GAS-TO-LIQUID (GTL) AS AN OPTION TO RELATIVE ZERO GAS FLARING IN THE NIGER DELTA

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ABSTRACT

Nigeria is associated with a total gas reserve that is well over 187Tscf, which in 2014 had produced over 2,524,268,444Mscf and flared about 300MMMscf. Over the years the average of total gas flared from the current to the previous year has reduced by 71%. In order to minimize gas flaring; this work proposes to design a gas to liquid (GTL) plant of capacity of 64952bpd and 21434113bpa to take a feed gas of 1000MMscfpd and more than 300billionscfa. The essence of the design capacity is to meet up relatively zero gas flaring and to contribute to fuel supply in the country. Distributing the GTL products across the country, the tanker system from cost-to-benefit analysis shows the best option, followed by the pipeline system, where the GTL products are commingled or batched. A pressure drop model was developed to ascertain which modes of transportation would consume less energy and less cost of pump along the pipelines. Since the higher the pressure drop in the pipeline, the higher the energy (the brake horsepower) needed to push the fluid. The commingled mode was selected.

Keywords: Gas utilization, Zero Gas Flaring, GTL, Batching, Commingling

INTRODUCTION

Nigeria is estimated to have over 187Tscf of natural gas that represents about 37.2billion barrels of oil equivalent (Chukwu, 2014).

In the process of oil exploration and production, these gases in association with oil are wasted and flared, which had contributed negatively to the health of the citizenry of those host communities, which are mainly helpless Niger Delta of Nigeria.

Thus, the problem of effective gas utilization option that can extinguish gas flaring in the Niger Delta has been a great concern to the host community and now the government appears to be singing a way out of this menace.

Several options of gas utilization with the aim of extinguishing gas flaring in the country has been developed, among which are: Liquefied Natural Gas (LNG) option that is operational, Gas-to Liquid (GTL) option that is more like a pilot option operating at Escravos, Gas to Power (GTP) that is only proposed, Gas to Gas (GTG) comprises of LNG, Compressed Natural Gas (CNG), etc and Gas to Solid (GTS) is commonly known as Natural Gas Hydrates (NGH).

This work seeks to extinguish gas flaring with the gas to liquid (GTL) option.

The flared gas is usually incidental to oil production, since natural gas and oil occurred in the same habitat, thus, gas been associated.

Across the globe, associated gas (AG) accounted for $1/5^{th}$ of the total gas reserve, of which figure is much higher in Nigeria (Chukwu, 2014). This quantity is flared.

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Recently, the percentage of total gas flared to total gas produced reduces yearly on the average of 71% (Table 1).

Table 1.Total Gas Produced, Utilized and Flared (NNPC Yearly Bulletin)

YEAR	TOTAL GAS PRODUCED (Mscf)	TOTAL GAS UTILIZED (Mscf)	TOTAL GAS FLARED (Mscf)	% Gas Flared
2015				
2014	2,524,268,444.00	2,234,668,430.00	289,600,014.00	0.114726
2013	2,325,137,449.00	1,916,531,001.00	409,311,430.00	0.176038
2012	2,580,165,626.03	1,991,498,901.85	588,666,724.18	0.228151
2011	2,400,402,880.00	1,781,370,022.00	619,032,858.00	0.257887
2010	2,392,838,898.00	1,811,270,545.00	581,568,354.00	0.243045
2009	1,837,278,307.00	1,327,926,402.00	509,351,905.00	0.277232
2008	2,287,547,344.00	1,668,148,489.00	619,398,854.00	0.27077
2007	2,415,649,041.00	1,655,960,315.00	759,688,726.00	0.314486
2006	2,182,432,084.00	1,378,770,261.00	803,661,823.00	0.368241
2005	2,093,628,859.00	1,282,313,082.00	811,315,777.00	0.387517
2004	2,082,283,189.00	1,195,742,993.00	886,540,196.00	0.425754
2003	1,828,541,855.00	983,562,969.00	844,978,886.00	0.462105
2002	1,651,591,488.00	897,789,582.00	753,801,906.00	0.456409

This requires more gas utilization infrastructure to be put in place to utilize more of the remaining gas to achieve relatively zero flaring.

CONTEXT AND REVIEW OF LITERATURE

Gas utilization in Nigeria is a monumental task that is perceived by the people to be unachievable by these oil operators and the national oil companies in Nigeria, because of the kind of politics they play with human lives, especially in the host communities and the neighborhood.

Researchers have developed alternative strategies for utilizing the abundant gas reserves in the country (Joseph, 2011) by increasing internal utilization and gas export project as tool for extinguishing gas flaring (Adegoke, 2002).

Several of these gas utilization options developed have informed the government of Nigeria to come up with gas infrastructure blue print that would transport gas across the country and beyond.

Also, Odusina (2009) contributed that the Nigerian gas infrastructure blueprint suggest the creation of three domestic processing hubs at Warri/Forcados in the Western Niger Delta, further East of Obiafu near Port Harcourt, and the third one around Calabar in the far East of the Delta, where Liquid Petroleum Gas (LPG) and condensate would be separated and collected at these hubs, while dry gas would be supplied through a network of gas transmission lines. The blueprint further calls for the development of three major domestic gas transmission systems: a Western system built close to the existing Escravos-Lagos pipeline, a South-North gas transmission line stretching as far as Katsina on the border with Niger Republic, and an East-West inter-connector (Fig.1).

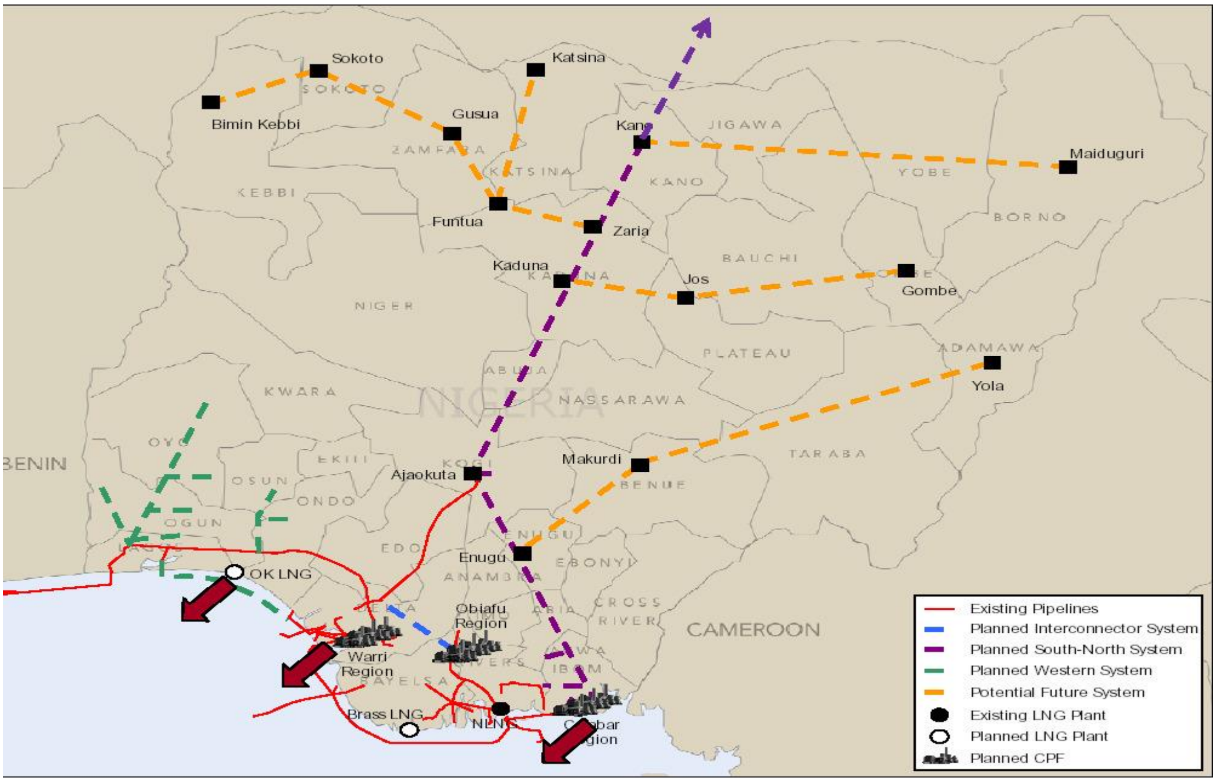

Figure 1: Nigeria Gas Infrastructure Blueprint (NAPIMS, 2013)

The export line (the West African gas pipeline project and the Trans-Sahara gas pipeline project) are connected from the domestic gas transmission system via the Escravos to Lagos pipeline and the South-North gas transmission lines stretching to Katsina respectively.

Some of these works were unable to establish at what economic point can GTL plant be located and transport GTL product through which means that would be cost effective in the country? In this work, the Obiafu hub near Port Harcourt appears to be central to the gas gathering station across the Niger Delta, as such the GTL plant would be better located here.

The source of production of crude oil is also close to Obiafu for purposes of batching and commingling of crude oil with the GTL product for transportation, distribution and collection at these hubs for separation.

GTL products are very high premium fuel with high cetane number (Chris, 2009) than the conventional refinery products. They can be mixed together or blended to improve the quality of the conventional refinery product in Nigeria.

According to Chukwu (2007), when GTL product is mixed together with crude oil and sent to the refinery, it takes less time to separate.

The Escravos gas to liquid (GTL) plant is capable of converting well over 300MMscf of natural gas a day into premium fuel, diesel and GTL naphtha products that is environmentally friendly. The Escravos gas to liquids facilities combines technology from Sasol, a South African-based Fischer-Tropsch technology company, and Chevron-specializing in hydro processing technology. Project cost $1.7bn and initial plant capacity designed for 34000 barrels per day and expected to expand to a 120,000bpd capacity within ten years of completion. The near-by gas plant to Escravos processes about 1,000 bpd of LPG produced by GTL. The initial estimated cost of the project was reviewed twice and new estimate now cost $8.4bn. Due to the delays and costs increase, the project was completed in 2012 and will be operational in 2013. It was test-run in 2014.

In this work, the GTL plant would be designed to convert 1000MMscf of natural gas into premium fuel. This is to meet up the blending ratio of GTL product to the conventional refinery product to meet the equivalent fuel consumption level in Nigeria estimated at 40million litre per day (NNPC, 2015), which is equivalent to 28777barrels of fuel per day. The blending ratio would be predicated on the octane number of fuel.

Before blending at the refinery, the GTL product is either commingled or batched with crude oil at the point of production and gathering.

Therefore, cost to benefit ratio is used to ascertain which means of transportation (New Pipeline, Existing Pipeline or Tanker System) would be economical to take the GTL to the refineries or direct distribution for sales.

Transporting GTL in Batch or Slug

Slug flow occurs because of the velocity difference in gas and liquid flow. The liquid phase grows in amplitude until; it succeeds in bridging the entire cross-section of the pipe to form a "slug". The slug is immediately accelerated to an average stable velocity, by the gas behind it (Govier and Aziz, 1972). The length of the gas bubble depends on the flow rates and the fluid properties (Sankey, 2008), and for given flow rates, it depends on the manner in which the fluids are introduced. It also depends on the system pressure and therefore increases as the pressure declines in the direction of flow (Govier and Aziz, 1972).

Govier and Aziz (1972) later discovered that the model was oversimplified and inadequate.

A model showing reference point for the analysis of gas-liquid slug flow in pipes by Donnelly and Charles (1975) permits the prediction in detail of the unsteady hydrodynamic behavior of gas-liquid slug flow. It is based on the observation that a fast moving slug overruns a slow moving liquid film, accelerating it to full slug velocity in a mixing eddy located at the front of the slug. A new film is shed behind the slug ("scooping mechanism") that decelerates with time.

Over the years, various researchers have modified the basic assumptions inherent in the Dukler and Hubbard model, and have derived new models or procedures for obtaining the parameters required for the description of slug flow as reviewed by Akwukwaegbu (2001).

Based upon this, a pressure drop expression was developed to predict the pressure drop in the slug during transportation in the pipe.

Transporting GTL by Commingling or Blending

According to Inamdar (2006), this mode of transportation requires the Crude Oil and GTL blended together, and then sent through the pipeline; as a single liquid phase mixture. This mode is known as blending or commingling. The transport of such fluid mixtures in horizontal or nearly horizontal pipes has become the norm, especially in the gathering and processing of hydrocarbons. This enables major cost savings in pipeline construction, and permits the centralization of processing facilities as well as conserving resources.

For fluids flow in a system, the component fluids can be distributed in a variety of flow configurations or patterns depending on the operating parameters, physical properties of the fluids and the geometrical variables (Thomes, 2015). The flow may also be affected by pressure losses in the system, liquid hold-up (as a result of density differences) and other factors.

Since GTL and Crude Oil are both hydrocarbons, and as such may have very similar fluid properties, the possibility exists of blending both fluids into one homogeneous single phase mixture. According to Ramakrishnan (2000), it was observed that the laboratory

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testing to determine the actual fluid properties of the resulting fluid mixture showed that the mixture blended into single homogeneous liquid with no separation into distinct layers or boundaries when mixture was left to stand.

This then allows the flexibility of treating the mixture as a single-phase homogeneous liquid, with its own unique fluid properties. In studying the commingled flow of GTL and Crude Oil through the Trans-Alaska Pipeline System, the Bernoulli equation of pressure for the flow of fluids in pipes was used (Inamdar, 2006; Chukwu, 2007). This equation would not be an exception in this research.

Issues of Crude Oil and GTL in Pipelines

The Niger Delta (ND) has very vast natural gas reserves, which has a very good future for the country's (Nigeria's) economic fortune.

Converting this abundant gas reserves to gas-to- liquid products (GTL), blending it with ND crude oil and transporting the resulting liquid alongside through the Nigerian pipeline system to the hubs separation or further blending with the refinery product and distribution is a veritable option to boost fuel supply and improve fuel quality in the country.

Gas-to-liquid (GTL) conversion technology is one in which natural gas is chemically converted to transportable hydrocarbon liquid products.

Making money out of stranded gas using GTL technology has received much attention from both the government and private industry. As new GTL technologies have matured, energy companies are investing in moving from small pilot GTL facilities, that can produce up to 300bbl/d as completed and tested by the British Petroleum Exploration Alaska (BPXA) to commercial developments in the future.

According to Chukwu et.al (2007), two modes of GTL product transportation are suggested: batching mode and commingling. He concluded that the batching mode was favorable based on higher rate of return on the capital investment. The study concluded that, the major concern with batching is the length of mixing zone or interface and the purity of GTL products as it arrives the terminal or hub as the case of Nigeria. He also asserted that the expected loss of purity in the blended product and a trade-off between loss in product value due to contamination and the capital costs involved in delivering a pure product to the terminal are major issues.

The reason for using GTL as a means of effective utilization of gas in Nigeria would not be limited to continuous usage of the existing oil pipelines and other infrastructure for GTL transportation but also using GTL products to increase pipeline throughput.

However, the issues of loss in product value and capital cost involved in delivering a pure product to the marketers and end users in Nigeria by commingling these fluids would call for an economic summit in Nigeria considering the economic attitude of our Nigerian state (government) with respect to investment that would yield return in the future has never been cordial but rather consume the proceed of the existing investment without adequate maintenance. This would be a potential challenge to transporting GTL products by any of the two modes above coupled with the distance and topography of Nigeria as well as the cost and risk associated with transporting GTL to far North of the country. Thus, the option of commingling or batching of GTL with crude for further separation at a bye pass or hub might not be favorable because of the economic attitude of Nigerian leaders at different spheres.

Therefore, the available option that is perceived to be economical and with less risk compared to transporting the GTL product by batching or commingling with crude oil is the

tankers system of transportation. Here, the GTL product is taken from the source (GTL plant) and distributed to the marketers or end users via tankers system.

RESEARCH METHODS

This work proposes to design by simulation a GTL plant that is capable of converting 1000MMscf/d using the Escravos data as a prototype. Here, the capacity relationship for chemical plant was used, where n is found to be equal to 0.6 (Black, 1984; Signot, 2005); where C_2 is the cost of a plant with capacity S_2 and C_1 is the capital cost of a plant with capacity S_1

$$C_2 = C_1 \times \left(\frac{S_2}{S_1}\right)^n \quad (1)$$

Other plant data that required for computation in this work were generated.

Since it has been established that GTL option of gas utilization is significantly and economical viable means of gas utilization in the Niger Delta area of Nigeria. But the question still remains "by what economical means would the GTL products be transported or distributed to the market or to the final user?"

Here, we employ cost to benefit ratio using excel spread sheet to analyze which means of transportation between pipeline (existing or new) and tankers system, while our bases still remains that the quantity of GTL products to be transported through the pipeline (existing oil pipeline or new GTL product pipeline by any modes of transportation -batching or commingling) or using the tankers system is 21434113bbls/annum, which is equivalent to 64952bbls/d and is well over the quantity of fuel consumed in Nigeria.

Product/Feed Gas Pricing

The pricing of GTL products is a function of the price of crude oil at that time, the refined product premium as well as the GTL product price premium (Behnam, 2003; Gaffney et. al 2001). Another report is that GTL products have a premium of 125% over the crude oil price (Khataniar and Chukwu, 2007). However, the GTL diesel, kerosene and naphtha premium shall be the current pump price in Nigeria as at August, 2015, which is: #268.00 ($1.553), #167.00 ($0.932) and #109.00 ($0.563) respectively.

Therefore, the natural gas price for this work is $2.8/MMbtu, LNG price is $9.0/MMBtu, and LPG price is $5.25/MMBtu while condensate is $78/bbl.

Cost to benefit ratio is calculated by dividing the expected benefits or revenue of the project by the proposed cost (Encyclopedia Britannica, 2015). In a general term any project having high benefit-cost ratio takes first priority over others with lower ratios.

Also, the revenue so generated from the sales at the distribution point shall remain the same because all products are assumed to be transported and sold within the same region.

The risk associated with any of the transportation routes, is in this work called cost of surveillance, which remains the variable cost.

The plant load factor or utilization capacity for GTL plant is taking to be 60%, while it is assumed that plants utilize its load factor at 100% from the very first year through the project life of 20years. The reason for this choice is based on the fact that the Escravos GTL plant uses 60%.

The useful life for most chemical plant is between 20 to 25 years from start-up, which confirms the perception that most plants give their best at approximately 20 years of

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production, from the report in NLNG Encyclopedia (2006) that 15 of the 19 customers of LNG producers in Nigeria signed 20 years LNG contract.

The operating time of a plant is the plan time required for the process plant to remain in operation. The actual operating time for a chemical plant is approximately 300 to 330 days per year. Therefore, 330days is assumed as the operating time per year for this research work.

According to Chukwu et.al (2007), it is assumed that the tanks to be used have holding capacity of 4400barrels/foot. For a plant capacity of 64952bbls/d of GTL product would require footage of storage of

$$\frac{64952}{4400} = 14.76ft.$$

He further added that the maximum allowable height by Operational Command Centre (OCC) is approximately 32ft and 8ft minimum level, leaving out 24ft.

$$\frac{14.76ft}{24ft} = 0.615 \approx 1 storage\ tank$$

And each of the storage tanks is estimated to cost about $50million and separation cost for different GTL slugs' sizes is $1.39/bbl.

The total CAPEX will be the cost of linking the GTL product line from the plant to the existing oil pipeline is assumed to be the cost of 1km of the total new pipeline length plus cost of storage tanks is estimated to cost about $50million plus separation cost for different GTL slugs' sizes is $1.39/bbl.

The fixed OPEX is assumed to be the cost of maintaining a new pipeline which is 5% CAPEX of the new pipeline.

The total CAPEX will be the cost of linking the GTL product line from the plant to the existing oil pipeline is assumed to be the cost of 1km of the total new pipeline length plus cost of storage tanks is estimated to cost about $50million plus separation cost for different GTL slugs' sizes is $1.39/bbl plus cost of blending. The fixed Opex is same as in batching mode and the span of the construction is one (1) year.

Transporting by Batching/Commingling

Fluid property like the crude API gravity was collected from one of the Niger Delta fields between Andoni and Eastern-Obolo as at August, 2015 and Escravos GTL density was also collected and others were simulated.

$$API = 141.5/\gamma + 131.5 \qquad (2)$$

According to Glaso correlation (1980), visocity of oil,µ at atmospheric pressure, and system temperature is given as

$$\mu_{od} = 3.141 \times 10^{10}(\mathrm{T} - 460)^{-3.444}[\log(\mathrm{API})]^{\mathrm{a}} \qquad (3)$$

and,

$$a = 10.313[log(T - 460)] - 36.447 \qquad (4)$$

Thus the average density of GTL product and crude oil to be transported through the Niger Delta pipeline is assumed to be 785kg/m^3 and the average viscosity is 1.9392cp (Table 2)

Table 2. Fluid Basic Data

FLUID BASIC DATA				
Density of water	62.4	lb/ft3	1000	kg/m3
API Gravity of Oil	45.2	API		
API Gravity of GTL	52.3	API		
Density of Crude Oil	800.447104	Kg/m3		
Viscosity of Oil	0.00257194	kg/m.s		
Density of GTL Product	770	Kg/m3		
Viscosity of GTL	0.00130643	kg/m.s		
Density of Mixture	785.223552	Kg/m3		
Viscosity of Mixture	0.00193918	kg/m.s		

Other data used in this work are the pipe data (Table 3), which also indicates some assumptions made during the analysis.

Table 3: Pipe Basic Data

PIPE BASIC DATA				
Flow Rate, Q	64952	bbl/d	0.1195	m3/s
Pipe Outer Diameter	0.6	m		
Pipe Thickness	0.016	m		
Pipe Length	12000	m		
Pipe Inner Diameter	0.568	m		
Pipe Roughness	0.00004572			
ASSUMPTIONS				
Height of Film	0.7	m		
Radius of Film	0.54314001	m		
Lockhart Martinelli Cons	a	1190		
	b	0.82		
Ambient Temperature	60	F	520	R
Acceleration Due to Gra	9.81	m/s2		

We also assumed that the pipe is a steel pipe of 24 inches outer diameter with 16mm thickness carrying the fluid for a total length of 12km and it's important to state that other data needed in cause of this work were simulated with valid assumptions.

Subsequently, to ascertain which mode (batching or commingling) of transportation is more energy and cost consuming than the other, a pressure drop model was developed for batched and commingled modes.

Batching Mode of Transportation

Batch transportation mode is also called slug. The study of pressure drop in pipe that would occurs during transportation in slugs or batches mode will be based on the minimum slug length because some mixing between crude oil and GTL will take place at the leading and trailing edges of the slugs, length of the interface or void space between the slugs, as well as the length of the mixing zone.

Assumptions

The following assumptions are made in batch transportation:

1.) The fluid flow is incompressible, steady state and fully developed
2.) Uniform length of slug
3.) Bubble or void between the slugs is occupied by air
4.) Constant thickness of liquid film
5.) Isothermal fluid flow with constant fluid properties
6.) There is mixing level between head and tail of slug

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According to Akwukwaegbu (2001), Kokal and Stanislav (1989), and Taitel and Barnea (1990), the pressure drop across one slug unit can be calculated as follows:

$$\Delta P = \Delta P_f + \Delta P_a + \Delta P_h$$
(5)

Where ΔP_f = pressure drop due to friction

ΔP_a = pressure drop due to acceleration

ΔP_h = pressure drop due to hydrostatic pressure

Pressure Drop Due to Friction: The liquid slug and the void (the air pocket and liquid film) are believed to be contributed by pressure drop due to frictional force, such that Taitel and Duckler (1976) presented a relationship thus, if we make in this work the effect of air bubble negligible

$$\Delta P_f = \frac{2 f_s P_l {V_m}^2 l_s}{\mathrm{D}} + \frac{2 f_f P_{mz} {V_f}^2 l_m}{D_f}$$
(6)

Where f_s = frictional factor of the slug

f_f = frictional factor of the liquid film (fluid interface zone)

D_f = hydraulic diameter occupied by the interface zone

D = Diameter of the slug

These fictional factors are based on the Reynold number of the slug, R_{es}; air bubble, R_{eg} and the film, R_{ef}.

Pressure Drop Due to Acceleration: Kokal et.al (1989) presented that the film velocity, V_f just before slug pick-up is lower than the velocity in the main body of the slug, V_s which resulted to pressure drop.

$$\Delta \mathrm{P_a} = \rho_l \mathrm{E_{ls}} (V_t - \mathrm{V_s})(V_s - \mathrm{V_f})$$
(7)

Hydrostatic Pressure Drop: This caused as a result of pipe inclination or orientation

$$\Delta \mathrm{P_h} = \rho_{ms}(g\sin\beta) l_s + \rho_f (g\sin\beta) l_f$$
(8)

Where

$$\rho_f = \rho_{l1} E_{lf} + (1 - E_{lf})\rho_{l2}$$

β= angle of inclination of the pipe = $\beta = \frac{h}{L} = \Delta Z/L$

Equation 9 can be rewritten as

$$\Delta \mathrm{P_h} = (\rho_{ms} l_s + \rho_f l_f) g \frac{\Delta Z}{L}$$
(9)

$$\Delta \mathrm{P_h} = (\rho_{l1} l_s + \rho_{ms} l_m) g \frac{\Delta Z}{L}$$
(10)

Average Pressure Gradient: This is determined for one complete slug unit, by dividing the total pressure drop across a slug by the effective slug length

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$\frac{\Delta P}{L} = \frac{\Delta P_f + \Delta P_a + \Delta P_h}{l_m}$
(11)

Commingling or Blending Model of Transportation

Here the GTL and the crude oil are pre-mixed or blended before transportation through a pipeline as a single liquid phase mixture since they are both hydrocarbon with close or similar fluid properties, as such possibilities exist of blending both fluids into one homogeneous mix.

Assumptions:

1.) Incompressible fluid flow, steady and fully developed
2.) Flow is isothermal with constant fluid properties
3.) Fluid exhibit Newtonian behaviour
4.) No separation into constituent fluids
5.) Equation relates the states at two points along a single streamline

Employing the energy balance in the pipe streamline, the total energy at any point for fluid flow, if no energy is added or removed is equal to

$E = E_1 = E_2 = F_E + P_E + K_E$
(12)

On the other hand, if energy is added or removed to aid or impede flow respectively is equal to

$E = F_E + P_E + K_E + h_p + h_f + h_l$
(13)

Potential energy which relates the elevation of the pipe is given as

$P_E = W \times Z$ (14)

And,

$W = Q \times \gamma = Q\rho g$

Where, Q=volumetric flow rate

γ = specific weight of fluid

ρ = density of fluid

g = acceleration due to gravity

v = velocity of fluid

h_p = head added to the fluid by pump

h_f = frictional pressure loss between point X and Y

h_l = represents the minor losses contributed by bends,

Kinetic energy explains the energy due to motion of the fluid as a result of its velocity

$$K_E = \frac{WV^2}{2g} \quad (15)$$

Also the pressure energy or flow energy is the force exerted to allow for free flow

$$F_E = \frac{WP}{\gamma} \quad (16)$$

So that Equation 1 become

$$E = \frac{WP}{\gamma} + WZ + \frac{WV^2}{2g}$$

$$\frac{\rho_1}{\gamma} + Z_1 + \frac{V_1{}^2}{2g} = \frac{\rho_2}{\gamma} + Z_2 + \frac{V_2{}^2}{2g} \quad (17)$$

Equation 17 is the Bernoulli's Equation required for the analysis of the single phase fluid flow.

Pressure drop in a turbulent flow: The pressure drop is given as follows

$$P_1A - P_2A - \tau_w L w_p + W sin\theta = 0$$
(18)

Where,

P_1= pressure at entry

P_2= pressure at exit

A= area of the pipe

L= length of pipe

W_p= wetted perimeter (Given as Лd)

T_w= pipe wall shear stress

W= weight of the pipe

Ө= angle of inclination

But, $= \rho g A L$ and $sin\theta = \frac{-\Delta Z}{L}$; so that equation 14 becomes

$$A(P_1 - P_2) - \tau_w L w_p + \rho g A L \frac{-\Delta Z}{L} = 0$$

$$A(P_1 - P_2) - \tau_w L w_p - \rho g A \Delta Z = 0 \quad (19)$$

$$\left(\frac{(P_1 - P_2) - \rho g \Delta Z}{L}\right) - \tau_o \frac{w_p}{A} = 0 \quad (20)$$

So the shear stress at the wall of the pipe and the pressure in the piezometer as well as the mean velocity is given as

$$\tau_o = f \frac{\rho V^2}{2} \quad (21)$$

Pump Brake Horsepower

This is used to know which pipeline route will require more or less pump. The more energy or brake horsepower, the more pumps on the line to boost the flow of fluid.

$$BHP = \frac{100QH}{3960n} \quad (22)$$

n= efficiency of the pump

H= total head, (m)

Q= flow rate (m^3/s)

FINDINGS

Route Screening

From the chemical plant relationship, the following plant data were generated (Table 4)

Table 4. GTL Based CAPEX and Capacity

scenario	Gas Utilized (MMscf/d)	GTL Plant Capacity (bbls/d)	GTL Plant Capacity (bbls/annum)	GTL Plant CAPEX ($B)
Initial Data	340	34000	11220000	8.4
Based Data	1000	64951.8562	21434113	16.047

An economic model was developed from the plant data and some valid economic data generated (CAPEX, OPEX, inflation, royalty, plant load capacity, price of fuels, etc), while some assumptions were made to generate Cost-Benefit Ratio of each of the transportation options (Table 5).

Table 5. Generated Data for Transportation Routes Analysis

Fixed OPEX	5%	CAPEX		59%	29%	12%
Total pipe length	12	km	Capacity	64952	bbls/d	
Capitalized n Exp	70%	30%		330	days/yr	
Royalty	5%					
Prices			Quantity @ 59,29,12% of 64952bbl/d			
Diesel	267.79	$/bbl	38321.68	bbls/d		
Kerosene	167.37	$/bbl	18836.08	bbls/d		
Naphtha	108.79	$/bbl	7794.24	bbls/d		
Pipelines						
CAPEX (Existing)						
CAPEX (New)	2431.6	MM$	2.432E+09	$		
Fixed OPEX (Ne	1.2158	MM$	1215800	$		
Fixed OPEX (Existing)				$		
Variable OPEX(cost)			100000000	$		
Batching						
1km Pipe	202.63	MM$	202633333			
Cost of Seperatic	1.34	$/bbl	28721774	$/YEAR		
Storage Cost	50	MM$	50000000			
Total FIXED OPEX			281355108	$/YEAR		
Commingling						
Cost of Blending	2	MM$	2000000	$		
Total FIXED OPEX			283355108	$/YEAR		
Tankers System						
CAPEX	25.3	$M	25300000	$		
Variable Cost	149811	$/d	50000000	$/year		

From the foregoing, the following results of the best economic route to transport the GTL products were generated using the cost to benefit analysis (Table 6).

Other options using the new pipeline has a ratio of 16.5248, while using the existing pipeline for batching or commingling has a cost to benefit ratio of 15.563 and 15.5565 respectively (Table 6).

Table 6. Cost to Benefit Analysis

Decision	BENEFIT ANALYSIS OF THE TRANSPORTATIC				
	COST ($MM)				REVENUE ($MM)
	COST OF NEW PIPELINE	COST OF EXISTING PIPELINE		COST OF TANKERS SYSTEM	Uniform Revenue
	Pure GTL	Batching	Commingling	Pure GTL	Pure GTL
	4532.82	4812.9551	4814.9551	3506.9	74904.01
Cost to Benefit R	16.5248	15.562997	15.556533	21.359	
Benefit to Cost R	0.06051	0.064255	0.0642817	0.04682	
Profit	70371.2	70091.052	70089.052	71397.1	

Also, from simple arithmetic profit of a venture is deduced from a simple relationship:

$$\text{Profit} = Net\ Revenue - Total\ Cost\ of\ Investment \qquad (23)$$

The tankers system having the highest cost-to-benefit ratio also has the highest profit margin compared to other options of transportation route. This is because the tankers system is simple and safer than the pipeline routes in Nigeria owing to pipeline vandals and the cabals diverting the products to unknown destination, which could be a replica case recorded in the Nigeria refineries products causing product shortage in the country.

$$Profit\ for\ Tanker\ System = 74904.01 - 3506.9 = \$71.39711 billions$$

Similarly, the new pipeline option is second in the rank and is a little favorable, while the existing pipeline options of commingling and batching are not favorable. The high cost recorded using the existing pipeline is contributed by high cost of separation of the slugs in a case of batching and separating the crude from the GTL products in a case of commingling at the hubs.

$$Profit\ for\ New\ Pipeline = 74904.01 - 4532.82 = \$70.37119 Billions$$

$$Profit\ for\ existing\ (Batched) = 74904.01 - 4812.9551 = \$70.0911 Billions$$

$$Profit\ for\ existing\ (Commingled) = 74904.01 - 4814.955108 = \$70.0891 Billions$$

PRESSURE DROP MODEL

Fluid Properties were generated from the GTL plant in Warri, which is the first in Nigeria remains the reference in this work, has one of its products (diesel) having a density of 770kg/m^3 (CNL-Sasol, 2008) that corresponds to an API Gravity of 52.3 and viscosity of 1.30645cp, while the crude oil sample as analyzed from one of the Niger Delta fields between Andoni and Eastern-Obolo as at August, 2015 has an API Gravity of 45.2 with a specific gravity of 0.8 and viscosity of 2.5719cp.

The pressure drop model indicates the following results for both modes:

Batched Mode

This mode is treated as a two-phase fluid flow at the mixing zone. The slug has a head, which is the point the GTL product pumped into the line first have interfacial contact with the crude (μ_{l1}) to form a slug and a tail (μ_{l2}), which is the end of the GTL product pumped. Then, the length of the slug (l_s) is calculated and the length of the mixing zone, l_m.

Therefore, the pressure drop (Table 7) across the slug is the summation of the pressure drops due to acceleration, due to friction and pressure drop due to hydrostatic head which gives a total of 67.26Pa.

Table 7: Batch Pressure Drop Model

Pressure Drop Model		
Area of the interface, As	72.5765158	m
Vm=Vs	0.44623199	m/s
Transitional Velocity, Vt	0.698084312	m/s
Drift Velocity, Vd	0.162605923	m/s
Interface Velocity, Vf	0.185216904	m/s
Slug Frequency, ω	0.063329449	rad/s
Length of Mixing Zone, Lm	14.64949506	m
Slug Length, Ls	1.42838E-11	m
Liquid Slug Hold-Up, Els(theoritical)	0.572963133	m
Liquid Slug Hold-Up, Els(actual)	0.581920803	m
Liquid Slug Hold-Up in the Mixing Zone, Elf	0.285762173	m
Wetted Perimeter, Wp	176.0887373	m
Interface Hydraulic Diameter, Df	0.471117533	m
Density of the mixing Zone, Pmz	778.8589017	kg/m3
Viscosity of the Mixing Zone, Umz	0.001674641	kg/m.s
Reynold Number of Mixing Zone, Remz	40583.26114	
Reynold Number of slug, Res	313264.6851	
Change in Elevation, ΔZ or Head Loss,Hf	0.097941832	m
Frictional Factor of Liquid Film, Ff	0.022203922	
Frictional Factor of Slug, Fs	0.014863616	
Pressure Drop Due to Friction, ΔPf	36.89547492	N/m2
Pressure Drop Due to Acceleration, Δpa	29.4554849	N/m2
Hydrostatic Pressure Drop, ΔPh	0.913560743	N/m2
Pressure Drop across one Slug, ΔP	67.26452056	N/m2
Pressure Gradient, ΔP/L	4.70915E+12	N/m
Vapor Phase Correction Factor, ϕ	2339.735811	
Vapor Phase Formed, 〖ΔP〗_(Vapor phase)	1.22872E-05	

The pressure gradient is determined from the pressure drop in pipe divided by the pipe length which is represented in Figure 2.

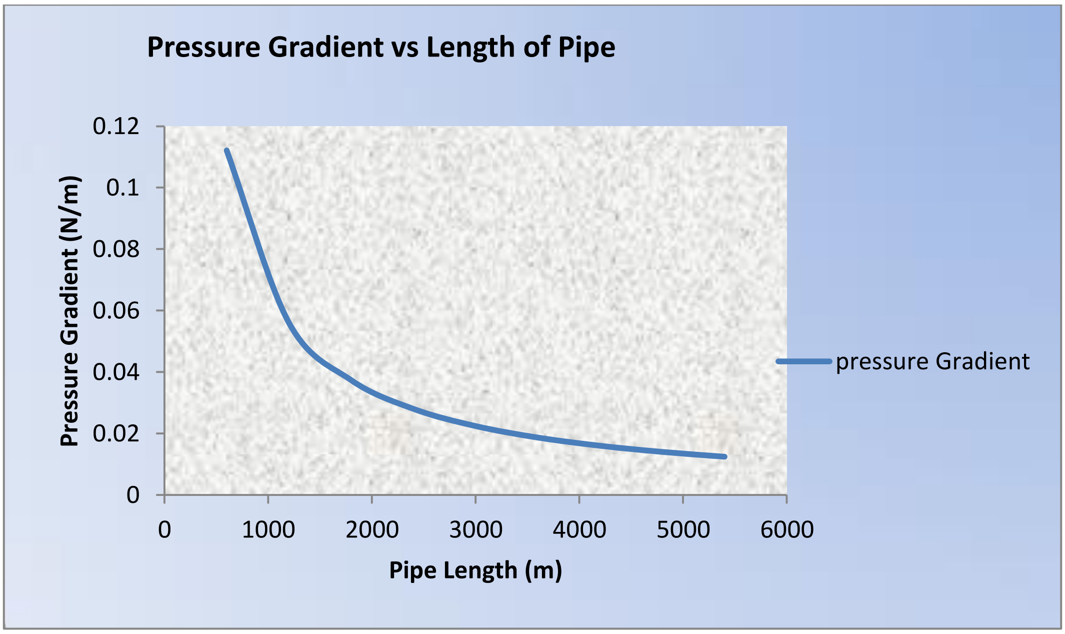

Figure 2: Relationship of Pressure Gradient with Pipe Length

Commingled Mode

Commingled flow is treated in this work as a single-phase fluid flow, where the GTL product and the crude oil are premixed and then pumped into the line a homogeneous fluid. The flow is turbulent with a Reynold Number of 211046 with a hydraulic mean depth of 0.073.

Table 8. Commingled Flow Model

Pressure Drop Model for Commingled Flow		
Area of the Pipe, A	0.26786453	m2
Average Fluid Velocity,Vs	0.44623199	m/s
NRE	211046.4907	
Frictional Factor, f	0.015924509	
Wetted Perimeter, Wp	3.66937712	m
Hydraulic Mean Depth, Hm	0.073	m
Head Loss, hf	0.00012543	m
Change in Elevation, ΔZ	6.536476103	m
τo	5.87769E-06	
τw	4.89808E-10	
Pressure drop (P1-P2)	50.35075688	pa
Lockhart and Matinelli, X	324.3310799	
Vapor Phase Correction, ϕ	4994698.63	
Vapor Phase Formed, 〖ΔP〗_(V	2.01831E-09	

The pressure drop here is **50.35Pa** as indicated in Table 8.

Also, the pressure gradient was simulated from the pressure drop across the pipeline with respect to pipeline length taking it purely horizontal (Figure 3).

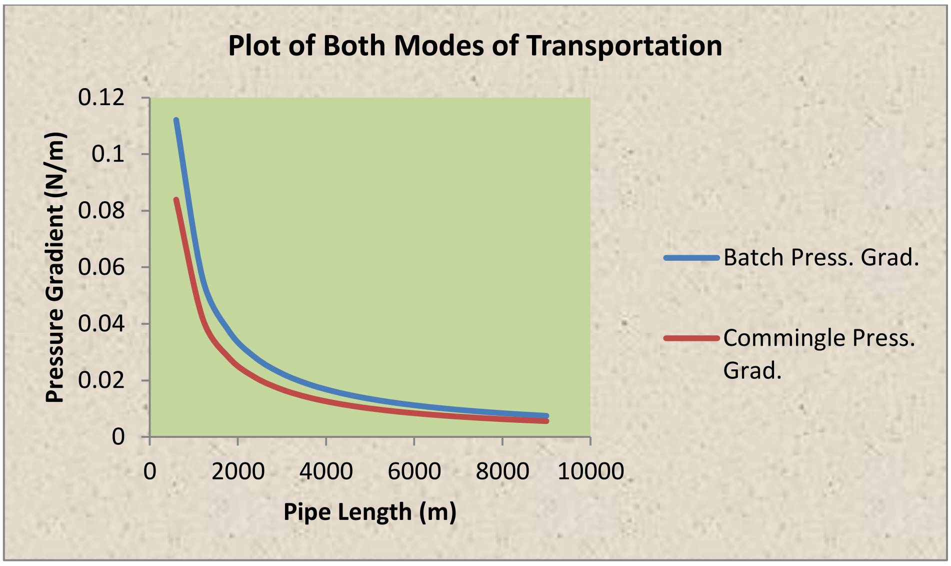

Figure 3: Pressure Gradients with Pipe Length

ENERGY CONSUMPTION

The energy consumed per mode of transportation is given in table 9.

The power to the fluid flow given as $P = \dot{m}H_f g$

$$P_{(Batched)} = \rho Q H_f g = 785\frac{kg}{m^3} \times 0.1195\frac{m^3}{s} \times 0.097941832m \times 9.81\frac{m}{s^2} = 90.1792W$$

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$$P_{(Commingled)} = 785\frac{kg}{m^3} \times 0.1195\frac{m^3}{s} \times 0.00012543m \times 9.81\frac{m}{s^2} = 0.1155W$$

Taking the above results from Watt to Horsepower yields 0.121 and 0.000155hp for batching and commingling respectively (Table 9).

Table 9. Energy Consumption per Mode

Energy Consumed by each mode of Transportation			
Parameter	Batching	Commingling	unit
Mass Fow Rate, m	93.8575531	93.85755308	kg/s
Power to the Fluid	90.1792168	0.115489139	j/s or w
Power to the Fluid	0.12093033	0.000154871	hp
Brake HorsePower	0.14227098	0.000182201	hp

Therefore, the energy consumed by the plant working on the fluid and in pushing the fluid across the pipe is greater for batching mode than in commingling mode, assuming pump efficiency of 85%.

DISCUSSION

It is important to note that the location of the GTL plant is a function of much cost the investor is ready to cut as such the Obiafu hub area is economical and central to other gas gathering stations around the Niger Delta and closest to the gas line following the GMP, thus, recommended.

The West African Gas Pipeline Project to transport natural gas from the Lagos terminal to three delivery points over a distance of 681km with a capacity of 170MMscfd at present to 474MMscfd in the future. And the Trans-Sahara Gas Pipeline Project takes gas from Southern Nigeria and run through Niger to Algeria to connect to Europe hub with a capacity of 30billioncma; while other gas networks will consume more gas.

It is important to note that GTL option of gas utilization would not only boast the seeming economic misfortune of Nigeria but would also reduce gas flaring above 70% based on the trend of total gas flared per year in Nigeria. The consumer is the destination of gas-to-liquid products. Therefore, the routes through which we transport these products to its destination were analyzed based on its merits using cost-to-benefit ratio; the tanker system of transportation of these products was considered economical, while the risk associated with road transportation is quantified as cost of surveillance which also applies to other routes.

The tankers option of GTL transportation across the country is the best option with cost to benefit ratio of approximately 21.4 compared to the pipeline routes (whether new of 16.5248 or existing pipeline -commingled or batched of approximately 15.557 and 15.563 respectively).

In analyzing the transportation routes the cost of risk was taken generally as the cost of surveillance, the cost of storage tanks, blenders, separators, etc, constituted the operating cost (OPEX) and cost of building a new pipeline was calculated in per kilometer using a linear regression analysis. The cost of natural gas depends on the cost of crude oil and is $2.8/MMbtu.

However, from the analysis of the pressure drop using commingling or batching route option shows that commingling option with a pressure drop of 50.35Pa compared to batching of pressure drop of 67.26Pa and a brake horsepower of 0.00018hp and 0.1423hp respectively. Therefore, the commingling option is economical because the energy needed to push or transport the fluid (GTL products) is less than in the batching option which requires large energy.

CONCLUSION

Having reviewed the basic options of gas utilization as contained in the gas master plan (GMP), the government should pursue the GTL option of gas utilization as it has reduced total gas flared by almost 71% on the average, which hopefully Nigeria would achieve zero flaring in the near future, as Nigerians continue to develop habit for LPG usage.

On the other hand, if pipeline route is considered as the economy improves, then the question of whether to commingle or batch the GTL products with crude oil before transporting to its destination and /or build a new pipeline for GTL products in the country is an option to cut down on cost of transportation of GTL products. Here, the cost to build new pipeline to transport a single-phase GTL products higher than the existing pipelines to commingle or batch, but the enormous technical problems of commingling or batching is a major disadvantage.

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