequent use of horn by motorists support this assertion. The noise levels and noise power from these sources obtained in this investigation are higher than those that have been used as input to acoustic energy harvesters (AEHs) such as piezoelectric based and triboelectric nanogenerators (TRENGs) to achieve known efficiencies as reported elsewhere.

Conclusion: The noise power is such that it could be used in powering microelectronic components, devices and in lighting light emitting diodes (LEDs). Power supply (PS) audio noise harvesters (ANHs) have been identified as potential noise energy sources since there is wide range use of air-conditioned by the political class, elites and government agencies in Nigeria where maximum temperature of 47.2°C is attainable. These findings show the viability of AEH in Nigeria and their addition to the existing body of knowledge in the emerging area of AEH will open a new window of research in AEH in this part of the world. Other prospects of AEH in Nigeria, technical problems and socio-economic obstacles are highlighted.

Keywords: Acoustic energy; Nigeria; global energy demand; noise power; conversion efficiency; challenges; technical problems; socio-economic obstacles.

1. INTRODUCTION

1.1 Overview: Global Energy Demand and Popular Energy Sources

It has long been known that there is global energy crisis. Solar, nuclear and renewable sources of energy such as photovoltaic energy, wind energy, geothermal energy and wave energy were hitherto identified as possible resources to match the anticipated demand. Others are hydroelectric, wet geothermal, tidal and ocean energies. Gholap [1] had estimated that the contribution of these renewable sources of energy was 1 TW at maximum feasible expectation. This is equivalent to 3.15×10^6 J/annum and represented only about 0.001% of world energy consumption then. It was asserted then that the consumption of energy in the world was 2.30×10^{23} Jyear^{-1}, which is equivalent to the energy produced when 1.84×10^{15} kg of coal is burnt [1]. Still on world energy demand, Gholap [1] posited that in 2030, the world consumption of energy will be 6.23×10^{23} Jyear^{-1}. It was estimated that with nuclear (fission) source of energy, available ore (uranium and thorium) can supply energy for the next 50 years [2] when the annual energy consumption of 1.00×10^{24} Jyear^{-1} or more for the year 2050 is taken into account [3]; and that the global demand of energy of 3.35×10^{24} Jyear^{-1} is expected by the year 2100 when the world population would grow to about 13 billion. Global population was later

projected to increase from 6.7 billion in 2008 to 9.2 billion in 2050 [4]. Rapid population growth, industrialization and urbanization have been identified as reasons for the rapid increase in the global energy demand; and unless a radical energy policy is taken and implemented by every country of the world, there will be a serious problem of energy crisis in the future [5,6].

Onuu [5] re-examining existing data on energy, obtained an empirical relationship between world energy demand, *E(t),* as a function of time, *t,* in years. The exponential equation is of the form [5]:

$$E(t) = E_o \exp bt \tag{1}$$

where

E_o is energy in joules/annum.

Analysis of the data points yielded values for the regression coefficients, E_o and *b* as 433.3×10^{22} and 0.024, respectively. Hence, eqn. (1) becomes

$$E(t) = 433.3 \times 10^{22} \exp(0.024)t \tag{2}$$

E_o and *b* characterize the energy demand curve. Although energy supply in many countries of the world comes from oil and coal reserves which stand at about 274 and 76,000 billion tons,

respectively, their rapid depletion for electricity generation and the fact that they are impure sources of energy have necessitated the vigorous search for alternative sources. Also, the anthropogenic emission of CO into the atmosphere arising from the extensive use of coal, and other sources of CO, will bring about an increase in mean temperature of the earth's surface by 2-3 K, and will in turn cause recession of the polar ice cap by 10^0 of latitude [1,7].

1.2 Problems of Popular Energy Sources

Although conventional, nuclear and other sources of energy have some advantages, they also have some problems as highlighted below.

1.2.1 Conventional and nuclear sources of energy

I.   **Oil and coal:** The major problem of oil and coal is that their reserves are being depleted [4,8-11]. In addition, they pollute the environment and also cause global warming [7,12,13].
II.   **Nuclear fuels:** Schlissel and Biewald [14] reported that there is high capital cost of nuclear power stations, particularly. Apart from life of nuclear fuels being short, confinement problem of the plasma is difficult to solve even with the TOKOMAK, the Russian acronym for toroidal chamber with magnetic coils, in the area of magnetic confinement [15].

1.2.2 Renewable energy sources

I.   **Solar energy:** Solar energy is difficult to exploit because of its intermittence, irregularity and storage problem and the fact that it requires a large series of measurements. Other problems are reliability and distribution of instruments in solar radiation measurement: climatic data (aerosols, visibility, etc.), choice and follow-up of installations as well as socio-economic obstacles [16]. Solar energy has very low thermodynamic energy of thermal converters compared with fossil fuels and nuclear sources. It has large size of converters which arises from the bulky materials used [1]. Low efficiency of photovoltaic modules based on amorphous silicon (a-Si)/crystalline Si is the major problem of such modules.

II.   **Wind energy:** For maximum power to be generated, the area swept by the rotor, *A*, in m^2, in the turbine of wind energy conversion systems (WECS) is much which means bulky materials are required [17]. Also, wind speed should be high enough, which may not be obtainable because of environmental factors.
III. **Hydroelectric energy:** Although hydroelectric power is a very important source renewable energy, it has some environmental consequences as it can destroy the ecosystems. It is expensive to build and maintain because of the draining expenses; has potential for droughts and takes long time, in years, to build a new hydroelectric power plant.
IV.   **Acoustic (sound) wave and energy:** Audible sound wave is perceived by the normal human ear in the frequency range 20 Hz-20 kHz. It is a form of mechanical energy that can be converted to electrical energy as shown in Figure. 1.

A measure of pressure variation in the medium, sound is a longitudinal wave when it propagates in air and obeys the expression:

$$\frac{\partial^2 p}{\partial x^2} - \frac{1}{C^2}\frac{\partial^2 P}{\partial t^2} = 0 \qquad (3)$$

where

p is pressure, x is distance and c is speed of sound in air (= 343 ms^{-1} at 20^oC). Sound pressure level (SPL), L_p , the measured root-mean-square pressure, *p*, and the reference sound pressure, $p_{ref.}$ varies as shown in eqn. (4):

$$L_p = 20log_{10}\left(\frac{p}{p_{ref}}\right) \qquad (4)$$

where

$$p_{ref} = p_0 = 2 \times 10^{-5} Pa = 20\mu Pa.$$

The unit of sound power lever (SWL), L_W is the decibel (dB) defined as

$$L_w = 10log_{10}\left(\frac{P}{P_{ref}}\right) \qquad (5)$$

where

P is power and P_{ref} is the reference power such that $P = P_0 = 10^{-12}W = 1pW$. Equation (5) is used to convert decibel to sound power, *P*.
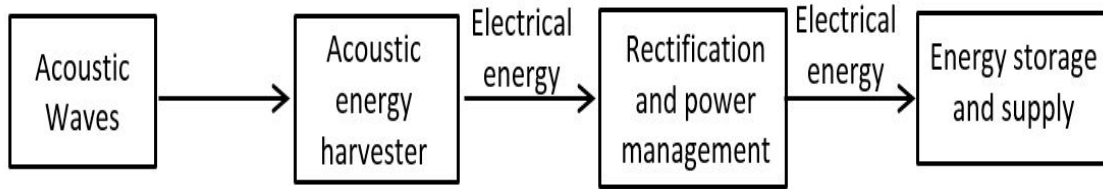
Figure. 1. Schematic diagram of a typical acoustic energy-harvesting (AEH) system [18]

Sound propagating through narrow tubes or small-scale structures has viscous loss which contributes to acoustic damping and the thickness of the viscous layer, d, related to the frequency by [19]:

$$d = \sqrt{\frac{2\mu}{\rho_o \omega}} \qquad (6)$$

where μ is the dynamic viscosity (=1.81 x 10^{-5} kgms = 18.1 μPa) , ρ_o is the density of air (= 1.225kgm-^{3}) and ω is the angular frequency ($\omega = 2\pi f$). Therefore, effort should be made to decrease the effect of viscous layer when low frequency sound is propagated in air. For example, for a 100 Hz sound in air, d = 0.22mm.

Africa needs renewable energy very badly. It is projected that more than half a billion people would be added to Africa's urban population by 2040; and this is much higher than the growth in China's urban population between 1990 and 2010, the period when China witnessed the largest production of materials such as steel and cement in order to cope with the challenge and tried to battle with the consequent energy crisis [20]. As at now, there is no deliberate policy by any African country to address the energy challenge despite the fact that Africa has the richest resources in the world to harness solar energy using PV. Africa has installed only about 5 GW of solar PV which is less than the 1% of the global total [20]. Solar PV, it is expected, would provide the cheapest source of electricity for many of the 600 billion people who do not have access to electricity today [20,21]. According to Birol [20], wind and solar PV have been identified as star performers all over the world with hydropower (15% of total generation in 2040) and nuclear (8%) retaining major shares. Research on the new field of AEH has been conducted in some countries of the world, including a few African countries beside Nigeria, in the quest towards addressing the energy challenge. This is despite the fact that Nigeria is one of the countries in Africa that has the highest potentials for the production of acoustic/noise energy. The objectives of this study are, therefore, to investigate the prospects of AEH in Nigeria, highlight the technical problems and socio-economic obstacles in the quest towards solving the global energy problem.

1.3 Cost of Generated Electricity

In Nigeria, it is difficult to access electricity as electricity supply is unreliable. It is estimated that households spend ₦4.34 trillion ($12 billion) annually on self-generated power where ₦ is the symbol for the Nigerian Naira. International Monetary FUND (IMF), in a survey asserts that the economic loss is about ₦10.5 trillion ($29 billion)/annum. While 27% of Nigerian firms identified electricity as the main obstacle to doing business according to the survey, households that have access to on-grid electricity had an average power supply of only 9.2 hours a day in the first half of 2019 [22]. IMF further stated that electricity production per capita in Nigeria is less than 15% of the average of emerging- market economies and less than 25% of the sub-Saharan Africa average.

Generally, for all systems, the cost of generated electricity per *kWh* which depends on a number of variables is given as [17]:

$$C = (I \times F + O \ \& \ M) \ E^{1} \qquad (7)$$

where *I* is the total investment cost in dollars, *F* is the fixed charge rate, *O & M* is the annually generated energy in *kWh*. The depreciation of our money, naira, in terms of dollar therefore constitutes a serious problem in our quest to be energy sufficient.

1.3.1 Cost of power supply from electric generators

Cost of power supply from electric generators in Nigeria is high. Prices of electric generators vary

depending on the model and capacity or power rating. For example, Honda EM650Z 450 VA Portable Low Noise Generator costs between ₦50,000 ($138) and ₦57,000 ($157.5) while the price of Honda EU65iS 5.5 kVA Compact Low Noise Generator with built-in inverter is in the range ₦630,000 ($1,740.3)- ₦668,000 ($1,845.3). For the Fireman model, the prices are in the ranges: ₦31,000 ($85.6)-₦45,000 ($124.3) for Fireman 720 VA SPG 1200 and ₦215,000 ($594)-₦350,000 ($967) for Fireman 7 kVA 10990 ES. Fueling of the generators is a very expensive project with the attendant noise and air pollution. Petrol (PMS) costs ₦145 ($0.4) per litre while the price of diesel, Automotive Gas Oil (AGO) is between ₦241.88 ($0.67).

1.3.2 Cost of solar energy

Some Nigerians are now managing to cope with the challenge of epileptic power supply by using alternative power sources. Solar panel and a 12 V battery of 200 AH rating that can charge panels that have power rating that range from 125 W-400W to full capacity are available. A combination of a solar panel with a power wall inverter and a controller cost as much as ₦725,000.00 ($2,002.8) depending on the

number of batteries. For example, a 5 kVA inverter with four 200 AH batteries and eight 250 W solar panel cost ₦1,450,000 ($4,005.5). A solar panel costs as much as ₦120,000 ($331.5) per unit. Although, these prices depend on the various solar panel brands and type of battery in Nigeria, the price difference is not much.

1.3.3 Cost of harvesting acoustic energy

A simple cost-effective approach for the construction of high performance triboelectric nano generator (TRENG) to convert ambient noise into electricity that enables self-powered sensing applications with potential applications in military surveillance, artificial intelligence, Internet of Things (IoT) and jet engine noise reduction was developed by Chen [23]. Although wind energy, geothermal, biogas and photovoltaic (PV) when used alone as renewable sources is not fully promising economically, Rahman [24] proposed a technique which improved power production using a combination of renewable sources like solar PV, speed breaker (roller) and sound of traffic for hybrid electricity generation for street light application (Figure. 2).
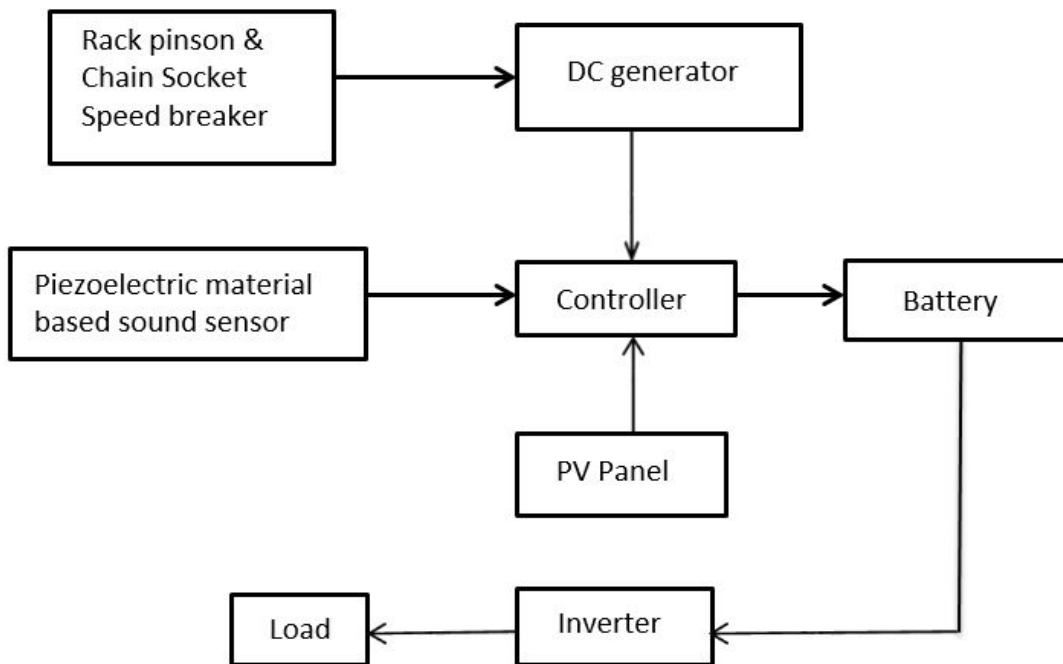

Figure. 2. Block diagram for the working of the proposed integrated system [24]

2. METHODOLOGY AND ANALYSIS

Noise level measurements of road traffic noise, aircraft noise, industrial/occupational noise, outdoor and indoor noise were made using the precision sound level meter, SLM, (Bruel and Kjaer 2203) with ½-octave band filter and sound level recorder (B & K 7005) which has frequency modulation for clarity. SLM, EXTECH 407750 with RS232 was also used for *in situ* measurements of noise levels. The B & K SLM and EXTECH SLM were placed on a tripod stand and held in the hand, respectively, with the microphone pointed to the noise source during measurements. In all the measurements, preliminary surveys were undertaken to identify points with high noise levels or "intolerable" noise levels in the case of the industries. The microphone was calibrated each time that field measurements were to be made. The noise source determined the type of physical measurements to be conducted. Generally, measurements were similar to other noise monitoring programmes in Ontario [25] and U.S.A. [26] and was in conformity with International Electrotechnical Commission (IEC), British Standards Institute (BSI) and International Standards Organization (ISO).

2.1 Road Traffic Noise

The microphone was placed 1.0 m from the facades of houses/offices and from any reflecting surface and 1.2 m above the ground corresponding to the ear of an average human height. Counting was done for 20 minutes with the help of field assistants to estimate hourly volume of vehicles and composition. Approximate number of vehicles which included the "heavies", buses, cars, tricycles and motorcycles were then counted and recorded from where hourly traffic volume and composition were determined. The survey covered 60 sites in eight (8) major cities in Nigeria with a wide range of urban conditions. At some of the sites, measurements were made each day for 24 hours: during daytime (0700-2200) and nighttime (2200-0700) periods, Monday to Friday [27].

2.2 Aircraft Noise

Survey of aircraft noise was conducted in three (3) of the major Nigerian airports. The environmental noise climate at the airports and maximum noise levels $L_{Amax.}$ at landing and take-off were measured at 50-100 m from the aircraft.

2.3 Industrial Noise

At any particular industrial plant, measurements were made at various points between 1 and 2 m from the source. To determine the point having the highest noise level, several measurements were made within a particular industrial plant and noise levels were recorded. There were 27 industries in southeastern Nigeria where measurements were made [28] apart from the five (5) quarries located in Old Netim and Obung communities in Akamkpa Local Government Area of Cross River State [29]. These comprised: Cross River State (12), Akwa Ibom State (7) and River State (8).

2.4 Indoor/Household Noise

Indoor or household noise measurements were made during the nighttime period (2200-0700) in over 20 homes with varying noise features. Apartments chosen for measurements were spacious enough to drastically reduce the effect of reverberant sound. Measurements were made at such times when the background noise level due to aircraft, industries, humans, animals and other outdoor noise was less than the indoor noise being measured by, at least, 10 dB [30].

Unless in cases where *in situ* measurements of noise levels were made, the tapes were subsequently played back sampled at two (2) seconds and analyzed using the noise level (statistical) analyzer (B & K 2121) within the audio frequency range (20 Hz to 20 kHz) in the Applied Acoustics Laboratory of the Department of Physics, University of Calabar, Cross River State, Nigeria to determine the required noise levels, indices and descriptors. Thereafter, the needed/corresponding noise power was computed using equation (5).

3. NOISE-(SOUND-) ENERGY CONVERSION AND RESULTS

3.1 Perspective

Sound being a form of mechanical energy can therefore be changed to another form of energy, say, electrical energy in accordance with the law of conservation of energy or the third law of thermodynamics mainly through the principle of electromagnetic induction. Vibration or structure-borne noise can generate enough electricity to power nearby phone-charging stations and illuminate electronic signage and advertising.

Cohen-Tanugi [31] noted that though still in the research phase, the technology of harvesting acoustic noise is more about mechanical vibrations than sound itself. The idea is definitely there, and it is quite promising [31]. Although this is feasible, the loudest noise is only equivalent to about a hundredth of watts per square metre (Table 1) [32].

The four main approaches to convert sound energy to electrical energy are by heating, by using diaphragm, through piezoelectric materials and an acoustic grating [31,32-35] demonstrated the possibility of converting sound into electrical energy by using a speaker and a transformer to convert noise produced by a car horn. A similar set up was used to demonstrate that vibration produced by noise can be converted into electrical energy. They also placed a speaker and a transformer at the distance of 1 metre from the exhaust pipe of 350 cubic centimeter engine of a motorcycle and harvested the energy.

Farghaly and Hemeida [36] produced electrical energy from an area of 1.45 m^2 containing 690 piezoelectric QB220-503YB transducers. Electrical energy produced by noise from the piezoelectric material from each of the selected stations was about 0.024 Watt-hr [36]. The suggested maximization of this application was hundreds of square metres in order to produce useful energy that can light 1 LED street lamp or it can be stored and used when needed for applications that need more energy. Road traffic noise level index, L_{DEN}, was calculated for each of three locations in Alexandria [36]. The study was conducted during weekdays and weekends in order to study the noise produced in the selected stations and the amount of electric energy that could be produced and utilized in street lighting (Table 2).

Choi and Kang [37] has pointed out recently that sound energy harvesting is one of the promising technologies due to the abundant and clean sound sources. It can be the semi-permanent alternative power supplies for wireless sensor networks (WSNs), which is significant in the Internet of Things.

A comprehensive review of sound energy harvesting, focusing on presenting principles, examples and enhancement methods of sound energy harvesters has been conducted recently [37] while a comprehensive assessment of development of acoustic energy harvesting has been done [38]. There is, therefore, a clarion call

to researchers all over the world, especially developing countries such as Nigeria, where noise is adjudged by many as the necessary consequence of urbanization and industrialization, to join in the research towards the exploitation of noise as a source of clean sound energy.

3.2 Efficiency of Acoustic Energy Conversion Systems

Experimental results obtained by Noh (Table 3) [39] show that approximately 0.7 V was generated when sound pressure level (SPL) of 100 dB was incident on a large rectangular piezoelectric plate. Tables 3 and 4 [23,40] show the efficiency analysis from various types of piezoelectric unit and acoustic energy harvesting conversion efficiency, respectively.

3.3 Noise-energy Conversion in Nigeria

Commencement of research in the area of environmental acoustics and noise pollution in Nigeria dates back to the late 1970s [41] and was continued in the 1980s [42-44] when it was observed that noise levels well exceeded recommended limits in Nigeria. This appears to be the very first set of studies conducted in this area of study in Nigeria and in West Africa. Later, different researchers of Nigerian nationalities have joined in the study making significant progress in advancing the frontiers of environmental acoustics and vibration or structure-borne noise in this part of the world [27-30,45-55]. A chronicle of work in environmental acoustics in Nigeria could be found in [52], a paper in honour of Professor Alex I. Menkiti where the status of acoustics in Nigeria was assessed. Some of these studies have identified road traffic noise as the major form of environmental noise pollution in Nigeria being persistent over time with measured maximum levels, $L_{max.}$ as high as 110 dB(A) (i.e. $W_{max.}$= 0.1 W) in some cases with indiscriminate use of horn by motorists [27,45].

Researches bothering, in part, on levels of household noise, industrial/occupational noise, quarry noise, outdoor noise, aerodynamic noise and aircraft noise have been conducted with measurements and analyses undertaken [27-30,45,48,50,51,53]. Measured values of $L_{max.}$ as high as 131 dB ($W_{max.}$= 12.59 W) were reported in most cases.

Data obtained from the wide-range measurements and physical surveys have been assessed and re-examined towards determining the prospects of acoustic energy harvesting or noise-(sound-) energy conversion in Nigeria (Tables 5-17). Table 5 shows data for aircraft noise. Road traffic noise (Tables 6-11), aerodynamic noise in buses (Table 12), industrial/occupational noise (Tables 13-16) and outdoor noise (Table 17) are also shown while Figure. 3 shows levels and spectra of household noise.

Table 1. Typical sound power levels [32]

Source	L_W re 10^{-12} W (1 pW (dB)	Sound power (W)
Jet engine	160	10,000
Loudspeaker rock	140	100
2 pneumatic hammers	123	2
Pneumatic hammer	120	1
Outboard motor	100	0.01
Dishwasher	80	0.0001
Office	60	0.000001
Fridge	40	0.00000001
Whisper	20	0.0000000001
Threshold	0	10^{-12}

Table 2. Equivalent noise level, L_{Aeq}, in Alexandria, Egypt in three locations [36]

Timing	Equivalent noise level, L_{Aeq} (dB)	Level exceeding permissible limit (dB)
Daytime	75-85	10-20
Evening	80-85	20-25
Night	75-80	20-25

Table 3. Efficiency analysis from various types of piezoelectric unit [39]

Model	Area ($10^{-3}m^2$)	Max. voltage (V)	Efficiency($10^3 Vm^{-2}$)
Rectangular plate	3.500	0.70	0.20
Large Circular plate	0.527	0.43	0.82
Small Circular plate	0.314	0.37	1.18
Cantilever beans	0.130	0.19	1.46

Table 4. Acoustic energy harvesting conversion efficiency [23,40]

Acoustic energy harvester	Power range/Max. output power density	Resonant frequency
Piezoelectric based	0.66 pW-30 mW	146 Hz-6.7 kHz
Electromagnetic based	1.5mW-1.96 mW	143 Hz-470 Hz
Triboelectric nanogenerators (TRENGs)	7 W/m^2 at 170 Hz and 115 dB	20 Hz-1000 Hz

Table 5. Octave band pressure levels, BPL, in some Nigerian airports [51] *

Airport	Octave band pressure level, BPL (dB)										
	31.5	63	125	250	500	1k	2k	4k	8k	16k	32k
Margaret Ekpo Int'l Airport, Calabar.	81.0	82.0	80.0	80.5	82.0	81.0	79.5	79.0	83.0	80.0	82.0
Port Harcourt Int'l Airport.	95.0	92.0	90.0	89.5	85.0	86.0	95.0	80.6	86.0	84.0	81.0
Murtala Mohammed Int'l Airport, Lagos.	99.0	98.0	100.0	94.0	95.0	100.0	88.5	90.0	82.0	90.0	84.0

$L_{max.}$ was as high as 116 dB(A) (= 0.4 W) in each case

Table 6. Acoustic power spectra analysis I [46]

Parameter	Regression equation	Correlation coefficient, r
Summation spectrum, $W_s(f)$	$2.20 \times 10^{-3}\exp(-0.00134f)$	-0.9956
Spectral width, $z(f)$	$7.38 \times 10^{-3}\exp(-0.0011f)$	-0.9880
Lower bound spectrum, $W_l(f)$	$1.84 \times 10^{-4}\exp(-0.00105f)$	-0.8124
Upper bound spectrum, $W_u(f)$	$5.30 \times 10^{-3}\exp(-0.0098f)$	-0.8342

The regressions are valid within the frequency range 50 to 10,000 Hz

Table 7. Acoustic power spectral analysis in Nigeria II [46]

S/No.	Town	Power spectrum, W_o(W)	Speed parameter, R_m(Hz^1)	Frequency weighted N_A(W)
1	Aba	9.31×10^{-5} - 1.84×10^{-4}	1.05×10^{-4} - 2.34×10^{4}	0.12 - 0.45
2	Calabar	9.66×10^{-5} - 9.81×10^{-4}	4.56×10^{-4} - 7.68×10^{-4}	0.11 - 0.24
3	Enugu	3.14×10^{-4} - 9.14×10^{-4}	8.33×10^{-4} - 9.01×10^{-4}	0.30 - 0.77
4	Ikot Ekpene	2.15×10^{-4} - 9.30×10^{-4}	4.86×10^{-4} - 8.70×10^{-4}	0.19 - 2.05
5	Onitsha	5.17×10^{-5} - 5.06×10^{-3}	8.99×10^{-4} - 1.31×10^{-3}	0.04 - 2.10
6	Owerri	7.85×10^{-5} - 5.30×10^{-3}	6.44×10^{-4} - 9.86×10^{-4}	0.30 - 3.79
7	Port-Harcourt	9.41×10^{-4} - 2.03×10^{-3}	7.91×10^{-4} - 1.08×10^{-3}	0.57 - 2.15
8	Uyo	1.81×10^{-4} - 9.69×10^{-3}	1.00×10^{-4} - 1.62×10^{-3}	0.13 - 0.56

Table 8. Noise levels, traffic volume and composition at Akanu Ibiam Round About, Abakaliki

Location	Traffic Volume/Composition					$L_{max.}$ (dB)	
	Heavies	Buses	Cars	Tri-/motorcycle	Total	Morning	Afternoon
From Enugu	8,460	9,600	12,900	1,650	32,610	75.1	84.8
From Int'l Market	1,920	1,200	4,080	1,002	8,202	77.4	76.2
From Onueke	780	2,460	4,680	1,026	8,946	75.8	75.5
From Vanco Junction	3,600	6,180	12,900	1,890	24,570	85.4	77.0
Total	14,760	19,440	34,560	5,568	74,328	-	-

Table 9. Noise levels, traffic volume and composition at PRESCO Round about, Abakaliki

Location	Traffic Volume/Composition					$L_{max.}$ (dB)	
	Heavies	Buses	Cars	Tri-/motorcycle	Total	Morning	Afternoon
From Enugu	1,500	3,900	12,840	36,060	54,300	74.7	78.3
From Akanu Ibiam Round About	1,620	2,100	4,860	19,560	28,140	73.1	69.7
From PRESCO, EBSU Campus	60	1,200	3,420	16,840	21,520	83.2	79.5
From Ezza Road	1,140	7,800	12,000	16,500	37,440	77.2	69.8
Total	4,320	15,000	33,120	88,960	141,400	-	-

Table 10. Vehicle composition (%) [30]

S/No.	Vehicle Type	% composition (hr^{-1})
1.	Heavies	1.1-17.8
2.	Buses	0.0-29.6
3.	Cars	41.1-77.8
4.	Tricycle/ Motorcycles (*keke na pep*)	1.5-68.3

Table 11. Mean noise levels at different sites in Ikeja, Nigeria [54]

Location	Noise Level (dB)		
	L_{Aeq}	$L_{min.}$	$L_{max.}$
Junctions/Roundabout	67.5 - 90.5	66.0 - 76.5	68.0 - 82.5
Roads (inter & intra city)	69.5 - 88.1	60.8 - 76.5	68.0 - 83.1
Loading parks (garage)	75.7 - 88.7	68.0 - 82.1	67.5 - 85.6

Table 12. Aerodynamic noise inside a bus at various speeds (with bus glasses all half-wound down) [50]

S/No.	Speed (kmh^{-1})	L_{Amax} (dB)
1.	20	60.5 - 64.0
2.	40	64.0 - 64.6
3.	60	62.0 - 68.2
4.	80	63.0 - 69.0
5.	100	72.8 - 73.0
6.	120	74.0 - 76.0

Table 13. Industries in Southeastern Nigeria included in industrial survey [28,57]

S/No.	Industry	Activity	A-weighted SPL (dB)
A	**Cross River State**		
1	Strabag Company, Old Netim, Akamkpa	Road construction	120
2	Crushed Rock Company, Old Netim, Akamkpa	Stone breaking	116
3	Hi-Tech Company, Old Netim, Akamkpa	Stone breaking	119
4	Pamol (Nig.) Ltd. Calabar	Rubber production	123
5	Pamol, Plastic Division, Calabar	Plastic production	113
6	System Metal Company, Calabar	Roofing sheets production	112
7	Mechanical Workshop, University of Calabar	Cutting, fitting and welding	102
8	Bao Yoa Huan Jian Iron/Steel Co. Calabar	Iron and steel production	111
9	Kevin Wood Industry, Calabar	Wood processing	102
10	Ayos wood Int'l Company, Calabar	Wood processing	110
11	Lama Gold Industry, Calabar	Textile production	105
12	Niger Mills Company, Calabar	Flour production	129
B	**Akwa Ibom State**		
13	AK-RUWATSAN, Uyo	Bore-hole drilling	115
14	Plasto-Crown (Nig.) Ltd., Uyo	Plastic making	109
15	Agrofeed Mills (Nig.) Ltd., Uyo	Animal food production	103
16	Peacock Paints Ltd., Etinan	Paint Production	109
17	Uso Metal Construction Co., Ikot-Ekpene	Metal work and welding	101
18	Samcolee Construction Co., Ikot-Ekpene	Metal work and welding	104
19	Ibok Construction Co., Ikot-Ekpene	Metal work and welding	114
C	**Rivers State**		
20	Snig (Nig.) Ltd., Trans-Amadi, Port Harcourt	Machine tool manufacturing	101
21	ACM (Nig.) Ltd., Trans-Amadi, Port Harcourt	Machine tool manufacturing	114
22	Bertola Machine Tools (Nig.), Port Harcourt	Machine tool manufacturing	112
23	Galloa (Nig.) Ltd., Trans-Amadi, Port Harcourt	Machine tool manufacturing	110
24	Eastern Bulkcem Cement, Port Harcourt	Cement production	119
25	Crushed Rock Company Ltd., Port Harcourt	Stone breaking	115
26	Zenith Plastic Company Ltd., Port Harcourt	Plastic Making	107

Table 14. Noise levels generated by 63 kVA caterpillar power generator

[a]Distance from power house door (m)	Noise Levels		
	L_{max} (dB	L_{dn} (dB)	L_{eq} (dB)
4.0	90.2	88.0	97.4
7.0	84.0	80.5	87.0
14.0	81.5	81.7	91.0
15.0	74.0	72.0	89.5
25.0	70.0	67.5	75.0
50.0	60.5	60.0	70.0

[a]4m and 7m are outside power house and radio room, respectively

Table 15. Summary of occupational noise levels in Nigeria [28]

State	Noise level (dB)		
	Background	A – weighted	$L_{max.}$
Cross River	42.5 - 61.0	101.5-129.0	108.5-131.0
Akwa Ibom	45.5 - 64.0	101.0-115.0	108.0-119.5
Rivers	45.5 - 68.5	100.5-127.0	104.0-130.5

Table 16. Summary of results of noise level measurements in some industries in Nigeria [57]

Type	Noise level (dB)
Background	44.5 - 68.0
A - weighted	100.5 - 127.0
$L_{max.}$	104.0 - 131.0

Table 17. Maximum noise levels at various locations in a University in Nigeria [53]*

S/No	Location	$L_{max.}$ (for quiet period) (dB)		$L_{max.}$ (for noisy period) (dB)	
		Indoor	Outdoor	Indoor	Outdoor
1	Physics Lab. 1	44.0	46.0	74.2	77.0
2	Chemistry Lab. 1	44.0	45.0	64.5	68.0
3	Geology Lab. 1.	43.5	43.7	65.0	67.0
4	Biological Science (Room 222)	43.5	43.9	68.0	75.0
5	New Science Lecture Theatre (NSLT)	45.5	48.0	65.5	77.0
6	NSLT 2	46.0	47.5	66.0	75.0
7	New Library (NL) (Room 201)	46.5	48.0	67.0	75.5
8	NL (Room 202)	43.5	44.0	74.0	75.0
9	Law Lecture Room	46.5	47.5	76.0	79.0
10	Physiology Lab	43.0	44.0	75.0	77.0
11	Faculty of Arts Lecture Complex	45.0	46.5	64.0	69.5
12	New Art Theatre (NAT)	43.8	44.2	65.0	69.0
13	Lecture Room 202, Main campus	45.5	48.5	67.0	35.0
14	DBA Lecture Hall	43.5	44.0	74.0	88.0
15	Theatre Arts Display Hall, Main Campus	43.5	44.0	33.5	69.5
16	ETF Lecture Complex	43.8	44.0	57.0	66.0
17	Computer Centre, open space	-	46.5	-	84.0

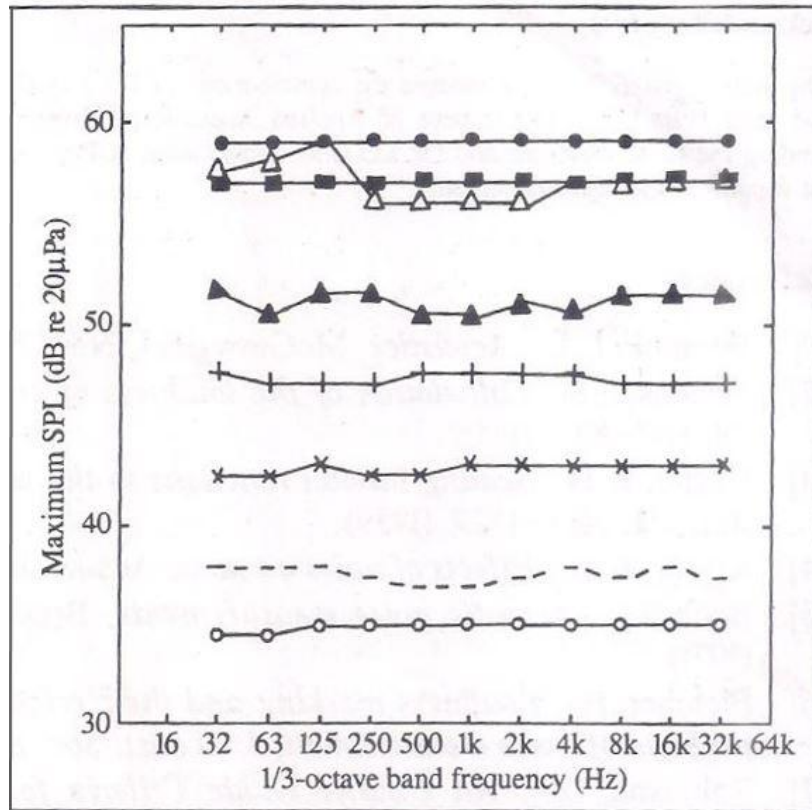**All indoor measurements were made with windows open*

Figure 3: Indoor noise spectra [30]: o – water flowing into WC tank; - - - - frying; x – water running into a bath; + - flushing of WC toilet; ▲, △ - grinding in kitchen (▲, with load; △ without load) and ■, ● - power change-over (■, TV receiver; ●, radio receiver).

4. DISCUSSION

4.1 Aircraft Noise

Aircraft noise measured in the three (3) airports depicts flat response with octave band pressure levels values between 79.5 dB and 100.0 dB (Table 5) [51]. $L_{max.}$ as high as 116 dB were measured in each case. Such high levels were measured during landing and take-off with the associated vibration or structure-borne noise. This results in noise power of 0.04 W. Aircraft noise is promising for acoustic energy harvesting in Nigeria.

4.2 Road Traffic Noise

Tables 6 and 7 show that the acoustic power spectra of road traffic noise vary between 5.17 x 10^{-5} and 9.69 x 10^{-3} W [40] Hourly road traffic composition and volume of (Tables 8 and 9) showed: heavies (14,760), buses (19,440), cars (34,560), tricycles/motorcycles (74,320), volume

(74,328) and heavies (4,320), buses (15,000), cars (33,120), tricycles/motorcycles (88,968), volume (141,400), respectively, were recorded for the different roundabout (sites). Typical values of percentage composition for a site is shown in Table 10 [30]. Maximum noise levels for the locations in Tables 8 and 9 range from 75.1-85.4 dB (for morning) to77.0-84.8 dB (for afternoon) and 74.7-77.2 dB (for morning) to 69.8-78.3dB (for afternoon), respectively. Mean noise levels in dB at different locations are shown (Table 11) [54]: L_{Aeq} (67.5-90.5), $L_{min.}$ (66.0-76.5) and $L_{max.}$ (68.0-82.5) for junction/roundabout/intersections; L_{Aeq} (69.5-88.1), $L_{min.}$ (60.8-76.5) and $L_{max.}$ (68.0-82.5) for roads; and L_{Aeq} (75.7-88.7), $L_{min.}$ (68.0-82.1) and $L_{max.}$(67.5-85.6) for loading parks (garage). Aerodynamic road traffic noise levels have the same range (Table 12). From the survey, it was observed that intra-city road traffic noise is more steady unlike those from intercity traffic. Also, it was observed that the higher noise levels, on the whole, were generated by motorcycles and

tricycles. The fact that road traffic noise is steady along major intra city roads with cumulative noise levels and wide range use of horn by motorists which can increase the environmental noise climate of a city to a level as high as 95 dB makes road traffic noise more promising in the acoustic energy harvesting project in Nigeria. This is more promising particularly because of the in the purchase and acquisition of motorcycles and tricycles also known as *keke na pep* for transport business in Nigeria. McNulty [56], former adviser to WHO on noise and vibration had observed that the competitive climate of the motorcycle industry has obviated any possible noise reduction measures despite clarion calls reduce output noise levels of motorcycles.

4.3 Industrial/Occupational Noise

Occupational noise levels that vary between 101 and 127 dB were measured in the 27 industries that vary in activities (Table 13). Table 14 shows the measured noise levels and indices, generated by a 63 kVA caterpillar power generator, as a function of distance. $L_{max.}$, equivalent continuous noise level, L_{eq}, and day-night levels vary from 88.0-60.0 dB, 88.0-60.0 dB and 98.0-70.0 dB, respectively, for the distances indicated. Background and ambient noise levels as high as 68.5 dB and 131.0 dB, respectively, are summarized in (Tables 15 and 16) [28,57]. This corresponds to the highest noise power of $10^{1.1}$ W. Also, industrial or occupational noise is promising in the acoustic energy harvesting project in Nigeria except its intermittence and the fact operating period of most industries is between the hours of 8.00 and 17.00, Monday to Friday.

4.4 Outdoor Noise

Maximum outdoor noise measurements at various locations (Table 17) show noise levels for indoor/outdoor as high as 46.5 dB(A)/75.0 dB for quiet/noisy periods. This gives noise power of 0.00000005 W/0.000032 W for quiet/noisy periods.

4.5 Household/Indoor Noise

Household noise spectra presented (Figur. 3) is for water flowing into WC tank; frying; water running into a bath; flushing of WC toilet; grinding in the kitchen and during power changeover for TV and radio receivers. L_{max}. As high as 60 dB

corresponding to noise power of 10^{-6} W (1 μW) during power changeover for radio receiver was obtained [30].

Generally, noise levels measured in rooms with windows open were higher than the corresponding values obtained when windows were closed by about 5-10 dB. Also, noise levels and noise power obtained in the study involving various acoustical (noise) measurements in Nigeria are higher than those used as input for AEHs elsewhere. For example, data obtained from measurements of noise levels and indices at different sites in Nigeria which are higher than those obtained in noise measurements in Alexandria, Egypt and elsewhere in the study of AEH lend credence to this assertion. Therefore, the noise power obtained in the wide range of acoustical/noise measurements in Nigeria will produce higher efficiencies than those reported in literature which are (Table 4) [23,40]: 0.66 pW-30 mW for piezoelectric based AEH at resonant frequencies of 146 Hz-6.7 kHz and 1.5 mW-1.96 mW for electromagnetic based power harvester at resonant frequencies between 143 Hz and 470 Hz as well as triboelectric nanogenerators (TRENGs) at resonant frequencies in the range of 20 Hz-1000 Hz with maximum output power of 7 W/m^2 at 170 Hz and 115 dB.

Existing literature on AEH has so far been concerned only with results of road traffic noise surveys. The addition of the findings from data on road traffic noise and other noises in Nigeria to the body of knowledge in the emerging area of AEH and the possibility of obtaining higher efficiencies, shows the viability of AEH in Nigeria; and will therefore open a new window of research in AEH in this part of the world. This is so notwithstanding the limitations of this study which are: intrusive noise during measurements; reflections from hard surfaces; wide range of conditions of the measurement sites being open, congested or closely built-up, error in the determination of road traffic composition and volume, and uncertainty in the measurement of the distance between the aircraft and microphone caused by the occasional disruption by staff of Federal Aviation Authority (FAA).

5. OTHER PROSPECTS

Further, there is hope for the acoustic energy project in Nigeria. This assertion is predicated upon the following:

5.1 Availability and Market for PS Audio Noise Harvesters

PS audio noise harvesters convert all the noise into light and are now in the market. These devices, which have cumulative effect, convert air-conditioned (AC) line noise into light for cleaner power. All that is required is to simply plug the harvester into an AC outlet, and it begins converting unwanted noise into light. Many harvesters can be used simultaneously for even cleaner power. Any system will reap the benefits of the noise harvester.

5.2 High Environmental Noise Climate

Environmental noise climate in most cities in Nigeria is high with road traffic and industrial noise levels being reasonably steady over a period of time in a day with relatively high power (Tables 5, 6 and 9). This is so because of road traffic noise which composition is dominated motorcycles and tricycles (*keke na pep*) with high output noise levels and frequent use of horn by motorists. In most parts of South Eastern Nigeria, for example, road traffic noise dominates low frequency spectrum because of wide range use of low gear since most roads are bad and some of the cities are located on hills. Also, high noise levels emanate from worship centres such as churches and mosques, discothèques, markets, music shops and street traders advertising their goods.

5.3 Frequent use of Electric Generators

Power supply by the Power Holdings Company of Nigeria (PHCN) is far from being constant. Therefore, solar energy and electric generators are fast becoming good alternative sources of power supply. Frequent use of electric generators in Nigeria with high noise levels, occasioned by incessant power outage, is yet another incentive for the possibility of the noise- (sound-) energy conversion project in Nigeria.

5.4 Greater Use of Airconditioner

There is greater use of air conditioner by ministries and government agencies, political class, elites, business men and those who can afford them in Nigeria. This is so because, Nigeria, located in the tropics, has climate that is seasonally damp and very humid. For example, Sokoto in North West, Nigeria is the hottest State with an annual average temperature of 28.3°C.

The State had the highest recorded temperature of 47.2°C in the year 2010 - the highest in the country.

In Nigeria, the maximum daytime temperatures are a little below 40°C most of the year. Greater use of air conditioner will in Nigeria, therefore, attract the use of PS audio noise harvesters and make the noise- (sound-) energy conversion project in the country very attractive.

6. TECHNICAL PROBLEMS

There are some technical problems that need to be addressed/overcome in the quest for the conversion of noise energy into electrical energy, particularly, in Nigeria. Such problems are highlighted below.

6.1 Noise (or noisy) Farm

Noise farm is very important in the search for appreciable noise levels for acoustic energy harvesting in Nigeria. Expects will be needed to plan for the establishment of noise (or noisy) farms all over the country, ensure that adequate noise energy is generated for conversion to electrical energy. As at now, there may not be available manpower to plan and undertake any noise farm project.

6.2 Noise Collectors

Building noise collectors has been a challenge that should be surmounted the world over. How should noise from various sources be collected? Should dish be used and if yes what should be the size? How will the noise so collected be piped from the focus (focal point)? These and other questions need answers on how to collect or concentrate the noise (sound) energy in an attempt to convert it into electrical energy.

6.3 Reverberant Chambers or Rooms

Sine noise is to be harvested, we would need reverberant chambers or rooms rather than soundproof or anechoic chambers. Reverberant chambers or rooms are important as they enable incident sound to be involved in successive reflections in order to build the acoustic energy. In this case, materials such as non-acoustic panels are needed for padding the interior of the rooms. Again, there may not be experts to be used in the construction of such reverberant or echoic rooms necessary for the harvest of

enough acoustic energy for any meaningful energy conversion project.

6.4 Coupling of the Vibration Produced

The vibration produced by the noise or sound has to be necessarily coupled or channeled to the output from where it will be tapped as electrical energy. this technology requires special thin membrane or cantilever beams to actualize. They are made of piezoelectric crystals as a transducer mechanism. When the transducer is put under strain by the kinetic energy of the vibration a small amount of current is produced – piezoelectric effect. This, again, requires technical know-how which may be lacking.

6.5 Transmission and Storage

Transmission of the electrical power that has been obtained from acoustic energy to the load and storage device without losses is yet another technical problem that will greatly affect acoustic energy harvesting in Nigeria. As at now, all transmission lines in Nigeria are lossy as superconducting cables are not yet in use in this country [58]. The problem is that since noise or acoustic power is low, it cannot be transmitted to the load or storage device without becoming evanescent after being greatly attenuated. We need lossless medium for the transmission of acoustic power if the acoustic energy harvesting in Nigeria is to be feasible.

7. SOCIO-ECONOMIC OBSTACLES

Despite some prospects in harvesting electrical energy from noise in Nigeria, there are some socio-economic obstacles that have to be overcome. These socio-economic obstacles are highlighted hereunder.

7.1 Lethargy of Researchers

There is likely going to be lack of enthusiasm on the part of researchers on noise- (sound-) energy conversion project not only in Nigeria but the world over. This will result due to the fact that electrical power of only a fraction of watts is realizable in this project. It should be borne in mind, however, that no additional amount of electrical energy added to the system is small. It has been observed, and rightly too, that the ability of piezoelectric generators on such a small scale to generate electricity, is the main advantage of this method over electromagnetic

generators, especially when the generator is being developed to power microelectronic devices [34].

To increase the interest of researchers on AEH, Governments, agencies and individuals should be encouraged to sponsor researches on AEH. Apart from other incentives, researchers should be encouraged to delve into AEH by giving them grants and providing the enabling environment for them to conduct their research.

7.2 Lack of Patronage by Consumers

In this part of the world, and particularly Nigeria, people like to patronize big projects that have wide margin gain or benefits. Therefore, consumers may not see the need to patronize acoustic energy harvesting projects that will only result in low electrical energy output. Efforts should be made by researchers to increasing the efficiency and cost effectiveness of AEHs to be able to attract consumers.

7.3 Lack of interest by Governments and Other Envisaged Sponsors

Governments and anticipated sponsors of acoustic energy harvesting projects may not be interested and forthcoming. They may likely see the project as not viable and unnecessary. Governments and sponsors should be encouraged to show interest and participate in the project. After all, the beauty of research is in producing positive results, no matter how little, that will, in future, completely impact on the society positively. Governments and sponsors should be encouraged researches more on acoustic energy harvesting. It should be made clear to them that dividend of research efforts is not at the early stage. After all, this is barely five years of serious research on AEH.

7.4 High Cost of Acoustic Energy Harvesting

Although annually generated electricity from acoustic energy will be relatively small, the total investment cost in dollars, I, and the fixed charge rate, F (equation 10) will be very high. This is because exchange rate is very high and Nigerian currency (Naira) can buy only very little commodity, especially outside the country. This is considered a great severe setback for the acoustic energy harvesting project in Nigeria. With increased sponsorship and research on

AEH, acoustic energy harvesting is expected to be more cost-effective.

8. CONCLUSION

This study has appraised global energy demand, highlighted sources of energy and their drawbacks. Levels and power of various environmental noises in Nigeria from analysis of data obtained from *in situ* and recorded measurements, analysis and re-examination of some existing data, typical harvesting or conversion efficiency of acoustic energy and cost effectiveness of AEH project have been presented. Findings show that noise sources in Nigeria produce output power as high as 0.36 mW for road traffic, 0.63 mW in the homes, 0.4 mW for aircraft and 12.59 W for industry, which can power microelectronic components, light LEDs and power other devices in this era of wireless communication and internet of things (IoT). These values are higher than those applied as input to AEHs in other countries of the world. At this stage, therefore, it is clear that acoustic energy harvesting in Nigeria has prospects as is viable. Technical problems and socio-economic obstacles to be encountered in this quest and recommendations to overcome such obstacles have been highlighted.

COMPETING INTERESTS

Author has declared that no competing interests exist.

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