Technology and Economics of Utilizing CNG as Automobile Fuel in Nigeria

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Abstract

Natural gas flaring in Nigeria's oil-producing regions remains a significant loss of potential revenue and a serious environmental threat. Compressed Natural Gas (CNG) offers numerous economic benefits and environmental advantages, especially for its application as an automobile fuel. Adopting CNG in Nigeria's transportation sector could boost the economy and address issues like fuel scarcity and volatile gasoline prices, presenting CNG as a sustainable energy alternative. Despite these potential benefits, there has been limited research on public perception, acceptance, and the cost-efficiency of vehicle conversions to CNG in Nigeria. This study addresses this research gap by analyzing primary data obtained from CNG stations, interviews, and secondary data from company reports. Results indicate that the initial cost of converting a gasoline engine to CNG can be quickly recovered. The study recommends that the Nigerian government promote CNG usage and invest in the necessary infrastructure for its effective adoption.

Keywords: *Natural Gas, Compressed Natural Gas (CNG), Automobile Fuel, Alternative Energy, Nigeria.*

➢ *Highlights:*

- Adopting CNG supports Nigeria’s efforts to combat climate change and improve urban air quality.
- CNG offers lower operational costs than gasoline and diesel, making it a cost-effective fuel choice for consumers.
- CNG-powered vehicles exhibit higher thermal efficiency and better fuel economy than traditional Internal Combustion Engine (ICE) vehicles using liquid fuels.
- Nigeria holds significant natural gas reserves, providing a readily available and sustainable energy source for widespread CNG adoption in the automotive sector.
- While the initial cost of converting vehicles to run on CNG can be substantial, payback periods are short due to lower running costs, offering long-term economic savings.
- Transitioning to CNG can reduce Nigeria's dependence on liquid fuels, contribute to economic diversification, and position the country as a leader in sustainable transportation in Africa.

I. BACKGROUND

Natural gas is less hazardous than air, tasteless, odorless, colorless, and highly flammable. It comprises gases occurring in deposits in either liquid or gaseous form. When it burns, it gives off roughly 1,000 standard cubic feet (SCF) of British thermal units (Btu) [1]. It consists mainly of methane with the chemical formula of CH_4 and other hydrocarbons like ethane, propane, butane, nitrogen, hydrogen sulfide, oxygen, and carbon dioxide. Depending on the gas field, natural gas composition might vary greatly. When it contains hydrocarbons other than methane, it is called a wet gas; when it is nearly pure methane, it is called a dry gas; and when it has a sizable amount of hydrogen sulfide, it is called a sour gas. Natural gas can either be produced alone as non-associated gas or together with crude as associated gas. It can also be recovered as methane from coal mines (colliery/seam gas) and shale (Shale Gas). As a bio-methane, natural gas is renewable and is generated from municipal or industrial waste, sewage, or decomposing organic compounds, including cattle manure, wastewater, and landfill garbage [2, 3]. Nigeria ranks among the top natural gas producers globally, with reserves of Associated Gas and Non-

Associated Gas at 102.59 TCF and 106.67 TCF respectively [4]. Globally, Natural gas ranks second in energy consumption, after petroleum. It is used widely in domestic and commercial (mainly for heating), industrial (such as in the raw material for the manufacture of fertilizer), and electricity areas. At over 40% of the world's gas demand, the power industry is the largest user of natural gas. About 24% of all gas consumption is accounted for by industrial usage, and 22% is accounted for by residential and commercial use. Other uses including that of the energy industry are about 10% [5].

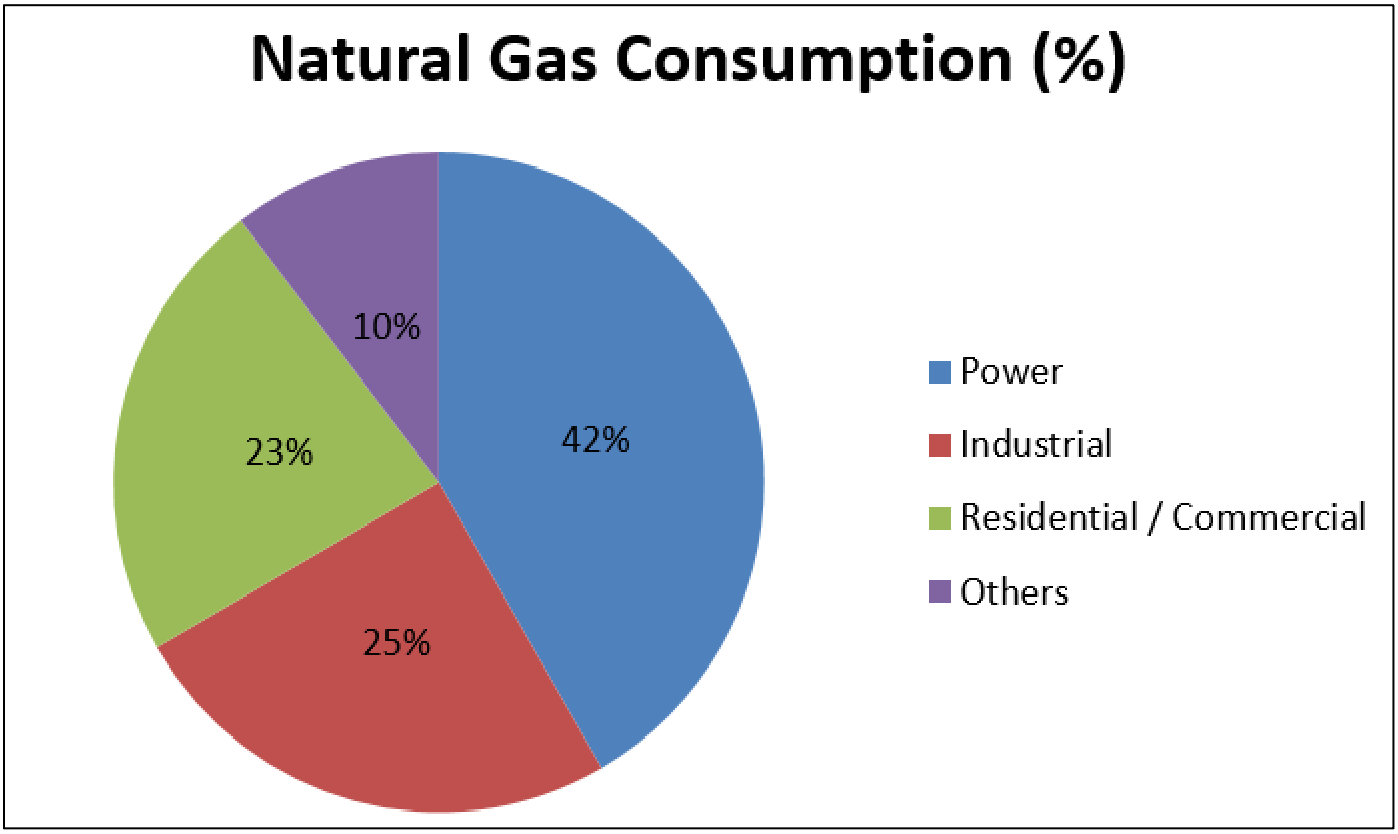

Fig 1 Global Natural Gas Consumption
Source: International Energy Agency

According to [6], the Nigerian government's directive to cease natural gas flaring in hydrocarbon exploration and production (E&P) operations by 2008 is an attempt to capitalize on the vast gas reserves in the country for economic gain. With over 250 oil and gas fields and known gas reserves, over half of Nigeria's gas reserves are associated with crude oil and the other half are not. Nigeria is a significant prospective gas provider and the seventeenth-largest gas producer globally as of 2023, having about 43.7 BCM [7]. Nigeria's natural gas reserve is estimated to have proven gas reserves of roughly 159 TCF, of which 40% is still flared and 12% re-injected to enhance oil recovery [8]. It occurs mainly in the Niger Delta and some deep offshore blocks. About 1.5 TCF of dry gas was produced yearly between 2012 and 2021 in the country [9]. According to the United States Energy Information Administration, an analysis of Nigeria's hydrocarbon shows that a sizable portion of the total natural gas output is flared because some of its oil fields lack the infrastructure required to collect associated gas [10]. Nigeria's natural gas resources now have domestic demands in electricity, cement and steel production, fertilizer manufacturing, and aluminum smelting, they are also exported through Nigeria Liquefied Natural Gas (NLNG) and West Africa Gas Pipeline projects, etc., but yet remain underutilized as a result of the difference between the quantity produced and the quantity flared but 2023 had an improved result according to [11], that stated that Nigeria produced 2.503 trillion cubic feet of gas in 2023, a slight decrease from 2022. Associated gas makes up 4.213 BCF/D (61.4%) of daily production, while non-associated gas makes up 38.6%. 7.25% of the gas was flared, and 0.21% was shrinkage. 92.54% of the gas was used, representing the output of 47 oil and gas firms. These data are explained in detail in Table 1 and Fig. 3. As a result of challenges facing the country, ranging from unavailability to unsteady and high price of gasoline (petrol) and also, the need for a safe and cleaner environment to meet the environmental regulations and concerns, it is, therefore, necessary we consider using natural gas alongside with gasoline in Nigeria as it will take care of the problems mentioned above.

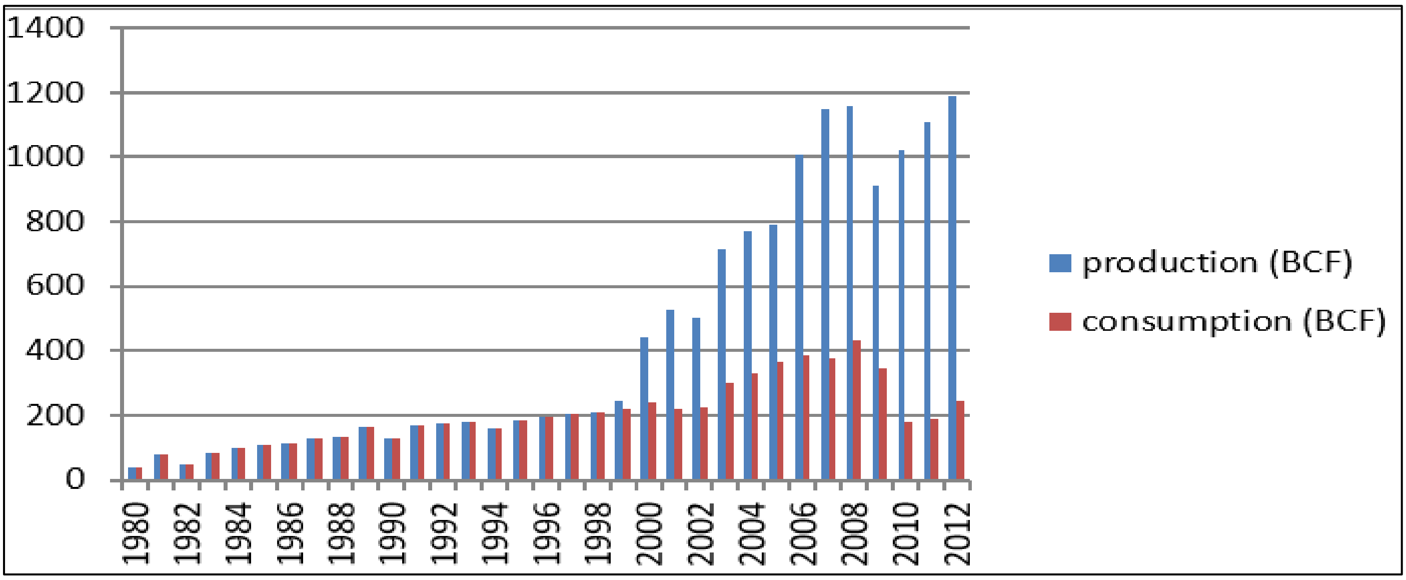

Fig 2 Nigeria Natural Gas Production / Consumption (1980 – 2012).
Source: United States Energy Information Administration

Table 1 2023 Annual Gas Production, Utilization and Flare Data (MMSCF)

S/NO	COMPANIES	CONTRACT TYPE	TERRAIN	GAS PRODUCTION AG	NAG	AG+NAG	GAS UTILIZATION	GAS FLARED	GAS SHRINKAGE	% GAS FLARED
1	SHELL	JV	Onshore/Offshore	67,241.50	281,397.61	348,639.11	332,682.45	15,956.66	-	5
2	SNEPCO	PSC	Deep Offshore	34,099.63	-	34,099.63	33,450.23	649.40	-	2
3	CHEVRON	JV	Offshore	134,087.24	123,755.08	257,842.32	243,278.97	14,563.35	-	6
4	CHEVRON STAR DEEP	PSC	Deep Offshore	153,521.54	-	153,521.54	150,240.74	3,280.79	-	2
5	MOBIL	JV	Onshore/Offshore	305,096.59	-	305,096.59	282,133.45	22,963.14	-	8
6	ESSO	PSC	Deep Offshore	150,749.44	-	150,749.44	141,540.23	9,209.22	-	6
7	NAOC	JV	Onshore/Offshore	97,858.44	92,916.61	190,775.04	176,418.06	10,654.90	3,702.08	6
8	TEPNG	JV	Onshore/Offshore	181,297.08	103,770.20	285,067.27	278,497.22	4,899.49	1,670.56	2
9	TUPNI	PSC	Deep Offshore	187,178.66	-	187,178.66	184,179.81	3,056.88	-	2
10	NAE	PSC	Deep Offshore	10,454.37	-	10,454.37	6,486.46	3,967.91	-	38
11	ANTAN PRODUCING	PSC	Onshore/Offshore	21,641.38	-	21,641.38	6,595.43	15,045.95	-	70
12	PAN OCEAN	PSC	Onshore	10,072.50	-	10,072.50	9,013.89	1,058.61	-	11
13	NEPL	SR	Onshore/Offshore	96,688.66	152,345.09	249,033.74	217,029.57	32,004.17	-	13
14	ENAGEED	PSC	Onshore	931.58	-	931.58	87.97	843.60	-	91
15	AMNI	SR	Offshore	2,350.77	-	2,350.77	1,759.70	591.07	-	25
16	MONIPULO	MF	Offshore	192.41	-	192.41	16.41	176.00	-	91
17	ARADEL	MF	Onshore	3,573.22	6,117.54	9,690.76	9,623.98	66.78	-	1
18	CONTINENTAL	SR	Offshore	2,446.67	-	2,446.67	233.17	2,213.51	-	90
19	CONSOLIDATED	SR	Offshore	197.13	-	197.13	77.36	119.77	-	61
20	DUBRI	SR	Onshore	667.51	-	667.51	8.14	659.37	-	99
21	PLATFORM	MF	Onshore	3,454.25	6,990.44	10,444.68	9,961.29	483.40	-	5
22	WALTER SMITH	MF	Onshore	448.77	3.67	452.44	297.82	154.62	-	34
23	MID WESTERN	MF	Onshore	799.36	-	799.36	60.63	738.73	-	92
24	PILLAR	MF	Onshore	647.44	-	647.44	381.66	265.77	-	41
25	GENERAL HYDROCARB	MF	Offshore	1,502.27	-	1,502.27	-	1,502.27	-	100
26	ENERGIA	MF	Onshore	-	6,896.50	6,896.50	4,333.88	2,562.61	-	37
27	Britania-U	MF	Offshore	97.57	-	97.57	74.05	23.52	-	24
28	SEPLAT	JV	Onshore	17,059.66	84,640.78	101,700.45	93,803.24	7,897.21	-	8
29	ORIENTAL ENERGY	MF	Deep Offshore	5,252.86	-	5,252.86	4,128.18	1,124.68	-	21
30	SEEPCO	PSC	Onshore	8,924.55	42,705.95	51,630.49	51,623.91	6.58	-	0
31	FRONTIER	MF	Onshore	226.85	46,900.51	47,127.36	46,856.62	270.74	-	1
32	New Cross E&P	JV	Onshore	6,486.10	-	6,486.10	3,436.73	3,049.37	-	47
33	EROTON (NOEL)	PSC	Onshore	-	5,666.93	5,666.93	5,608.67	58.26	-	1
34	UNIVERSAL ENERGY	MF	Onshore	544.03	-	544.03	40.45	503.58	-	93
35	AITEO	JV	Onshore	4,292.99	-	4,292.99	1,729.38	2,563.61	-	60
36	NETWORK	MF	Onshore	924.30	-	924.30	35.34	888.96	-	96
37	BELEMA OIL	JV	Onshore	115.88	-	115.88	64.15	51.74	-	45
38	YINKA FOLAWIYO	SR	Deep Offshore	-	-	-	-	-	-	#DIV/0!
39	GREEN ENERGY	MF	Onshore	1,988.86	-	1,988.86	-	1,988.86	-	100
40	EXCEL	MF	Onshore	183.32	-	183.32	101.17	82.15	-	45
41	MILLENIUM	MF	Onshore	481.78	-	481.78	-	481.78	-	100
42	SGORL	PSC	Onshore	149.84	-	149.84	147.38	2.45	-	2
43	CHORUS ENERGY	MF	Onshore	-	3,968.10	3,968.10	666.08	3,302.02	-	83
44	FIRST E& P COMPANY	MF	Deep Offshore	9,182.36	-	9,182.36	618.48	8,563.88	-	93
45	ALL GRACE ENERGY	MF	Onshore	207.66	-	207.66	-	207.66	-	100
46	HEIRS HOLDING OIL & (	JV	Onshore	7,034.29	7,056.37	14,007.57	11,244.64	2,762.93	-	20
47	NEWCROSS PETROLEUM	PSC	Onshore	7,479.23	-	7,479.23	7,479.23	-	-	-
				1,537,830.5	965,131.4	2,502,878.8	2,316,046.3	181,517.9	5,372.6	7.3

Adapted from Nigerian Upstream Petroleum Regulatory Commission

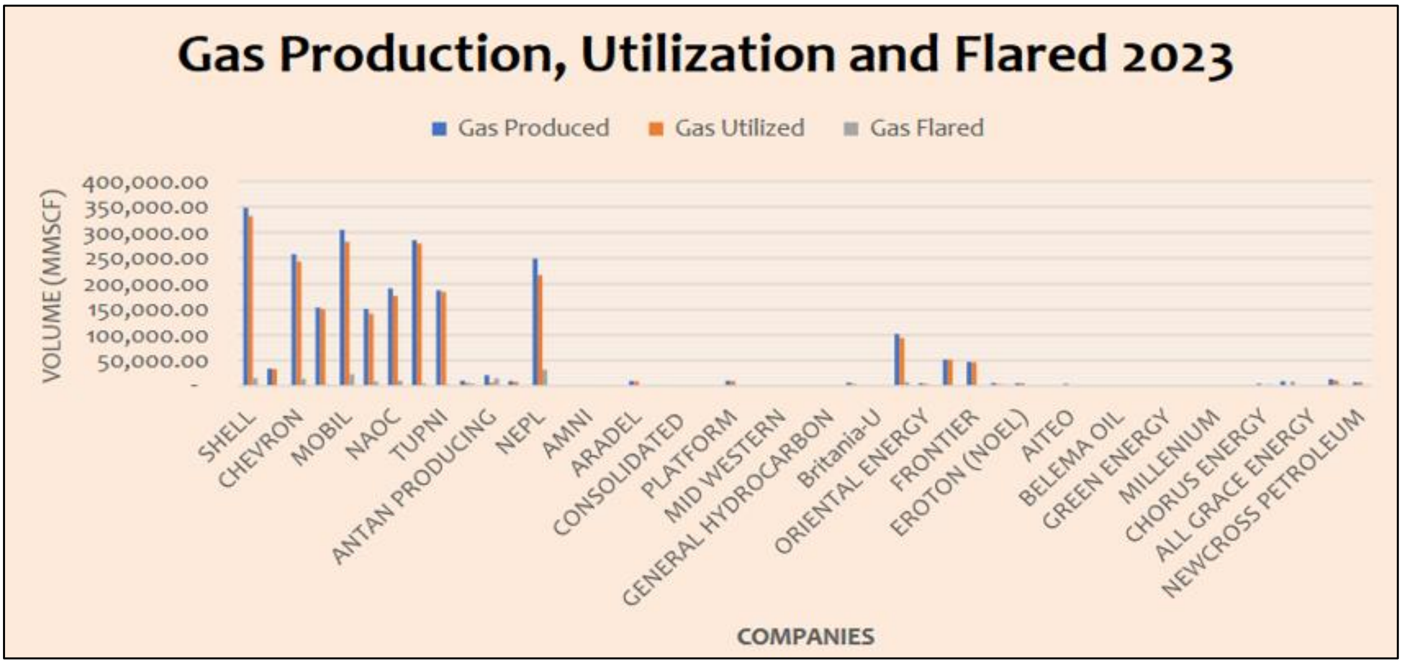

Fig 3 Gas production, Utilization & Flared 2023
Source: Nigerian Upstream Petroleum Regulatory Commission

The hazardous emissions from CNG are the lowest of all hydrocarbon fuels since it is a single hydrocarbon, i.e. about 90% methane. In contrast, all other fuels (gasoline and diesel) are a mixture of hydrocarbons. Based on the global concern about The adverse emissions from automobiles and the devastation they cause to the environment, a CNG car has one of the cleanest engines of all fuels, it releases low amounts of emissions of greenhouse gases and is regarded as an emission-free car for some years and therefore, should be considered an automobile fuel of the future [12,13 ,14]. The air a natural gas vehicle releases is cleaner than the air drawn into the engine on particularly hazy days. Natural gas emits 25% less carbon dioxide (the primary gas causing climate change) than gasoline, the fuel used in all other cars. When comparing overall emissions, a natural gas vehicle emits 90% less than a car that runs on gasoline. When gasoline and diesel burn, harmful substances such as methanol, formaldehyde, aldehydes, acrolein, benzene, toluene, xylene, etc. are released into the atmosphere but utilizing gas fuel mitigates the adverse effects of automobiles on the environment, and will not only enhance environmental performance but also prolong engine performance and service life, preserve the condition of components over time, and yield several other beneficial outcomes [15].

According to [16], CNG is pure, odorless, and non-corrosive. It is a cheaper, greener, and more efficient alternative to conventional fuels. CNG is compressed to above 3000 psi which reduces the volume and enables more fuel to be stored in the vehicle thereby increasing the driving range. A typical CNG vehicle can have a capacity of approximately 15 litres of gasoline equivalent to CNG which can travel to about 200 km. There are several benefits CNG offers over gasoline and diesel. Looking at it from a natural perspective, [15] concluded that using gasoline and diesel fuels in automobile engines poses environmental and health risks due to engine overheating, while CNG fuel is a more environmentally friendly alternative. Since CNG is lighter than air, it disperses upward quickly in the event of rupture, but gasoline and diesel, which are liquids, will pool on the ground and increase the risk of fire. Since CNG is not toxic, spilling it won't contaminate groundwater. Additionally, modern CNG engines are superior to traditional diesel and gasoline engines. Because of its gaseous nature, clean and complete burning without leaving carbon deposits behind, its maintenance costs are lower than those of gasoline or diesel engines. Furthermore, gas engines use less lubricant than gasoline or diesel engines since the fuel in gas engines does not combine with lubricants to dilute or lessen its viscosity. Hence, CNG is attractive for four reasons [17]:

- It is a cheaper fuel than gasoline or diesel.
- It has inherently lower air pollution emissions.
- It reduces the burden on gasoline and diesel as automobile fuels.
- There are large quantities of fuel reserves available.

According to [18], research carried out by several organizations shows that CNG buses produce roughly 50% fewer nitrogen oxides (NOx), 90% fewer sulfur oxides (SOx), and approximately 97% fewer tiny particles than traditional diesel buses. Other advantages over conventional fuels are their low cost (their price is significantly lower than that of gasoline and diesel), inherently clean-burning qualities (since they also boast of a very high calorific value of 50000 KJ / Kg, second only to hydrogen, and much safer than gasoline and diesel vehicles because the gas is stored in thick containers with few chances of leakage. It is filtered from sulfur and other impurities, burns cleanly, and improves the engine's efficiency [19]. Although there are disadvantages associated with CNG namely: drive range, truck space, and infrastructure costs. [20] described how a CNG engine functions identically to a spark ignition engine. The diesel engine is commonly found in buses and trucks because it uses a compression ignition engine, which necessitates the removal of its fuel system to be substituted with a gas system. To match the operating pressure of the engine's fuel management system, the highly compressed natural gas is transferred by the CNG fuel system from the storage tank to the engine, lowering pressure along the way. A spark plug ignites the compressed gasoline and air combination, causing the gasses to expand and drive pistons that propel the car forward. New fuel injectors, valves, and a pressure regulator are needed to accept the pressurized, gaseous CNG.

- *Compressed Natural Gas (CNG) as a Transportation Fuel*

According to [16], CNG is a pressurized natural gas that is odorless, clear, and non–corrosive. It is a cheaper, greener, and more efficient alternative to conventional fuels. CNG is compressed to above 3000 psi which reduces the volume and enables more fuel to be stored in the vehicle thereby increasing the driving range. A typical CNG vehicle can have a capacity of approximately 15 litres of gasoline equivalent to CNG which can travel to about 200 km.

There are three types of CNG vehicles based on their modifications and unique applications:

- *Dedicated Vehicles*

This involves the modification of a gasoline (Otto cycle) engine to CNG combustion. Here, the vehicles are designed to run only on natural gas. The dedicated vehicles have better performance and lower emissions than bi-fuel vehicles. Additionally, dedicated NGVs only have one fuel tank, so they aren't as heavy as bi-fuel NGVs and offer more cargo capacity. The driving range of NGVs is generally less than that of comparable conventional vehicles because of the lower energy density of natural gas. Extra storage tanks can increase range, but the additional weight may displace payload capacity [19]. An example of a light-duty consumer CNG dedicated vehicle is the Honda CNG Civic GX.

Fig 4 an installed CNG engine (Dedicated)
Source: Johns Hopkins University Applied Physics Laboratory

- *Bi-Fuel Vehicles*

This involves altering a gasoline engine to support CNG or gasoline (two-way / bi-fuel) burning; it includes a dual conversion system and a high-pressure fuel tank integrated into a pre-existing gasoline car, allowing it to operate on either natural gas or gasoline. In this setup, the driver can switch to gasoline fuel once the natural gas fuel has been depleted, whether the car is in motion or stationary. The natural gas components can be easily removed from this configuration. A key benefit is the capacity to use the more affordable CNG while maintaining the versatility of the gasoline system if natural gas is not accessible at a specific location [21].

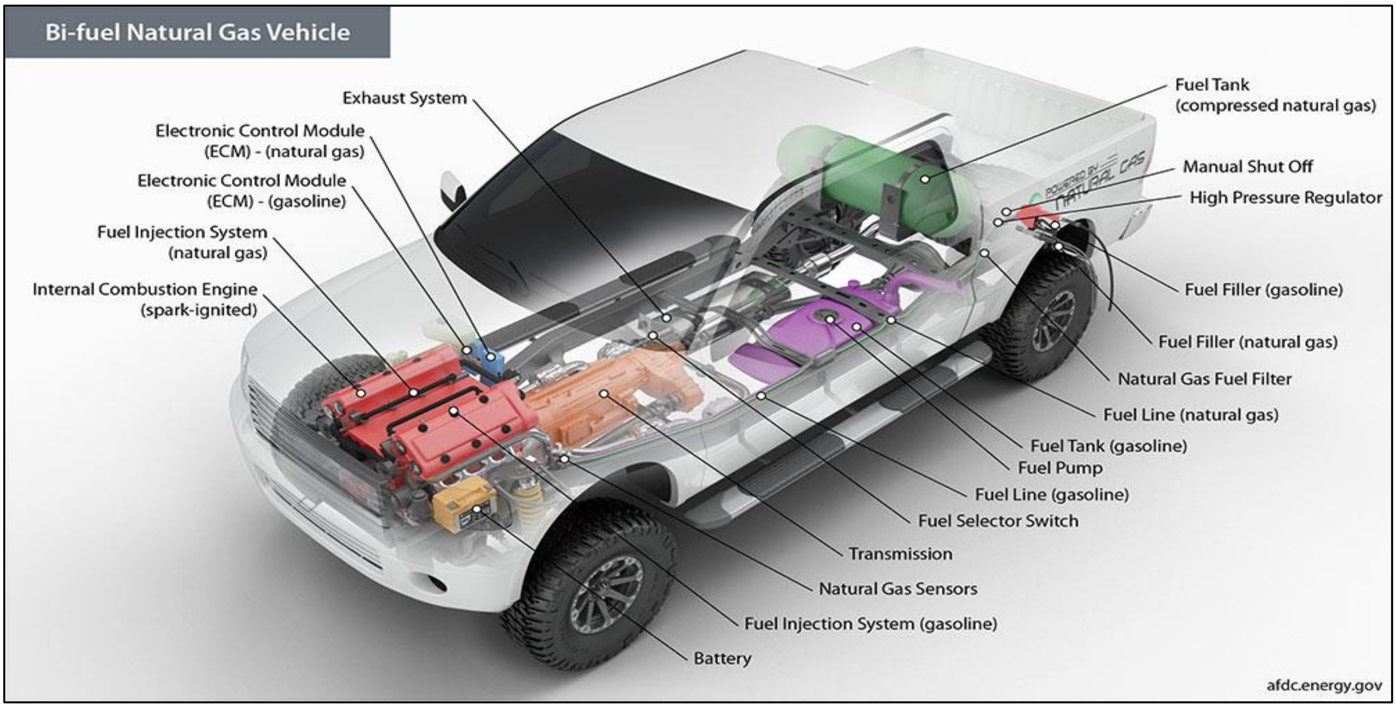

Fig 5 Components of a Bi-fuel Natural Gas Vehicle
Source: Alternative Fuels Data Center

- *Dual-Fuel Vehicles*

Conversion of a diesel engine to dual fuel (gas and diesel combined) combustion; these vehicles are traditionally limited to heavy-duty applications, have fuel systems that run on natural gas, and use diesel fuel for ignition assistance. When the engine is idle the vehicles run 100% on diesel but once they start moving and build up speed, natural gas is injected. The ratio of CNG fuel to diesel fuel is 80:20 [19].

➢ *Advantages of CNG Fuel*

CNG fuel has various advantages that make it viable to be used as a vehicle fuel, and some of these advantages are listed below;

- *Cost and Maintenance*

Though the initial cost of purchasing a natural gas vehicle or converting to it is higher than that of a gasoline vehicle, this is mainly because they are not yet as popular as gasoline cars. However, with more manufacturers making natural gas vehicles, the cost is bound to reduce in the future. Also, the long-term savings experienced with buying a natural gas vehicle are huge, as natural gas has a much lower purchase price than gasoline. Natural gas engines offer significantly lower maintenance costs than gasoline or diesel engines due to the cleaner combustion of gaseous fuels. Natural gas combusts cleanly compared to liquid fuels, minimizing the formation of carbon deposits and thereby reducing strain and wear on engine components [22]. Furthermore, gaseous fuels do not mix with engine lubricants, avoiding dilution or viscosity reduction in gasoline and diesel engines.

As a result, lubricant consumption is lower in natural gas engines, leading to less frequent oil changes. The cleaner-burning characteristics of compressed natural gas (CNG) allow car oil in CNG-powered vehicles to maintain its quality for longer periods compared to gasoline-powered vehicles, further reducing operational costs [23].

- *Mileage*

Further studies need to be done, but generally, you will get more output from a natural gas tank than a gasoline tank. The mileage you receive on natural gas depends heavily on the size of the vehicle and what it is being used for. Also, a tank full of natural gas will cost you far less than a full gasoline tank in Nigeria today [24].

- *Safety*

The characteristics of CNG make it a safe fuel. As reported by [25], compressed natural gas (CNG) is lighter than air, and in the event of a leak, it naturally rises and disperses into the atmosphere. Combustion risks are minimal because ignition occurs only if the gas mixes with air at a specific concentration of 5–15%. However, if the gas concentration in the air is either below 5% or exceeds 15%, it remains non-combustible and will not ignite, even in the presence of a spark. Compared to gasoline, CNG is safer, and tank explosions are rare. It is anticipated that its tanks hold 250% of their rated capacity. Because CNG tanks are subjected to burst tests that sometimes require pressures greater than 40,000 psi, this suggests that a tank with a rating of 3,600 psi can safely support up to 9,000 psi. Because CNG's auto-ignition temperature is 540°C rather than 360°C like gasoline's, it is also safer. In the worst situation, the pressure relief device releasing would cause a "torch" effect. Given their excellent construction, CNG tanks seem to be the most durable component of automobiles.

However, compliance with standards and regulations has to be maintained.

II. MATERIALS AND METHODS

➢ *Procedure*

An installer with CNG certification converts an existing gasoline engine to CNG (bi-fuel). It only involves a few alterations. An additional CNG tank (1) will be connected to a regulator (2). The regulator reduces the pressure of CNG from the tank between 3600 and 125 psi. With that, gasoline is delivered to a parallel fuel rail (3), and an adapter (4) is used to connect new secondary injectors. A parallel wire harness (8) connects to the stock engine control unit through a wiring harness (5) that plugs in and intercepts throttle information. It then sends the data to a new fueling computer (6), which modifies it slightly before delivering it to the CNG injectors (7) [26].

Fig 6 CNG Retrofitting Kits Alternative Fuels Data Center.

➢ *Storage Technologies*

Compressed Natural Gas (CNG) tanks are designed to meet and often exceed the stringent standards for impact and puncture resistance, comparable to or surpassing the safety requirements of under-car gasoline fuel tanks. Over time, the development of CNG tanks has resulted in four distinct types, with each successive type being lighter yet more expensive [27.

- *Type 1:*

Constructed entirely from steel or aluminum, these tanks are the heaviest and least expensive but remain widely used due to their durability.

- *Type 2:*

This type Comprises a thinner metal base reinforced with fiberglass or carbon composite wraps around the middle, they offer a moderate reduction in weight.

- *Type 3:*

Featuring a fully wrapped composite over a thin metal base, these tanks provide significant weight savings compared to Types 1 and 2.

- *Type 4:*

These are made from a plastic liner fully encased in carbon fiber composite, making them extremely lightweight, and the most expensive option [28].

The evolution of CNG tanks highlights the trade-off between cost and weight, with Type 4 tanks being particularly favored for applications requiring reduced weight, such as in light-duty vehicles.

As a result of the low density of CNG and the bulky nature of some of these storage tanks in vehicles which also occupy more cargo space, much research has been conducted and some technologies are now put in place to handle these problems. These technologies are;

Adsorbed Compressed Natural Gas (A - CNG).

The volumetric energy density of compressed natural gas (CNG) or energy per volume, is only 0.12% of that of gasoline at room temperature and atmospheric pressure. Since the compression or liquefaction method uses multi-stage compressors, which are large, energy-intensive, and space-consuming, it will be expensive to use them to increase the density of CNG. Even at that pressure, the density will only rise to 9MJ/L at 3600 psi or about 26% of gasoline's density.

Alternatively, studies have been conducted on adsorbents to store CNG at higher densities under room temperature and pressure [29].

A-CNG is a new storage technology that applies adsorption technology. The ability of a solid to adsorb will depend on its chemical properties and physical structure.

A - CNG functions by allowing the storage of CNG at a lower pressure of about 500 psi or the same higher pressure of about 3600 psi but increased volume in sponge-like nanoporous materials, such as activated carbon, Metal-Organic Frameworks (MOF), etc. A-CNG technology helps in achieving greater efficiency in CNG storage. This technology stores fuel at a similar or greater energy density than CNG. It also means that vehicles can be refueled from the natural gas network without extra compression and as a result, the fuel containers can be made in any shape or slimmed down and be made of lighter, weaker materials.

Activated Carbon made from various materials like; rice husk, nut shells, coconut fiber, and biomass is used as an adsorbent material inside a CNG cylinder. The CNG fuel clings to the surface of the adsorbent. Activated Carbon having a large surface area because of its porous nature helps it to adsorb large volumes of the CNG thereby increasing its density. Activated carbon has been in use for a decade but the need for a more effective adsorbent as regards higher volumetric energy density led to the consideration of MOF [30, 31].

MOF is a coordination network with organic ligands containing potential voids. Its applications are in the areas of gas storage, gas/vapor separation, catalysis, drug delivery, and luminescence. Due to its high porosity and tunable pore surfaces, MOF has received significant attention as a new class of adsorbent. It works more effectively than activated coal in the area of density increment.

➢ *Using ANG Makes it Possible to Either*

- Store a larger volume of CNG in the same container at the same pressure or
- Store the same volume in the container at a lower pressure.

➢ *Advantages of A – CNG*

- ANG allows the use of lightweight, conformable fuel tanks that can be integrated into the limited space available with a small car
- More driving range
- Reduced tank volume
- Fuel is stored at a higher density.

➢ *Integrated Storage System (ISS)*

In 1998, the Johns Hopkins University Applied Physics Laboratory (JHU), in collaboration with Lincoln Composites, developed a groundbreaking Integrated Storage System (ISS) as part of the Advanced Natural Gas Vehicles (ANGV) program. The essence of this initiative is to advance the technology and promote the adoption of light-duty natural gas vehicles (NGVs) in the marketplace.

The ISS features lightweight, all-composite, high-strength cylinders capable of withstanding service pressures of up to 3,600 psi. These pressure cells are encapsulated in impact-absorbing foam to protect them in case of falls or collisions. The cylinders are further housed within a high-strength fiberglass shell, providing additional durability. To address spatial constraints commonly associated with NGVs, the ISS cylinders were designed with smaller diameters and configured into a compact, three-cylinder unit that mimics the size and shape of a conventional gasoline tank [32] as shown in plates 1a and b.

This innovative design significantly improved the practicality of natural gas storage, overcoming a major limitation of NGV adoption. The ISS facilitated easier integration of natural gas storage systems into passenger cars, paving the way for broader acceptance of natural gas technology in the automotive industry. By addressing the challenges of storage size, weight, and safety, the ISS marked a significant milestone in advancing NGV technology and expanding its marketplace potential [33].

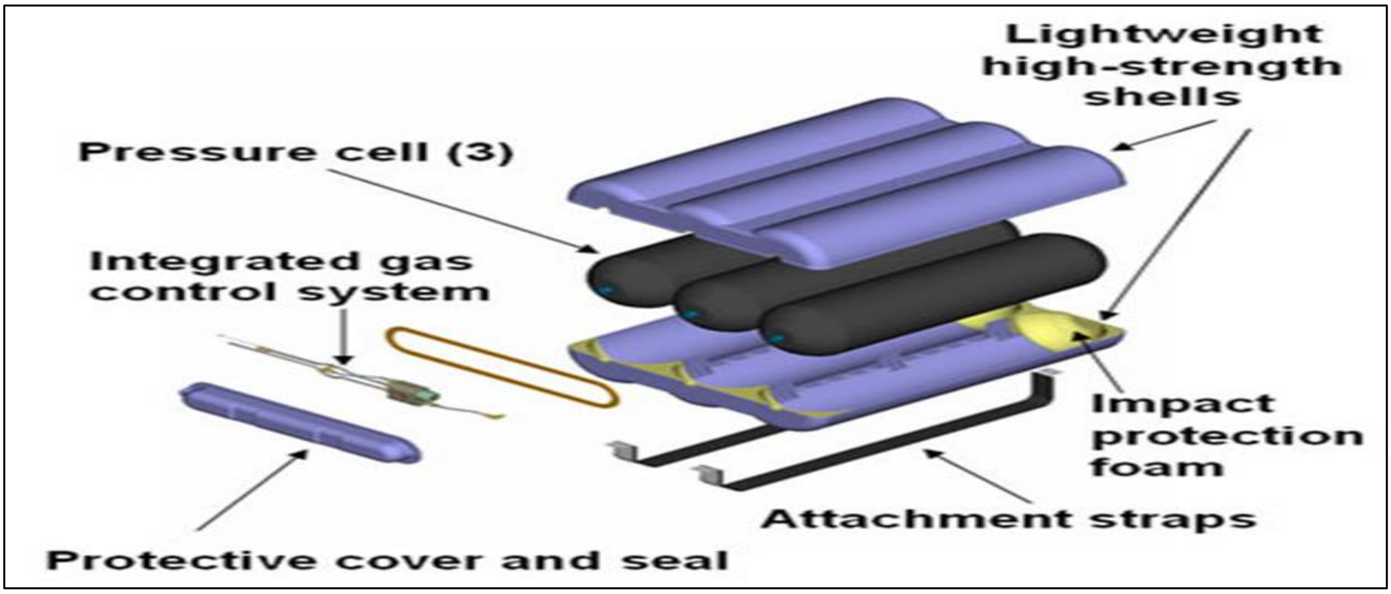

Fig 7 CNG Integrated Storage System
Source: Johns Hopkins University Applied Physics Laboratory

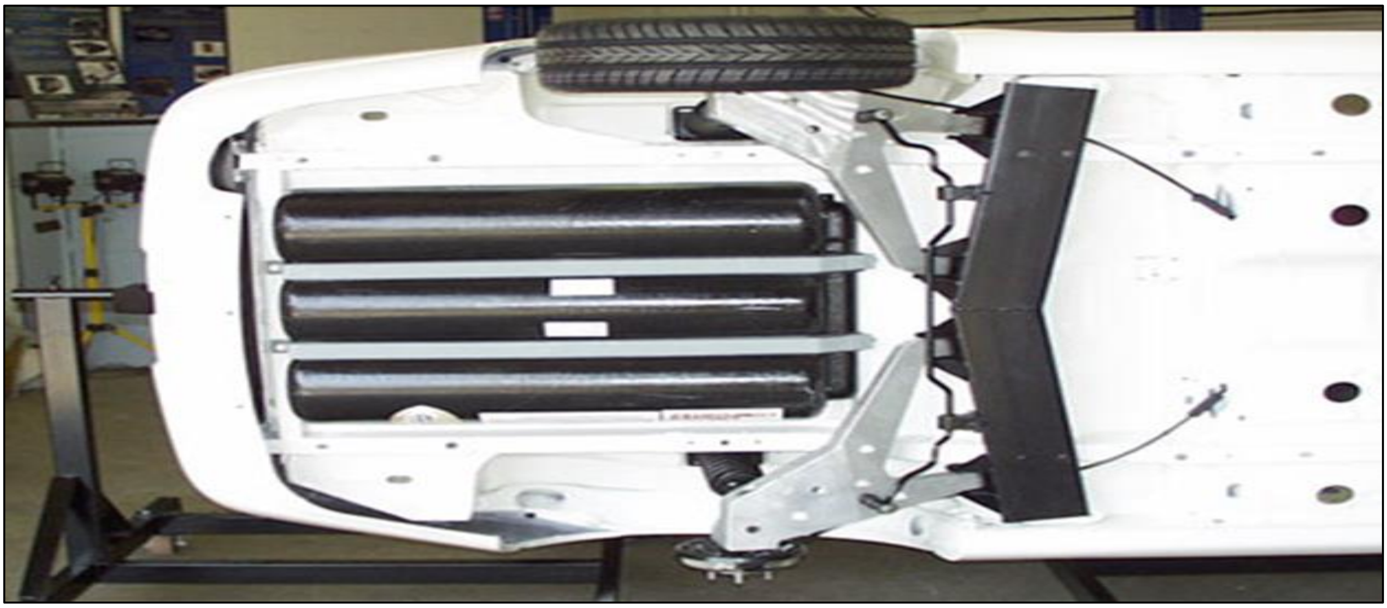

Fig 8 Rear undercarriage Showing Fuel Cylinders
Source: Johns Hopkins University Applied Physics Laboratory

- *The Technology of CNG Emission Reduction*

Since emissions from vehicle exhaust are of great concern to the environment and our health, some technologies have been put in place that can drastically reduce Emissions and achieve a very high efficiency. Two of these technologies are discussed below and they are;

- *Catalytic Converter*

This is an emission control device used in the exhaust system of an internal combustion engine to convert harmful compounds to less harmful ones through a redox reaction [34].

The catalytic converter uses a catalyst such as platinum, rhodium, and palladium. The catalyst is coated on a ceramic honeycomb or beads in a muffler-like package attached to the exhausted pipe [34].

- *Catalytic Converter:*

Although it has a long-term life, it is in the circuit and will often be checked because of what this device brings: if there are physical problems with it, the volumes of exhaust gases emitted outside will increase or the performance of the engine itself inside can decrease – most commonly due to thermal expansion in the pipe system. As unburnt fuel flows into the exhaust, catalysts sometimes can reach well over 1000 degrees Celsius and melt catalyst dunnage. The internal honeycomb is easily broken when the catalytic converter is rapidly cooled, and the exhaust pipe exit is blocked.

- *Two-way Catalytic Converter*

Two–way catalytic converter is used in compression engine. It has two simultaneous tasks which are;

- ✓ Oxidation of carbon monoxide to carbon dioxide expressed as,

$$2NO_x \rightarrow {}_xO_2 + N_2 \text{ and} \quad 1$$

- ✓ Oxidation of unburned hydrocarbons to carbon dioxide and water expressed as,

$$2CO_2 + O_2 \rightarrow 2CO_2 \quad 2$$

- *Three-Way Catalytic Converter*

Three-way catalytic converter is used in a spark ignition engine. It has three simultaneous tasks which are;

- ✓ Oxidation of carbon monoxide to carbon dioxide expressed as,

$$C_xH_y + nO_2 \rightarrow {}_xCO_2 + mH_2O \text{ and} \quad 3$$

- ✓ Oxidation of unburned hydrocarbons to carbon dioxide and water expressed as,

$$2CO_2 + O_2 \rightarrow 2CO_2 \quad 4$$

- ✓ Reduction of nitrogen oxides to nitrogen and oxygen and it can be expressed thus,

$$2NO_X \rightarrow {}_XO_2 + N_2 \quad 5$$

A CNG engine's lean operation promotes the oxidation of carbon monoxide and hydrocarbons, while its rich operation promotes the reduction of nitrogen oxides. See Fig. 7. Theoretically, if a rigorous stoichiometric condition is upheld, it could attain 100% conversion efficiency [34].

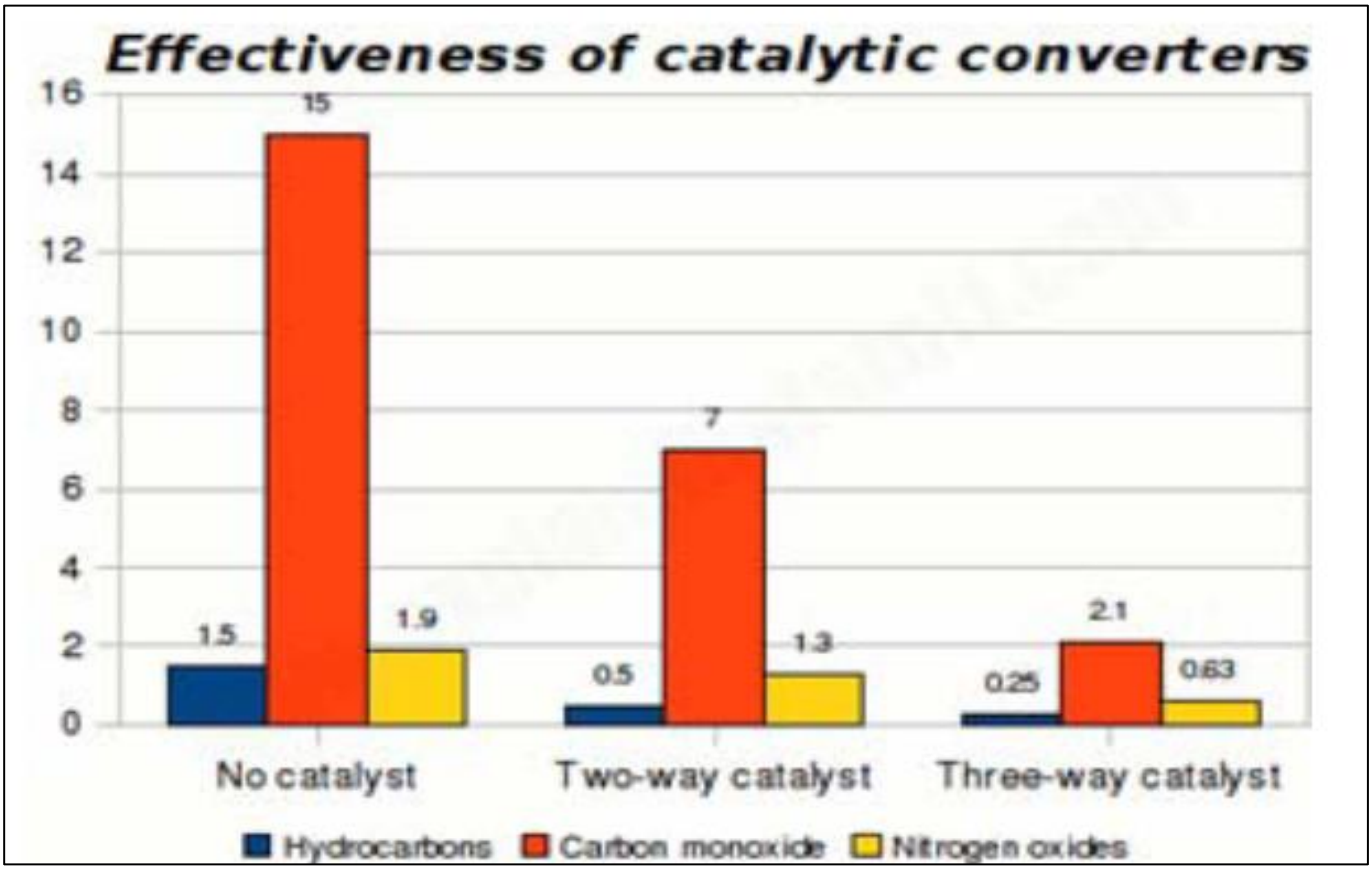

Fig 7 Effectiveness of catalytic converters
Adapted from Review Paper on Catalytic Converter for Automobile Exhaust Emission

➢ *Lambda Sensor and ECU*

This device helps to reduce carbon emissions. It monitors the percentage of oxygen in the exhaust gases and transmits information to the engine management system or Electronic Control Unit (ECU) [35].

The ECU utilizes the information from the oxygen sensor and constantly adjusts the air-fuel mixture to achieve the cleanest and most efficient combustion under all operating conditions.

The ideal ratio of air-fuel to achieve complete combustion is 14.7:1. The chemically correct air-fuel ratio is known as a stoichiometric ratio or lambda (λ) = 1.0. The fuel-rich mixture has a lower value of 0.8 and a lean mixture has a higher value of 1.2. Lambda sensors are classified into three types: zirconia binary, titania, and wideband or air–fuel sensors [36].

➢ *CNG Efficiency and Economy Technologies*

For vehicles to run efficiently mainly as the regulations and economy demand, automobile engineers have been working tirelessly to proffer solutions as a result, so many technologies have been put in place, and these technologies if managed well can enhance the efficiency of car engines. Some of these new technologies are listed below:

- *Variable Valve Timing (VVT) and Lift*

It is a process of changing the timing of the valve lift event to match the engine speed, torque requirement, and valve overlap, this improves performance and fuel economy, reduces emissions (especially nitrous oxides), and decreases pumping losses.

In this method, the exhaust and inlet valve opening and closing times are varied, affecting the engine efficiency. When and how long the valves open (timing) and how long it takes the valves to move (lift), affect the engine efficiency. The potential efficiency improvement of VVT is up to 8 % [37, 38].

Two main types of VVT are cam phasing and cam changing. In cam changing, the Exhaust Control Unit (ECU) selects a different cam profile based on engine load and speed while in cam phasing, an actuator rotates the camshaft, changing the phase angle [39].

VVT optimizes power and torque across a wide RPM (Revolution per Minute) band. The most noticeable results are;

- ✓ The engine can rev higher, thereby raising peak power. For example, the Nissan 2-liter Neo VVL engine produces 25% more peak power than the non-VVT version [40]
- ✓ Low speed torque increases, thus, improving drivability. i.e. Fiat Barchetta's 1.8 VVT engine provides 90 % peak torque between 2,000 and 6,000 RPM.

➢ *The Disadvantage of VVT is that;*

- In some designs, valve lift can vary according to engine speed. At high speeds, a higher lift quickens air intake and exhaust, thereby further increasing the breathing, and at lower speeds such lift will generate counter effects like deteriorating the mixing process of air-fuel, which causes a decrease in the output or even leads to misfire.
- According to [41], Honda developed the CNG engine with VVT electronic control. The engine was designed to improve power and efficiency: increased engine displacement and a variable–length air intake manifold to achieve a 15 % improvement in power. Also, the engine fuel consumption was reduced by 5 % through a combination of reduced pumping loss as a result of inlet valve control delayed closure and charging stroke injection timing that harnesses the properties of gaseous fuel.

- *Turbocharger*

A turbocharger is an exhaust gas recovery device designed to increase and boost air pressure, thereby optimizing combustion. Turbochargers enhance engine efficiency by approximately 7–8%, particularly boosting fuel efficiency in Otto-cycle gasoline engines, although they are predominantly used in diesel engines [42]. The device operates by recycling exhaust gases through a system that integrates two bladed wheels—a compressor and a turbine—mounted on the same shaft.

The engine's hot exhaust gases drive the turbine, which in turn rotates the compressor. The turbine recovers energy from the hot exhaust gases, which are then directed to heat exchangers for cooling. The cooling process reduces the density of the hot air, enabling the compressor to supply denser, oxygen-rich air to the engine for combustion. This cycle enhances engine performance while reducing waste emissions. Excess exhaust gases are expelled through the exhaust system, while cooled air is recirculated to the compressor for continuous operation [43].

Modern turbochargers employ complex valve systems and computerized controls to optimize performance under varying power demand levels. These innovations ensure that turbochargers deliver peak efficiency at different operating conditions. According to Tom Grissom, the Director of Business Development at BorgWarner Turbo Systems, "a turbocharged 3.5-liter engine has the same power today as a 4.0 or 5.0-liter engine had without a turbo" [44].

- *Direct Fuel Injection CNG Injector*

The advent of direct fuel injection systems in compressed natural gas (CNG) engines has revolutionized fuel delivery, improving efficiency and drivability. Unlike previous systems where fuel is mixed with air before injection, modern direct injection systems inject CNG directly into the combustion chamber. The mixing process is optimized based on the combustion chamber's profile, resulting in an 11–13% increase in efficiency and up to 60% more torque at low RPM compared to manifold gas injection systems [45, 46]. Direct injection offers several advantages, making CNG systems more dynamic and sustainable. Improved volumetric efficiency, precise fuel regulation, and enhanced combustion quality result in better power delivery and fuel consumption. The benefits of direct fuel injection CNG systems include:

✓ *Environmental Benefits:*

Reduction in CO_2 emissions by up to 25%, CO emissions by up to 80%, and near-zero particulate emissions. These features align with Euro 6 emissions standards, ensuring compliance with stringent environmental regulations [45].

✓ *Enhanced Efficiency:*

Direct injection systems exhibit superior combustion efficiency compared to gasoline direct injection systems, contributing to reduce fuel consumption and operating costs.

✓ *Improved Durability:*

CNG injectors are designed for high wear resistance, even in lubricant-free gaseous fuel operations. Tests have demonstrated up to 400 million cycles under CNG conditions [46].

✓ *Operational Benefits:*

Systems operate with low noise and are fully compatible with conventional engine controllers, facilitating seamless integration into existing engine architectures.

Moreover, the high torque available at lower RPMs provides drivability comparable to gasoline direct injection engines, further enhancing vehicle performance [45]. These advancements position CNG as a viable alternative to traditional fuels, meeting both environmental and performance demands in modern vehicles.

The lower cost of compressed natural gas and reduced fuel consumption help reduce vehicle operating costs for consumers. No technology directly injects CNG into the combustion chamber, but research is ongoing to develop a direct injection system that exclusively runs on CNG.

- *Cylinder Deactivation (Multiple Displacement Technology*

Cylinder deactivation, a multiple displacement technology, is a fuel-saving mechanism commonly employed in large internal combustion engines (ICE) such as six- or eight-cylinder configurations. Similar in principle to Variable Valve Timing (VVT) and lift systems, this technology temporarily deactivates some of the engine's cylinders when a low power demand, which effectively reduces the engine's total displacement and fuel consumption.

The system is particularly beneficial where less power is needed, such as cruising at constant speeds or driving under light load conditions. For example, an eight-cylinder engine can function as a four-cylinder engine, and a six-cylinder engine can operate as a three-cylinder engine, reducing fuel consumption while maintaining drivability [47].

According to the U.S. Department of Energy, cylinder deactivation technology can improve engine efficiency by approximately 7.5% [47]. This improvement is achieved by reducing the amount of fuel burned and the work required from the deactivated cylinders. The system seamlessly reactivates the cylinders when higher power demand is detected, ensuring a balance between fuel efficiency and performance.

Cylinder deactivation is a popular choice for heavy-duty vehicles and high-performance engines due to its simplicity and effectiveness in reducing fuel consumption and emissions without significant engine redesigns [48].

- *Economics of Utilizing CNG as Vehicle Fuel*

There are different methods for measuring the profitability of an investment. However, in this research, only two are used because we are only interested in when the money spent on CNG conversion will be realized. They include:

✓ Payback Period Method
✓ Discounted Payback Period Method

➢ *Payback Period*

The payback period is the period required to recover an investment's cash flow from the cash inflows generated by the investment. The payback period of a given investment is an important determinant of whether to undertake a project. It is also one of the simplest investment appraisal techniques. An investment with a shorter payback is considered a better investment.

The payback period is calculated based on whether the project is even or uneven.

The even payback is calculated using the formula below;

$$\text{Payback period} = \frac{initial\ investment}{cash\ inflow\ per\ period} \quad (6)$$

When cash inflows are uneven, the cumulative net cash flow is calculated for each period and the following formula is used;

$$\text{Payback period} = A + \frac{B}{C} \quad (7)$$

Where A is the last period with a negative cumulative cash flow;

B is the absolute value of cumulative cash flow at the end of the period A;

C is the total cash flow during the period after A.

➢ *Advantages of the Payback Period*

- It is simple to calculate
- It can be a measure of risk inherent in a project
- It provides a good ranking of projects that would return money early for companies facing liquidity problems.

➢ *Disadvantages of the Payback Period*

- It does not take into account the time value of money which is a serious drawback since it can lead to wrong decisions
- It does not account for the cash flows after the payback period.

The first quantitative analysis performed on the vehicle was the payback period analysis. It shows that, the more fuel a vehicle consumes, and the more distance it covers, the better the economic payback.

The payback period for a specific natural gas vehicle was used to determine if the benefits of the investment would outweigh the costs within a desired period. The analysis was done using an Excel spreadsheet. The data required to perform this analysis include the capital costs associated with converting a vehicle to a CNG engine, total vehicle kilometers traveled, and fuel economy in km per kg. The difference in fuel price between natural gas and gasoline was also considered in the analysis.

➢ *Discounted Payback Period*

The discount payback period is a kind of payback period that considers the time value of money by discounting the cash inflow of the project.

In the discounted payback period we have to calculate the present value of each cash inflow taking the start of the first period as zero point. As a result, management has to set a suitable discount rate. The discounted cash inflow for each period is to be calculated using the formula:

$$\text{Discounted Cash Flow} = \frac{Actual\ Cash\ Flow}{(1+i\ )^n} \quad (8)$$

Where,

i = the discount rate;

n = the period to which the cash inflow relates.

The present value factor is expressed as;

$$\left(\frac{1}{(1+ii)^n}\right) \quad (9)$$

Thus discounted cash flow is the product of actual cash flow and present value factor.

The rest of the procedure is similar to the payback period calculation except that we have to use the discounted cash flows as calculated above instead of actual cash flows. The cumulative cash flow will be replaced by cumulative discounted cash flow.

$$\text{Discounted Payback Period} = A\ \frac{B}{C} \tag{10}$$

Where,

A = Last period with a negative discounted cumulative cash flow;

B = Absolute value of discounted cumulative cash flow at the end of the period A;

C = Discounted cash flow during the period after A.

The project will be accepted if the discounted payback period is shorter than the target period.

III. RESULTS AND DISCUSSION

Two Maritus Zen cabs running on gasoline and CNG were compared and the differences in their fuel prices, and mileages were recorded and used by calculating their running costs and the difference between the two fuels. The CNG engine conversion price was also considered [49].

The calculation and comparison in Table 2 are based on the Nigerian National Petroleum Corporation Limited (NNPCL)'s official current price of petrol at N1060 / L [50] report, and NIPCO's official current price of CNG at N200 /Kg, [51]. The conversion price of the CNG engine used for the calculation is N200, [52].

Table 2 Cost Comparisons and Payback Period for CNG (M.ZEN Cab)

Fuel	Petrol	CNG
Fuel Price	N1060 / L	N200 / Kg
Mileage	13 Km / L	20 Km / Kg
Running Cost	N81.54 / Km	N10 / Km
The Difference in Cost Savings of the Two Vehicles		N71.54 / Km
Conversion Price for CNG Vehicle		N200,000

Three M.ZEN cabs running only on CNG fuel were selected this time and made to run three different distances each daily. To calculate the duration, it would take to recover the cost of the CNG engine conversion, the cost savings for each car were calculated by multiplying the distance by the difference in cost savings between the two fuels (see Table 2), dividing the conversion money by the cost savings per day, and recording the result for each taxi in days, months, and years, respectively.

By determining the daily mileage by dividing the total number of days on the road by three, the overall distance covered by the three cars was established.

$$Cost\ Saving = Distance * Difference\ in\ the\ price\ between\ gasoline\ and\ CNG \tag{11}$$

$$Days = \frac{Conversion\ Price}{Cost\ Saving} \tag{12}$$

$$Total\ Distance\ Covered = Days * Distance \tag{13}$$

The computation of the month and year involved multiplying the respective values by the thirty days in a month and the twelve months in a year.

Table 3 Payback Period for CNG Vehicle (M.ZEN Cab)

Payback details	CNG		
Distance (Km / Day)	50	75	100
Cost Saving (N) Day)	3577	5365.5	7154
Days	55.913	37.275	27.956
Total Distance Covered (Km)	2795.65	2795.63	2795.6
Months	1.864	1.2425	0.932
Years	0.153	0.102	0.0766

As seen in the right-end column of Table 4, the net present value (NPV) became positive within the second month. This shows that the discounted payback period works faster than the simple payback period due to the discount rate.

Table 4 Discounted Payback Period Calculation Example for a CNG Vehicle

Years (n)	**Cash flow (N)**	**Present Value Factor = $1/(1+i)^n$**	**Discounted Cash Flow CF*PV (N)**	**Cumulated Discounted Cash Flow (N)**
0	-200000	1	-200000	-200000
1	121362.5	0.91	110329.55	-89670.45
2	121362.5	0.83	100299.59	210629.13
3	121362.5	0.75	91181.44	191481.03

4	121362.5	0.68	82892.22	174073.66
5	121362.5	0.62	75356.56	158248.78
6	121362.5	0.56	68505.97	143862.53
7	121362.5	0.51	62278.15	130784.12
8	121362.5	0.47	56616.50	118894.65
9	121362.5	0.42	51469.55	108086.05

$$Discounted\ Payback\ Period = \frac{1+(-89670.45455)}{100299.59} = 0.1\ year \qquad 14$$

It was noted that the capital was recovered after a short period for both payback and discounted payback calculations. Based on the above results, it is therefore imperative that CNG is used as an alternative to gasoline.

IV. CONCLUSIONS

This study provides an in-depth analysis of the technical and economic feasibility of using CNG as an automobile fuel in Nigeria.

The findings suggest that CNG is a viable option, offering economic and environmental benefits.

RECOMMENDATIONS

The following recommendations were made after some careful consideration:

- *Government Involvement:*

The federal government should actively promote CNG as an alternative fuel to reduce gas flaring and create economic opportunities.

Policy interventions and investments in CNG infrastructure to support its adoption.

- *Infrastructure Development:*

Adequate fueling stations and maintenance facilities must be established nationwide.

- *Public Awareness:*

Awareness campaigns should be launched to educate the public on the benefits of CNG.

- *Training Programs:*

Mechanics and drivers should be trained on CNG vehicle maintenance and operation.

Further research is needed to address the limitations of CNG fuel, including truck space, driving range, and fueling facilities.

- *List of Abbreviations*

CNG = Compressed Natural Gas

NGC = Nigeria Gas Company

Btu = British thermal unit

SCF = Standard Cubic Feet

CH4 = Methane

TCF = Trillion Cubic Feet

NNPCL = Nigeria National Petroleum Corporation Limited

NLNG = Nigeria Liquefied Natural Gas

NUPRC = Nigeria Upstream Petroleum Regulatory Commission

SOx = Sulphur Oxides

KJ / Kg = KiloJoule / Kilogram

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