Performance Evaluation of Transportation Fuel Technologies from Natural Gas - A Comparative Analysis

Obo-Obaa Elera Njiran[1]; Prof. Joseph A. Ajienka[2]; Franklin Okoro[3]
[1,2]Centre For Gas, Refining And Petrochemicals Engineering University Of Port Harcourt
[3]Cleanscript Group

Abstract*:- With Nigeria's large and growing population, and rapid growth in urbanization, there is the likelihood that the energy demand including that for transportation will continue to increase and, thus, put further pressure on the country's environment, intensify the climate change threat and exacerbate transportation energy challenges. This study critically evaluated Autogas and CNG, and the factors impeding its utilization in Nigeria. The study also discussed other gas utilization options. Technological modifications needed to boost the utilization of CNG as a transportation energy source were discussed. Finally, a comparative analysis of Autogas, CNG, natural gas to hydrogen and natural gas to electricity technologies in transportation sector was conducted using Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS). From the TOPSIS analysis and results, the best natural gas transport technology considering fuel life cycle efficiency and life cycle greenhouse gas emission is Natural Gas to Electricity technology with a score of 0.691. This is followed by Natural gas to hydrogen technology with a score of 0.689. This is followed by LPG with the score of 0.459. CNG is the least efficient technology in this analysis with a score of 0.308. The TOPSIS analysis indicated that Autogas and CNG is superior to the other transport fuel technologies in terms of greenhouse gas emissions but performed poorly against them in the area of fuel life cycle efficiency. Hence, more focused researches on how to improve the fuel life cycle efficiency of CNG in order to maximize its utilization in the transportation sector and boost the Nigerian Economy need to be conducted.

***Keyword*: Performance evaluation, transportation fuel technologies, natural gas**

I. INTRODUCTION

Nigeria is among the world's ten most populous countries (United Nations, 2015), and the eighth largest producer of crude oil (Nigerian National Petroleum Corporation, 2014). In addition, Nigeria has the seventh largest proven reserves of Natural Gas (NG) in the world, estimated at 187 trillion cubic feet (Tcf) (Nigeria Liquefied Natural Gas Ltd, 2011). The Nigerian NG is of high quality; rich in liquids hydrocarbons and low in sulphur. The country's proven gas reserves were discovered during oil exploration and it is believed that these could increase to 600tcf if intentionally explored (Nigeria Liquefied Natural Gas Ltd, 2011).

The Nigerian economy is dependent on the income generated from the production, processing, export and consumption of fossil fuels and associated energy-intensive products, as oil and gas exports accounts for more than 98% of export earnings and over 40% of gross domestic product (GDP) (World Bank, 2011). Although there are conflicting figures on the contribution to GDP after the rebasing of the economy in 2013, the contribution is still significant – ranging from 14% (NBS, 2014, 2018) to 35% (OPEC, 2015). Nonetheless, the sector continues to account for more than 90% of export earnings. Oil and gas exports contributed USD 77 billion out of the total export earnings of USD 84 billion in 2014 (OPEC, 2015).

Despite the contribution of the oil and gas sector to the economy, the disposal of Associated Gas (AG), the raw NG that is found during oil exploration and production, creates social and environmental challenges (World Bank, 2004) and results in the waste of valuable natural resources.

The composition of AG produced in Nigeria can be roughly described as 90% methane, with 1.5–2.0% CO2, 3.9–5.3% ethane, 1.2–3.4% propane, 1.4–2.4% heavier hydrocarbons and trace amounts of Sulphur (Ashton-Jones *et al*., 1998). Nonetheless, volume and composition of AG produced at any oil well depend on multiple factors, such as the nature and the degree of depletion of the reservoir, and the type of lift used in the production process (PFC Energy, 2007).

AG was considered a by-product to be disposed of because of safety considerations in the oil exploration and production processes. The disposal processes include discharge into the atmosphere, known as venting, and burning during discharge, known as flaring. Venting releases the entire constituent of AG, predominantly methane, into the atmosphere, while flaring emissions range between raw NG and ideal methane combustion emissions of water vapour and CO2, depending on the efficiency of the operation (Buzcu-Guven *et al*., 2010).

Consequently, the impact of venting on the environment would be greater than if the equivalent amount of gas was flared, because hydrocarbons have higher potential for global warming than CO_2 (Houghton *et al*. 2001). Nonetheless, venting and flaring both result infugitive emissions, which predominantly consist of methane, are invisible to the naked eye, difficult to detect and measure, and are significantly hazardous to public health, the environment and eco-systems.

There is a paucity of data on vented volume globally, as many oil-producing countries including

Nigeria- do not report on this.

Data of the World Bank-led Global Gas Flaring Reduction Partnership indicates that more than 150 billion cubic metres (bcm) of NG are flared annually, and that the top ten countries – Russia(26.7%), Nigeria (10.4%), Iran (8.1%), Iraq (6.7%), USA (5.1%), Algeria (3.6 %),Kazakhstan (3.4%), Angola (2.9 %), Saudi Arabia (2.6%) and Venezuela (2.5%) – account for over 70% of the global volume of gas flared (World Bank, 2015).

Self-reported figures by the state-owned Nigerian National Petroleum Corporation (NNPC) indicate that 51% – that is, 459bcm of the 902bcm of AG produced between 1990 and 2010 –was flared (NNPC, 2013). In perspective, the volume represents 53 billion liters gasoline equivalent, which translates to over 14.5 years' worth of national gasoline consumption (NNPC, 2014).

While there are no official figures for the economic losses associated with gas flaring in Nigeria, it was reported that Nigeria lost about USD 72 billion of unearned revenue between1970 and 2006 due to gas flaring (Bassey, 2008) while Eboh (2015) estimated the cost of gas flared in 2014 at USD 869 million.

Figure 1.1 shows images of some gas flare sites in the Niger Delta area of Nigeria.

Figure 1. 1: Gas flaring in the Niger Delta area of Nigeria (Source: http://azibegna.wordpress.com/2010/01/22/nigeria-luci-sullacqua)

Nigeria has made efforts to exploit its NG resources and reduce the environmental impact and economic losses associated with gas flaring and venting using various instruments including legislation, fiscal incentives, and the development of a gas-export market for both dry and liquefied NG, construction of gas pipelines and promotion of Autogas and the domestic use of CNG as an automotive fuel. These initiatives are yielding results, particularly in gas exports and domestic use of gas in the power and industrial sectors, and have been further boosted by the institution of the domestic gas supply obligation, which mandates oil and gas companies to make a portion of the gas they produce available to the domestic market. Compressed natural gas is NG compressed at high pressure to a much lower volume, typically about 1/200th of the original volume (Economides and Mokhatab, 2007).

The Federal Ministry of Petroleum Resources (MPR) (2012) reported that the domestic gas obligation initiative contributed 28 million cubic metres (mcm) of NG to the domestic market per day between 2011 and 2012, and that the country has initiated an accelerated gas development and utilization programme geared towards the collection of gas from flare sites and making it available to indigenous third-party companies. It further reported that a pilot programme had installed gas flare meters at a number of flare sites to help determine the actual volume of gas flared and levy appropriate fines or penalties. These initiatives and previous gas projects - such as the Oso Condensate, the Nigeria Liquefied Natural Limited and the Escravos Gas Project – have played a part in reducing both the percentage volume and absolute volume of gas flared. However, NNPC (2012) data indicate that whereas the percentage volume of gas flared reduced significantly, dropping from 77% in 1990 to 18% in 2012, the absolute volume only reduced by 26%, dropping from 27 billion cubic meters (bcm) to 20 bcm.

Despite the reduction in both the volume and percentage of gas flared, World Resources Institute (WRI, 2014) data indicate an increase in the absolute volume of energy-related greenhouse gas (GHG) emissions and showed that fugitive emissions and transportation are still the two largest sources in Nigeria, contributing 31.34% and 8.94%, of total volume respectively. The data further showed that methane is the dominant gas, unlike many other countries where CO_2 dominates. Moreover, Obioh *et al*. (1994) observed the gas flare content includes sulphur dioxide (SO_2), despite the low sulphur contents of AG produced in the country. The increasing volumes and the composition of the GHG present long-term risks, with implications for public health and the national economy – especially as hydrocarbons have significantly higher impact on public health, climate change and potential for global warming than CO_2 (Houghton *et al*., 2001). In addition, SO_2 is hygroscopic, i.e., it reacts with humidity when it is in the atmosphere and forms sulphuric and sulphurous aerosol acid that is later part of acid rain. Ite and

Udo (2013) gave a detailed account of the adverse effect of gas flaring and venting on humans and the environment in Nigeria, particularly the Niger Delta region where most of the flare sites are located.

According to World Bank data, the Nigerian population grew by 384%, from 45.2million in 1960 to 173.6 million in 2013, and witnessed significant urban drift, from 14% of the population living in urban areas in 1960 to 50% in 2013. These changes indicate the likelihood of increased demand for transportation energy, which will in turn put further pressure on the country's environment and intensify the climate change threat. On the other hand, pump price subsidies of gasoline and kerosene complicate the energy situation. As reported by the Economist (2012) and widely known, the petroleum subsidy is fraught with corruption, ineptitude and inefficiency, which sometimes results in delays in the importation of products by the oil marketing companies; this in turn results in perennial fuel scarcity. Figure 1.2 shows why the NNPC-initiated a Mega Station scheme to make gasoline available at a lower price per litre compared to the price obtainable at privately owned refuelling stations (NNPC was hitherto not involved in downstream operations). However, this intervention has not solved the problem and calls for an increased effort in harnessing the use of NG in Nigeria.

Considering the options for using natural gas for transportation - and their energy and environmental consequences - can help ensure that we get the most possible value from this new era of natural gas. In this study, the life cycle efficiencies and life cycle greenhouse gas emissions of the three natural gas transportation technologies will be evaluated using the Technique of Order Preference by Similarity to Ideal Solution (TOPSIS).

These technologies include:

i. Liquefied Petroleum Gas via burning using internal combustion engine vehicle
ii. Compressed Natural Gas via burning using internal combustion engine vehicle.
iii. Natural Gas to Hydrogen via reforming using Fuel cell electric vehicle.
iv. Natural Gas to Electricity via generation using Plug-in electric vehicle.

TOPSIS is one of the most useful Multi Attribute Decision Making (MADM) techniques that are very simple and easy to implement, such that it is used when the user prefers a simpler weighting approach. TOPSIS method was firstly proposed by Hwang & Yoon (1981). According to this technique, the best alternative would be the one that is nearest to the positive ideal solution and farthest from the negative ideal solution (Benitez *et al*., 2007). The positive ideal solution is a solution that maximizes the benefit criteria and minimizes the cost criteria, whereas the negative ideal solution maximizes the cost criteria and minimizes the benefit criteria (Wang & Chang, 2007; Wang & Elhag, 2006; Wang & Lee, 2007; Lin *et al*., 2008). In other words, the positive ideal solution is composed of all best values attainable of criteria, whereas the negative ideal solution consists of all worst values attainable of criteria (Ertuğrul & Karakasoğlu, 2009).

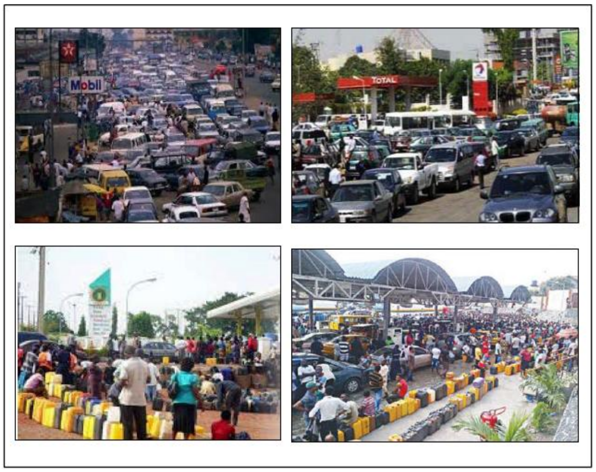


Figure 1. 2: Long queues at filling stations due to fuel scarcity (Source: Information Nigeria, 2014)

II. METHODOLOGY

The analysis, evaluation and comparison of the different natural gas transport technologies is done via a multi-criteria decision-making approach using the Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS). The technologies compared here include: Liquefied Petroleum Gas, Compressed Natural Gas, Natural Gas to Hydrogen and Natural gas to Electricity. These technologies are compared and evaluated based on two broad criteria: fuel life cycle efficiency and life cycle Greenhouse Gas Emissions.

Technique for Order Preference by Similarity to Ideal Solution (TOPSIS)

In multi-criteria decision-making analysis, there are important terms worthy of note and these include (Beg and Rashid, 2014):

Alternatives – These are the options which are going to be compared and analyzed for selection.

Criteria/Attributes – These are factors on which the evaluations and comparisons will based on.

Weights – These are scores or points assigned to each criterion based on their relative importance to the comparison. Each criterion is assigned certain scores on a scale of 1-10 or 1-100 by the decision maker(s).

Decision maker(s) – These are experts or someone who has been appointed to assign scores to the alternatives with respect to the criteria. There can be any number of decision makers.

Decision matrix – This is a table that is developed to enable the objective selection of an option from a range of options or alternatives.

TOPSIS hypothesizes two artificial solutions:

Ideal solution: This is the alternative with the best attribute values

Negative Ideal Solution: This is the alternative with the worst attribute values.

TOPSIS chooses the option that is closest to the ideal alternative and farthest from the negative ideal alternative (Beg and Rashid, 2014).

Steps involved in analysis with TOPSIS (Greene et al., 2011)

Step 1 – Standardize the decision matrix

This step changes the attributes from dimensional to dimensionless attributes, thereby allowing comparisons across the criteria. For standardizing to be achieved, each column of the decision matrix is divided by the root of sum of square of respective row.

Step 2 – Develop weighted standardized decision matrix. This is achieved by multiplying the assigned criteria weight to each rating in the standardized decision matrix

Step 3 – Compute ideal solution and negative ideal solution. The ideal solution is a set of maximum ratings for each criteria. Similarly, a set of minimum scores for each attribute is the negative ideal solution.

Step 4 – Compute the separation from ideal solution Si*. This is the square root of the sum of the difference between the ideal solution and the corresponding ratings across the rows of the weighted standardized decision matrix.

Step 5 – Compute the separation from negative ideal solution Si'. This is the square root of the sum of the difference between the negative ideal solution and the corresponding ratings across the rows of the weighted standardized decision matrix.

Step 6 – Compute the relative closeness to ideal solution. This is done using the formula:

C_i^*=(S_i^')/((S_i^*+S_i^')) 3.1

The option with value closest to 1 and farthest from 0 is the best option.

The outcomes of this analysis in the present study will be presented in chapter 4 (Results and Discussions).

The normalized decision matrix $rij = x_{ij} / \left(\Sigma x_{ij}^2\right)^{\frac{1}{2}}$ 4.1

is presented in table 4.3 and 4.4.

The weighted normalized decision matrix $v_{ij} = w_j r_{ij}$ 4.2

is constructed by multiplying each column of the normalized decision matrix (table 4.4) by its corresponding weight (table 4.1) and the new matrix

$$rij = x_{ij} / \left(\Sigma x_{ij}^2\right) \tag{4.3}$$

is constructed as presented in table 4.5. A set of maximum values for each factor (from table 4.5) also referred to as the ideal Alternative

$$A^* = \{v_1^* \dots v_n^*\} \tag{4.4}$$

is determined as presented under step 3 below. In the same way, a set of minimum values for each factor (from table 4.5) also referred to as the Negative ideal Alternative

$$A' = \{v_1' \dots v_n'\} \tag{4.5}$$

is determined as presented in step 3.

The separation from the ideal Solution I,

$$S_i^* = \left[\Sigma\left(v_j^* - v_{ij}\right)^2\right]^{\frac{1}{2}} \tag{4.6}$$

is determined as presented in table 4.6 and the outputs are presented under step 4a. Also, the separation from the negative ideal Solution,

$$S_i' = \left[\Sigma\left(v_j' - v_{ij}\right)^2\right]^{\frac{1}{2}} \tag{4.7}$$

is determined as presented in table 4.7 and the outcomes are presented under step 4b.

The relative closeness to the ideal solution,

$$C_i^* = S_i' / (S_i^* + S_i') \tag{4.8}$$

is calculated and the outputs are as presented in table 4.8.

Table 4.1 below presents the weights scored against each of the criteria on a scale of 1-10 based on their relevance to the analysis. The weights shown here are average of the scores from experts' judgements.

Table 4. 1: Weights scored to the factors

CRITERIA	SCORE	SCORE RATING SCALE
Fuel efficiency	8	10 implies highly relevant, 1 implies not relevant
Greenhouse gas emissions	8	10 implies highly relevant, 1 implies not relevant

The alternatives to be compared include:

Option 1: Liquefied Petroleum Gas (LPG)

Option 2: Compressed Natural Gas (CNG)

Option 3: Natural Gas to Hydrogen (NGH)

Option 4: Natural Gas to Electricity (NGE)

Table 4. 2: x_{ij} = rating of alternative i with respect to factor j

Criteria	**LPG**	**CNG**	**NGH**	**NGE**
Fuel efficiency	0.4	0.2	0.6	0.8
Greenhouse gas emissions	0.7	0.7	0.6	0.4

Step 1: Standardizing the decision matrix

Table 4. 3: Standardized the decision matrix

Criteria	LPG	CNG	NGH	NGE	$(\Sigma x^2_{ij})^{1/2}$
Fuel efficiency	0.4	0.2	0.6	0.8	1.095
Greenhouse gas emissions	0.7	0.7	0.6	0.4	1.225

Step 1 (b): divide each row by $(\Sigma x_{ij}^2)^{\frac{1}{2}}$ to obtain r_{ij} which is the normalized decision matrix as presented in table 4.4 below.

Table 4. 4: The normalized decision matrix

Criteria	**LPG**	**CNG**	**NGH**	**NGE**
Fuel efficiency	0.365	0.183	0.548	0.731
Greenhouse gas emissions	0.571	0.571	0.489	0.327

Step 2: Construct weighted standardized decision matrix by multiplying the factor weight (as shown in table 4.1) with the corresponding score provided in table 4.4 above. The weighted standardized decision matrix is as shown in table 4.5 below:

Table 4. 5: The weighted normalized decision matrix

Criteria	**LPG**	**CNG**	**NGH**	**NGE**
Fuel efficiency	2.92	1.464	4.384	5.848
Greenhouse gas emissions	4.568	4.568	3.912	2.616

Step 3: Determine ideal alternative and negative ideal alternative

A set of maximum values for each factor across the rows is the ideal alternative while a set of minimum values for each factor across the row is the negative ideal alternative.

Ideal alternative A*: {5.848, 4.568}

Negative ideal alternative A': {1.464, 2.616**}**

Step 4: Determine separation from ideal alternative, S_i*

Step 4 **(a):** calculate separation from ideal solution A* = {5.848, 4.568} and $S_i^* = \left[\Sigma\left(v_j^* - v_{ij}\right)^2\right]^{\frac{1}{2}}$ for each column. This is computed and results are presented in table 4.6 below.

Table 4. 6: The ideal alternative

Criteria	**LPG**	**CNG**	**NGH**	**NGE**
Fuel efficiency	8.573	19.219	1.638	0
Greenhouse gas emissions	0	0	0.430	3.810

$S_i^* = \left[\Sigma\left(v_j^* - v_{ij}\right)^2\right]^{\frac{1}{2}}$ **= {2.928, 4.384, 1.438, 1.925}**

Step 4 (b): calculate separation from negative ideal alternative A' = **{**1.464**,** 2.616**}** and $S_i' = \left[\Sigma\left(v_j' - v_{ij}\right)^2\right]^{\frac{1}{2}}$ for each column as presented in table 4.7 below.

Table 4. 7: Separation from the negative ideal solution

Criteria	LPG	CNG	NGH	NGE
Fuel efficiency	2.119	0	8.526	19.219
Greenhouse gas emissions	3.810	3.810	1.679	0

$S_i' = \left[\Sigma\left(v_j' - v_{ij}\right)^2\right]^{\frac{1}{2}}$ **= {2.485, 1.952, 3.195, 4.384}**

Step 5: Compute the relative closeness to the ideal solution $C_i^* = S_i' / (S_i^* + S_i')$

The matrix of the closeness to the ideal solution is shown in table 4.8 below:

Table 4. 8: The relative closeness to the ideal solution

Criteria	**LNG**	**CNG**	**NGH**	**NGE**
Si*	2.928	4.384	1.438	1.952
Si'	2.485	1.952	3.195	4.384
Si*+Si'	5.413	6.336	4.633	6.336
$\boldsymbol{S_i' / (S_i^* + S_i')}$	0.459	0.308	0.689	0.691

From the TOPSIS analysis and results, the best natural gas transport technology considering fuel life cycle efficiency and life cycle greenhouse gas emission is Natural Gas to Electricity technology with a score of 0.691. This is followed by Natural gas to hydrogen technology with a score of 0.689. This is followed by LPG with the score of 0.459. CNG is the least efficient technology in this analysis with a score of 0.308 (see Figure 4.4).

Section 4.3 (fig. 4.2) showed that CNG also has the least emission of CO_2 compared to the other two transport technologies (natural gas to hydrogen and natural gas to electricity.

Therefore, the main improvement needed for CNG as a transport technology is in the area of the fuel efficiency. When this is done, it will be of a great benefit to the consumers and Nigerian economy.

Safety of NGVs

NG offers safety advantages over gasoline and diesel as it is non-toxic, non-corrosive, mixes with air easily and evenly when dispersed, and has no potential for ground or water contamination in the event of a fuel release. It is also less combustible, has a significantly higher kindling point – it can only ignite between 5% to 15% concentration in air, and it has a high ignition temperature of about 640°C, compared with a range of 230–280°C in the case of gasoline (J.E. Sinor Consultants Inc., 1994). Thus, NG requires high compression energy for auto-ignition and is less likely to auto-ignite on hot surfaces when compared to gasoline or diesel. NG has a much higher octane number and lower cetane number compared to gasoline and diesel respectively. This makes it superior in respect of engine performance for spark ignition engines. Furthermore, the lead fouling of spark plugs and lead or benzene pollution in gasoline- and diesel-powered engines are eliminated in NGVs, due to the absence of any lead or benzene content in CNG and because of the high octane number; no anti-knock additives are required in NG (Gaslink, 2014).

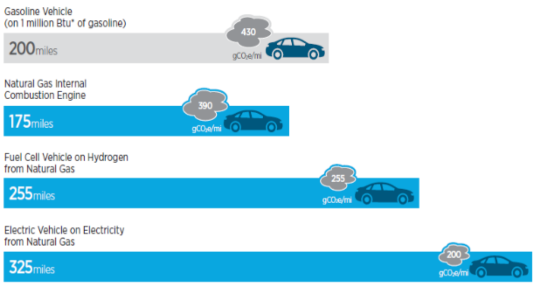
Considering Life Cycle Efficiency

Each of the four pathways for using natural gas has strengths and weaknesses that determine where efficiency losses and emissions occur across the entire life cycle. Vehicle efficiency determines only part of the story.

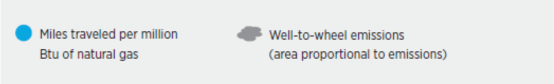
Understanding Life Cycle Greenhouse Gas Emissions

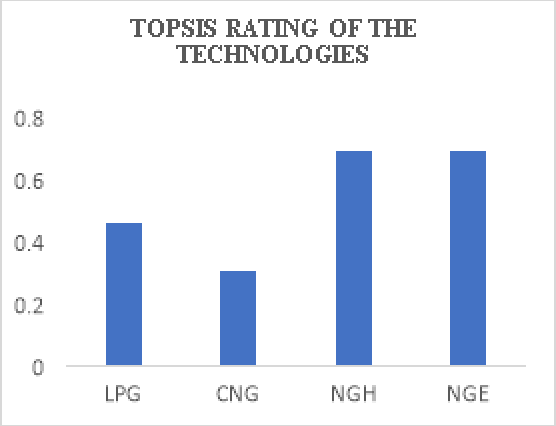
An accounting of greenhouse gas emissions involves more than vehicle fuel economy and life cycle system efficiency. With natural gas, a variable and uncertain portion of greenhouse gas emission occurs due to leakage of methane throughout the life cycle. Using GREET, greenhouse gas emissions can be compared across pathways with very different distributions of emissions across the fuel life cycle.

Distance Capacities of the Different Natural Gas Transportation Technologies Powered Cars



How far a car can go on 1 million Btu of natural gas (Wang & Elgowainy, 2015).





III. CONCLUSIONS

There is sufficient scientific evidence that gas flaring contributes to environmental degradation, as well as economic losses associated with the opportunity cost. Consequently, it is widely acknowledged that a reduction in the incidences of gas venting and flaring will result in a reduction of GHG emissions, and this will have a positive impact on the environment and the social and economic fabric of Nigerian society. While there are a number of studies on gas flaring in Nigeria, the research on the utilization of CNG as transportation fuel is limited. Cognizant to this, Compressed Natural Gas was critically evaluated in this study. The factors impeding its utilization in Nigeria and globally were evaluated. Technological modifications needed to boost the utilization of CNG as a transportation energy source were discussed. Finally, a comparative analysis of CNG, natural gas to hydrogen and natural gas to electricity technologies in transportation sector was conducted using TOPSIS.

From the TOPSIS analysis and results, the best natural gas transport technology considering fuel life cycle efficiency and life cycle greenhouse gas emission is Natural Gas to Electricity technology with a score of 0.691. This is followed by Natural gas to hydrogen technology with a score of 0.689. This is followed by LPG with the score of 0.459. CNG is the least efficient technology in this analysis with a score of 0.308.

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