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Determination and Comparison of CO_2 and Air Pollutants Emitted From the Exhaust Gas of Selected Electric Generators

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ABSTRACT: The study is aimed at providing information on the composition of the exhaust gas and concentration of air pollutants that are generated by different commonly used electricity generators in an average Nigerian household. The generators used for this study were a 0.7 kVA petrol engine, a 2.5 kVA petrol engine and an 8.8 kVA diesel engine. The gases include: CO_2, CO, SO_2, NO_2, NO, O_3, Total Volatile Organic Compounds (TVOC), Total Suspended Particles (TSP) and respirable and inhalable particulates ($PM_{2.5}$ and PM_{10}). The mean concentrations of the air pollutants measured for 0.7, 2.5 and 8.8 kVA generators respectively were as follows: NO had a value of 14.84, 15.8 and 21.84 ppm, NO_2 had a value of 6.44, 4.14 and 5.54 ppm, NOx had a value of 21.27, 19.94 and 27.37 ppm, The mean concentration of the air pollutants recorded for 0.7, 2.5 and 8.8 kVA generators includes: 98.0, 60.24 and 0.00 ppm for SO_2; 1006.67, 1391.54 and 69.80 ppm for CO; 1000.00, 1266.67 and 1733.34 ppm for CO_2; 62.67, 362.34, 80.67 µg/m^3 for O_3 respectively. The mean value for TSP, PM_{10} and $PM_{2.5}$ were 844.57, 1288.57 and 1249.00 µg/m^3; 510.80, 763.04 and 760.74 µg/m^3; and 333.77, 525.54 and 488.27 µg/m^3 for 0.7 kVA, 2.5 kVA and 8.8 kVA generators respectively. Due to the high risk of health hazards and ecological impacts associated with the air pollutants, it is advisable to switch to alternative sources of electricity that are clean and environmentally safe.

Keywords: Air pollutants; carbon (IV) oxide; diesel engine; exhaust gas; petrol engine.

تحديد ومقارنة غاز ثاني أكسيد الكربون وملوثات الهواء المنبعثة من عادم غاز المولدات الكهربائية المختارة

أوراكبونو.ه أوبيماتا و أوشينا كريستيان أوهابويكي

الملخص: تهدف الدراسة إلى توفير معلومات عن تكوين غاز العادم وتركيز ملوثات الهواء التي يتم إنشاؤها بواسطة مولدات كهربائية مختلفة شائعة الاستخدام في منزل نيجيري. المولدات المستخدمة في هذه الدراسة هي :محرك بنزين بقدرة مقدارها 0.7 كيلو فولت أمبير ومحرك بنزين بقدرة مقدارها 2.5كيلو فولت أمبير ومحرك ديزل 8.8 كيلو فولت أمبير .تشمل الغازات ؛ CO_2 ، CO ، SO2 ، NO_2 ، NO ، O_3 ، إجمالي المركبات العضوية المتطايرة (TVOC) ، إجمالي الجسيمات العالقة (TSP) والجسيمات القابلة للتنفس والاستنشاق ($PM_{2.5}$ و PM_{10})). تم قياس متوسط تركيزات ملوثات الهواء للمولدات 0.7 و 2.5 و 8.8 كيلو فولت أمبير على التوالي كما يلي ؛ NO_2 بقيمة 14.84 ، 15.8 و 21.84 جزء في المليون ، NO_2 بقيمة 6.44 ، 4.14 و 5.54 جزء في المليون ، أكاسيد النيتروجين كانت بقيمة 21.27 ، 19.94 و 27.37 جزء في المليون ، متوسط تركيز ملوثات الهواء المسجلة للمولدات 0.7 و 2.5 و 8.8 تشمل مولدات kVA: 98.0 و 60.24 و 0.00 جزء في المليون لثاني أكسيد الكبريت ؛ 1006.67 و 1391.54 و 69.80 جزء في المليون لغاز ثاني أكسيد الكربون ؛ 1000.00 و 1266.67 و 1733.34 جزء في المليون ل CO2 ؛ 62.67 ، 362.34 ، 80.67 ميكروغرام / م^3 لـ O_3 على التوالي .كانت القيمة المتوسطة لـ TSP و PM_{10} و $PM_{2.5}$ هي 844.57 و 1288.57 و 1249.00 ميكروغرام / م 3 ؛ 510.80 و 763.04و 760.74 ميكروغرام / م^3 ؛ و 333.77 و 525.54 و 488.27 ميكروجرام / م^3 لمولدات 0.7 كيلو فولت أمبير و 2.5 كيلو فولت أمبير و 8.8 كيلو فولت أمبير على التوالي .نظرًا لارتفاع مخاطر المخاطر الصحية والتأثيرات البيئية المرتبطة بملوثات الهواء ، يُنصح بالانتقال إلى مصادر بديلة للكهرباء نظيفة وآمنة بيئيًا.

الكلمات المفتاحية: ملوثات الهواء؛رابع أكسيد الكربون ؛ محرك ديزل؛ غاز العادم؛ محرك بنزين.

1. Introduction

The atmosphere is a collection of gases, particles, and clouds surrounding the earth, comprised of gaseous mixtures in various proportions [1]. In the troposphere, these gases include nitrogen, oxygen, carbon dioxide (CO_2), argon, water vapour, neon, helium, and so on [1]. These gases at their natural atmospheric concentrations do not pose any danger to the environment. Human activities and some natural occurrences like volcanic eruptions, however, alter the composition, while introducing other gases and particulates which are not naturally present in the atmosphere and are harmful to man and his environment [1,2]. The various human activities which cause an increase in the amounts of CO_2 and other air pollutants include: power plants running with fossil fuels, industrial activities, petroleum exploration and exploitation, mineral mining and processing, house warming, cooking, electricity generators and transportation [2,3]. Amongst all of them, one of the factors contributing most to air pollution is electricity generators. The challenge of power generation in Nigeria over the years is very burdensome. The nation is experiencing a severe electric crisis when compared to other countries; presently the nation generates about 4,500 megawatts of power to serve a population that is over 180 million, as against an estimated 30,000 that is required (which is to say it only generates 15% of the total electrical power that is needed by the population). This has resulted in a high percentage of the Nigerian population shifting to alternative electricity using electric power generators. In 2009, over 6 million Nigerians owned a power generating set, excluding the commercial and the industrial sector [4,5]. Due to the increase in industrialization and the usage of fossil fuels for power generation and other purposes, there has been an increase of over 75% in the atmospheric carbon dioxide and other corresponding changes in the composition of air [6,7]. As a result of this, there has been contamination of the air, water and soil which subsequently interferes with human health, the standard of living, and natural functioning of the ecosystem. [8-13]. CO_2 is a greenhouse gas of great concern, contributing greatly to global warming [14]. This is so because of its rate of increasing abundance in the atmosphere. CO_2 in the atmosphere increased from 290 ppm in the 19th century to slightly above 320 ppm in 1970 [3, 15]. The IPCC report of 2008 stated that the accumulation of CO_2 and many greenhouse gases in the atmosphere has the potential to significantly change patterns of climate; temperature and precipitation including regional weather events like hurricanes, flooding, and drought [16]. There is evidence that the global rate of sea-level rise is increasing (3.36 ± 0.41 mm/year from 1993 to 2007), mainly resulting from ocean expansion due to thermal heating [3, 16].

Greenhouse gases and air pollutants released due to fossil fuel burning include: CO_2, CH_4, CO, SO_2, NO_2, NO, hydrocarbons, ozone (O_3), and respirable and inhalable particulates ($PM_{2.5}$ and PM_{10}), etc., [7, 17-18]. High amounts of greenhouse gases and air pollutants in the atmosphere are detrimental to man and the environment [1]. The continuous rise in the amount of CO_2 and other greenhouse gases in the atmosphere is said to be the cause of the notable rise in atmospheric temperature, leading to climate change being observed [19]. The environmental effects of climate change have many adverse effects on man and other living things on earth [3].

The study is aimed at providing information on the composition of the exhaust gasses and the concentration of air pollutants that are generated by different commonly used electricity generators in an average Nigerian household in a time dependent nature, and to compare the level of pollutants contributed by the different electricity generating sets. This study will also contribute to the existing body of knowledge in the aspect of air pollution in Nigeria while the country is aiming to achieve the United Nations Sustainable Development Goals, numbers three (good health and well-being), six (clean water and sanitation), seven (affordable and clean energy) and thirteen (climate action).

However, seeing the effects of increased CO_2 and other air pollutants in the atmosphere, and the need to continue energy generation using fossil fuels, it is important to balance energy generation using fossil fuels with preserving the climate for human existence on earth.

2. Materials and methods

2.1 Experimental design

In the course of this study, an experiment was carried out using electric generators of different sizes or capacities. These generators were a 0.7 kVA BIRLA YAMAHA petrol engine generator of model: LG1000, 2.5 kVA TIGMAX electronics (constant) petrol generator of model TH3000 and the 8.8 kVA YOSHITA diesel generator of model S195NM. It was necessary to include the 0.7 kVA generator as a different class of generator due to the fact that the petrol is often mixed with engine oil (lube oil) in the proportion of 1 L: 20 ml of petrol/ engine oil mixture. This could have an impact on the amount of pollutants being released by the exhaust pipe of this generator. The 2.5 kVA generator has a different compartment for the engine oil unlike the 0.7 kVA generator; while the 8.8 kVA generator operates using diesel as its fuel.

Various air quality monitoring devices designed for measuring air pollutants released from hot gases were used to analyse the amount of CO_2 and other air pollutants being released from these generators. These air pollutants include: CH_4, CO, SO_2, NO_2, NO, hydrocarbons, ozone (O_3), and respirable and inhalable particulates ($PM_{2.5}$ and PM_{10}). First the 0.7 kVA generator was put on and allowed to run for 10 minutes. This was to allow the engine of the generator reach the standard operating temperature, hence achieve combustion efficiency and maintain a consistent emission rate. Afterwards, the air quality monitoring devices were used to measure the amount of CO_2 and other air pollutants emitted by the generator. These measurements were done on the exhaust gas directly coming from the exhaust pipe of the generator while it was running. The probes of these instruments were placed $\frac{1}{4}$" inside the exhaust pipe of the electric generators in order to obtain accurate and reliable results. This was done in order to avoid any external influence on the readings of the instruments. The generator was in operation for 30 minutes and the readings were taken per minute. The ambient values of the parameters of interest were taken before putting on the generators. This was to establish a background of the values of the air pollutants in the environment before the operation of the generators. The experiment was repeated using the 2.5 kVA generator and 8.8 kVA generator. The sampling time for all the experiments with the different classes of generator was the same.

2.2 Materials and validity/reliability of instrument

Reliably calibrated instruments were used to measure the various air quality parameters of the exhaust gas of the electric generators. These devices are suitable for these experiments because they were designed to read values of CO_2 and other air pollutants at high temperatures. The values for SO_2, NO, NO_2, NO_x, CO, CO_2, O_2 and ambient temperature were taken using the Madur Electronics Hot Flue Gas Analyzer of model GA- 21 plus. O_3 values were taken using the ω- Senser Ozone Gas Detector. TVOC values were taken using the ω- Senser TVOC Gas Detector. CH_2O values were taken using the ω- Senser Formaldehyde Gas Detector. $PM_{2.5}$ and PM_{10} values were taken using the Hinaway Handheld Air Tester of model CW- HAT200. Wind speed and the exhaust gas speed were measured using the Schoolab Cup Anemometer.

In order to validate the instruments, all the instruments were calibrated at the site of the experiment by an air quality monitoring expert specialized in using these instruments. All measurements and operation of the instruments were carried out by the air quality monitoring expert. For the Madur Electronics Hot Flue Gas Analyzer of model: GA-21 plus, the instrument hose was first attached to the connector Gas, and the plug from the probe holder was connected to the socket Probe. The outlet hose from the filter was attached to the connector Inlet. It was ensured that the gas flow from the base of the analyser was free from obstructions. Before the instrument was switched on, the filter elements were checked and cleaned accordingly. Immediately after switching the instrument on, the instrument was calibrated by allowing it to carry out the initial calibration automatically for 2 minutes. It was ensured that the probe of the instrument was not in the exhaust pipe of the generator during the initial calibration process. The initial calibration is of basic importance for measurement correctness and this process was not interrupted until completion. During the time of initial calibration, the oxygen sensor was calibrated to 20.95 % in ambient air, and other sensors (CO, NO, NO_2, CO_2, SO_2, etc) were zeroed.

After the initial calibration was completed, the instrument was ready for use. To take the readings of air pollutants being emitted by the generators, the probe of the instrument was placed $\frac{1}{4}$" into the exhaust pipe of the generators. The experiment was carried out using each of the generators and this process was replicated three times.

2.3 Statistical analysis

Various statistical methods of data analyses were used to analyze the data that was obtained. The results were summarized to show mean values, standard deviation, standard error etc. Column charts and line graphs were used to present results. To achieve all these, Microsoft Excel Package 2016 was used.

3. Results and Discussion

The results of the study are presented in the figures below. The mean values of pollutants emitted are presented in bar charts (Figure 1 to 5), while the instantaneous release of pollutants during the time of the experiment are presented in line graphs (time series) as seen in Figure 6 to 10.

3.1 Mean concentration of pollutants

Figure 1a shows the mean values of ambient temperatures during the time of the experiment with the different generators. The mean ambient temperature during the operation time of the 0.7 kVA generator was 31.50 ^oC, while it was approximately 31.40 ^oC during the operation of 2.5 kVA generator and the mean ambient temperature during the operation of the 8.8 kVA diesel generator was 32.60 ^oC.

Figure 1b shows the mean exit gas temperature during the time of operation of the generators. The mean exit gas temperature for 0.7 kVA, 2.5 kVA and 8.8 kVA generators were 40.50 ^oC, 54.50 ^oC and 44.30 ^oC respectively. It can be seen that the 2.5 kVA generator recorded the highest exit gas temperature which was higher than that of 8.8 kVA diesel generator. This could be due to the fact that the 2.5 kVA generator engine does not have a good cooling system whereas the 8.8 kVA diesel engine generator uses a radiator as a cooling system which could have resulted in the lower temperature observed.

Figure 1c illustrates the mean exit gas speed for the different generators. The 2.5 kVA generator had the lowest exit gas speed 3.68 ms^{-1}, the 0.7 kVA generator had 3.87 ms^{-1} as its exit gas speed, while the 8.8 kVA generator recorded the highest exit gas speed of 8.85 ms^{-1}. This could be due to the fact that the engine size/capacity of the 8.8 kVA generator is much larger than that of 0.7 kVA and 2.5 kVA generators. Also, a larger volume of air and fuel is released into the combustion chamber of the 8.8 kVA generator than into those of the 0.7 and 2.5 kVA generators. Again, the level of pressure achieved by the compression of the air fuel mixture by the piston and valves movement is higher in the 8.8 kVA generator than is the with the 0.7 and 2.5 kVA generators.

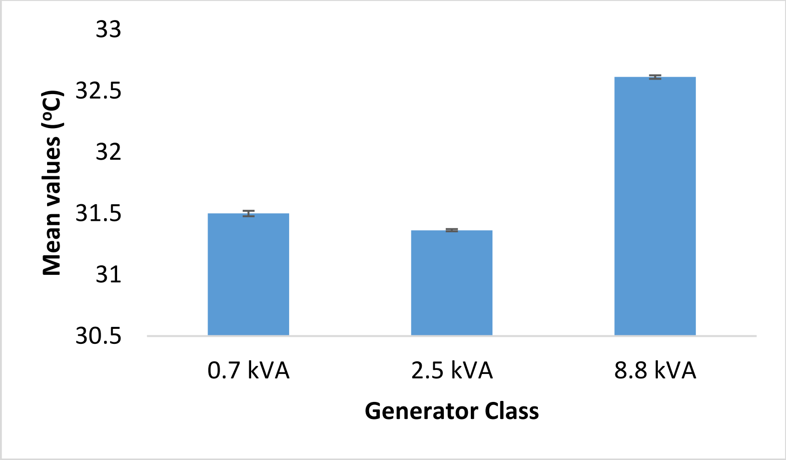

Figure 1a. Mean ambient temperature (±1 SE).

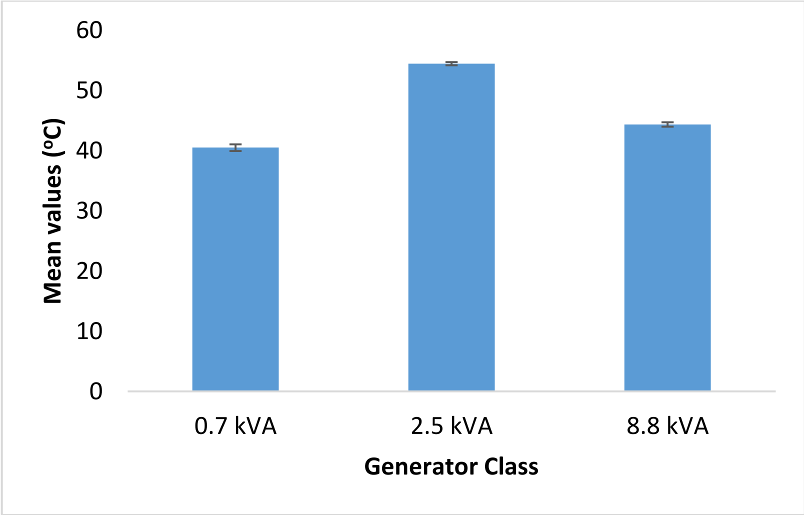

Figure 1b. Mean exit gas temperature (±1 SE).

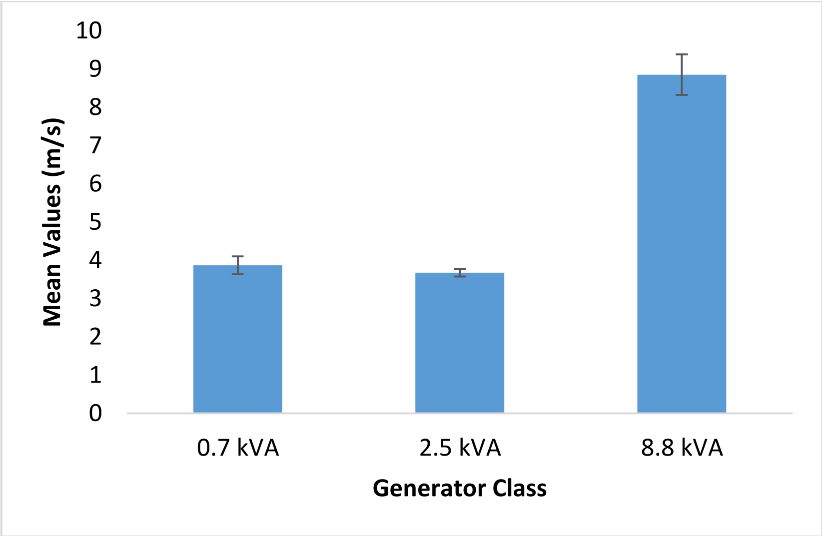

Figure 1c. Mean exit gas speed (±1 SE).

Figure 2a illustrates the mean concentration of SO_2 being emitted by the generators. The figure shows that the 0.7 kVA generator emitted the highest amount of SO_2 with 100.50 ppm per minute, while the 2.5 kVA generator emitted 60.20 ppm per minute and the 8.8 kVA generator did not emit SO_2 within the time of the experiment. The fact that the 8.8 kVA generator did not emit SO_2 could be related to the type of fuel (diesel) used by the engine, which suggests that the diesel used to operate the 8.8 kVA generator could have been efficiently desulphurized. That the 0.7 kVA generator emitted the highest level of was SO_2 probably due to the fact that the petrol used in operating the generator was mixed with engine lubricant oil, as stated in the 'Materials and methods' section. Petrol on its own contains a reasonable amount of sulphur or its compounds (as high as 1000.00 ppm or more) depending on the type of crude oil it was derived from and the level of purification done after the refining process. The engine lubricant oil mixed with the petrol used in operating the 0.7 kVA generator also contains sulphur.

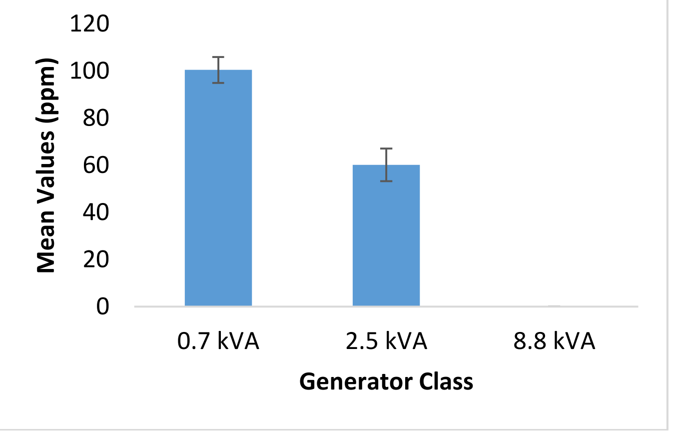

Figure 2a. Mean concentration of SO_2 emission (±1 SE).

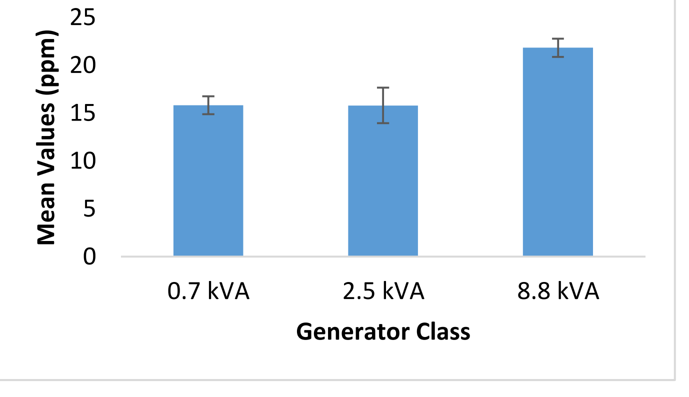

Figure 2b. Mean concentration of NO emission (±1 SE).

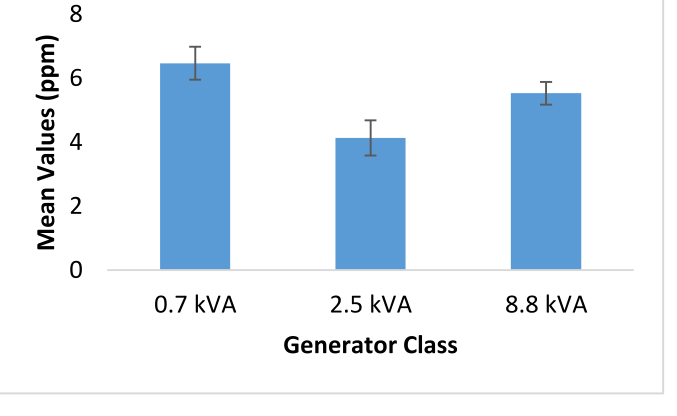

Figure 2c. Mean concentration of NO2 emission (±1 SE).

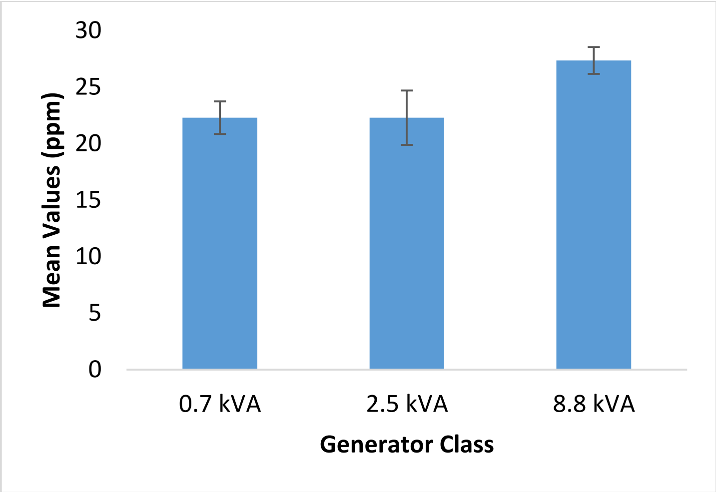

Figure 2d. Mean concentration of NOx emission (±1 SE).bars.

All these sources of sulphur end up introducing a high sulphur content into the combustion chamber of the generator, which could have resulted in the level of SO_2 being emitted by the generator, as observed. Note that the combustion product of sulphur or any of its compounds is SO_2 and in some cases SO_3. In China, studies revealed that air pollutants such as SO_2 may be a major contributing factor to the increase in the risk for lung cancer mortality [20]. Inhalation of SO_2 is associated with increased respiratory symptoms and disease, difficulty in breathing, and premature death [21,22]. Also, it has been established that the concentration of SO_2 in the atmosphere can significantly influence habitat suitability for plant communities, as well as animal life especially due to the formation of acid rain and atmospheric particulates [23].

Figure 2b illustrates the mean concentration of NO being emitted by the generators. The figure shows that the 0.7 kVA and the 2.5 kVA generators emitted an average of 15.83 ppm and 15.80 ppm per minute respectively; while the 8.8 kVA diesel generator had an average value of 21.83 ppm per minute, this being the highest emission of NO for all generators.

Figure 2c illustrates the mean concentration of NO_2 being emitted by the generators. The figure shows that the 0.7 kVA generator emitted the highest with 6.50 ppm per minute, followed by the 8.8 kVA generator (5.50 ppm) per minute, then the 2.5 kVA generator (4.10 ppm) per minute. The fact that these generators emit NO_2 is of great concern due to the fact that its existence in the atmosphere could lead to the formation of ground level ozone which is harmful to man. It also leads to the formation of photochemical smog, which can restrict visibility and affect human health. High levels of NO_2 are harmful to vegetation, can fade and discolour furnishings and fabrics, and react with surfaces.

Figure 2d illustrates the mean concentration of NO_X being emitted by the generators. The figure shows that the 8.8 kVA generator emitted the highest amount of NOx (27.40 ppm per minute) on the average, while the 0.7 kVA and 2.5 kVA models emitted equal amounts of NOx (22.30 ppm per minute). NOx is described as the sum total of the concentrations of NO and NO_2. The nitrogen oxides, when released into the atmosphere, have many adverse effects on the environment and human health, as stated in the explanation for NO_2 emissions. This is why it is of concern that these generators used by an average home in Nigeria emit these nitrogen oxide pollutants.

Figure 3a illustrates the mean concentration of CO being emitted by the generators. The figure shows that the 2.5 kVA generator emitted the highest average value of CO (1391.50 ppm per minute), followed by 0.7 kVA generator (1016.20 ppm per minute), while the 8.8 kVA generator emitted the least amount of CO (69.80 ppm per minute).

CO is a product of incomplete combustion. Hence it can be suggested that the 8.8 kVA diesel generator emitted the least amount of CO due to the fact that diesel engines normally undergo a more complete combustion than petrol engines.

The emission of CO into the environment is particularly dangerous due to the fact that it is a silent killer, since it is an odourless and colourless gas which is very difficult to detect without an adequate device. In Nigeria, there have been several cases of families who all died as a result of CO poisoning. A number of these cases were reported to have been in homes using mostly the 0.7 kVA and 2.5 kVA generators overnight in a poorly ventilated environment. This is of great concern due to the fact that almost every home has and uses either the 0.7 or 2.5 kVA generators. Also, in numerous settlements, many families live in clusters within a compound which makes the use of such generators dangerous; however, they are still used, the normal effect in many such compounds being that one man’s generator emissions becomes a nuisance to his neighbour and vice versa. CO is highly toxic and it has the ability to combine with haemoglobin in the red blood cells to produce carboxyhemoglobin. Upon inhalation, the compound takes up the space in haemoglobin that normally transports oxygen, but is not efficient in delivering oxygen to the tissues of the body [24]. According to studies, a concentration of up to 667 ppm can result in the conversion of about 50% of the body’s haemoglobin to carboxyhemoglobin [22, 25]. The concentrations that were recorded in 0.7 and 2.5 kVA generators were higher than 667 ppm, which is the permissible limit of CO in the atmosphere. This implies that in a situation where there is poor ventilation, the generators when operated over a long period of time can pose sufficient risk that the individuals can be in life threatening situations. This might either result in seizure, coma or death. These effects can occur over short durations, as the absorption of carbon monoxide is cumulative, with a half-life of up to 5 hours in fresh air [26].

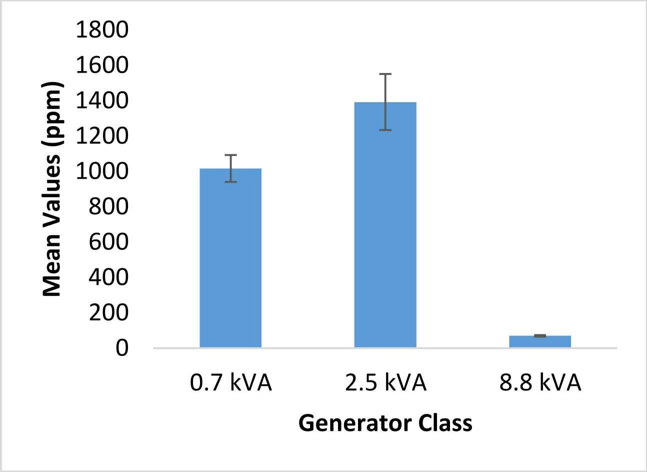

Figure 3a. Mean concentration of CO emission (±1 SE).

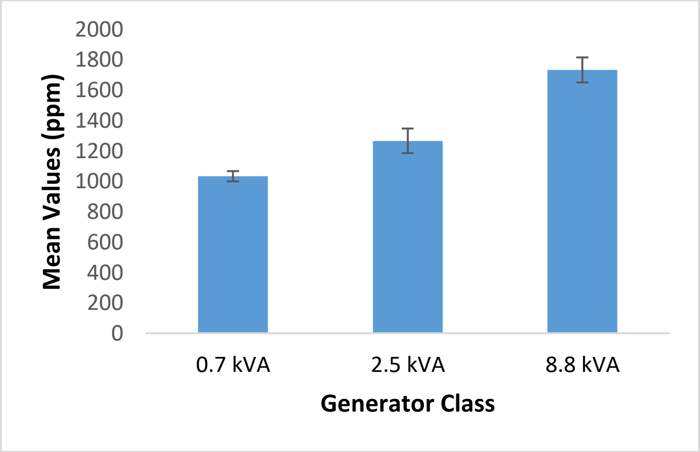

Figure 3b. Mean concentration of CO_2 emission (±1 SE).

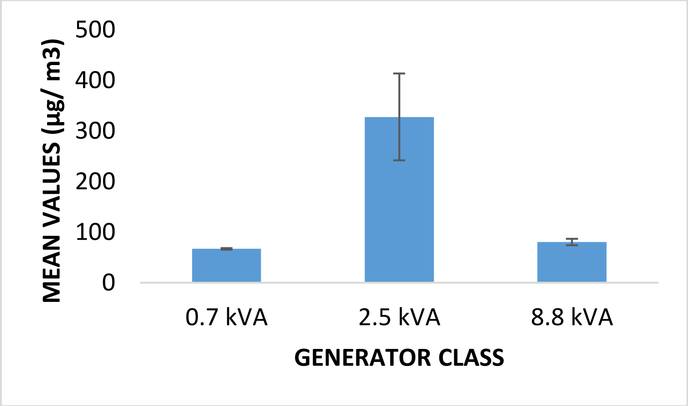

Figure 3c. Mean concentration of O_3 emission (±1 SE).

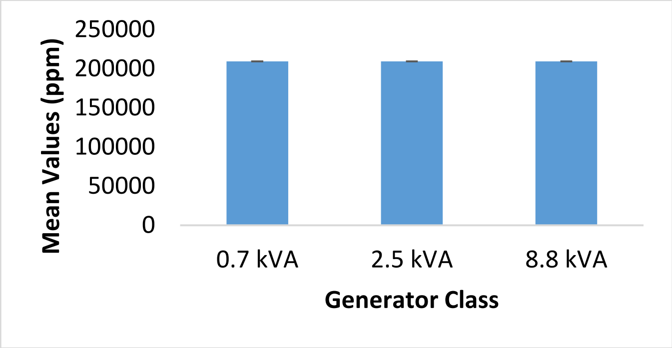

Figure 3d. Mean concentration of O_2 emission (±1 SE).

Figure 3b illustrates the mean concentration of CO_2 emitted by the generators. The figure shows that the 8.8 kVA generator emitted the highest average amount of CO_2 per minute (1733.30 ppm), followed by 2.5 kVA generator (1266.70 ppm), while the lowest was from the 0.7 kVA generator (1033.30 ppm). CO_2 emission is a product of complete combustion, hence it can be deduced that the 8.8 kVA diesel generator had the highest rate of complete combustion, leading to a higher value in the emitted CO_2.

From the observations in the results, it can be inferred that the level of emission being released by an electric generator can be dependent on the type of fuel used and the purity of the fuel, among other factors such as the engine combustion efficiency, air-fuel mixture, compression rate of the piston and valves of the engine, etc.

Figure 3c illustrates the mean concentration of O_3 being emitted by the generators. The figure shows that the 2.5 kVA generator emitted the highest average amount of O_3 per minute (327.60 µg/m^3), followed by 8.8 kVA generator (80.70 µg/m^3), while the least was from the 0.7 kVA generator (67.00 µg/m^3).

These electric generators emit ground level ozone O_3 in high amounts when in use and this could be detrimental to human health, as these generators are always operated in homes, particularly in places very close to the living rooms, and in most cases the areas are poorly ventilated. Breathing ground level O_3 can cause a variety of health problems including chest pain, coughing, throat irritation and congestion. It can worsen bronchitis and asthma. It can also reduce lung function and inflame the lining if the lungs. It is also a greenhouse gas in the lower atmosphere (troposphere). It contributes greatly to global warming when present in the lower atmosphere or at ground level. It is also a component of smog. All these factors, and more, make ground level O_3 harmful and needing to be regulated.

Figure 4a illustrates the mean concentration of TVOC being emitted by the generators. The figure shows that the 0.7 kVA generator emitted the highest average amount of TVOC per minute (0.86 ppm), followed by the 2.5 kVA generator (0.53 ppm), while the 8.8 kVA generator did not emit TVOC at all.

The 8.8 kVA generator emitted zero TVOC due to the fact that the fuel used (diesel) has no volatile organic compounds unlike the fuel (petrol) used in the 0.7 and 2.5 kVA generators, which has many volatile components. In a situation in which some fuels that enter the combustion chamber of an engine do not burn at all, they are emitted at the exhaust pipe as volatile organic compounds VOCs. The sum total of the various volatile organic compounds emitted by the generators was detected as TVOC by the air quality monitoring device.

Figure 3d illustrates the mean concentration of O_2 being emitted by the generators. The figure shows that all the generators emitted equal average amounts of O_2 per minute (209500.00 ppm).

The volatile organic compounds, VOCs, when released in the atmosphere are harmful to human health. The TVOC, when it undergoes atmospheric oxidation, results in the production of secondary pollutants such as ground level ozone or peroxy acetyl nitrate [27]. Common components of VOCs are benzene, ethylene glycol, formaldehyde, toluene, xylene, etc. However, VOCs are pollutants of concern because long exposures to low levels of VOCs is reported to increase the risk of health problems. Exposure to VOCs worsens symptoms for asthmatic patients or people who are particularly sensitive to chemicals. Acute/short term exposures cause eye, nose and throat irritation, headaches, nausea, dizziness, etc. Chronic exposures to VOCs can cause cancer, liver and kidney damage and central nervous system damage. This is why it is needful to moderate the manner in which VOCs are released into the atmosphere.

Figure 4b illustrates the mean concentration of CH_2O emitted by the generators. The Figure shows that the 0.7 kVA generator emitted the highest average amount of CH_2O per minute (12.10 ppm), followed by 2.5 kVA generator (11.10 ppm), while the 8.8 kVA generator emitted the least (9.10 ppm).

Exposures to CH_2O can irritate of the skin, eyes, nose and throat. High levels of exposure can cause myeloid leukemia and some types of cancer such as cancer of the paranasal sinuses, nasal cavity and nasopharynx. It is therefore important to put a check on the release of CH_2O into the environment through the use of generators, as continuing with the practice of using these electric generators would increase the risk of the exposure of humans to this pollutant.

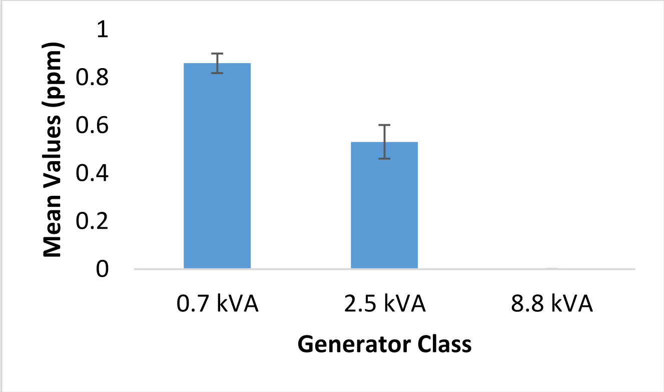

Figure 4a. Mean concentration of TVOC emission (±1 SE).

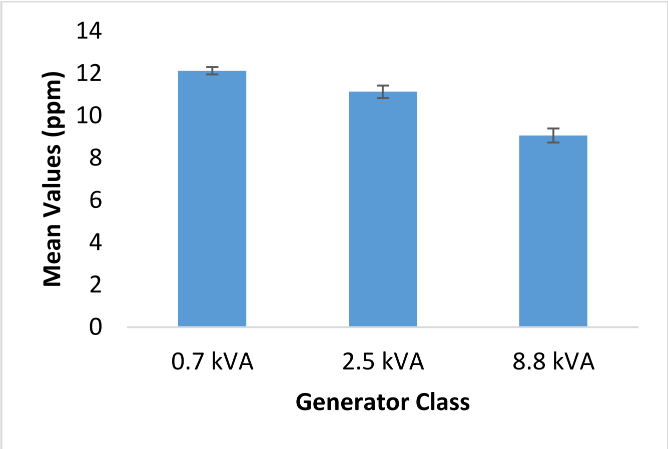

Figure 4b. Mean concentration of CH_2O emission (±1 SE).

Figure 5a illustrates the mean concentration of TSP being emitted by the generators. The Figure shows that the 2.5 kVA generator emitted the highest average amount of TSP per minute (1288.60 μg/m^3), followed by 8.8 kVA generator (12496.00 μg/m^3), while the 0.7 kVA generator emitted the least (873.30 μg/m^3).

TSP Total Suspended Particulate is a sum total of all the suspended particulate matter being emitted by the generators, in this case it includes the PM_{10} and the $PM_{2.5}$. The fact that the 2.5 kVA generator emitted the highest TSP could be related to its rate of incomplete combustion which made it to emit the highest amount of CO. This is because particulate matter is usually generated as a result of incomplete combustion. Also, the 8.8 kVA generator was second highest emitter of TSP due to the fact that its exit gas speed was highest among all the generators (more than double of the exit gas speed of the other generators). This implies that the volume of the exit (exhaust gas) and consequently, the volume of TSP it would release per time would be large.

It is important to note that suspended particulate matter can remain in the air for an extended of time and is a major component of air pollution and smog [22]. The size of the particles is responsible for the risk that it poses to the health of the environment. Particles with sizes below 10.00 μm in diameter are referred to as thoracic particles (PM_{10}), particles with sizes are below 2.50 μm in diameter are referred to as fine particles ($PM_{2.5}$) while particles with diameter less than 0.10 μm are known as ultrafine particles [28]. This particulate matter is very hazardous to human health because harmful contaminants bond to its surface through the process of adsorption. Some of these contaminants include heavy metals (such as lead, mercury, and cadmium among others) and organic compounds (such as polychlorinated biphenyls, dioxin, polycyclic aromatic hydrocarbons, and furans) and they can easily reach the deepest parts of the lungs, thereby resulting in respiratory ailments [22]. According to studies, ambient fine particulate pollution has been closely associated with an increment in the risk of cardiovascular diseases [29]. Long-term exposure to $PM_{2.5}$ is linked with an increase in the risk of cardiopulmonary mortality by 6–13% per 10 μg/m3 of $PM_{2.5,}$ and this leads to a reduction in the life expectancy of the population by about 8.6 months on average [30-33].

Exposure to particulates in the environment is harmful due to the fact that it leads to several health problems which include irregular heartbeat, aggravated asthma and decreased lung function. It also causes increased respiratory symptoms such as irritation of the airways, coughing or difficulty in breathing. It also contributes to the formation of acid rain and acidification of the oceans. It also plays a major role in global warming and climate change and its associated adverse effects. It can also have a great impact on forests, wildlife and coastal regions.

Figure 5b illustrates the mean concentration of PM_{10} being emitted by the generators. The Figure shows that the 2.5 kVA generator emitted the highest average amount of PM_{10} per minute (763.03 µg/m^3), followed by the 8.8 kVA generator (760.73 µg/m^3), while the 0.7 kVA generator emitted the least (532.77 µg/m^3). The reason for these differences are explained in Figure 5a above. PM_{10} is one of the major contributors to the effects attributed to TSP as described above.

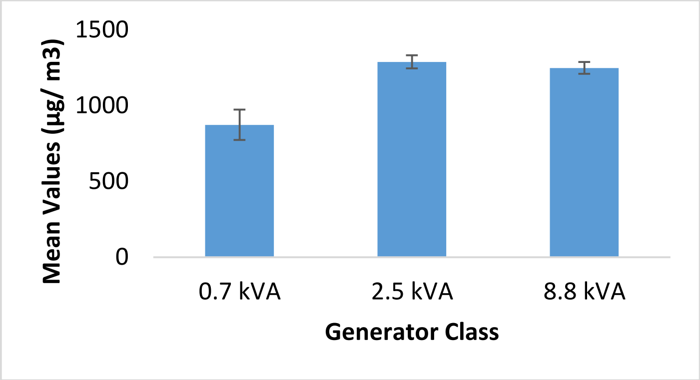

Figure 5a. Mean concentration of TSP emission (±1 SE).

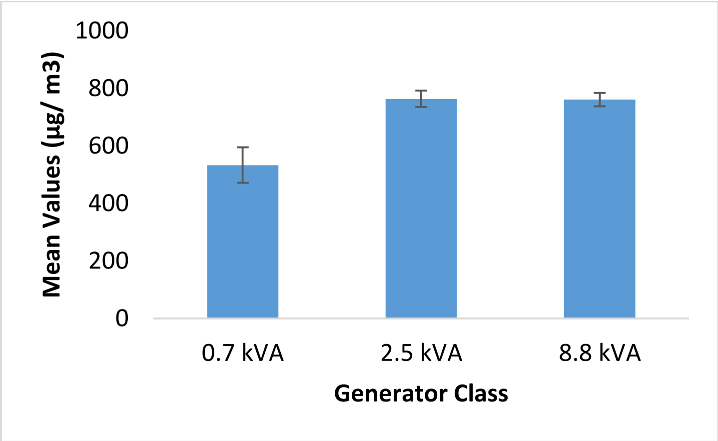

Figure 5b. Mean concentration of PM_{10} emission (±1 SE).

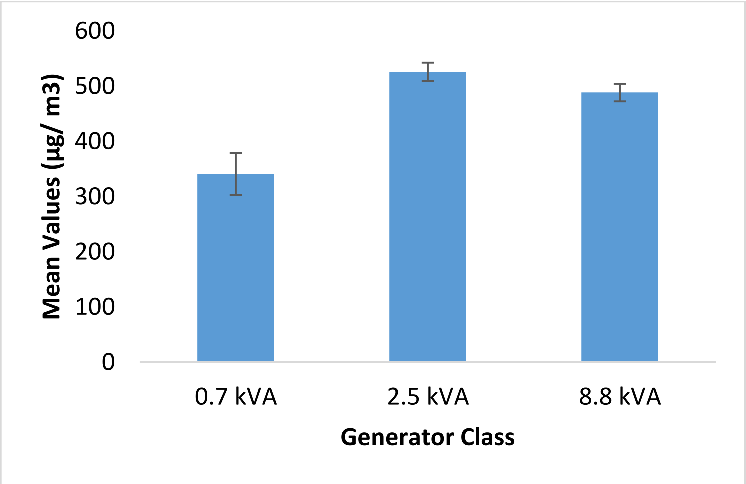

Figure 5c. Mean concentration of $PM_{2.5}$ emissions (±1 SE).

Figure 5c illustrates the mean concentrations of $PM_{2.5}$ being emitted by the generators. The Figure shows that the 2.5 kVA generator emitted the highest average amount of $PM_{2.5}$ per minute (525.53 µg/m^3), followed by the 8.8 kVA generator (488.27 µg/m^3), while the 0.7 kVA generator emitted the least (340.57 µg/m^3). The reason for these differences are explained in Figure 5a above. $PM_{2.5}$ is one of the contributors to the effects attributed to TSP as described above.

In Nigeria, health risks caused by uncontrolled emissions of pollutants into the environment have significant impact, and currently Nigeria has the highest burden of fatalities from air pollution in Africa and the fourth highest in the world with 150 deaths per 100,000 people attributable to pollution [34]. It is sad to note that an average Nigerian still depends on a generator for his daily electricity supply, and when the size of the population is multiplied by the amount of air pollutants generated by a petrol or diesel electricity generator, one can rightly say that we are the cause of the gradual deterioration of the earth's atmosphere.

1.1 Time series of pollutant emissions

Figure 6a illustrates the instantaneous release of SO_2 during the time of the experiment for all generators. The graph shows that the 8.8 kVA generator did not emit SO_2 during the period of the experiment. This could be associated with the type of fuel used (diesel), which suggests that the diesel used in this experiment could have been efficiently desulphurized to the required standard of less than 500.00 ppm. The trend of the graph shows that the emission of SO_2 by the 0.7 kVA generator had the highest peak at the 12-13th minute of the experiment. Also, it can be observed that the emission rate of SO_2 by the 0.7 kVA generator reduces with respect to the time of operation of the generator. This could be related to the improvement in the combustion efficiency of the generator, associated with increased engine temperature as the generator runs for a longer period of time. This means that the rate of emission of SO_2 is higher at the initial time of operation of the generator, when the combustion efficiency of the generator is lower, while the emission rate is reduced or lower when the generator is allowed to run for a longer time, thereby achieving a higher combustion efficiency. However, on the contrary, the SO_2 emission by the 2.5 kVA generator showed a different trend in which the concentration of SO_2 being emitted by the generator increased with time during the operation of the generator.

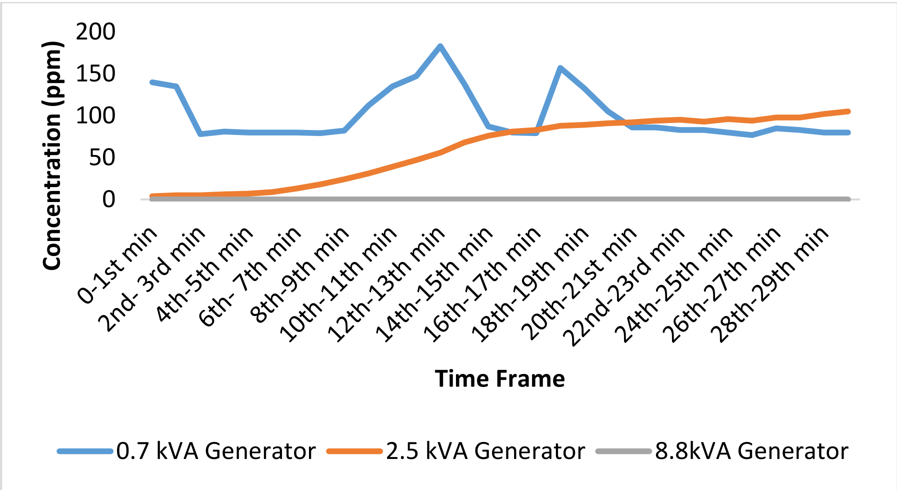

Figure 6a. SO_2 Emission time series.

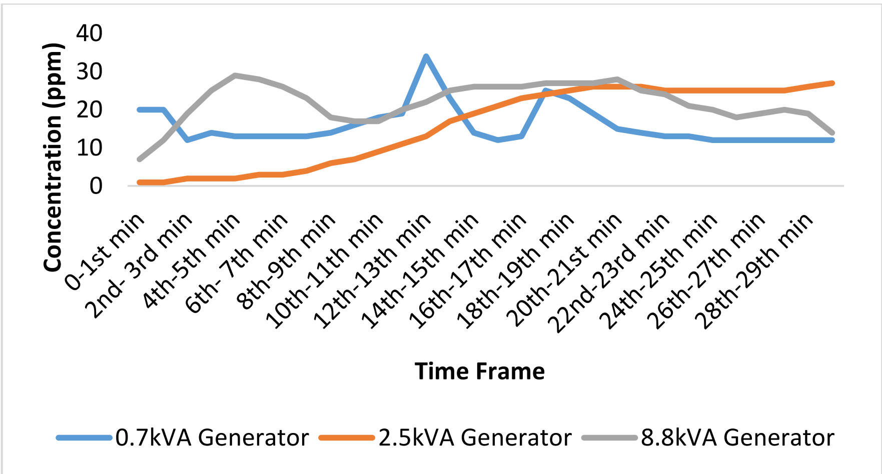

Figure 6b. NO Emission time series.

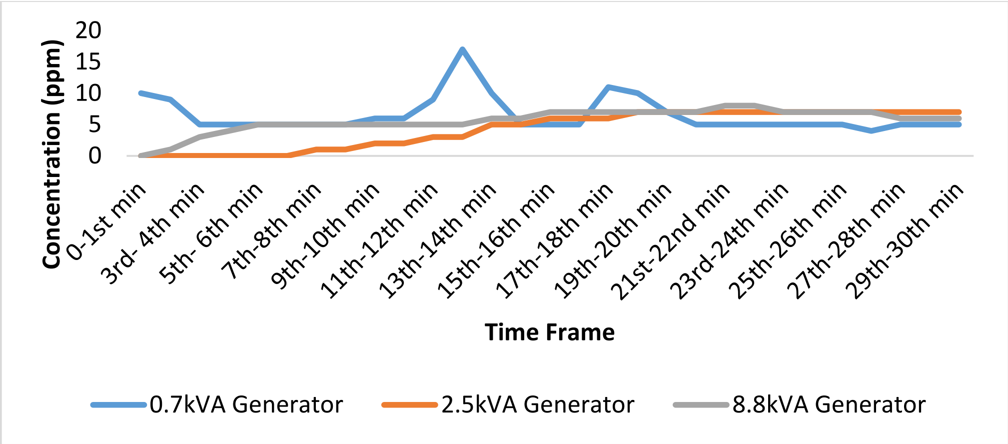

Figure 6c. NO_2 Emission time series.

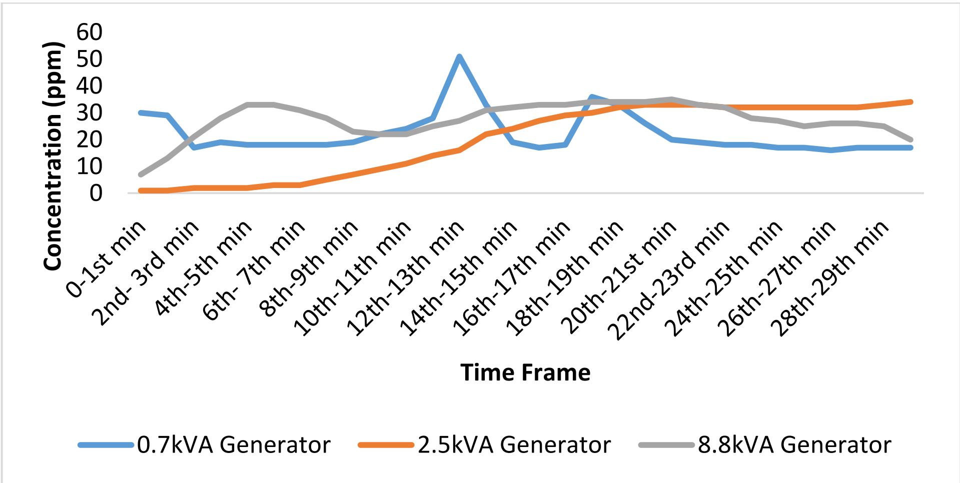

Figure 6d. NO_X Emission time series.

Figure 6b illustrates the instantaneous release of NO during the time of the experiment for all generators. The graph shows that the concentration of NO for the 0.7 kVA generator had the highest peak (34.00 ppm) at the 12 to 13th minute. The trend also shows that the concentration of NO being emitted by the generator reduces with respect to time of operation. The 2.5 kVA generator showed a different trend in which the concentration of the pollutant being emitted by the generator tended to increase with time of operation of the generator. The graph for the pollutant emission by the 8.8 kVA generator also shows a trend that tended to increase at the beginning, while sloping down or showing a reduction in the concentration of pollutant being emitted.

Figure 6c illustrates the instantaneous release of NO_2 during the time of the experiment for all generators. The graph shows that the concentration of NO_2 for the 0.7 kVA generator had its highest peak (17.00 ppm) at the 12th to 13th minute. Generally, the trend shows a reduction in the concentration of pollutant being emitted with respect to time. The 2.5 kVA on the other hand, shows a trend in which the concentration of the emitted pollutant tends to increase in general. Also, the graph for the 8.8 kVA generator shows a trend in which the pollutant concentration increased within the first 6 minutes and then remained approximately constant throughout the time of the experiment.

Figure 6d illustrates the instantaneous release of NO_X during the time of the experiment for all generators. The graph shows that the concentration of NO_X for all the generators shows a similar trend to that observed for NO and NO_2.

Figure 7a illustrates the instantaneous release of CO during the time of the experiment for all generators. The graph shows that the concentration of CO for the 0.7 kVA generator had the highest peak (2231.00 ppm) at the 12-13th minute of operation. Afterwards, the concentration started reducing with time. The 2.5 kVA generator on the other hand showed a trend in which the pollutant concentration increased with respect to time, while the 8.8 kVA generator showed a trend which remained approximately constant, mostly varying between 53.00 and 76.00 ppm within the time of the experiment.

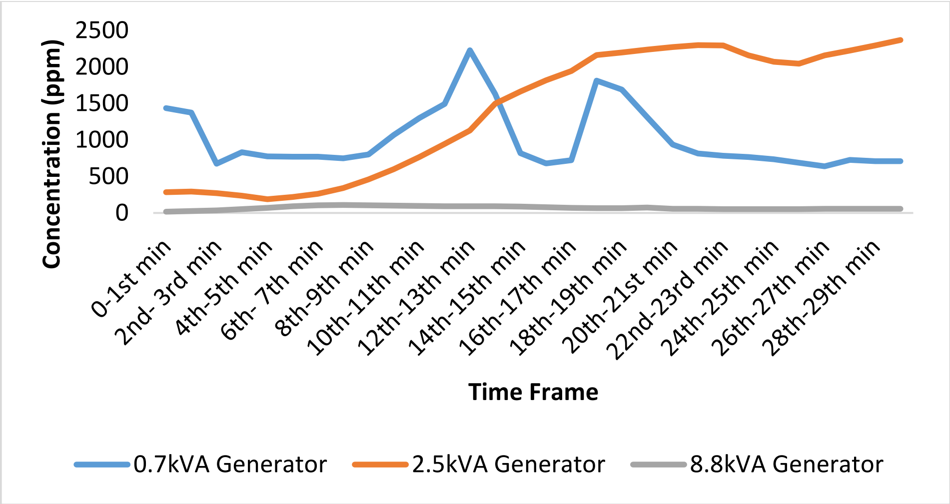

Figure 7a. CO Emission time series.

Figure 7b illustrates the instantaneous release of CO_2 during the time of the experiment for all generators. The graph shows that the concentration of CO_2 for the 0.7 kVA generator was constant (100.00 ppm) from the beginning to the 12^{th} to 13^{th} minute, where it attained the highest peak (2000.00 ppm) and afterward, remained constant at 1000.00 ppm till the end of the experiment. The 2.5 kVA generator also remained constant (1000.00 ppm) till the 18^{th} to 19^{th} minute, where it attained 2000.00 ppm, and afterwards, it varied between 1000.00 ppm and 2000.00 ppm. In a similar way, the 8.8 kVA diesel generator showed a trend in which the concentration remained constant (2000.00 ppm), till the 19^{th} to 20^{th} minute, where it reduced to 1000.00 ppm and was constant there for 8 minutes before increasing again to 2000.00 ppm.

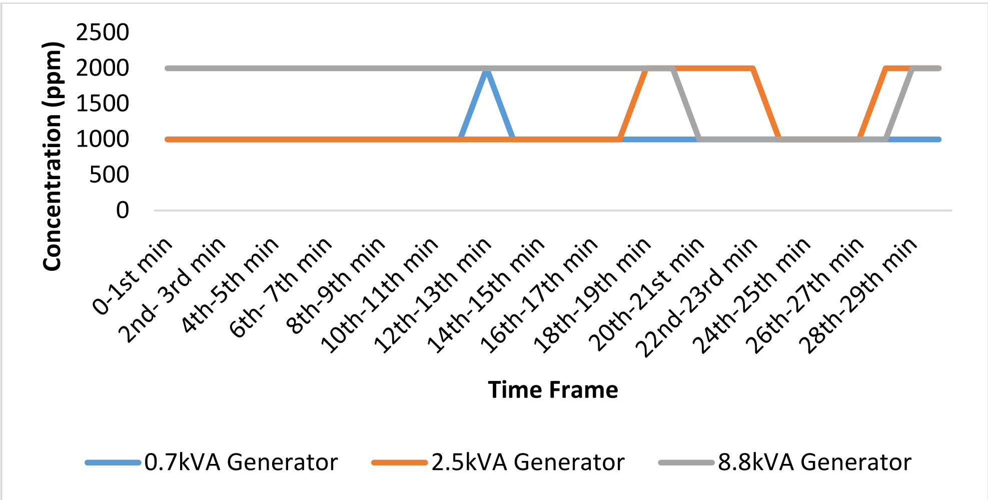

Figure 7b. CO_2 Emission time series.

Figure 7c illustrates the instantaneous release of O_3 during the time of the experiment for all generators. The graph shows that the concentration of O_3 for the 0.7 kVA generator varied between 60.00 and 80.00 µg/m^3 throughout the time of the experiment. For the 8.8 kVA generator also, the concentration of O_3 varied between 10.00 and 140.00 µg/m^3. The concentration of O_3 for the 2.5 kVA generator however, remained constant at 0.00 µg/m^3 from zero to the tenth minute of the experiment. It attained the highest value (1370.00 µg/m^3) from the 26^{th} to the 29^{th} minute, before dropping to zero.

Figure 7d illustrates the instantaneous release of O_2 during the time of the experiment for all generators. The graph shows that the concentration of O_2 for the generators remained constant (209500.00 ppm) from the beginning of the experiment to the end.

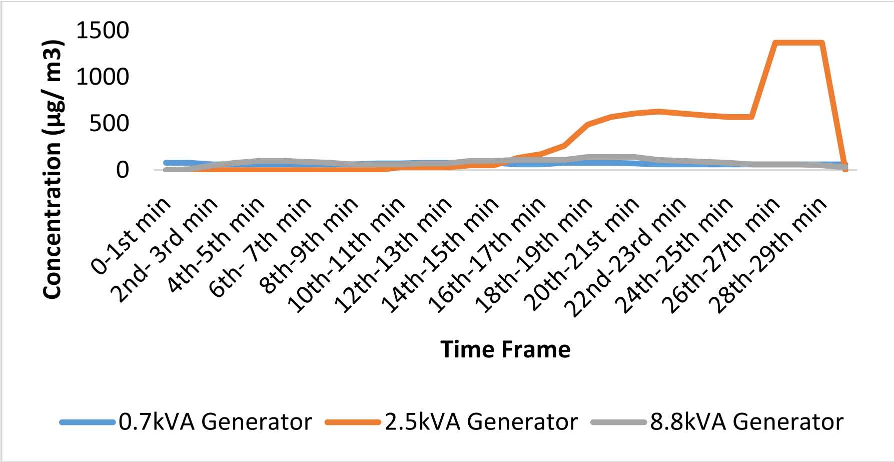

Figure 7c. O_3 Emission time series.

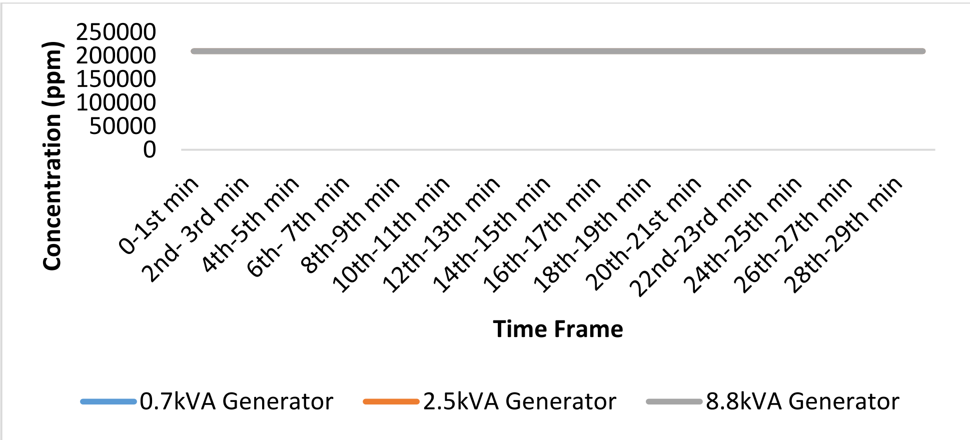

Figure 7d. O_2 Emission time series.

Figure 8a illustrates the instantaneous release of TVOC during the time of the experiment for all generators. The graph shows that the concentration of TVOC for the 0.7 kVA generator varied between 0.59 ppm and 1.29 ppm at different times during the experiment. It shows a trend that tended to reduce in value with respect to the time of the experiment. The TVOC value emitted by the 2.5 kVA generator remained constant at 0.00 ppm until the 9^{th} minute, before it then varied, increasing up to 0.98 ppm. It showed a trend that continued to increase in value with respect to the time of the experiment. The TVOC value for the 8.8 kVA generator, however, remained constant at 0.00 ppm throughout the experiment.

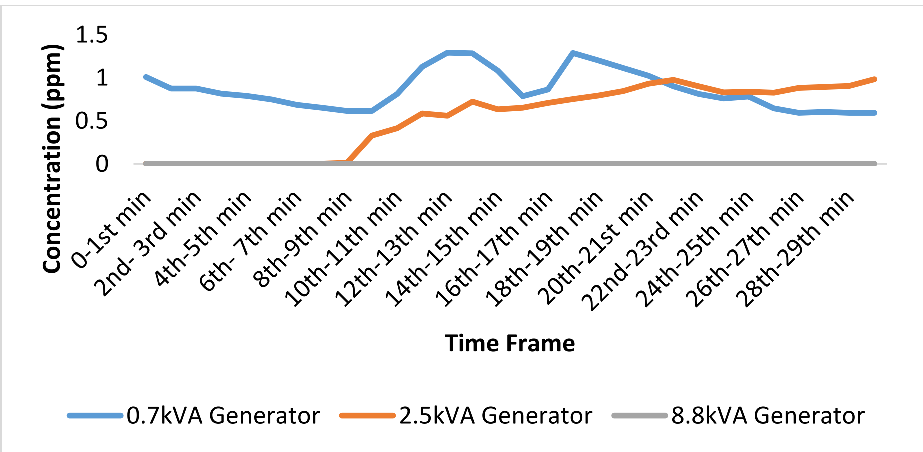

Figure 8a. TVOC Emission time series.

Figure 8b illustrates the instantaneous release of CH_2O during the time of the experiment for all generators. The graph shows that the concentration of CH_2O for the 0.7 kVA generator varied between 10.30 and 13.66 ppm, in an irregular pattern. This same kind of trend also applied to the CH_2O emissions of the other generators, with the value for the 2.5 kVA generator varying between 8.23 and 13.60 ppm, while that of 8.8 kVA generator varied between 4.83 and 11.45 ppm.

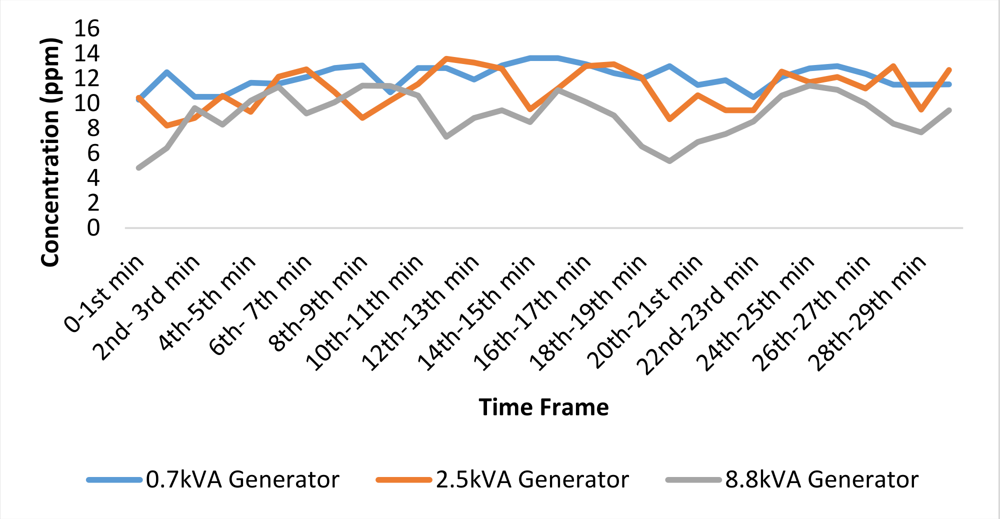

Figure 8b. CH_2O Emission time series.

Figure 9a illustrates the instantaneous release of TSP during the time of the experiment for all generators. The graph shows that the concentration of TSP for the 0.7 kVA generator varied between 93.00 and 1471.00 μg/m^3, showing a trend that increased with the time of the experiment. The TSP values for the 2.5 kVA generator varied between 950.00 and 1575.00 μg/m^3, showing a trend to reduce in concentration of emission with respect to the time of the experiment, while that of the 8.8 kVA generator varied between 998.00 and 1730.00 μg/m^3, with a trend that reduced in pollutant concentration with respect to time.

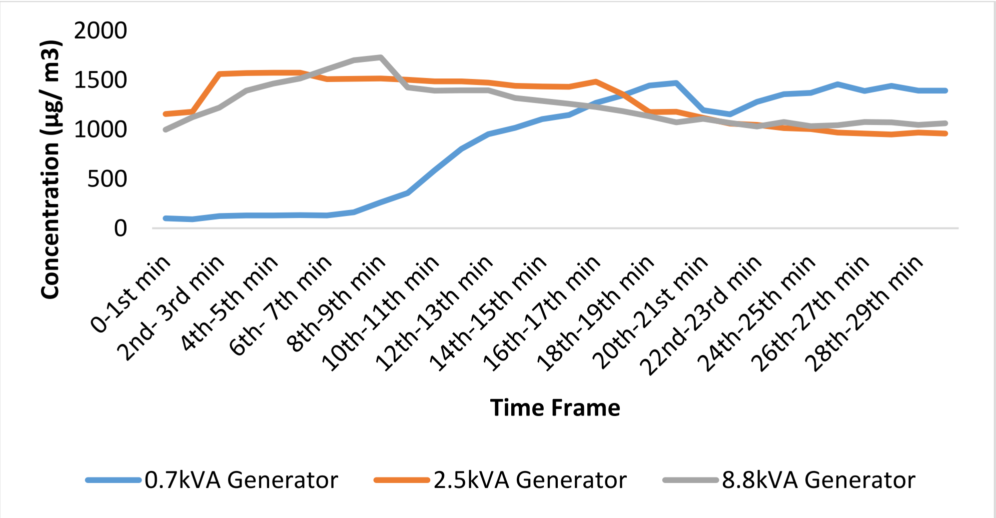

Figure 9a. TSP Emission time series.

Figure 9b illustrates the instantaneous release of PM_{10} during the time of the experiment for all generators. The graph shows that the concentration of PM_{10} for the 0.7 kVA generator varied between 54.00 and 889.00 μg/m^3, showing a trend that increased with the time of the experiment. The TSP values for the 2.5 kVA generator varied between 570.00 and 950.00 μg/m^3, showing a trend that tended to reduce in concentration of emission with respect to the time of the experiment, while those of the 8.8 kVA generator varied between 611.00 and 1050.00 μg/m^3, with a trend that reduced in pollutant concentration with respect to time.

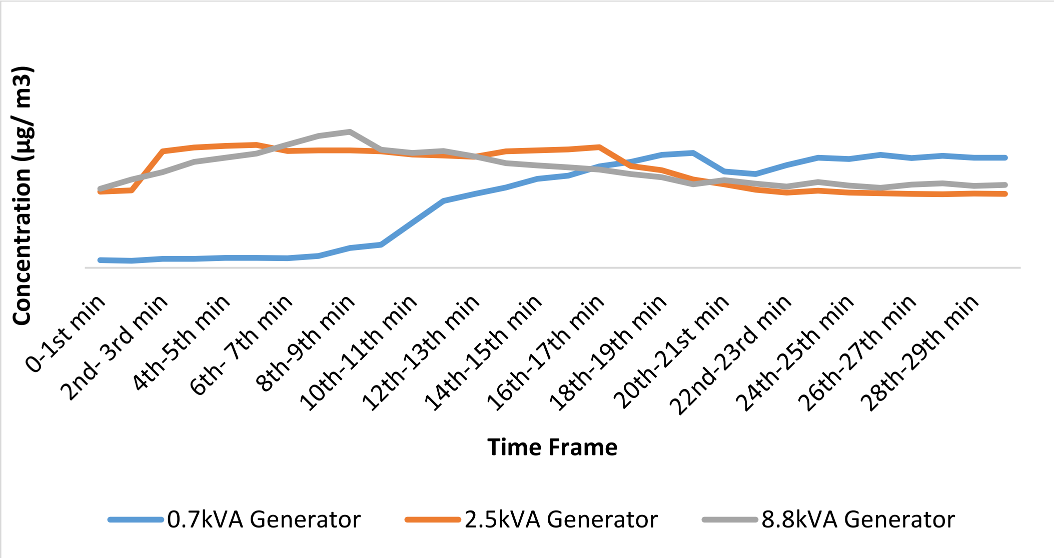

Figure 9b. PM_{10} Emission time series.

Figure 9c illustrates the instantaneous release of $PM_{2.5}$ during the time of the experiment for all generators. The graph shows that the concentration of $PM_{2.5}$ for the 0.7 kVA generator varied between 39.00 and 583.00 µg/m^3, showing a trend that increased with the time of the experiment. The TSP values for the 2.5 kVA generator varied between 380.00 and 660.00 µg/m^3, showing a trend that tended to reduce in concentration of emission with respect to the time of the experiment. That of the 8.8 kVA generator varied between 387.00 and 680.00 µg/m^3, with a trend that reduced in pollutant concentration with respect to time.

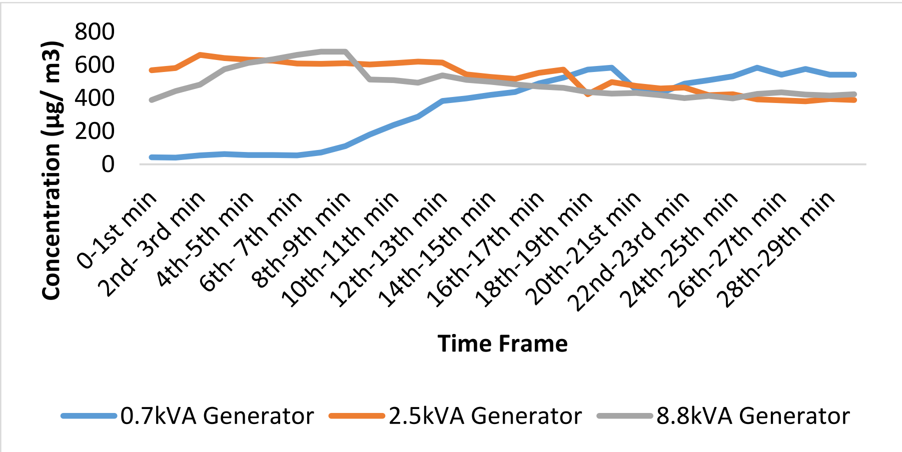

Figure 9c. $PM_{2.5}$ Emission time series.

4. Conclusion

The study concludes that the mean values of CO_2 and air pollutants being emitted by the use of different kinds of petrol and diesel engine electric generators are very high, but that the rate of pollutant emission by the generators reduced with time of operation. It further concludes that the emission rate of pollutants by the use of these generators is very high, and therefore that the continued use of generators as the main source of electricity supply by many households in Nigeria would increase pollutant emission into the environment, causing various acute and chronic health symptoms to users and residents within the area. It is, moreover, important to state that the continued use of electric generators in the current manner in Nigeria also greatly increases the amount of CO_2 being emitted into the atmosphere, thereby increasing the climate change risk and its associated negative or undesirable impacts. The study further concludes that on the average, the 2.5 kVA petrol generator emits the highest amount of pollutants, followed by the 0.7 kVA generator, while the 8.8 kVA diesel generator emits lowest of most of the pollutants, except for CO_2 and NO where it emits the highest; but, comparisons notwithstanding, it is important to note that all generators emitted very high amounts of pollutants and CO_2.

Conflict of interest

The authors declare no conflict of interest.

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