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Mathematical modeling and cost comparison for electricity generation from petrol and liquified petroleum gas (LPG)

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This article contributes to:
7 AFFORDABLE AND CLEAN ENERGY
SUSTAINABLE DEVELOPMENT GOALS

Highlights:

- The emission of fossil fuel engenders challenges in the ecosystem and is toxic to public health.
- The exploitation of liquefied petroleum gas (LPG) is a better alternative to the usage of petrol in small-scale power generation.
- The pace of development of any nation is a function of its capacity to distribute cost-effectively and high-quality power to both residential and industrial users.
- We found that the use of LPG is more profitable than pertol for small-scale generators at low loads.

Abstract

This study investigates and compares the cost of generating electricity from petrol and liquified petroleum gas (LPG) using a 2.5 kVA, 50Hz Elepaq generator. It also develops mathematical models that can be used to predict important parameters of the generator The generator is connected with a multi-fuel carburetor in the experimental setup, allowing both fuel sources to be fed alternatively. The electric bulbs of different ratings were connected and varied as load. The generator was first run using petrol. The time used to exhaust half litres of petrol was recorded. It was then run with LPG for a period equal to the time of run on petrol, taking note of the mass of LPG consumed. A cost comparison was carried out and mathematical models were developed for both fuels usage using MATLAB "polyfit" command. The results show that with less or equal 1350W connection of purely resistive load. It is more economical to run the generator using LPG. However, at any load beyond 1350 W, it is economical to run the generator using petrol. The two models developed best fit the experimental results obtained with a correlation of 0.9869 and 0.9962.

Keywords: Electricity, Power generation, Liquefied petroleum gas, Multi-fuel carburetor, Mathematical modeling, Chemical conversion

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1. Introduction

Research has proven that the world's energy demand directly relates to the increase in the world population [1]–[3]. The erratic power supply has been a growing cause of concern in developing countries. It becomes more challenging to supply adequate energy in countries with a high population due to the increased demand, which has led to load shedding in Nigeria [4]. Despite technological advancement in power and energy production, access to constant electricity in some developing nations is almost impossible despite billions of dollars spent on electrification projects [5].

Furthermore, other places with power can depend on sporadic, unpredictable, and unstable electric power. Insight demonstrates that 67% of the developing world has no accessible domestic power [4], [6], [7]. The pace of development and industrialization of any nation relies upon its capacity to distribute sufficient electric power to homes, ventures, banks, media, health care, and aviation [8]. It is profoundly evident in Nigeria as the power sector has over the years struggled to meet load demand regardless of its bounty of sustainable power sources. The exploitation and utilization of renewable generation like biomass, wind, photovoltaic and small hydro are still negligible [9]–[11]. This inconsistent power supply has caused a surge in the search for alternative forms of power generation with minimal operating costs. Industries adapted the use of natural gas generators as energy-saving was achieved compared to the traditional petrol or diesel-run generators [4], [12]. Generators are essential for various industries and provide power to remote and urban construction sites in case of a power outage. Generators are packaged units that provide electricity via an engine. The engine and various components turn a fuel source into usable electricity for many applications. With the recent increase in the petrol price, petrol shortages and the debate on the removal of fuel subsidy in developing countries, the populace is trying to source for other sources of fuel for generator that is economical. LPG is one of the fuels at the center stage of this consideration for various sectors due to lower emissions than petrol [13], [14]. While some people are portraying LPG to be cheaper than petrol, some are not sure of its cheapness, hence, this study compares the cost of running a generator on both petrol and LPG. This work also develops two mathematical models (each for petrol and LPG) that can be used to predict some important usage parameters of the generator.

The LPG applies widely to any mixture of propane and butane, the two constituents occurring naturally in oil and gas reservoirs, gaseous under normal atmospheric conditions but can be liquefied by pressure alone [6]. Works available in open literature have not really given much attention to this subject matter. However, few researchers have compared LPG and petrol in the past [6], [15]. The Romero's study [6] compared the fuel consumption of LPG and diesel in Cusiana. The load rating, he focused on was industrial and not residential. The generator used was a 1300 kW rated power generator set. The LPG consumption rate was converted to an equivalent diesel rate based on 47500 kJ/kg and 42500 kJ/kg for the diesel fuel. The main conclusion drawn by the author is that Cusiana LPG is a viable alternative fuel for diesel engines. Nwaokocha et al. [15] successfully modified a single-cylinder, 4-stroke Elepaq electric-generator to accommodate both petrol and LPG. Tests were conducted on this generator with both fuels by varying loads, fuel quantity and measuring fuel consumption with emissions. The loads considered are 0 W, 139W and 750W. The results show that at the equal mass of both fuels, LPG lasted for more time when compared to the time petrol lasted. It should be noted that the range of loads considered is not enough to effectively evaluate the usage of both fuels for electricity generation.

Unlike these two studies, this work evaluates the use of petrol and LPG for electricity generation for loads of 100W, 500W, 1000W, 1500W, and 2000W. This study is limited to using a 2.5kVA Elepaq generator, one of the popular generators used in residential buildings in Nigeria for alternative energy supply. By considering load, time of operation and other factors, the choice of either petrol or LPG as fuel for generating electricity can easily be made. The study is organized and structured as follows: Section 2 presents the methodology, which describes the experimental setup of the fuel generating system. Section 3 presents the results and discussion and lastly, the conclusion.

2. Method

The setup consists of a single-cylinder, 4-stroke 2.5kVA, 220-240V 50Hz Elepaq generator engine. This generator was designed only to operate on petrol as a fuel source, but a slight modification was made to accommodate both petrol and LPG for this project. The slight change made was removing the carburetor made for the generator, as shown in **Figure 1(a)**, and replacing it with a multi-fuel carburetor, as shown in **Figure 1(b)**. This multi-fuel carburetor is a type that allows the use of both petrol and LPG. It has a port that feeds it with petrol from the tank and another port with LPG from the cylinder. It also has a knob for switching and controlling the rate of the flow of the LPG. One piece of 100W and ten pieces of 200W incandescent bulbs were made available to achieve a variable electric loading.

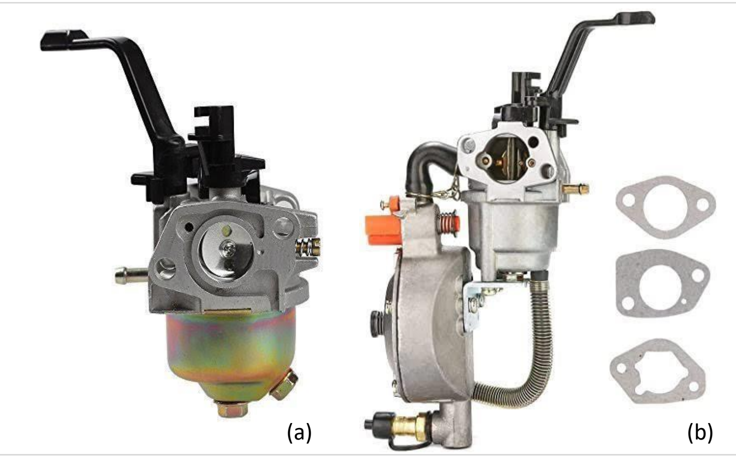

Figure 1. The carburetor that was replaced with a multi-fuel carburetor (a) and multi-fuel carburetor (b)

2.1. Evaluating petrol consumption

A well-calibrated beaker was used to measure 0.5 liters of petrol into the generator's tank. The generator was started and allowed to operate until it went off itself. Using a stopwatch, the run time was noted when no load was connected. This procedure was repeated for other loading conditions, including 100W, 500W, 1000W, 1500W, and 2000W. The time taken for the quantity of petrol to get exhausted under the load conditions were noted. For each loading, the experiment was carried out twice to ensure accuracy, and the average time was calculated.

2.2. Evaluating of LPG consumption

Using the same time obtained to power the loads when the generator was run on petrol, the mass of LPG needed to run the generator under the same load conditions was determined. A 13 kg cylinder filled with LPG was made available with a weighing scale. The cylinder was placed permanently on the scale throughout the test period. The generator was initially started with petrol and then switched to LPG. Immediately it was changed to LPG, the generator jerked, and it took some seconds before it became stable.

It should be noted that the LPG consumed during this period is negligible. After the stability of the generator, the initial mass of the LPG cylinder was taken, and the generator was allowed to run on no load for a pre-determined time (i.e. as obtained when run on petrol). After the expiration of the time, the final mass of the LPG cylinder was taken. The difference was calculated to get the actual mass of LPG consumed during this interval. The procedure stated was repeated for different loading conditions. The experiment was carried out thrice. The reason for the third experiment, in this case, is due to the high variation between the first and the second experiment. The average mass (m) of the LPG consumed was then calculated following Eq. (1).

$$m = \frac{m_1 + m_2 + m_3}{3} \quad (1)$$

Where m_1 to m_3 are the mass of LPG consumed.

2.3. Mathematical modeling

Using MATLAB software, some generator parameters when running on petrol and LPG are modeled using a command named polyfit. The parameter modeled for petrol is the time taken to run on the petrol at 0.5liters constant volume at a varying load, and the parameter modeled for LPG is the mass used at a variable load per second. At a fixed volume of petrol, the time taken (t) for the petrol is modeled as a function of the load (P) to the fifth order to establish a mathematical relationship between time of petrol usage and load. Also, the mass (m) of LPG used per second is modeled as a function of load (P) to the fifth order to have an equation that shows the relationship between mass of LPG per second and load.

3. Results and Discussion

3.1. Consumption and mathematical model for petrol usage

After running the generator under different load conditions using a constant volume of 0.5 liters, the time taken for each test is recorded in **Table 1** and the plot of load against time between experimented and calculated at a fixed volume of petrol is shown in **Figure 2**. As expected, **Table 1** and **Figure 2** show that as the load increases, the time taken for the fixed volume of petrol to get exhausted begins to reduce which implies that at a low load, less petrol is consumed and at high load, more petrol is consumed.

Table 1. Results for petrol usage: experimented, calculated, and error value

Test	Load (W)	Vol. of petrol (m^3)	Time (secs)				
			Exp. 1	Exp. 2	Ave (exp)	Calcu-lated	Error
1	0	0.0005	2611	2654	2633	2579	54
2	100	0.0005	2350	2405	2378	2463	-85
3	500	0.0005	2106	2180	2143	1957	186
4	1000	0.0005	1737	1685	1711	1747	-36
5	1500	0.0005	1405	1530	1468	1452	16
6	2000	0.0005	1121	1100	1111	1114	-3

Using the time information recorded in **Table 1**, the time taken (t) for the petrol to get exhausted is factored into the load (P) to generate a polynomial equation of order five which is shown in Eq. (2) and makes it possible to make an estimation of time taken for a particular volume of petrol under specific load condition to run the type of generator under consideration. For example, a user of such generator with a load of 600 W and a volume of 0.5 litre of petrol will approximately power the load for 2109 seconds (i.e. 35 minutes, 9 seconds). If 5 litres of petrol is to be used, the 600 W load will be approximately powered for 21090 seconds (i.e. 5 hours, 51 minutes, 30 seconds). In another instance, if 5 litres is to be used to power 1800 W of load, the generator will approximately run for 16236 seconds (i.e. 4 hours, 30 minutes, 36 seconds). Using Eq. (2) to estimate time t, a comparison between the experimented and calculated time is shown in **Table 1** and a plot of the experimented and calculated time against the load is shown in **Figure 2**. **Table 1** also presented the error between the experimented and calculated time. Using MATLAB software, the correlation coefficient between the experimented and calculated time was determined by using a command named "corrcoef". The correlation coefficient was determined to be 0.9869, indicating that they are similar.

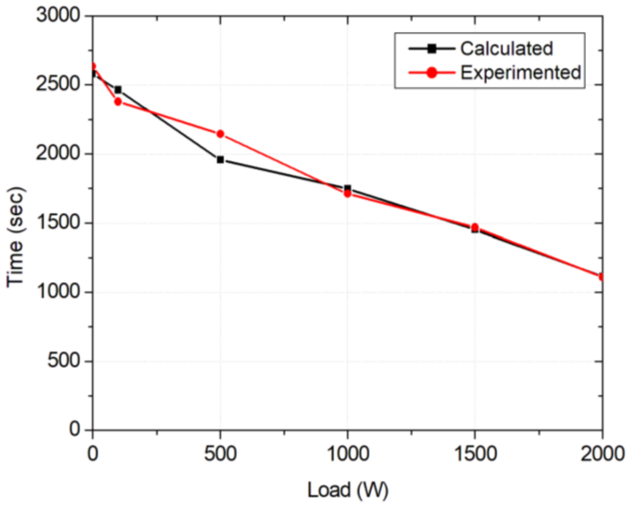

Figure 2. Comparison between experimented and calculated time at a fixed volume of petrol

$$t = 2V(8.33x10^{-15}p^5 - 1.612x10^{-10}p^3 + 5.2495x10^{-7}p^2 - 1.2032x10^{-3}p + 2.5785)sec \quad (2)$$

3.2. Consumption and mathematical model for LPG usage

The mass of LPG used to run the generator for the same time corresponding load conditions is recorded in **Table 2**. The mass of LPG consumed per second was calculated and recorded. The plot of the load (W) against the mass per second (kg/s) is shown in **Figure 3**. It could be deduced from **Table 2** and **Figure 3** that the rate of consumption of LPG increases rapidly as the load passes 1000 W when compared to before the load reaches 1000 W. This is an indication that the rate of LPG consumption is lesser between the load range of 0 W to 1000 W but as the load increases beyond this range, the rate of consumption of LPG increases.

Table 2. Comparison between experimented and calculated mass of LPG used

Test	Load (W)	Time (sec)	LPG consumed (kg)				LPG consumed ($\times 10^{-6}$ kg/s)		
			Exp. 1	Exp. 2	Exp. 3	Ave (exp)	Experimented	Calculated	Error
1	0	2633	0.02	0.02	0.02	0.02	7.60	7.60	0
2	100	2378	0.08	0.04	0.04	0.05	21.03	21.03	0
3	500	2143	0.08	0.04	0.04	0.05	23.33	23.33	0
4	1000	1711	0.10	0.08	0.06	0.09	52.60	52.58	0.02
5	1500	1468	0.22	0.12	0.12	0.15	102.18	102.13	0.05
6	2000	1111	0.30	0.22	0.22	0.25	225.02	224.96	0.06

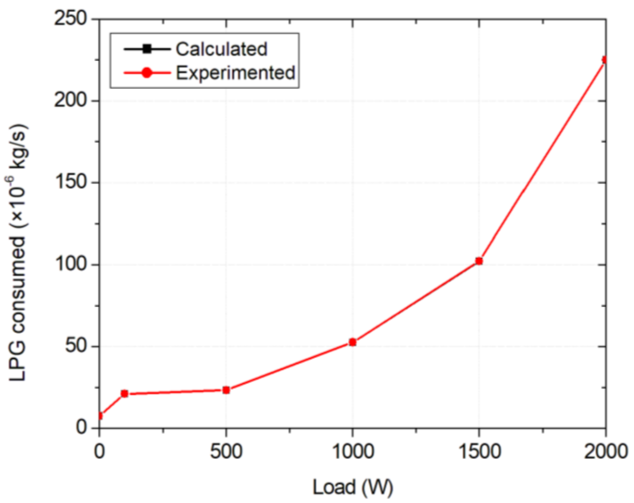

Figure 3. Comparison between experimented and estimated mass per second of LPG consumed

Using the information contained in **Table 2**, the mass of the LPG consumed per second (m) is factored into the load (P) to generate a polynomial equation of order five. The resulting equation is shown in Eq. (3). This equation makes it possible to determine an estimation of mass of LPG needed to run the type of generator under consideration at a particular load. For example, a user of such generator with a load of 600 W will approximately require 24.57 × 10^{-6} kgs^{-1} of LPG. If the user decides to use it for 5 hours, the mass of LPG needed will be 0.442 kg. Considering another scenario, if the user now decides to power a load of 1800 W for 5 hours, the mass of LPG needed will be 2.645 kg (i.e. 146.95 × 10^{-6} kgs^{-1}). Equation (3) was used to calculate the mass of LPG consumed per second for the load conditions considered for the experiment and these values were compared with the experimented values as shown in **Figure 3**. The error between the experimented and calculated mass per second is shown in **Table 2**Error! Reference source not found.. The correlation coefficient between the experimented and calculated mass was determined to be 0.9962, indicating that they are closely similar.

$$m = 1.3152x10^{-19}p^5 - 6.2679x10^{-16}p^4 + 1.0674x10^{-12}p^3 - 7.2377x10^{-10}p^2 + 1.9662x10^{-7}p + 7.6x10^{-6}\ kg/s \quad (3)$$

3.3. Cost comparison between petrol and LPG

Table 3. Cost comparison between petrol and LPG usage

Test	Load (W)	Time (sec)	Cost of petrol (NGN)	Cost of LPG (NGN)
1	0	2633	82.50 (USD 0.20)	14.00 (USD 0.034)
2	100	2378	82.50 (USD 0.20)	35.00 (USD 0.084)
3	500	2143	82.50 (USD 0.20)	35.00 (USD 0.084)
4	1000	1711	82.50 (USD 0.20)	63.00 (USD 0.150)
5	1500	1468	82.50 (USD 0.20)	105.00 (USD 0.250)
6	2000	1111	82.50 (USD 0.20)	200.00 (USD 0.480)

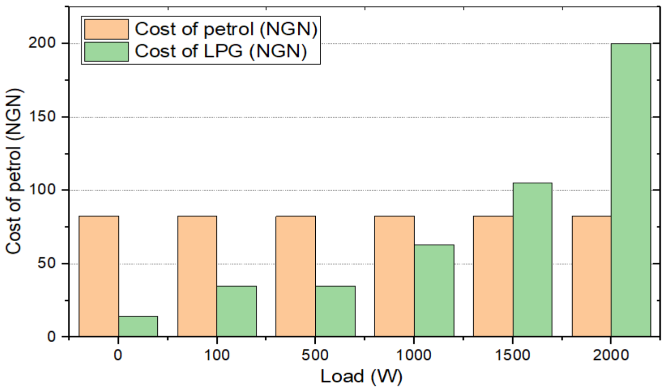

Figure 4. Cost comparison for petrol and LPG usage

Using a rate of ₦165 per liter, the cost of the fuel used is a fixed amount of ₦82.50, since 0.5 litres of fuel was used throughout the experiment. The cost of the LPG consumed was calculated using ₦700 per kg. The cost comparison of both fuels is shown in **Table 3** and **Figure 4**. It can be observed from the table and figure that the cost to run on LPG at no load until 1300 W is lesser than running on petrol, at 1350 W, the cost is the same but above 1350 W, the cost of running on LPG increases rapidly. This indicates that it is economical to run on gas at a low load than on petrol and it is economical to run on petrol at a high load than to run on LPG.

3.4. Discussion

This study uses the first-generation LPG kit, as presented in **Figure 1(b)**. As is known, the first generation of LPG kits, where LPG is fed into the intake manifold in the vapor phase, will affect the volumetric efficiency [13]. Engine output power is highly dependent on the intake manifold vacuum level. The LPG consumption that produces the right fuel-air mixture in the first-generation LPG kits may only apply partially to certain loads [16]. The increase in the mass flow rate of LPG due to engine load also requires sufficient heat supply for evaporation. In some types of converter kits that are installed in water-cooled engines, to improve the quality of the vapor, heat of vaporization is supplied from the engine coolant. Insufficient heat supply results in an increase in the density of LPG and it causes an increase in the mass flow rate of LPG to the engine. Control system interventions with input from engine load, intake manifold vacuum, and throttle valve can be applied to improve performance at all engine speeds and provide lower fuel consumption [14]. In addition, the cost of LPG against petrol is also affected by the price per unit mass [17]. The cheaper the price of LPG compared to petrol, the lower the operating costs of a generator fueled by LPG. Considering a cleaner environment, several countries also apply subsidies for LPG to reduce consumer operating costs.

4. Conclusion

A single-cylinder, 4-stroke, spark-ignition engine was successfully converted to utilize LPG fuel by carburetor modification. The use of LPG gives a better operation of the engine. There was a cool sound of the engine and less exhaust. The results obtained from the experiments conducted on the modified generator running on the rated loads of 2000 W, 1500 W, 1000 W, 500 W, 100 W show that at the load operation from 0W to 1350 W, it pays to run on LPG. However, at a heavy load, it pays to run on petrol because the rate of combustion of petrol is not as fast as LPG. Further experiments on the effect of pressure on the fuel consumption rate, the generator's stability at different load operating conditions, and other generator specifications can be carried out in a future work. In addition, future work identified is to develop a control system and sufficient heat supply for LPG evaporation at higher generator loads.

Contribution to SDG’s

The research contributes to SDGs in the following categories:

- The possible potential of a better environmentally friendly source of power generation is experimented with and highlighted.
- The generation technique is demonstrated and highlighted for ease of adaptation in every locality.

Authors’ Declaration

Authors’ contributions and responsibilities - The first author: Conceptualization, Methodology, Data curation and Supervision, the second author: Reviewing, Editing and Correspondence, the third author: writing of the original draft and experimental investigation, the fourth author: Visualization and experimental investigation.

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Availability of data and materials - All data are available from the authors.

Competing interests - The authors declare no competing interest.

Additional information - No additional information from the authors.

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