International Journal of Oil, Gas and Coal Engineering
2022; 10(1): 1-16
http://www.sciencepublishinggroup.com/j/ogce
doi: 10.11648/j.ogce.20221001.11
ISSN: 2376-7669 (Print); ISSN: 2376-7677 (Online)

Modelling Flare Gas Recovery System for Recovery and Utilization of Stranded Associated Gas in the Niger Delta

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To cite this article:
Mathew Chidube Udechukwu, Boniface Obah, Charley Iyke Anyadiegwu, Stanley Onwukwe, Ubanozie Julian Obibuike, Stanley Toochukwu Ekwueme. Modelling Flare Gas Recovery System for Recovery and Utilization of Stranded Associated Gas in the Niger Delta. *International Journal of Oil, Gas and Coal Engineering*. Vol. 10, No. 1, 2022, pp. 1-16. doi: 10.11648/j.ogce.20221001.11

Received: November 20, 2021; **Accepted**: December 8, 2021; **Published**: January 8, 2022

Abstract: In this paper, the modeling of a flare gas recovery system (FRGRS) for the recovery and utilization of stranded associated gas in the Niger Delta region of Nigeria was investigated. The gas recovery system is a novel modular plant with several integrated units and operational features. The FGRS was modeled for the recovery, treatment, processing of stranded associated gas. Two cases were considered, one was the compression of the treated gas from the FGRS to pipeline as sales gas while the other was the conversion of the treated gas to premium transport liquids by gas-to-liquids technology. 25 MMScfd of recovered stranded associated flare gas was used as feedstock and it yielded 23.22 MMscfd of treated natural gas and 1.77 Mscfd of acid gas. The treated gas met all pipeline sales gas specifications. In modeling the GTL plant, an autothermal reforming method of synthesis gas production was used and an H_2/CO ratio of 2.33 was recovered which was acceptable for Fisher-Tropsch reaction downstream. The entire GTL plant simulation was modeled in Honeywell Unisim with Peng-Robinson as the fluid property package. Gas-to-liquids (GTL) product produced from the 23.22 Mscfd treated gas fed to the GTL plant were 2350 b/d of liquid transport fuels comprising 1100 b/d of diesel and 1250 b/d of gasoline. Economic analyses revealed thata net present value (NPV) of US$ 109.9 million was realized from the sales of GTL liquids while an NPV of US$58.5 million was realized from the sales of pipeline quality gas. Thus, the sales of GTL products represent an increase in NPV of 87.8% when compared with that of pipeline gas. However, the Pay-out time (POT) for pipeline sales gaswas 1.16 years, the internal rate of return (IRR) was 86% while the profit-per-dollar invested was 16.18. Furthermore, the pay-out time for GTL product sale was 5.29 years, the internal rate of return was 18.3% and the profit-per-dollar invested was 2.78. The project showed that the gas may be sold outright (as pipeline gas) if the market was available and in the absence of a ready market for the gas, the gas could be converted to liquids that are easier to store and have greater market potentials in the long run.

Keywords: Gas Capture, Gas Recovery System, Gas-to-Liquids Technology, Fischer-Tropsch, Natural Gas Liquids

1. Introduction

As the world struggles with the challenge of climate change, there is an unprecedented need for nations to drastically reduce their carbon emissions. Carbon dioxide is one of the greenhouse gases that has been blamed for a variety of environmental challenges currently faced globally. Nations seek carbon neutrality, a situation where the carbon dioxide gas emitted to the atmosphere equals the amount absorbed by the atmosphere by carbon sinks while others even argue for net-zero [1].

The global climate change challenge has compelled many nations to seek ways to reduce carbon emissions to the atmosphere. Most of the carbon emitted comes from the use of fossil fuels. Fossil fuels include coal, oil, and natural gas. Amongst the fossil fuel usage, natural gas has been viewed as the most environmentally friendly as much lower carbon footprints are associated with its utilization as compared to other fossil fuels. For this reason, natural gas may remain long in usage as a future fuel even in the so-called global transition from fossil fuels to renewable and sustainable energy [2].

However, a good percentage of the natural gas produced in association with crude oil is flared. Flaring is the deliberate burning of the associated gas. This routine action has resulted not only in the loss of huge revenue to both the operator and the government but also to widespread global carbon emissions which altogether has increased the carbon levels in the atmosphere and ultimately the greenhouse gas effects [3].

As of 2019, 150 bcm of gas was flared globally while 142 bcm of gas was flared in 2020. The 5% decline in gas flaring in 2020 was due to the Covid-19 pandemic that reduced oil production by 8% [2]. Global gas flaring releases about 400 million metric tons of CO_2 into the atmosphere. Data from gas flaring satellites in 2020 reveals that Nigeria ranks the 7th position in global gas flaring levels [2, 4]. It was recognized that the existence of individual flare sites scattered in remote and difficult to access locations have been the common reason for gas flaring as evidenced in the reports of the top gas flaring nations [1, 2].

To harness the vas scattered remote associated gas volumes in Nigeria, innovative technologies aimed at recovering and utilization of the resource is imperative. Conventionally, natural gas has been used for power generation through large gas turbine systems situated often far away from gas production sites and requiring large pipeline infrastructure that supplies adequate volumes of gas. These pipelines run across major gas production fields and supply large volumes of gas for power generation. Usually, the construction of these pipelines is a critical economic decision that economically prohibits its construction across remote fields that have been known to individually contain smaller volumes of gas. The distance, volume, and pressure barrier notable with remote associated gas makes them economically and/or physically stranded thus increasing their chances of being flared.

Aside from pipelining and power generation, a notable route for the utilization of natural gas is liquefied natural gas (LNG). LNG involves the physical converting the gas to liquids by temperature reductions. The gas is refrigerated to its melting point typically around -162°C wherein it is turned into liquids. The gas in its liquid state substantially reduces in volume enabling larger volumes to be transported instantaneously through special cryogenic vessels. However, the gas would have to be regasified once it has reached its final destination before it can be utilized [5].

Gas-to-liquids technology is a viable alternative to utilize and monetize associated stranded gas. The technology achieves a chemical conversion of natural gas to liquids like fuels (eg, diesel, gasoline, kerosene, etc) and chemicals through catalytic processes that occur in several stages in the plant. One of the greatest drives for GTL products is that it is of premium quality which means that the fuels produced from GTL burns cleaner and performs better in internal combustion engines than the conventional fuels produced from crude oil refining. GTL technologies have been confirmed to be profitable especially for large plants. Large plants are plants whose capacity ranges from 10,000 b/d of GTL products and above [6]. Unfortunately, only five large-scale plants are operational in the world. The reasons are that large-scale plants have high initial capital costs that range in billions of dollars (this may not be affordable by independent private investors) and require substantial volumes of gas supplies to run. Only very few gas fields in the world can supply such enormous volumes of gas. For these reasons, fields with smaller volumes of gas production may not be economical for large-scale GTL projects.

Small-scale modular gas-to-liquids technology is a modern proven alternative for associated gas recovery and utilization. Modular GTL proves a market structure for the otherwise flared associated gas resource not only providing additional revenue for the investor or government by eliminating the environmental, health challenges posed by gas flaring while gainfully engaging the human resource at regions where they are situated [7].

This work seeks to compare the economic potential of using pipeline infrastructure and small-scale GTL plants for the recovery and utilization of associated stranded gas in the Niger Delta remote locations. An effort is applied to critically analyze the technical and economic implications of the two project alternatives for associated gas utilization and monetization with the bid to harness the gas and eliminate the flaring of associated gas in the geographical location considered. Many researchers have confirmed the economic potentials of small-scale GTL projects; Boyajian et al., [8] did a study on small scale GTL plants. He considered the means to achieve higher yields of GTL products while minimizing complexity, space, cost, and increasing efficiency. They made a comparison to the three notable GTL plant types which are the Fischer-Tropsch plant, the synthesis gas to gasoline plus (STG+), and the methanol to gasoline plant (MTG). From their results, they revealed that STG+ is more cost-effective than the other GTL plant types for plants of relatively small capacity.

Anyasse and Anyasse [3] studied means to mitigate the flaring of associated gas by utilizing small-scale GTL technologies. They highlighted the challenges of traditional GTL plants' synthesis gas production methods arguing for the need for an enhanced reforming method. They proposed the economic and technical advantage that accrues from the use of enhanced synthesis gas reforming technologies when combined with efficient Fischer-Tropsch technologies in the production of GTL liquids and how these processes would help curtail environmental impact the emanates from the flaring of associated gas.

He [9] conducted a study on the utilization/monetization of associated gas using modular GTL technologies. He considered the conversion of 4MMscfd of associated stranded gas into GTL gasoline using the synthesis gas to methanol method in a fixed catalytic bed reactor. The method proved to be efficient and viable for such a small capacity highlighting the potential attractiveness of small-scale modular GTL plants.

Fulford et al., [10] worked on a new methodological approach to the monetization of gas in Nigeria. They presented a detailed study o the utilization of GTL for gas monetization, highlighting conditions that would accelerate GTL technology in Nigeria. They analyzed critically, the impact of long term and short term constraints on the profitability and economic viability of GTL projects in Nigeria, as they proposed GTL to be the solution to the gas flaring in Nigeria occasioned by the prevalence of smaller volumes of associated gas separated from the market in many remote locations in the Niger Delta regions of Nigeria. They blamed the huge gas flaring in Nigeria to be due to high costs of gathering the gas, cost of processing and treatment especially for small volumes, lack of infrastructure and funding to deliver gas to the markets.

Kanshio and Agogo [11] conducted a study on the techno-economic assessment of mini-GTL technologies for flare gas monetization in Nigeria. They highlighted some technologies that are promising and have the potentials to turn gas below 1 MMscfd into premium marketable gas-to-liquids products. In their study, they focused on the production of diesel, methanol, and anhydrous ammonia. They conducted technical and economic analyses to justify these technologies. They discovered under prevailing economic circumstances that methanol was the most attractive of the three products considered.

Ekwueme et al., [6] conducted a novel study on the economic analyses of GTL plants by comparison oftwo GTL synthesis gas production technologies which are the autothermal reformer and steam/CO_2 reformer. They modeled a 50 MMscfd of plant for both methods using F-T syngas liquids conversion reactor in Unisim. They discovered that the steam/CO_2 method that uses steam/CO_2 instead of oxygen as in the autothermal reformer performed better than the ATR method in terms of NPV, POT, IRR, and even emissions characteristics.

Izuwa et al., [5] conducted astudy on the optimization of GTL plants using novel and advanced synthesis gas options. They took a case study of natural gas flare site in Egbema in the Niger Delta region of Nigeria. They compared the technical performance of ATR and steam/CO_2 reformer in the production of an adequate ratio of synthesis gas for the downstream F-T reactor. They discovered that the steam/CO_2 synthesis gas method produces a more favourable H_2/CO ratio closer to 2.0 than the ATR synthesis gas method and is more suitable in terms of thermal and carbon efficiency for GTL operation.

Ekwueme et al., [7] conducted a study on the developments in gas-to-liquids plants through novel synthesis gas reforming options. They highlighted the imperatives of synthesis gas optimization sequel to enhance GTL products recovery. They proposed the steam/CO_2 method as a better synthesis gas reforming method than the autothermal reactor the production of a more favourable H_2/CO ratio for the downstream Fischer-Tropsh reactor and the production of lighter end hydrocarbon liquids.

2. Technologies and Options for Gas Monetization

There are different routes taken to monetize natural gas. These entail measures taken to get the gas resource to the market. For natural gas to be available to the market, it does so either in its gaseous state or in other states or forms wherein it is converted to. In most cases, the gas can be converted to other forms to increase its value and market worth. This can be either in temporary or permanent conversion forms [12].

These options utilized for natural gas resources include the following:

2.1. Pipelines

Pipelines have been used for centuries in the transportation of fluids. Pipelines present the most efficient and cost-effective means to transport hydrocarbons and their products from one place to another. This includes production sites to processing, storage, or utilization areas. Pipelines are specially constructed metallic or plastic vessels that enable fluid transportation from one point to another due to differences in pressure from the inlet to the outlet regions [13]. For gas pipelines pressures are supplied at the upstream region by use of gas compressors. Each gas compressor has a rating and a maximum distance it can deliver the gas based on the hydraulic properties of the flowing fluid in the pipeline. For long-distance transportation of natural gas, compressor stations are usually constructed at strategically calculated locations. At these locations, further compression of the gas is achieved until the gas reaches its delivery point at the downstream end of the pipeline loop [14].

In Nigeria, many networks of trunk-lines continue to be developed and expanded delivery gas both for local consumption and for export. Nigeria is a huge player in the supply of gas to African markets. Major natural gas pipelines in Nigeria are the West Africa Gas Pipeline (WAGP) that runs across Nigeria, Ghana, Benin, and Togo covering a distance of 421 miles, the Escravos-Lagos Pipeline system that runs from Escravos in Delta state Nigeria to Lagos in Nigeria covering a distance of 341 km with an initial capacity of 1.1bscfd and intended capacity increase to 2.2 bscfd. It delivers gas to the southwestern part of Nigeria and also supplies gas to the WAGP. Although pipelines are very efficient in natural gas transportation, certain factors such as long-distance, difficult topography/terrain, sabotage and vandalism, political instability, and economic volatility in energy usage bedevil the economic sustainability of pipelines especially for large scale long-distance destinations [14].

2.2. Liquefied Natural Gas (LNG)

Another obvious means gas owners take to transport their gas especially for large volumes of gas that require long distances is liquefied natural gas (LNG). Liquefied natural gas as the name implies is the liquefaction of the gas resource. This deliberately converts the gas to liquid via a physical conversion process using a peculiar refrigeration process. The gas is chilled below its melting point at about (-162°C) at atmospheric pressure conditions to achieve liquefaction. As the gas is liquefied, the volume substantially reduces to about 1/600 of its original volume. This enormous volume reduction is harnessed in transporting the gas from one region to the other as special container vessels equipped cryogenically are used to transport more volumes of the gas at an instance. This significantly reduces the gas and increases the volume transported per time. However, it must be noted that LNG is a special process and the gas is not usable in its liquid state until it has been regasified at the final destination [14]. LNG typically makes natural gas available throughout the world bridging the gap between natural gas producers and users. Nigeria's LNG plant is a large 7-train plant that accounts for more than 7% of globally traded LNG [10]. However, with America and Australia closing up their LNG imports, global demand for LNG remains limited, and large-scale LNG plants may no longer find the profitably they once enjoyed. Small-scale LNG projects are emerging and have been proven to be economically attractive in future value chains [10].

2.3. Power Generation

Natural gas has long been used for power generation. This utilizes large turbines situated often far from natural gas production sites and requires pipelines as means to supply adequate volumes of processed natural gas. Gas operators have an agreement with power generation companies to supply certain uninterrupted volumes of gas on daily basis. The gas to satisfy this large contract demand is usually provided by fields with large gas deposits. Unfortunately, some of the oil production platforms produce associated gas that is by far lower than the volume needed by these electricity-generating companies [15]. This has increased the risk of such gas being flared. Some of the gas power plants in Nigeria are the Afam gas power plant, the Egbin gas power plants, etc. Although Nigeria has many gas reserves, it has not been able to produce enough electricity for its teeming population. The reason is chiefly because of corruption that bedeviled the power sector, bureaucracy, and incompetence. Some researchers have analyzed the situation in Nigeria's power sector and suggested that the situation will be ameliorated by using small-scale modular gas-to-power plants that are capable of converting natural gas to electricity even at the site of gas production [16].

2.4. Compressed Natural Gas (CNG)

Natural gas can be converted to liquids through pressure increase unlike temperature reduction as in the case of LNG. There is a certain pressure for which every gas would turn to its liquid state. CNG provides options to transport and use the gas in its liquid form. The pressures to liquefy natural gas depend on the mole composition of its constituents [17]. For rich gases laden with significant portions of higher molecular mass hydrocarbon suchas ethane, propane, butanes, pentane plus, the gas can be liquefied around 1800 psig while for very lean gases like methane it takes higher pressures typically 3600 psig to liquefy the gas. CNG presents a viable fossil fuel alternative for gasoline, diesel fuels. CNG has many prospects for vehicular use. In some countries, many vehicles have been retrofitted to use CNG solely or together with conventional gasoline (Ekwueme et al., 2020).

2.5. Natural Gas to Hydrate (NGH)

It has been proven that the properties of natural gas hydrate could be harnessed and put to useful use. Natural gas hydrates have been viewed as a foe because of the great menace it poses in the oil and gas industry. Natural gas hydrates have been known to cause severe flow assurance problems during the transport of natural gas from various phases of the petroleum industry including drilling, production, processing, and transportation. However, more recently, the judicious use of natural gas hydrates has been discovered. This lies in the deliberate conversion of natural gas to hydrates to enable its transportation and storage. It is easier to store liquids and solids than gases. The conversion of natural gas to hydrates enables the storage and utilization of natural gas throughout the year. Natural gas can be converted to solids or semi-solids phases using special hydrate-forming processes that have been proven to be technically and economically viable. This significantly reduces the volume of the gas and enables its bulk transportation from one region to the other. The stored gas can be used in the future and for peak-shaving applications to obtain a higher price for the natural gas as well as to ensure adequate natural gas supplies during periods of peak usage [18, 19].

2.6. Gas-to-liquids Technology

GTL technologies provide a means to convert stranded/flare gas into marketable premium liquid products either for transport or for chemicals. GTL involves the catalytic chemical conversion of natural gas into liquid hydrocarbons. It is one of the most appropriate options in the utilization of associated stranded/flare gases. Many products are realized from GTL processes, these include naphtha, diesel, gasoline, jet fuels, white oils, waxes, methanol, DME, etc. GTL produces clean premium liquid hydrocarbons fuels that with lower carbon footprint emissions when combusted than the same fuel produced from crude oil refining. GTL technologies can be in a large scale or a small scale (mini GTL). Large-scale GTL technologies are capital-intensive investments whose economy profitably has been greatly hampered by the recent drop in oil price occasioned by the covid-19 pandemic. New opportunities for GTL lie in downscaling by accommodating small volumes of stranded gases for monetization. The idea for this is the use of modular GTL units with the potentials to convert small volumes of gases scattered in various fields in the Niger Delta in the production of transport fuels that are in high demand in Nigeria. While there is an already existing large scale GTL plant in Nigeria which has been operational for a few years now, there is potential for modular GTL units to leverage on the small volumes of stranded gas that cannot be factored for utilization and hence flared [6].

2.7. Processes in a GTL Plant Technology

There are four basic stages encountered in the conversion of natural gas to liquids using GTL technology:

1) The gas treatment stage.
2) Synthesis gas production stage.
3) The liquids synthesis/production stage.
4) The product upgrading stage.

2.7.1. The Gas Treatment Stage

This stage involves the removal of entrained impurities in the natural gas stream and the recovery of higher molecular mass hydrocarbons known as natural gas liquids. The impurities in the natural gas stream that are removed include acid gases (CO_2 and H_2S, sulfur compounds, nitrogen, helium, oxygen, water vapour, etc. The type and amount of impurities depend on the source of the gas and the geological features of the reservoir from whence the gas was produced. For instance, natural gas from the Niger Delta region of Nigeria is known not to contain sulphur compounds (such as mercaptans, H_2S, etc). Treatment of natural gas before entry into GTL plant as feedstock pays off in the longevity of the life of the catalysts as these impurities cause catalysts poisoning, corrosion, and a host of other challenges that ultimately reduces the operational efficiency of the GTL plants thereby increasing the operational costs of the GTL projects. However, the nature and degree of treatment depend on the type of GTL plant used and the method for synthesis gas production [9, 20].

2.7.2. The Synthesis Gas Production Unit

Synthesis gas production is an inevitable process in many petrochemical applications. Synthesis gas has been viewed as an intermediate step in the manufacture of a wide range of petrochemicals. Synthesis gas is a mixture of carbon monoxide and hydrogen. For GTL technology application, synthesis gas production produces the necessary products for the manufacture of liquids in the Fischer-Trospch reactor downstream. The synthesis gas unit in the GTL plant represents more than 50% of the entire capital costs of the overall GTL plants and represents an area for optimization by many researchers. In the synthesis gas unit, the process to convert natural gas to synthesis gas is known as reforming. There are various technologies and methods used to achieve this. Each has its specific advantages and limitations and is suited for some areas of applicability. The basic synthesis gas reforming methods includes steam-methane reforming, partial oxidation reforming, autothermal reforming, CO_2 reforming, or steam/CO_2 reforming. These technologies or methods of synthesis gas production have their peculiar advantages and demerits [7].

i. Steam methane reforming

In the steam reforming process, natural gas and steam are converted to a mixture of CO and H_2 through an endothermic conversion process. This process requires heat supply which is achieved by external heat supply usually from the combustion of fuels (usually natural gas) outsides of the reformer tubes. The equation of reaction for steam methane reforming is given as:

$$CH_4 + H_2O \leftrightarrow CO + 3H_2 \; \Delta H^0_{298} = 206 KJ/mol \quad (1)$$

$$CO + 3H_2O \leftrightarrow 3H_2 + CO_2 \; \Delta H^0_{298} = -41 KJ/mol \quad (2)$$

Equation 1 is the methane conversion by steam while equation 2 is the water gas shift reaction. During the reaction, CO_2 and unconverted methane are also produced.

The general stoichiometric formula for the steam methane reforming process is given as

$$C_nH_m + nH_2O \leftrightarrow nCO + (n + 0.5m)H_2 \; \Delta H^0_{298} =< 0 \quad (3)$$

Steam reforming faces some major challenges; these include the provision of an adequate amount of energy into the system to maintain the required reaction temperature. This requires large capital investment to produce the heat required for complete combustion to avoid coking. Another challenge of steam reforming peculiar to its use in GTL is the H_2/CO ratio; steam methane reforming produces H_2/CO ratio that is much higher than the optimum required H_2/CO ratio for the downstream F-T reactor. The actual H_2/CO ratio for steam methane reforming is 5:1 (but theoretically it is 3:1). Steam methane reformers are very large. Furthermore, size constraints limit the application of steam reforming as its typically large sizes make it less a choice where sizing and compactness is major factor to consider [5, 17].

ii. Partial Oxidation Reforming (POX)

Partial oxidation reforming is an exothermic synthesis gas production method that utilizes natural gas and oxygen in the manufacture of H_2 and CO. This process can either be in catalyzed or non-catalyzed reactions. Non-catalyzed POX reactions require a very high temperature as a consequence of operating without a catalyst. In catalytic partial oxidation, the chemical reaction takes place in a catalytic reactor without a burner. In either POX process, the oxygen used is usually gotten from an air separation unit (ASU) [6]. This usually adds to the total cost of the plant. POX systems produce an actual H_2/CO ratio of 1.8 but the theoretical ratio is 2:1. The equation for the reaction of POX systems is given below

$$CH_4 + \tfrac{1}{2}O_2 \rightarrow CO + 2H_2 \; \Delta H^0_{298} = -36 KJ/mol \quad (4)$$

$$CH_4 + 2O_2 \rightarrow CO_2 + 2H_2O \; \Delta H^0_{298} = -803 KJ/mol \quad (5)$$

iii. Authothermal Reforming (ATR)

Autothermal reforming is an ingenious innovation in the field of reforming. It is a hybrid reforming method that combines the best performance features of steam methane reforming and partial oxidation reforming

It represents one of the most promising technologies for the production of synthesis gas in the world. It utilizes methane, steam, and oxygen for the production of hydrogen and carbon monoxide. However, CO_2 and unreacted methane are produced alongside in the reformer.

The equation of reaction for Authothermal reforming is given as

$$CH_4 + \tfrac{3}{2}O_2 \rightarrow CO + 2H_2O \; \Delta H^0_{298} = -519 KJ/mol \quad (6)$$

The methane combustion in equation 6 is followed by steam methane reaction according to equation 1 and water-gas reaction given in equation 2

$$CH_4 + H_2O \leftrightarrow CO + 3H_2 \; \Delta H^0_{298} = 206 KJ/mol \quad (7)$$

$$CO + 3H_2O \leftrightarrow 3H_2 + CO_2 \; \Delta H^0_{298} = -41 KJ/mol \quad (8)$$

One notable advantage of ATR requiresno external heating source because the heat is produced from the partial oxidation reaction process. Both exothermic and endothermic reactions occur concurrently in the plant and compensate for each other. ATR is more compact, simpler, and more efficient than steam reforming and is proposed as the GTL technology for commercial or mega GTL projects. ATR has an actual H_2/CO ratio of 2: 1 but the theoretical H_2/CO ratio is 2.3:1. Thus, it is an ideal method for GTL reactors because of the favourable H_2/CO ratio optimal for the F-T reaction downstream.

2.7.3. The Liquids Synthesis / Production

The synthesis gas produced in the synthesis gas unit is passed to the liquids synthesis units for the production of long-chain hydrocarbon liquids. There are two types of technologies for the production of synthetic liquids after syngas production in for a GTL plant. These includes

1) The Fischer-Tropsch method
2) The methanol to gasoline method

However, the F-T process has been more widely studied and utilized in several GTL applications. F-T reactor is a complex reactor that is used to produce hydrocarbon liquids of varying lengths. The reaction in the F-T reactor is catalyzed. One of the conscious optimization efforts in F-T optimization concepts is the catalyst activity, reactor size, and product distribution. There are about three basic types of reactors used for F-T GTL plants, they are: circulating fluidized bed reactors, fluidized bed reactors, tubular fixed bed reactors, and slurry phase reactors. F-T reactions can be low-temperature FT reaction (LTFT) or high-temperature FT (HTFT) processes. The most common metals used for F-T reaction are group VIII metals [7]. Iron, cobalt, nickel, and ruthenium, all of which have sufficiently high activities for the hydrogenation of CO that drives their application. The two most common catalysts based on costs and selectivity are iron and cobalt. The chemical reaction for the F-T method is generally written as.

$$nCO + 2nH_2 \leftrightarrow (-CH_2-)_n + nH_2 \quad (9)$$

Methane production is also possible according to the equation of reaction below:

$$CO + 3H_2 \leftrightarrow CH_4 + H_2O \quad (10)$$

2.7.4. Product Upgrading Stage

In this stage, the liquids produced in the F-T reactor are processed into final salable and usable liquid products. The upgrading involves the conversion of the syncrude into varieties of liquids of varying density, boiling points, etc through cracking, isomerization, distillation, etc. the product upgrading process is similar to the processes involved in conventional oil refinery [7].

3. Methods

The methodology comprises the stranded gas recovery and conversion system used for the recovery and conversion of stranded associated gas. Two routes of gas conversion shall be considered, this includes conversion to Gas-to-liquids and Pipeline sales gas. The methodological approach shall comprise the technical and economic investigation of these processes.

The block diagram below shows the steps to methodology in this work.

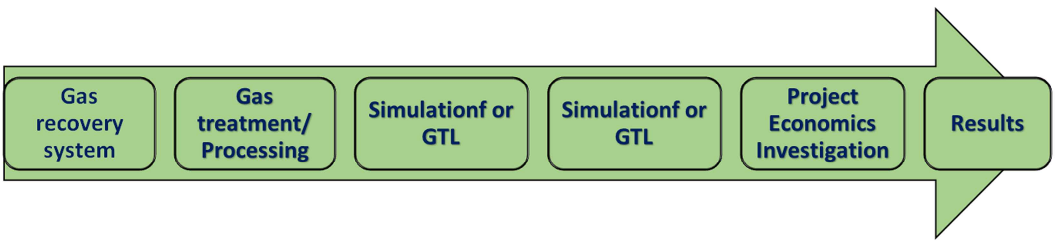

Figure 1. *Stages in the methodology.*

3.1. Technical Investigation

The technical investigation of the study involves the various stages in the recovery and processing of the stranded associated gas. Three basic stages have been identified for the stranded gas recovery system in making available pipeline quality gas or GTL products, this includes:

1) Gas recovery
2) Gas treatment/processing
3) Gas compression/conversion

3.1.1. Gas Recovery

The gas intended to be used is that originally marked for flaring. Proper means to recover this gas from the flare line is necessary. The flare gas system originally put in place for the flaring of the gas is represented in figure 2.

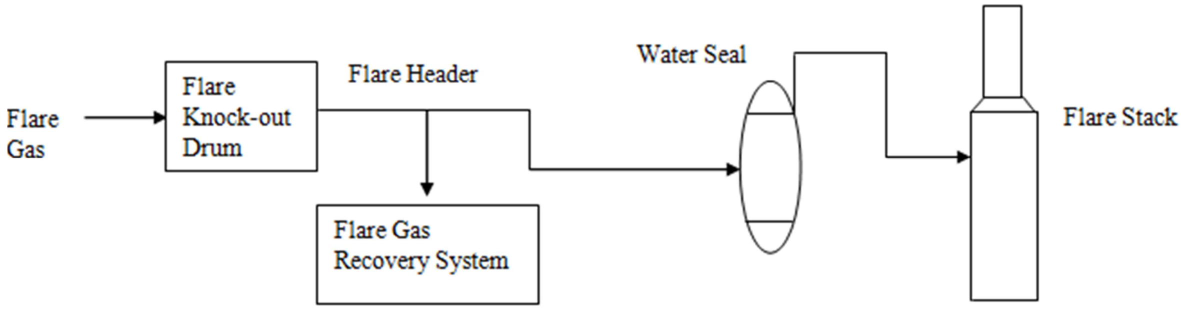

Figure 2. *Block diagram of flare design for the flaring of the associated stranded gas.*

Figure 2 shows a conventional flare process line. In this, the knock-out drum removes the free liquids which are mainly condensates and free water. The gas from the flare knock-out drum goes to the flare header and the water seal, the water seal removes some of the water and the gas is flared at the flare stack. Conventionally, in the operating lines, some of the gas is recovered for use while the others are flared. The flare gas recovery system enables the recovery of the flare gas. The recovery is done at the flare line by re-routing the gas for specific usage.

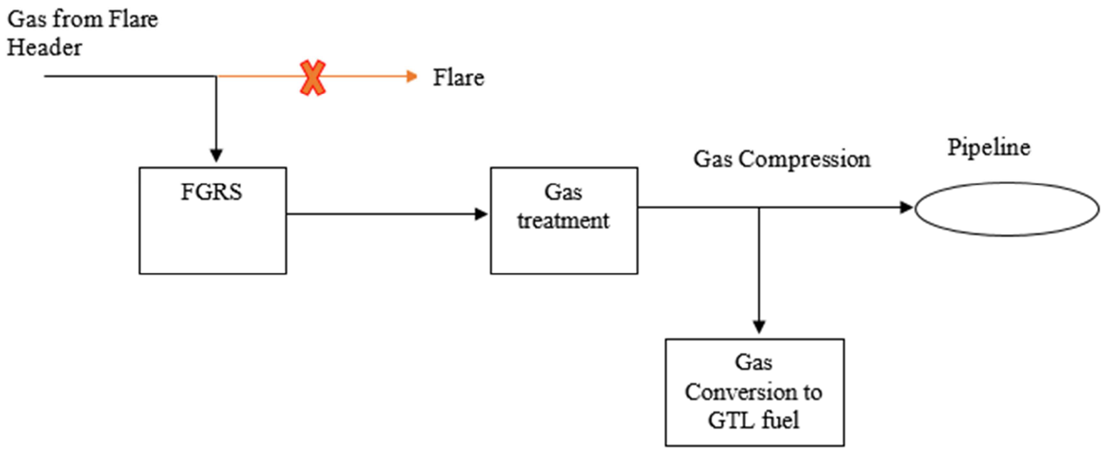

Figure 3. *Block diagram of the flare gas recovery system and utilization technology.*

Figure 3 shows the block diagram of the gas recovery system and utilization technology. This design typically extinguishes the flares by totally routing the stranded associated gas to the flare gas recovery system. The gas is captured and processed either to be sold as pipeline quality sales gas or converted to premium liquid transport fuels through a gas to liquids technology. From figure 3, the route to flare gas is blocked and all the gas is routed to the flare gas recovery system, from the flare gas recovery system, the recovered gas goes to the treatment plant where it is treated and NGLs recovered. From the gas treatment unit, the gas is either compressed to the pipeline or sent for further conversion to liquid products via the gas-to-liquids technology.

3.1.2. Gas Treatment

Treatment of recovered stranded associated gas from the flare lines is necessary to remove entrained impurities and makes the gas safe for either pipeline transportation or GTL plant. Lack of or improper treatment of the recovered gas can be inimical to the operation and performance of the downstream processes which in this case is either pipeline transportation of the gas or conversion to liquids products via GTL technology. Treatment is done to remove acid gases (CO_2 and H_2S), other sulfur components, Nitrogen, water vapour, etc. the degree of treatment depends on the downstream utilization requirement. If the gas is to be sent to the pipeline, there is certain pipeline sales gas specification given by countries to be met. The treated gas having met the pipeline sales gas specification can be allowed to be sold as sales gas to buyers. Alternatively, the degree of processing may be influenced by other uses of the gas. If the gas is to be used for GTL, the degree of processing will depend on the type of synthesis gas unit to be used. Acid gas content in the gas is usually checkmated as they constitute the side range of problems such as the corrosion of metallic parts, catalyst posing, etc. Dew point and hydrocarbon dew point requirements set a limit on the amount of water vapour and liquid hydrocarbon portions allowable in the sales gas stream. Figure 4 shows the gas treatment process flow diagram (PFD) in Unisim.

25 MMscfd of recovered gas with a temperature and a pressure of 86°F and 1000 psia respectively is fed into the amine contactor. Diethanolamine (DEA) strength of 28 wt. % in water is used as the absorbing medium. The rich amine is flashed from the contactor pressure of 1000psia to 90 psia to release most of the absorbed hydrocarbon gas before entering

the lean/amine exchanger. In the Lean/rich amine exchanger, the rich amine is heated to a regenerator feed temperature of 200°F. Acid gas is rejected from the regenerator at 120°F while the lean amine is produced at 255°F. The lean amine is cooled and recycled back to the contactor. The mole composition of the recovered flare gas is given in table 1.

Table 1. *Mole composition of raw associated flare gas.*

Parameter	Composition before treatment	Composition after treatment
Nitrogen	0.16	0.17
Carbon dioxide	4.13	0.06
Methane	87.92	93.21
Ethane	4.65	4.19
Propane	0.93	0.98
Iso-butane	0.26	0.27
N-butane	0.29	0.29
Iso-pentane	0.14	0.13
N-pentane	0.12	0.11
N-Hexane	0.18	0.14
N-Heptane	0.72	0.39
Water	0.5	0.06
Inlet Flowrate	25 MMscfd	23.22 MMscfd

From table 1, the inlet conditions of the feed gas are a temperature of 86°F, a pressure of 1000 psia, and a flowrate of 25 MMscfd. The gas is a typical gas from the Niger Delta with no sulphur content; this means that there is no H2S content in the untreated gas stream.

From table 1, the untreated gas contains 4.13% CO_2 with an inlet flowrate of 25MMscfd. The DEA removed most of the CO_2. A typical sales gas is not more than 2 vol% CO_2 and 4ppm (volume) H_2S. The mole composition of the treated (sweet) gas after treatment. The treated gas contains 0.06% CO_2 and 0.06% H_2O. The volume of acid gases is within the specification for pipeline quality gas.

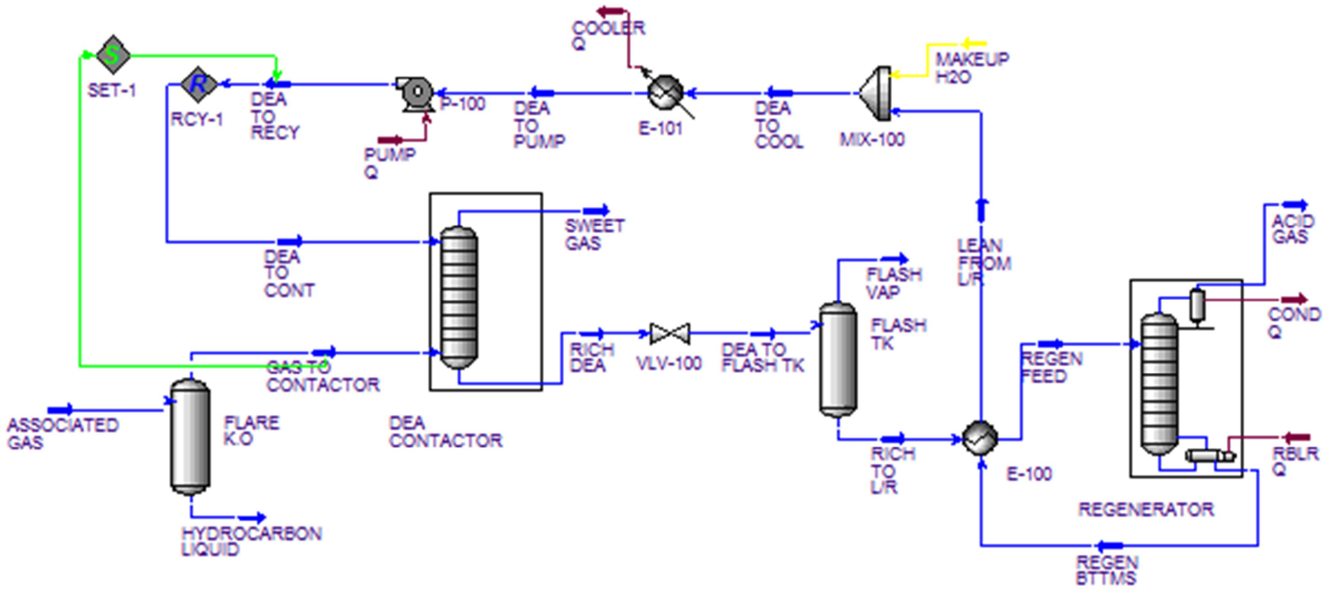

Figure 4. *PFD of flare capture and treatment.*

3.1.3. Compression of the Gas/Conversion to GTL Products

For this study, the treated gas can either be sold as pipeline sales gas or can be further converted to liquid fuels via GTL technology. For this to be achieved to cases are considered. Case 1 is the compression of the gas to pipeline and case 2 deals with the processes involved in the production of liquid fuels via GTL technology.

1. Case 1: Gas Compression to Pipeline

The resulting sweet gas is compressed and sold as pipeline quality gas known as sales gas. The distance from point of gas treatment to point of sale is given as 1000 miles. For this reason, compressor stations are required to compress the gas yielding more energy of flow at intermediate locations. It is necessary to determine the number of compressor stations that will be required to transport the gas from point of treatment to the sales point.

From figure 5, the hydrate formation utility reveals that hydrates will form at 59°F and 8213.48 psia temperature and pressure conditions. This means that hydrates will not form at the operating temperature of 86°F and pressure of 1000 psia.

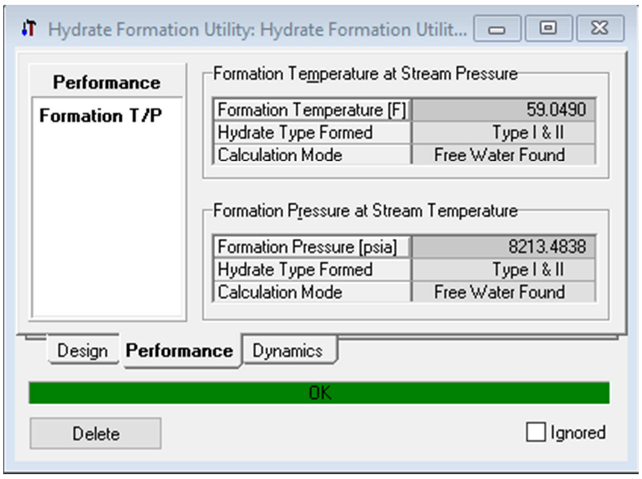

Figure 5. *Hydrate Formation Utility shows conditions at which hydrates will form.*

2. Case 2: Simulation of the GTL Process Plant

Honeywell Unisim R380 was used in the simulation of the GTL plant. Peng-Robinson fluid property package was used in the model setup. All the C_4^+ components were added as n-type hydrocarbons and $C_{21}\rightarrow\infty$ was modeled as C_{30} due to similarities in their properties. The Pre-reformer and the reformer were modeled separately using separate reactors

In the plant simulation, the first natural gas is heated from 86°F to 850°F by a heater. This is the common range for pre-reformer. The initial temperature of the steam was set at 485°F. The heated natural gas and steam are sent to the pre-reformer. The pre-reformer was modeled as a conversion reaction while its water gas shift reaction was modeled as an equilibrium reactor. The pre-reformer temperature and pressure were set at 986°F and 435 psia respectively. The outlet gas from the pre-reformer was sent to the ATR. The ATR was modeled as a conversion reactor while its water gas shift was modeled as an equilibrium reaction in a distinct equilibrium reactor. Because of the exothermic nature of the ATR reaction, its upper temperature was set at a limit of 1886°F to avoid soot formation.

A heat exchanger was connected downstream of the ATR to bring the temperature of the syngas down to 100.4°F so that the steam generated in the ATR is converted to water that can be separated before the FT-reaction, reducing the volume flow and hence the reactor size. However, 100.4°F is too low for the low-temperature Fischer-Tropsch (LTFT) process which runs at 392-464°F, and hence a heater was included in the model heating up the FTR inlet to 410°F.

The FTR was modeled as a plug flow reactor (PFR) as this is the flow pattern that mostly resembles a multi-tubular fixed bed (MTFB) reactor and a starting volume of 1000m^3 was chosen. The FT reaction set was defined as kinetic and it included both the FT reaction and the methanation reaction. The stoichiometric coefficients for the FT reactions are modeled based on the ASF distribution and the kinetics was implemented by the use of Iglesias rate of reactions.

The products of the MTFB reactor are gaseous and liquid, gas and liquid products are separated inside the reactor by gravity- gas leaving at the top and liquid products trickling down and exiting the bottom. The gaseous products are cooled by heat exchanging with water to 100.4°F before entering the 3-way separator together with the liquid products. This was done to separate water that left the reactor as steam. This will eliminate unnecessary recycling and water being sent to product upgrading.

In the 3-way separator, more water is separated, liquid products are sent to the upgrading unit and the remaining gases are split in a purge and a recycle stream. Table 2 gives the inlet conditions of the reactants.

Table 2. *Base case input conditions for natural gas, steam, and oxygen.*

Input	Temperature (°F)	Pressure (Psia)	Molar Flow (Kmol/hr)
Natural Gas	86	435	1157 (23.22MMscfd)
Steam	485	590	9000
Oxygen	392	435	2500

The overall view of the GTL process schematics done on Unisim R380 software is given in the figure below.

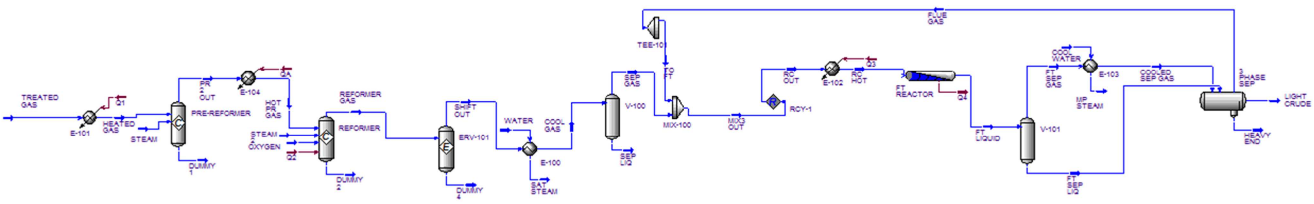

Figure 6. *GTL Simulation diagram.*

From figure 6, the pre-reformer was modeled as a conversion-type reactor. Also, the reformer was modeled as a conversion-type reactor while the water gas shift reaction was modeled as an equilibrium-type reactor. Three reactors in total were used in the simulation of the GTL plant. The water-gas shift (WGS) achieved by the two equilibrium reactors is necessary to achieve the desired H_2/CO ratio for the F-T reactor downstream. Water-gas shift reaction is typically used to adjust and control the H_2/CO ratio during synthesis gas production. This is done by converting carbon monoxide and steam to carbon dioxide hydrogen gas.

The hydrocarbons obtained from the F-T unit consist of hydrocarbons mix which includes: i) light hydrocarbons, ii) Olefins, iii) liquid hydrocarbons and iv) waxy, long-chain paraffinic molecules. These components were processed and to their final state in the upgrading unit and premium transport fuels were recovered as end products.

3.2. Project Economics Investigation

The economics of the FGRS is analyzed in this section. The economic analyses are done for pipeline sales gas utilization route and GTL products route. The economic parameters for the project are given below.

i. The natural gas feed rate of 23.22 MMscfd
ii. GTL products capacity of 2350 b/d, comprising 1100 b/d diesel and 1250 b/d gasoline
iii. Modular flare gas recovery technology for GTL has CAPEX of 180 million dollars
iv. Modular flare gas recovery technology for gas compression to the pipeline has a CAPEX of 5 million dollars
v. Flare natural gas price is $1.5/Mscf since gas is flared gas
vi. OPEX is 2% of CAPEX (excluding natural gas price)
vii. Plant operational period of 20years
viii. Plant operational days of 350 days per year
ix. Refined GTL product price of $100/bbl for diesel and $55/bbl for gasoline
x. Straight-line depreciation method
xi. Salvage value of zero
xii. Income tax of 35% base case
xiii. 100% owners' equity

4. Results and Discussion

The result is presented for each of the cases i.e. the gas compression to pipeline and the GTL. Technical and economic results shall be presented and compared.

4.1. Technical Results from Unisim Simulation

The technical results for the pipeline and GTL products simulated in Unisim are given in this section. From the 25 MMscfd of associated flare gas recovered, 23.22 MMscfd of pipeline quality sales gas was realized. Additionally 1.77MMscfd of acid gas comprising CO_2, and water vapour was realized.

4.1.1. Technical Results for Sales Gas

Figures 7, 8, and 9 show the plots from simulations conducted on the pipeline sales gas to evaluate its properties as a pipeline gas and whether it can be transported through a pipeline without flow assurance problems.

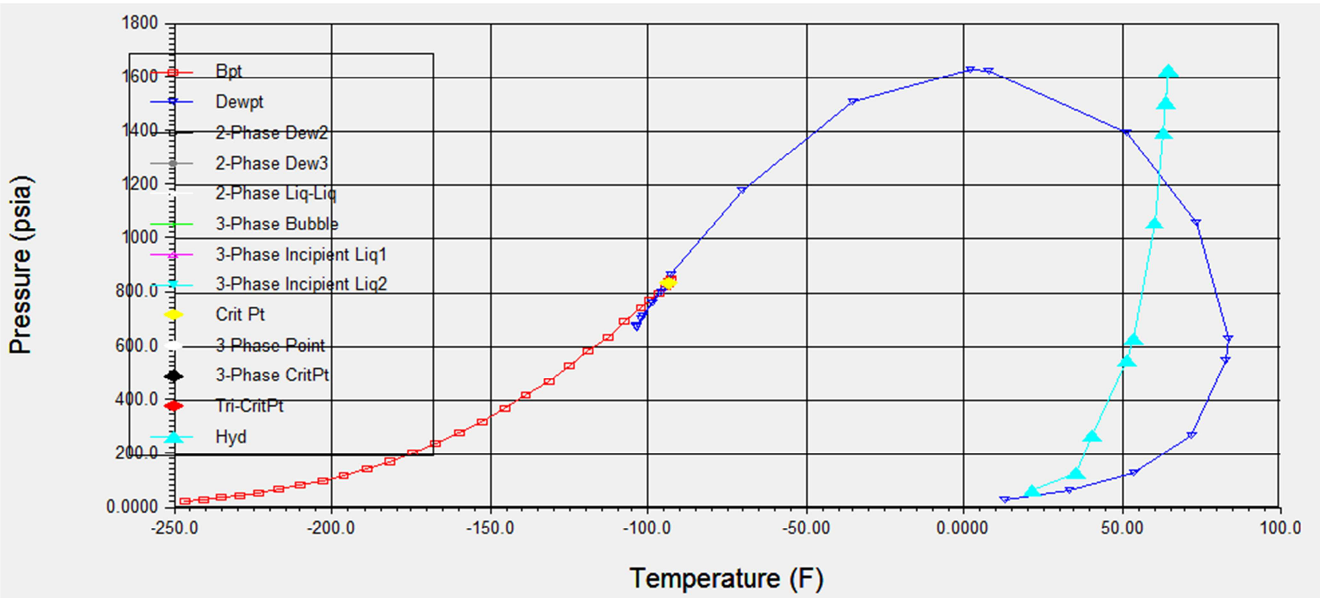

Figure 7. *Phase-envelope for treated gas showing conditions for hydrate formation.*

Figure 7 shows the hydrate formation envelope for the pipeline sales gas. It is important to determine if hydrate will form in the pipeline. Hydrate forms as a result of water present in the pipeline which reacts with the methane at a certain temperature and pressure conditions. The hydrate formation is investigated by the phase-envelop. From the phase-envelop plot, the green line represents the hydrate formation line. Hydrates will form in the pipeline if the pressure-temperature conditions experienced in the pipeline fall on the green line in the phase envelope plot otherwise hydrates will not form. Hydrates formation can be prevented by adjusting the pressure-temperature conditions and making sure it does not fall on the hydrate formation line. This is achieved by either reducing the pressure or increasing the temperature. Temperature control is one of the commonest means of controlling hydrates formation in the pipeline.

The sales gas compressed into pipelines and sold has the properties given below.

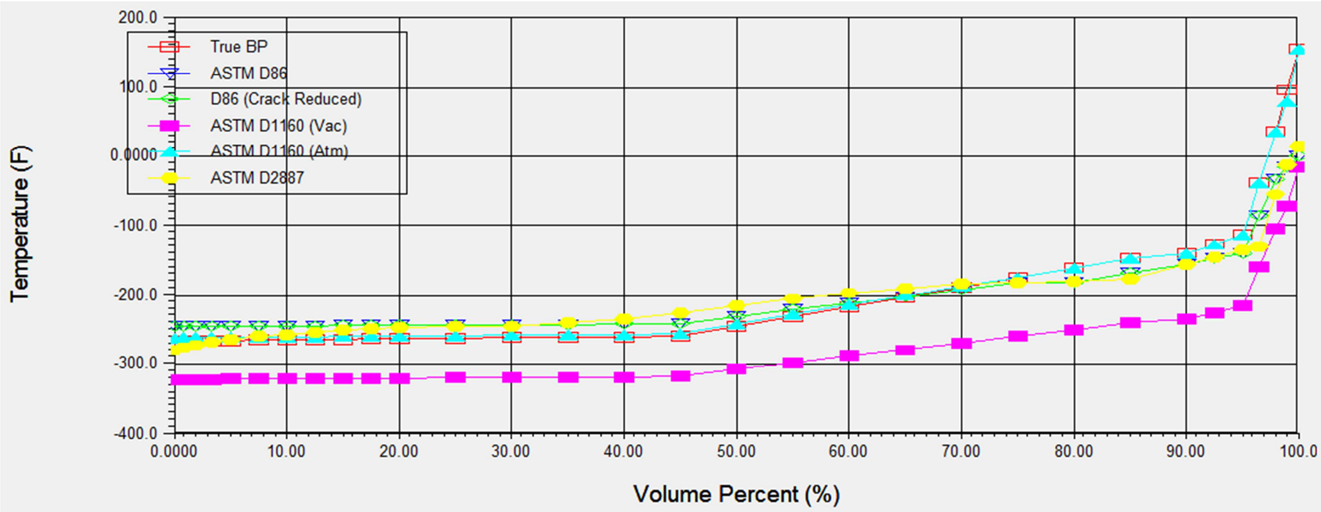

Figure 8. *B oiling point curves for treated gas (sales gas).*

From figure 8, the temperature increases with increasing volume percent. At approximately 96°F. There is a very sharp increase in temperature with percentage volume.

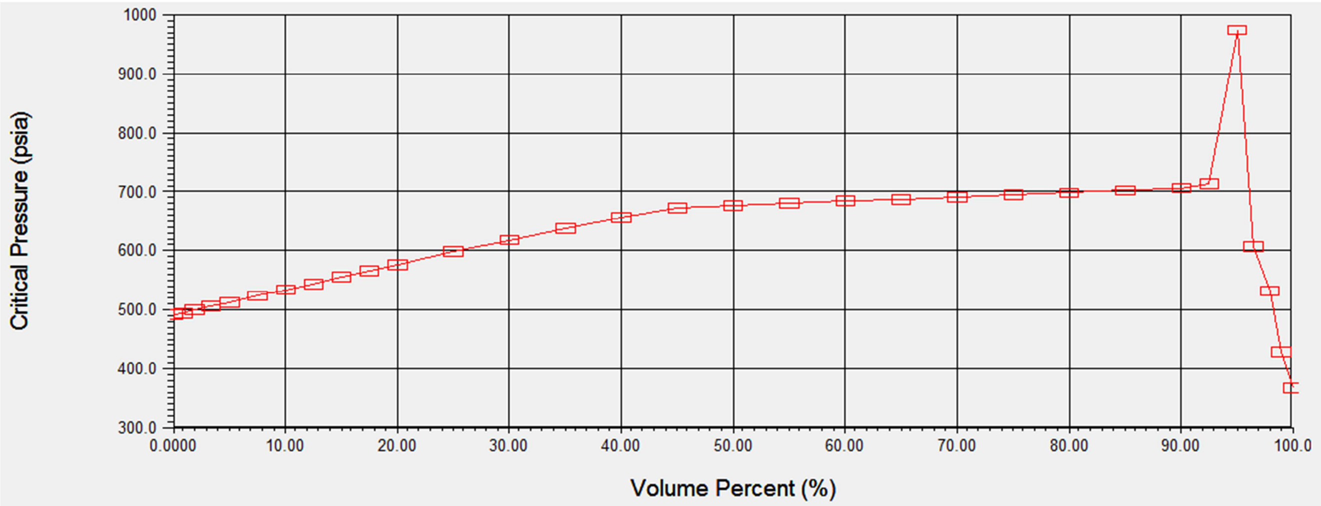

Figure 9. *Critical pressure vs. volume percent for treated gas.*

The critical pressure increases with increasing percentage volume until a percentage volume of 96% in which the pressure is reduced steeply. At 100%, the critical pressure is 360 psia and highest at 96% with 985 psia.

4.1.2. GTL Plant Technical Result

Table 3. *General technical performance parameters for ATR reforming method.*

Parameter	Value
H_2/CO ratio at F-T inlet	2.33
Carbon efficiency (%)	74.25
Thermal efficiency (%)	62.32
CO_2 emission (MMscfd)	23.18
Diesel production (b/d)	1100
Gasoline production (b/d)	1250
Total Product Yield (b/d)	2350

The technical result for the GTL plant simulation is given below under the following heading:

1) H_2/CO ratio
2) Thermal and carbon efficiencies
3) Pollutants and emission characteristics
4) Product Yield
5) CO_2 production/emission

From table 3, the H_2/CO ratio for the syngas unit is 2.33. This is slightly higher than the ideal ratio of 2.0 best suited for downstream Fisher-Tropsch plant for the production of diesel and gasoline. Nonetheless, the H_2/CO ratio of 2.33 is favourable as it is rarely possible to get the ideal ratio of 2.0.

The carbon and thermal efficiency is 74.25% and 62.32% respectively, this shows that the GTL plant is efficient because most conventional GTL plants have efficiencies of not more than 60%.

The product yield is a diesel with a yield of 1100 b/d and gasoline with a yield of 1250 b/d. The total yield is 2350 b/d. The plant gave a high yield as expected for the GTL plant. Most conventional GTL plants have a rule of thumb of 1b/d for each 10

Mscf of feed gas. Using the rule of thumb the GTL is expected to produce 2322 b/d of liquid products. The GTL plant produced above expectations with 28 b/d higher liquid productions.

4.2. Economic Result Presentation

The result for the economic analyses is presented in this section. As expected it is presented for each of the cases considered.

4.2.1. Revenue Calculation

The revenue for each case is calculated and presented in table 4.

Table 4. *Revenue Table for the two cases considered.*

Pipeline Gas				
Product	**Volume (B/D)**	**Unit Price US$/bbl)**	**Daily Revenue (US$)**	**Annual Revenue (US$)**
NGL (C2+)	121.7	18	2190.6	766710
Sales Gas	23.22	3.5	81270	28444500
Total				29211210
GTL products				
NGL (C2+)	121.7	18	2190.6	766710
Gasoline	1250	55	68750	24062500
Diesel	1100	100	110000	38500000
Total	2471.7		180940.6	63329210

From table 3, the annual revenue generated from the sale of the pipeline quality gas is US$ 29.2 million while the annual revenue generated from the sale of the GTL premium liquid transport fuels is US$ 63.3 million. The revenue from the sales of GTL Products is higher than that realized from the sale of the pipeline quality gas via pipeline.

4.2.2. Results for Operating Expenditures

The Operating expenses for the two cases are summarized in Table 5.

Table 5. *Operating Expenses for the two cases.*

Case 1: Pipeline sales gas				
Parameter	**Volume**	**Unit Price**	**Daily Expenses**	**Annual Expenses (million US$)**
Feedstock (Natural gas)	23.22	US$1.5/Mscfd	34830	12.19
Pipeline transport	23.22	US$0.8/Mscfd for 1000 miles	18576	6.5
Other OPEX		2% of CAPEX		0.16
Total				18.85
Case 2: GTL products				
Feedstock (Natural gas)	23.22	US$1.5/Mscfd	34830	12.19
Variable OPEX		2% of CAPEX		3.6
Total				15.79

From table 5, the Total annual OPEX incurred for case 1 i.e. sales of pipeline quality gas is US$ 18.85 while that of GTL products is US$ 15.79. The OPEX for the sale of pipeline quality gas is more than that for GTL. The transportation of the gas via pipeline represents the highest cost contribution to the OPEX for case 1.

4.2.3. Results for Economic Indicators

Economic indicators for the two cases are presented in Table 6.

Table 6. *Economic indicators presentation.*

Parameter	**Value**	
	Case 1: Gas sales	**Case 2: GTL Product sales**
NPV @ 10% (MMUS$)	58.5	109.9
POT (yrs)	1.16	5.29
IRR (%)	86	18.3
NCR (US$	6.87	34
P/$	16.18	2.78

From table 6, for the sales gas, the NPV at 10% discount rate is US$ 58.5 million, the net cash recovery is US$ 6.87 million, the Pay-out time is 1.16 years, the internal rate of return is 86% while the profit-per-dollar invested is 16.18. For the conversion of the gas to GTL products and sale of the GTL product; the Net present value (NPV) is US$ 109.9 million, the Pay-out time is 5.29 years, the internal rate of return is 18.3% and the profit-per-dollar invested is 2.78. Conversion of the treated gas to GTL yields higher NPV when GTL products are sold than sales of the pipeline quality gas. However, other economic appraisal parameters such as Pay-out time, internal rate of return, and profit per dollar invested favours the sale of the gas than conversion to GTL. For a short time project, it is advisable to sell the gas as pipeline quality gas, this is because it has a very short payout time and a very high internal rate of return. It is even more justified by the profit per dollar invested which is very high. But if there are no buyers for the gas, the conversion to GTL remains the option to convert the gas into readily usable premium transport liquids.

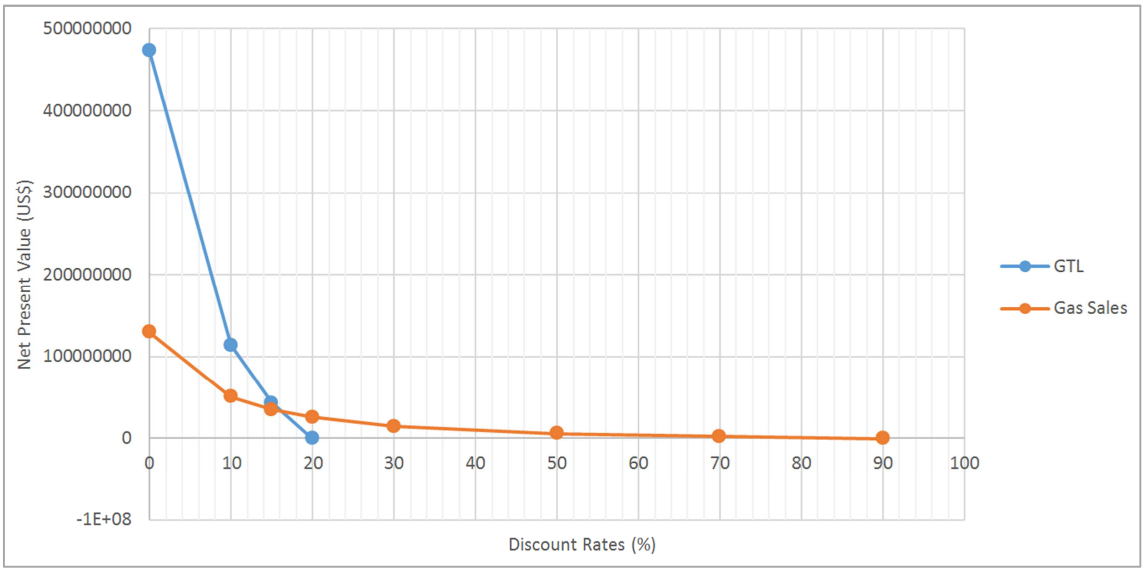

Figure 10. *IRR for the two cases at a natural gas price of US$1.5/Mscf.*

From figure 10, the IRR for GTL is far lower than thepipeline gas sales. The GTL project will not be viable for discount rates above 18.6%. The two lines intersect at a discount rate of 16%. When the discount rate is below 16% then GTL will be considered at the expense of Gas sales because of higher NPV.

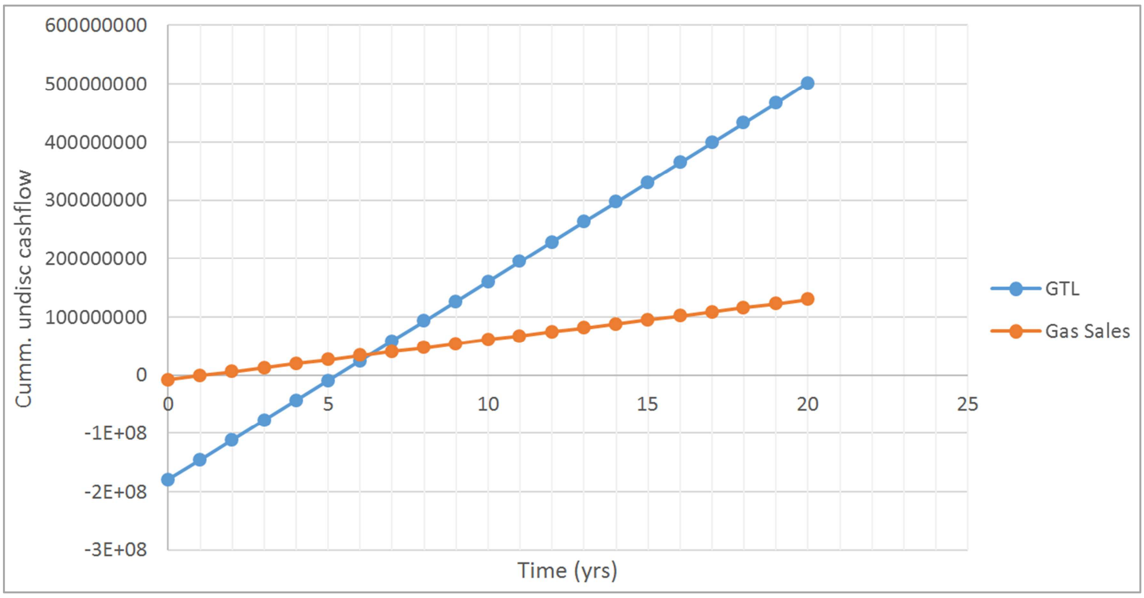

Figure 11. *POT for the two cases at a natural gas price of US$1.5/Mscf.*

From figure 11, Gas sales have a lower pay-out time than GTL products. The pay-out time lines intersect each other at 5.5 yrs.

4.3. Sensitivity Analyses

Sensitivity analyses are performed by changing some variables while keeping others constant. It is done to determine relationships between variables at various conditions. The sensitivity is performed for the following:

1) Discount rates of 10%, 15% and 20% Natural gas cost of US$2.5/Mscf and US$3/Mscf
2) Changes in non-feed stock OPEX of 2% and 2.5%
3) Changes in CAPEX of US$65,000 PBLD and US$80,000 PBLD
4) natural gas price of US$1.5/Mscfd and US$2.0/Mscfd
5) The sensitivity is performed based on natural gas price. For natural gas prices of US$1.5/Mscfd and US$2.0/Mscfd, sensitivity is performed for various discount rates, non-feedstock OPEX, and CAPEX.

Table 7. *Economic results for GTL product sales for natural gas price of US$1.5/Mscf.*

GTL: NG Price US$1.5/Mscf	CAPEX: $65,000 PBLD		CAPEX: $76,596PBLD		CAPEX: $80,000 PBLD	
	OPEX (% OF CAPEX)					
Discount Rates	2%	2.5%	2%	2.5%	2%	2.5%
10%	136094243.8	131867791.6	109888219.6	104907784.8	90894862.6	85367963.4
15%	59613697	56506330.2	33131247.6	29469538.7	13937545.6	9874065
20%	12462844.2	10045402.2	-14190023.6	-17038728	133507239.7	-36668510.3
NCR	33927536.5	33431099	340501161.5	33465161.5	34139036.5	33489849
IRR	21.8	21.4	18.3	17.9	16.2	15.9
POT	4.50	4.57	5.29	5.38	5.85	5.96
P/$	3.44	3.38	2.78	2.71	2.42	2.62

From table 7, it can be observed that the NPV decreases as the CAPEX and OPEX are increased. CAPEX has a profound effect on the Net present value. The effect of varied OPEX on the NPV is not as large as that of varying CAPEX on the NPV.

Table 8. *Economic results for GTL product sales for natural gas price of US$2/Mscf.*

GTL: NG Price US$2.0/Mscf	CAPEX: $65,000 PBLD		CAPEX: $76,596PBLD		CAPEX: $80,000 PBLD	
	OPEX (% OF CAPEX)					
Discount Rates	2%	2.5%	2%	2.5%	2%	2.5%
10%	11360780.5	109381128.5	874015556.6	82421121.8	68408199.6	62881300.4
15%	4308108.3	39973714.4	16598631.8	12936923	-2595070	-6658549.8
20%	-399055	-2816497	-27051923	-29900627	-46369139	-49530409
NCR	31286261.5	30789824	31408886.5	308238886.5	31497761.5	30848574
IRR	19.9	19.6	16.6	16.3	14.8	14.4
POT	4.88	4.96	5.73	5.84	6.34	6.48
P/$	3.10	3.03	2.49	2.42	2.15	2.09

Table 8 gives the economic results for the natural gas price of US$2/Mscf. When table 7 and table 8 are evaluated, it can be observed that an increase in natural gas price reduces the NPV for all parameters considered.

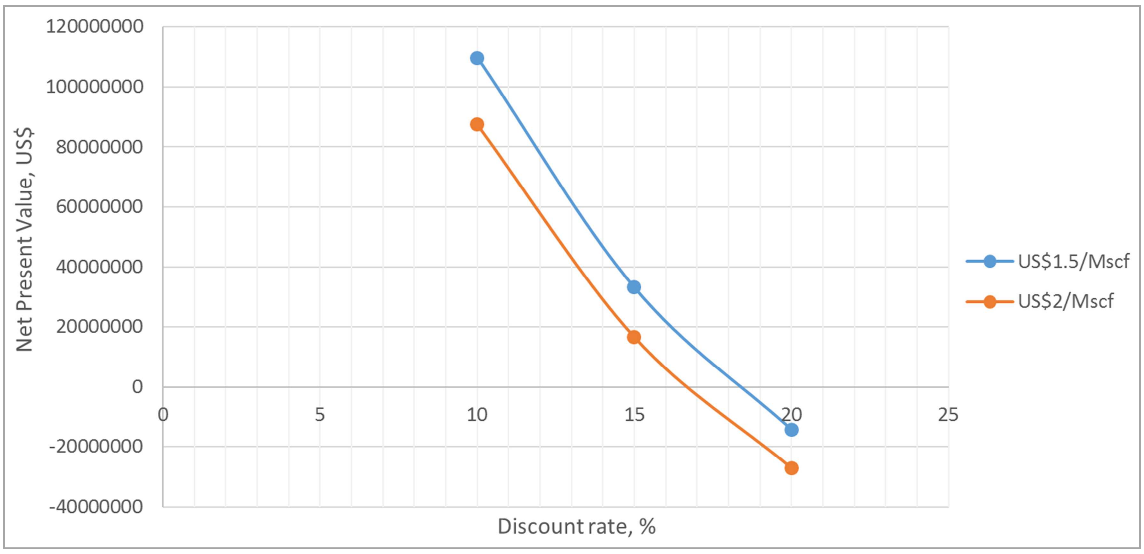

Figure 12. *NPV vs. discount rate for different natural gas prices.*

From figure 12, it can be observed that lower natural gas price favours the profitability of GTL conversions processes. Natural gas price constitutes the highest source of operating expenses. Government can encourage GTL conversion as means of utilizing associated flare gas by subsidizing natural gas prices or by making associated flare gas at zero cost since it was a candidate for flaring.

5. Conclusion

Design and modeling of stranded associated using Unisim software have been conducted in this study. The following conclusion has been drawn

1. Unisim model has been designed for the capture and utilization of stranded gas and subsequent conversion to end products. The gas was treated using 28wt% DEA in water and it produced pipeline quality gas which was tested to be free from hydrate formation as long as the operating conditions are maintained. The GTL plant was simulated using the autothermal reforming synthesis gas method. In this method, natural gas, oxygen, and steam are the reactant species.

The pipeline quality gas produced met all gas specifications as a sales gas. The GTL products produced was of premium quality and was greater than the rule of thumb for conventional GTL plants because of the optimization performed in the GTL process system.

2. A modular GTL plant was a model which produced 2350 b/d of GTL products comprising 1100 b/d of diesel and 1250 b/d of gasoline. These products are in high demand in Nigeria and constitute widely the products that make up vehicular transport in Nigeria. Being that vehicular transport constitutes the major means of transportation in Nigeria, and because of the higher performance of GTL products when compared to transport fuels from crude oil distillates, GTL products sales are highly sought after.
3. GTL product and pipeline sales are the two products realized in this study. It is to be realized that some conditions favour the conversion of the stranded gas to pipeline gas, for instance for a short-run condition where there is the availability of pipeline to transport the gas and there is a market for the gas, the gas may be processed and sold as pipeline gas. But in the long run, GTL is more profitable than pipeline gas because of higher revenue accruable from GTL product sales over pipeline sales gas.
4. The economic analyses reveal a higher NPV from the GTL product sales than selling the gas outright as pipeline gas. However, other economic indicators like pay-out time, IRR, and profit-per-dollar invested favours the sale of the gas as pipeline quality gas at the expense of GTL product production.

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