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Evaluation of the Economic Potentials of a Mini Gas-to-Liquids (GTL) Plant in Nigeria

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Abstract: In this paper, the economic potential of using a mini gas-to-liquids (GTL) plant for monetization of stranded associated gas in Nigeria was extensively evaluated. Feedstock to the plant comprises 50 MMscfd of treated stranded associated gas from Assa North in the Niger Delta region of Nigeria. 5000 b/d of GTL diesel product was realized after simulation using Fischer-Tropsch (FT) type modular gas-to-liquids technology. Economic analyses were performed for a wide range of economic conditions to determine the economic potentials of the GTL project. From the result, it was realized that for base case, the net present value (NPV) of the project was US$32,421 barrel-liquid-per-day (BLPD) corresponding to US$162.1 million for 5000 b/d of GTL diesel produced. The payout time (POT) was 4.48 years while the net cash ratio (NCR) was US$81.83 million. The internal rate of return (IRR) was 22.2%. From the sensitivity analyses performed, it was realized that the variable having the most influence on the NPV was the GTL product price (the price of diesel) followed by the capital cost of the GTL plant and then the natural gas price. It was also realized that the operating cost of the plant has the least (negligible) effect on the NPV of the project. Furthermore, it was realized that GTL project remained profitable for diesel prices above US$80/bbl as long as the price of natural gas was maintained below US$2.2/Mscf at 15% discount rates. In general, it was realized that the mini-GTL project was profitable for diesel prices equal to or greater than US$80/bbl as long as discount rates remained below 20% for base CAPEX and OPEX. It was recommended that the government of Nigeria subsidizes the price of natural gas to increase the profitability of mini-GTL projects creating a greater participation by the private investors and thereby reducing the volume of associated gas flared.

Keywords: Gas-to-Liquids, Stranded Gas, Barrel-liquid-per-day, Fischer-Tropsch, Economic Analyses

1. Introduction

As of the first quarter of 2021, the total associated gas flared in Nigeria amounted to 45.33 billion cubic feet. This represents an average daily flare volume of 505 MMscf [1]. This indicates a 36% reduction from the average daily flare volume of 790 MMscf recorded in 2018. Nigeria crude has been classified as 'foamy', a crude with high gas-oil-ratio. Thus, the associated gas produced in Nigeria alone could almost meet the domestic gas needs of the country; unfortunately, this resource has been targeted for routine flaring. Aside from the gas produced alongside crude oil, Nigeria has a proven gas reserve of 206.53 tcf as of July 2021. This resource has been underutilized as Nigeria's rate diversification to other energy aside oil is still slow and over-politicized [2].

There is an urgent need for Nigeria to develop its gas economy. The global shift to renewable holds great tragedy for Nigeria if nothing is done in prospect. There is an urgent need for energy that has no or very low carbon footprint as the environmental consideration has become major political debate in many nations. The COP26 convention held in the UK is one of the several global awareness initiatives on climate change. Because of the uniqueness of natural gas in terms of its availability, cost, emission characteristics, and caloric value it will remain as the dominant energy source in the future even when other fossil fuels have been abandoned. Researchers have regarded natural gas as the bridge fuel in the transition from fossil fuel to renewable energy mix.

Several gas projects have sprung up in Nigeria, but many have been bedeviled by escalating political instability, high capital and operational costs, and unpredictable market conditions. Furthermore, those that managed to remain in existence struggle with remaining productive and profitable. A notable gas project in Nigeria is the Escravos GTL plant. This 34,000 b/d plant costs more than 10 billion dollars to be built, but since its commissioning, it has struggled with operational and economic challenges [3].

Portable small-scale GTL technology provides a hub for the monetization of the vast stranded gases candidate for flaring in not less than 180 flare sites in the Niger Delta. Amongst other gas monetization or conversion options like LNG, CNG, NGLs etc., gas-to-liquids technology stands out in Nigeria because of the high demand for liquid transport fuels which constitute more than 70% of the total fossil fuels consumption in Nigeria. Gas-to-liquids technology produces premium liquid products that out-perform the conventional crude oil-refined products like diesel, gasoline, jet fuels, kerosene, etc. [1]. Thus, it burns clean leaving a minimal carbon footprint.

However, GTL technologies face major drawbacks. First, conventional GTL plants are large facilities that are rarely are mostly operated by joint ventures between companies and/or host government (s). These plants require substantial volumes of gas to justify their operation. Owing to the large size, the capital cost of such a plant is high, this hampers individual investment opportunities. Secondly, the large space required by conventional GTL plants poses limitations where space requirement is an issue. Furthermore, conventional operational practices in synthesis gas production and synthesis crude productions have been noted to be operationally expensive. These in general have led to the skepticism and high risk associated with GTL projects [4, 5]

The emergence of compact reactors and modular systems has heralded an era of GTL technology with substantial reductions in size, cost, emissions and higher operational and economic performance indices. Miniaturization of GTL plants offers a cost-effective alternative to operators seeking to monetize their gas and a market for stranded gas in smaller volumes and disparate locations. These plants are portable and scalable and usually have room for integration of more units as well as capacity reduction or increment.

Boyajian et al., [6] worked on small-scale GTL plants. They described the methods to achieve higher quality and yield of GTL products. They suggested ways to minimize complexity, space, cost and increase efficiency and yield. They compared the efficiency of three notable syngas conversion technologies- Fischer-Trospch, STG+ and MTG. They highlighted the efficiency of Primus STG+ which achieved 5 gallons of GTL liquids products using 1 MMbtu of natural gas. They concluded that STG+ is more cost-effective than F-T, and MTG plants for relatively smaller capacity plants.

Anyasse and Anyasse [7] presented methods to mitigate gas flaring using small-scale gas-to-liquids technology. They began by presenting challenges faced by conventional GTL synthesis gas reforming methods. They highlighted the benefits and importance of the transition to newer and better GTL synthesis gas technologies such as catalytic partial oxidation reformers. They highlighted how the innovative new synthesis gas alternative designs when combined with efficient Fischer-Trospch technologies would yield profitable GTL products and hence mitigate the environmentally harmful act of gas flaring.

He [8] presented a study on flare gas monetization with modular GTL units. They considered the conversion of 4MMscfd of wellhead-associated gas into premium GTL gasoline. They utilized the synthesis gas to methanol (STM) process using fixed bed catalytic reactors.

Fulford et al., [9] conducted a study on a new approach to gas monetization in Nigeria. They gave comprehensive information on the use of GTL for gas monetization. They highlighted factors that favour GTL technology in Nigeria. They discussed the impact of long-term and short-term constraints on the profitability and viability of GTL. They proposed GTL as the solution for small volumes of associated gas. They insisted that operators usually flare gas with volume ranges of 1 MMscfd for individual flares and 10-20 MMScfd for a group of flares. They attributed the huge gas flaring in Nigeria to be due to excuses of gathering costs, gas processing and treating facilities especially for small volumes of gas in small fields, lack of infrastructure and funding to deliver gas to the markets.

Kanshio and Agogo [10] performed a techno-economic assessment of mini-GTL technologies for flare gas monetization in Nigeria. They identified some promising technologies with the potentials of converting small volumes of flare gas below 1 MMscfd to premium marketable gas-to-liquids products. They focused on the production of products like diesel, methanol, and anhydrous ammonia using Greyrock, GasTechno, and Proton Ventures technologies respectively. They made economic and technical comparisons between the products and the technologies for 500 MMscfd of natural gas. They discovered under prevailing economic circumstances that methanol was the most attractive of the three products considered.

Ekwueme et al., (2019) described effectively the economics analyses of GTL plants. They compared two GTL technologies on the basis of their synthesis gas units: the autothermal plant which uses oxygen, natural gas, and oxygen as feedstock and the steam/CO_2 method (which they proposed) that uses steam, CO_2, and natural gas as feedstock. They modeled a 50 MMscfd of plant for both methods using F-T syngas liquids conversion reactor in Unisim. They discovered that the proposed method performed better than the ATR method in terms of NPV, POT, IRR, and emissions characteristics.

Izuwa et al., [5] perform a technical investigation of synthesis gas optimization options for effective GTL projects. 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 produced a more favourable H_2/CO ratio (closer to 2.0) than the ATR synthesis gas method and hence more suitable in terms of thermal and carbon efficiency for GTL operation.

Ekwueme et al., [4] highlighted the developments in gas-to-liquids plants by focusing on the improvement and advancement in synthesis gas units. They highlighted the importance of optimization of the synthesis gas unit in the optimization of the GTL plant as the synthesis gas unit has the highest capital cost in the entire GTL plant. They suggested optimization factors like H_2/CO ratio, OPEX and CAPEX reductions, Profitability increase, emissions reductions, size reduction, thermal and carbon efficiencies as the notable optimization parametres of concern in GTL plants for improvements.

2. Gas Monetization Options

The methods to monetize natural gas either associated or non-associated can be conveniently categorized into methods that aim to transport the gas to user destination and methods to convert the gas to other forms to enable utilization. These methods are discussed in their sub-classifications.

2.1. Gas Monetization by Transportation Methods

More often than not, gases have to be transported from regions of production to utilization points. The distance between the production and utilization centers is a function of whether the utilization is domestic or not. Non-domestic utilizations are usually associated with very long distances of which long-term market conveniences are key to sustainable gas supply between producer nations and utilization nations. For the reason of gas transportation, gases can be transported in their gaseous form or physically turned to other states that reduce their volume thus enabling cost-effectiveness in transportation and storage such as liquid, solid or, slurry states [11].

Pipelines provide a means to transport natural gas in its gaseous form using specially fabricated metallic or plastic containers called pipelines. Pipelines are the most efficient means of natural gas transportation, especially where the terrain, market conditions, political and security situations permit. Usually, pipelines represent the transport means that are prone to the most perturbation from external sources. Pipelines are prone to vandalism, ruptures from man-made or operational issues. Also, the construction of pipeline requires convenient long-term market conditions because of its high capital cost of construction [12]. There are cases where pipelines construction may be technically or economically prohibitive. In such cases as trans-continental shores with uneven market conditions, the construction of pipeline may not be a justifiable economic decision since it may become a wasted project should market conditions change and the user declines from the resource. In this case, other forms to convert natural gas for the sole aim of achieving transportation, storage, and handling are required. Among these is the technology that liquefies the gas physically for the sake of transportation, this technology is called liquefied natural gas technology. The gas is liquefied by temperature reductions to the melting point of the gas usually at -162°C. This enables the conversion of the gas to liquids that are kept in special low-temperature or cryogenic vessels and transported to areas of need and utilization [13]. This method is characteristically useful when it comes to gas export to other continents like Europe, Asia, and America etc. The gas that was initially turned into liquid is further regasified when it has reached its destination. The gas is utilized in the gaseous form afterward or used for the production of other commodities [9].

Compressed natural gas enables the conversion of gas physically to liquids by pressurizing the gas and storing into pressure-tight containers. CNG is usually achieved by pressures or 1800 psig for rich gases and 3600 psig for lean gases. CNG presents a viable fossil fuel alternative for gasoline, diesel fuels. CNG has many prospects for vehicular use. In some countries, many vehicle have been retrofitted to use CNG solely or together with conventional gasoline [10].

Natural gas to hydrates offers a means to harness hydrate formation capabilities to useful means. Hydrates have been regarded as a menace in many areas of petroleum engineering including drilling, production, transportation, processing, and storage. It has been blamed for several flow assurance problems in gas transport and has been noted to cause pipeline integrity problems like leaks, corrosion which increases the operational costs of pipeline gas transport. However, hydrates are useful if conveniently and technically harnessed [14]. Natural gas can be converted to gas hydrates to enable storage and transportation from one place to another. The conversion of natural gas physically to hydrates significantly reduces its volume requirements. It was reported that natural gas hydrates only represent 1/600 of their volume in the gaseous phase. This enormous volume reduction reduces the cost of storage and transportation. 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 [15, 16].

2.2. Gas Monetization by Conversion of the Gas to Other Energy Products

Natural gas can be conveniently converted to other utilizable forms. These include energy products or commodities which can be used in the further production of other products. Gas-to-liquids technology, gas-to-power, and gas-to-chemicals fall into this category. Gas-to-liquids technology is the chemical conversion of natural gas to liquids such as diesel, kerosene, kerosene etc. GTL offers a broad range of choices for the gas producer to monetize his resource. The products from GTL are premium quality with little carbon footprint. They have been reported to outperform conventional crude oil fuel products when used in vehicles and other equipment in terms of performance and emission index. Gas-to-chemicals is a technology that converts natural gas to chemical products like methanol, ammonia, dimethylethene (DME). This technology is still in the developmental stage and a lot of research ongoing is geared towards innovative approaches that would make it more profitable [9].

Gas-to-power is one of the notable uses of natural gas. In Nigeria, more than 60% of the electricity generation comes from gas plants. Gas-to-power is the conversion of natural gas to power via large electricity generating plants called gas turbines. These turbine plants are large facilities that require substantial volumes from uniquely constructed pipeline systems that feed it with natural gas feedstock. Notable gas plants in Nigeria are the Afam gas plant, Egbin gas plant, Egbema gas plant, etc. Natural gas can also be converted to electricity onsite at the point of production of the gas rather than transporting the gas to large gas plants. This process is called gas-to-wire. The gas produced at the point of gas production is used for onsite electricity needs, distributed to host communities nearby and sent to the national grid for sale [17].

2.3. Gas-to-liquids Technologies

Gas-to-liquids technology is an innovative technological breakthrough in science and engineering that leads to the conversion of natural gas to liquid fuels and chemical products. GTL provides an excellent opportunity to countries with gas resources with potential for monetization. GTL has prospects to become the largest gas processing and conversion route in the future. GTL has been proven to be commercially viable. Presently GTL technologies are in large-scale or small-scale designs [4, 5].

2.3.1. Large Scale and Small-scale GTL Technologies

Gas-to-liquids technologies come in various sizes depending on the volume of gas available and the size of the project by the investor. Traditional large-scale GTL plants have been in operation for many years. A GTL plant is referred to be large scale if its capacity exceeds 10,000 b/d of GTL products, they are designed to utilize a substantial amount of gas. Owing to this, they require enormous capital investment. Most large-scale GTL plants utilize Fischer-Trospch reactors. Some scholars have argued that large-scale GTL only become economical when the capacity is 30,000 b/d or more of GTL liquid products. Because of the high cost, only major operators or joint venture partnership sometimes venture into large-scale GTL projects [4].

Similarly, because of the large volume requirements, most existing fields in the world cannot sustain the vast gas volume requirement. It has been observed that only 6% of the gas fields in the world have the capacity to sustain commercial GTL plants. The combined cost and capacity constraints are the reason why only a few large-scale plants are globally operational.

Small-scale GTL plants were introduced with the invention of micro-channel reactor technologies. These technologies help to shrink or scale down the size of GTL plants. This provides cost-effective GTL configurations that provide at-site conversion of minimal volumes of GTL resources otherwise stranded or flared. The development of small-scale GTL plans focuses to intensify the performance properties of the syngas and the F-T reaction units by enhancing the heat and mass transfer properties and increasing productivity. Since heat transfer has inverse relationships with the size of the channels, reduction of the channel becomes an effective way of increasing heat transfer in GTL reactors and increasing productivity, hence the introduction of micro-channel reactors [4].

Small-scale GTL plants provide means to monetize gas near the gas resource or close to potential markets and obviates the need for the construction of a pipeline to transport the gas from the production site to GTL facility as is usually the case for large-scale GTL facilities. The plants can be scaled to match the size of the resource, expanded as necessary, and potentially integrated with existing facilities on refinery sites [18]. Most of the small-scale GTL plants are modular technologies. These technologies have a short construction time; they are designed once and constructed many times. Much of the plant can be standardized and shop-fabricated in skid-mounted modules reducing the level of onsite fabrication to be done. Owing to this, the total cost of building the plant especially in remote locations is greatly reduced.

Through small-scale GTL, the capital cost which relates to the entry price of GTL technology is reduced, this increases the number of locations where the installation of GTL plants is feasible. Small-scale GTL plants improve profitability by unlocking gas resources that otherwise would have been flared, thus, helping to harness the value-associated gas resources, widening access to global markets, and taking advantage of existing infrastructure [19].

It requires a conscientious economic decision to choose whether to operate on a large-scale or small-scale in GTL projects. The key challenge is the risk associated with the product price and the prices of the raw materials (natural gas), capital costs and lack of sustained developmental initiatives. Aside from capital cost reductions, focused research efforts in GTL optimizations can serve to facilitate investment in GTL ventures. Most research efforts are geared towards capital cost reductions, operational cost reduction by high-performance catalysts, emission reductions, and product volume reaction performance increase.

Table 1 below shows the operational GTL plants in the world today and those that are currently under construction.

Table 1. *Large-scale GTL plants in the world (both operational and under construction) (GGFR, 2019).*

Project Name	Company	Location	size	Status
Bintulu GTL	Shell BP	Malaysia	14700	Operational
Escravos GTL	Chevron and Sasoil, NNPC	Nigeria	33000	Operational
MosselBay GTL	Sasoil	South Africa	36000	Operational
Oryx GTL	Shell BP	Qatar	34000	Operational
Pearl GTL	Shell BP	Qatar	140000	Operational
Ovadan-Depe GTL	Turkmengaz	Turkmenistan	17000	Under Construction
Ovadan-Depe GTL	Turkmengaz	Turkmenistan	23000	Under Construction
OltinYo'l GTL	Sasol, Petronas, and Uzbekneftegaz	Uzbekistan	38,000	Under Construction
Sweetwater	Syntroleum	Australia	11,500	Under Construction

From table 2, aside from the five large-scale operational GTL plants in the world, there are four others under construction, but the high capital cost and fluctuating oil prices keep them from completion. Already some commercial plants in the world have been abandoned due to the combined effect of high capital cost and declining oil prices. These GTL plants include Shell Louisiana GTL project canceled in late 2013 which would have been the first large-scale GTL plant in the US, and the 96 Mbpd Sasol Lake Charles in Louisiana was abandoned because the declining oil price made the project not to be economical (GGFR, 2019).

Some of the small-scale GTL plants in the world are listed in table 2 below.

Table 2. *Some smaller-scale GTL plants (GGFR, 2019).*

Plant Name	Location	Owner	Capacity
Offshore GTL	Brazil	Petrobras	2000 bbls
Lake Charles GTL	Louisiana, USA	Juniper GTL	1100 bbls
Ashtabula	Ohio USA	Pinto Energy	2800 bbls
Pilot plant	Alaska, USA	BP PLC	300 bbls

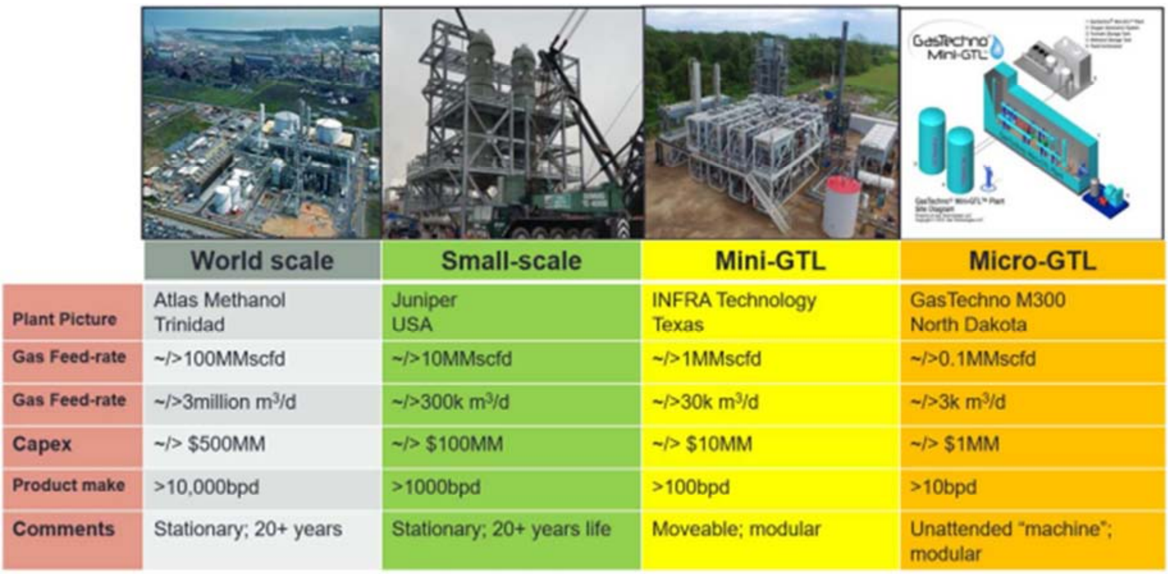

Figure 1. *Classification of GTL plant by on capacity (GGFR, 2019).*

Small-scale GTL plants can be mini-GTL plants or micro-GTL plants. Micro –GTL plants process as low as 1mmscfd and below of natural gas to GTL products. They are mostly used as pilot or demonstration plants. Mini-GTL plants fall between the micro-GTL plants and the large-scale GTL plants. Some companies currently in small-scale GTL plants are: G2X, CompactGTL, Siluria, Primus Green Energy, INFRA Technology, Juniper GTL, Velocys and ENVIA Energy, Juniper, Advantage Midstream, Rocky Mountain GTL, etc. Figure 1 shows the classification by the capacity of GTL plants in the world.

2.3.2. Processes in a GTL Plant Technology

There are fundamentally three units in a unique GTL plant. These three units comprise the three main stages of operations inside a GTL plant. These units are the

1. Synthesis gas production unit
2. The liquids synthesis/production unit
3. The product upgrading unit

Most GTL plants require that the input gas be treated to make it suitable for use in the GTL plant. Natural gas from the wellhead, flare line, pipeline or separator must be checked to ensure it meets the minimum requirements as GTL input feedstock. GTL plants require gas that is predominantly methane, although it has some tolerance for heavier molecular mass hydrocarbons like ethane, propane, butane, and pentane plus. However higher molecular mass hydrocarbons show a higher tendency for carbon formation which ultimately leads to catalyst breakdown reducing the efficiency of the GTL plant. GTL plant has a very low tolerance for acid gases like CO_2, H_2S, and sulphur components in the natural gas stream (Izuwa et al., 2019). These impurities must be removed via a preliminary treatment done onsite or by the supplier. In some literature, the pre-treatment of raw natural gas is regarded as the first stage of GTL plant operation. It is however to be noted that this operation happens before the entry of the gas into the GTL plant itself and is not one of the main operations that take place "inside the GTL plant".

1. The synthesis gas production Unit.

The production of synthesis gas is a necessary step in many petrochemical plants including GTL. Synthesis gas known commonly as syngas is a mixture of carbon monoxide and hydrogen. In GTL plants, syngas production happens as a necessary step and it represents more than 50% of the capital cost of the entire GTL plant. The process of converting natural gas (mostly treated) to synthesis gas is known as reforming. There are many types of technologies available for the production of syngas. These include, steam-methane reforming, partial oxidation reforming, autothermal reforming, CO_2 reforming, and steam/CO_2 reforming. These technologies or methods of synthesis gas production have their peculiar advantages and demerits [4].

i. Steam methane reforming

Steam methane reforming is the endothermic conversion of steam and methane into synthesis gas. Heat is being supplied externally 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

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

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

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

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

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

One of the challenges encountered in steam/methane reforming plant is the provision of adequate energy into the system for the maintenance of the required temperature of reaction. Usually, this would require large capital investment as an adequate amount of excess heat is required to prevent coking. 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. Its typical sizes make it less of a choice where sizing and compactness is major factor to consider [4, 5].

ii. Partial Oxidation Reforming (POX)

Partial oxidation reforming utilizes oxygen and methane in the production of syngas. This is an exothermic conversion process where oxygen is used to combust methane to produce hydrogen and carbon monoxide gases. Partial oxidation can process catalytically or non-catalytically. For non-catalytic POX, the reaction temperature is usually very high as a consequence of operating without a catalyst. In catalytic partial oxidation, the chemical reaction takes place in catalytic reactor without a burner. In either POX process, the oxygen used is usually gotten from an air separation unit (ASU) [11]. 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 of reaction of POX systems is given below

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

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

iii. Authothermal Reforming (ATR)

Authothermal reforming is a hybrid of SMR and POX. It combines the best features of the two reforming methods. 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. Although CO_2 and unreacted methane are also some of the products realized.

The equation of reaction for Authothermal reforming is given as

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

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

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

$$CO + 3H_2 \leftrightarrow 3H_2 + CO_2 \ \Delta H^0_{298} = -41KJ/mol$$

One of the good features of ATR is that it does not require external heating source because the heat is produced from the partial oxidation reaction process. 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.

iv. Dry CO_2 Reforming

Dry reforming is the production of hydrogen and carbon monoxide using methane and CO_2. One advantage is that it is needless to remove the carbon dioxide in the natural gas stream before use in the GTL plant because CO_2 goes into reaction in the reaction process. Thus, the CO_2 produced is captured and reused in the system thereby limiting the volume of CO_2 effluent as pollution. The equation of reaction for dry CO_2 reforming is given as

$$CH_4 + CO_2 \rightarrow 2CO + 2H_2 \Delta H^0_{298} = 247KJ/mol \quad (7)$$

v. Steam CO_2 Reforming

Steam CO_2 reforming is an emerging technology in synthesis gas production. It utilizes methane, steam, and CO_2 in the production of synthesis gas. There are generally three stoichiometric reaction steps which are the steam-methane reaction, the reaction of steam and produced CO, and the reaction of methane with CO_2. The general equation for steam CO_2 reforming is given as

$$CH_4 + CO + H_2O \rightarrow 4CO + 8H_2 \ \Delta H^0_{298} = 220KJ/mol \quad (8)$$

One of the main advantages of this reforming process over dry reforming of methane is the stoichiometric H_2/CO ratio of 2 which is desired by the F-T reactor downstream for a more optimal operation for the production of GTL liquids [9].

2. 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 many 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

i. The Fischer-Tropsch Method

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. 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.

$$nCO + 2nH_2 \leftrightarrow (-CH_2-)_n + nH_2O \quad (9)$$

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

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

ii. Methanol to gasoline method

The methanol to gasoline method first converts the synthesis gas to methanol before subsequent conversion to liquids. Gasoline is the predominant liquid produced in this method. There are many types of methanol to gasoline (MTG) GTL technologies; these include the synthesis gas to gasoline plus (STG+), the Mobil technology, and the Haldoe-Topsoe process.

STG+ is a thermochemical conversion of natural gas to synthetic liquid fuels. The process follows four main reactions in one continuous flow loop. These include methanol synthesis, the Dimethyl Ether (DME) Synthesis, gasoline synthesis, and gasoline treatment. It has been revealed by the study conducted by Primus Energy that STG+ provides substantial benefits than F-T methods in terms of cost, and efficiency.

The major difference between F-T technology and MTG technology is the type of catalysts used, the product type, and the economics. In F-T technology, there is a preference for use of unselective catalyst like cobalt and iron while MTG favours the use of molecular-size shape-selective zeolites. For the case of product types, F-T has been concerned with the production of linear paraffins such as synthetic crude while MTG can produce aromatics, such as xylene and toluene, and naphthenes and iso-paraffins, such as drop-in gasoline and jet fuel. The main product of the Fischer–Tropsch process, synthetic crude oil, requires additional refining to produce fuel products such as diesel fuel or gasoline. This refining typically adds additional costs [7, 9].

3. Case Study

Conscious effort to monetize the vast stranded gas reserve at Assa north in the Niger Delta region of Nigeria leads to the deployment of modular technology. The technology captures 50 MMscfd of associated gas in this location and turns it into marketable premium GTL liquid fuels. Preliminary economic project analyses indicate a high demand for diesel, gasoline, and kerosene from the nearby Owerri city, Onitsha city, and PortHarcourt city all in close proximity to the GTL plant operational site.

The composition of the raw natural gas and the pre-treated natural gas is given in table 3.

Table 3. *Flare gas composition from Assa North.*

Composition	Mole Fraction%
Methane	95.5
Ethane	3
Propane	0.5
N-Butane	0.4
I-Butane	0.2
Nitrogen	0.4
Total	100

The pre-treated gas is free from CO_2 and H_2S. It meets the minimum standards for GTL plant feedstock.

The economic parameter used for this research work are given below

i. Plant capacity is 5000b/d
ii. Capital cost is \$366.85MM corresponding to \$73370 BLPD for base case
iii. Feedstock cost is \$0/MMBTU since gas is flared gas
iv. Plant operational period of 25years
v. 350 plant operational days per year
vi. Plant construction period of 1 year
vii. Refined GTL product price of \$100/bbl
viii. Straight-line depreciation method
ix. Salvage value of zero
x. Income tax of 35% base case
xi. 100% owners' equity

4. Results and Discussions

The result of the economic analyses is given in the table below. The economic analyses were done on per barrel-liquid-a-day (BLPD) basis. Thus the total monetary equivalence is the product of the BLPD and the total volume of products produced (in barrels).

4.1. Base Case Results

The result for the base case simulation is given below. The parameters for base case include 15% discount rates, CAPEX of $73370BLPD, and product price of US$80/bbl. The economic results for base case input parameters are given in table 4.

Table 4. *Economic profitability results for the project.*

Indicator	Value	Value
NPV @ 15% discount rate	US$32,421BLPD	US$162.1 million
POT, yrs	4.48	4.48
NCR, US$/BLPD	US$16,366BLPD	US$81.83 million
IRR	22.2%	22.2%

From table 4, it can be observed that the NPV of the project at a discount rate of 15% is US$32,421BLPD. This amounts to US$162.1 million for 5000 b/d of GTL diesel produced. The payout time is 4.48 yrs while the Net cash Ratio (NCR) is US$16,366BLPD which amounts to US$81.83 million. The internal rate of return (IR) is 22.2%.

4.2. Sensitivity Analyses

Sensitivity analyses on the GTL project are performed in the following areas.

i. Varying the product price of diesel.
ii. Varying the CAPEX of the project.
iii. Varying the OPEX of the project.
iv. Varying the natural gas price.

This is done for several discount rates of 15%, 20%, 30%, 40%, and 50%.

1. Varying the Product Price of GTL Diesel Product.

We determine the sensitivity of the product prices on NPV for both natural gas price of $0/Mscf and $3/Mscf for base CAPEX and OPEX.

i. Various product prices at base CAPEX, OPEX and natural gas price

The effect of the various prices of diesel on the NPV of the project is determined. The sensitivity analyses are performed for diesel price of $80/bbl which is the base price, $50/bbl and $100/bbl at base CAPEX, OPEX, and natural gas price. Note that for the base case, the CAPEX is $73370/bbl, OPEX is 6% of CAPEX while the natural gas price is $0/Mscf.

Table 5. *NPV at various discount rates.*

product	NPV at various discount rate (US$/BLPD)				
price	15%	20%	30%	40%	50%
50	-11697	-26166	-41613	-49523	-54289
80	32421	7601	-18895	-32465	-40640
100	61833	30112	-3749.6	-21092	-31540

It can be observed from table 5 that the GTL diesel is profitable (with positive NPV) for diesel prices of $80/bbl and $100/bbl for discount rates of 15% and 20% respectively. It is crucial to determine the critical price at which the GTL diesel is profitable for each of the discount rates considered. This critical GTL price can be defined as the price of GTL diesel below which the project will not be profitable at operating economic.

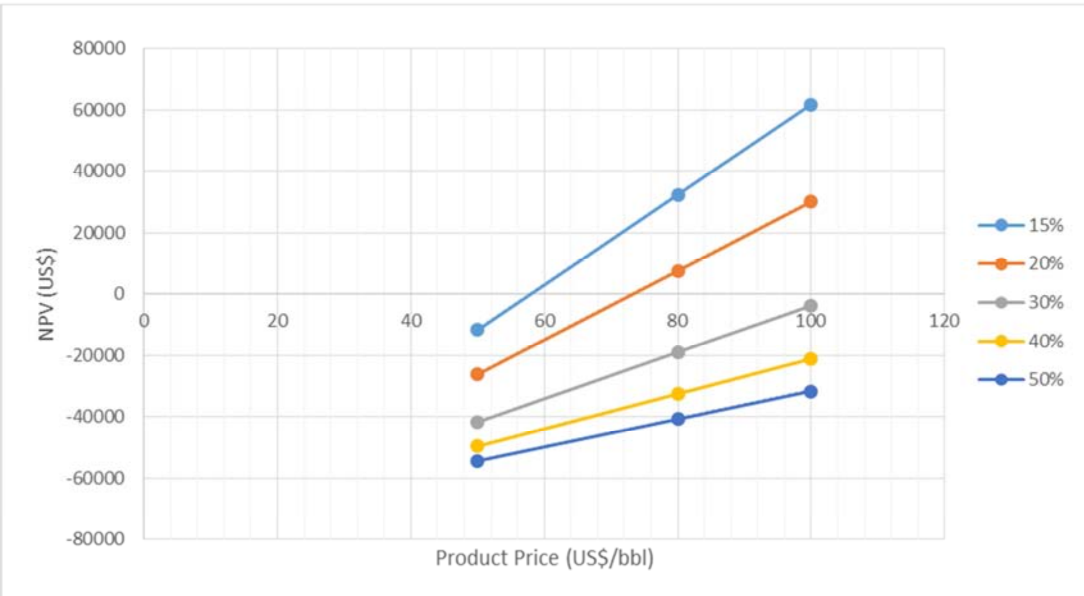

Figure 2. *Product price of various discount rates for base CAPEX and OPEX.*

Figure 2 shows the NPV of the base case at various discount rates. From figure 2, it can be observed only discount rates of 15% and 20% are profitable for diesel prices not greater than US$100/bbl. Thus, discount rates have significant impact on the NPV.

Table 6. *Critical product price of GTL diesel.*

Discount rate	Critical Product Price US$/BBL
15%	57.95
20%	73.24
30%	104.95
40%	137.09
50%	169.32

Table 6 gives the critical product price of GTL diesel at various discount rates. For product prices higher than the critical product prices given in table 6, the NPV is positive and the project is profitable. For the base case price of $80/bbl, it can be observed that only discount rates of 15% and 20% will yield positive NPV.

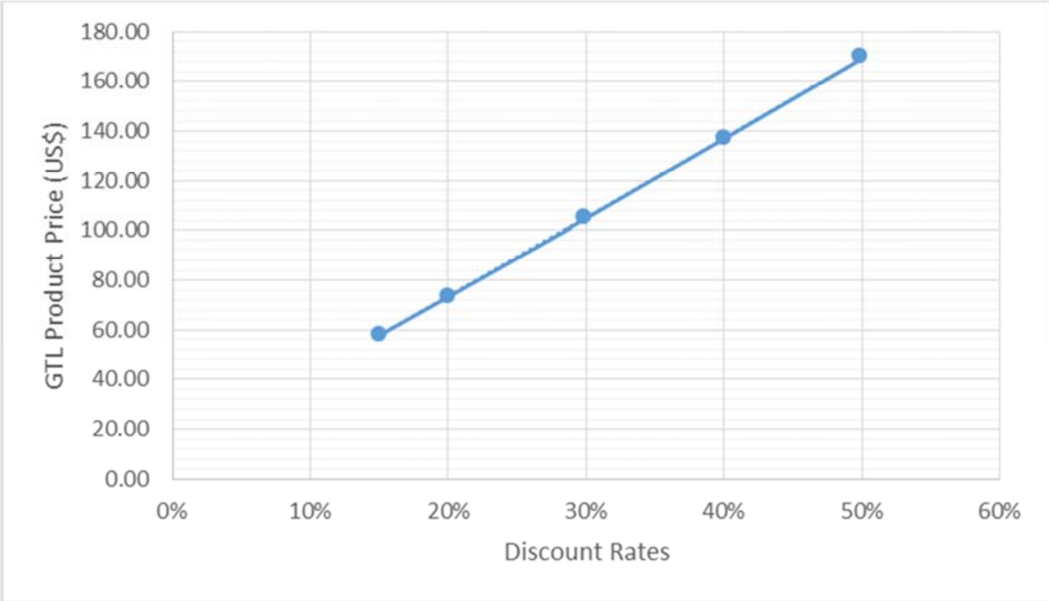

Figure 3. *Graph showing the critical price of diesel for different discount rates.*

Figure 3 shows the GTL critical product prices and the discount rates for which they can be profitable given base case conditions. Thus from figure 3, the product price to make profits can be determined by tracing it on the chart provided.

ii. Various product prices at a natural gas price of $3/Mscf

Here we determine the sensitivity of GTL diesel prices on NPV for a natural gas price of $3/Mscf using base CAPEX and OPEX.

Table 7 gives the NPV for various discount rates of GTL diesel forUS$3/Mscf natural gas price using base case CAPEX and OPEX. For natural gas price of US$3/Mscf, the negative values of NPV were realized for all discount rates considered.

Table 7. *NPV for different product prices of diesel.*

product price	NPV at various discount rates (US$/BLPD)				
	15%	20%	30%	40%	50%
50	-55815	-59934	-64330	-66582	-67939
80	-11697	-26166	-41613	-49523	-54289
100	17715	-3654.8	-26467	-38151	-45190

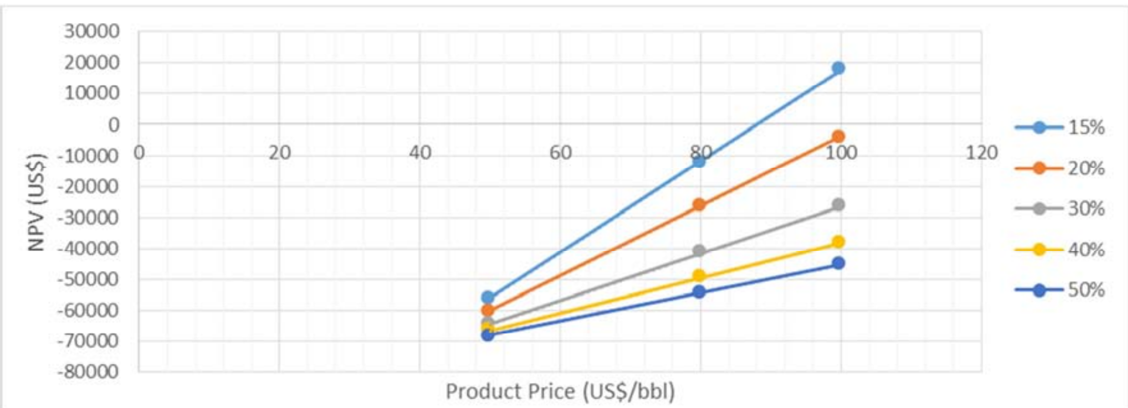

Figure 4. *Chart showing NPV and GTL diesel price for $3Mscf at base case CAPEX and OPEX.*

From figure 4, it can be observed that at a natural gas price of $3/Mscf the NPV is negative for a wide range of discount rates and product prices. The NPV was negative for discount rate of 15% when the product price is above$88/bbl. Thus, we determine the critical product price of the GTL diesel for various discount rates.

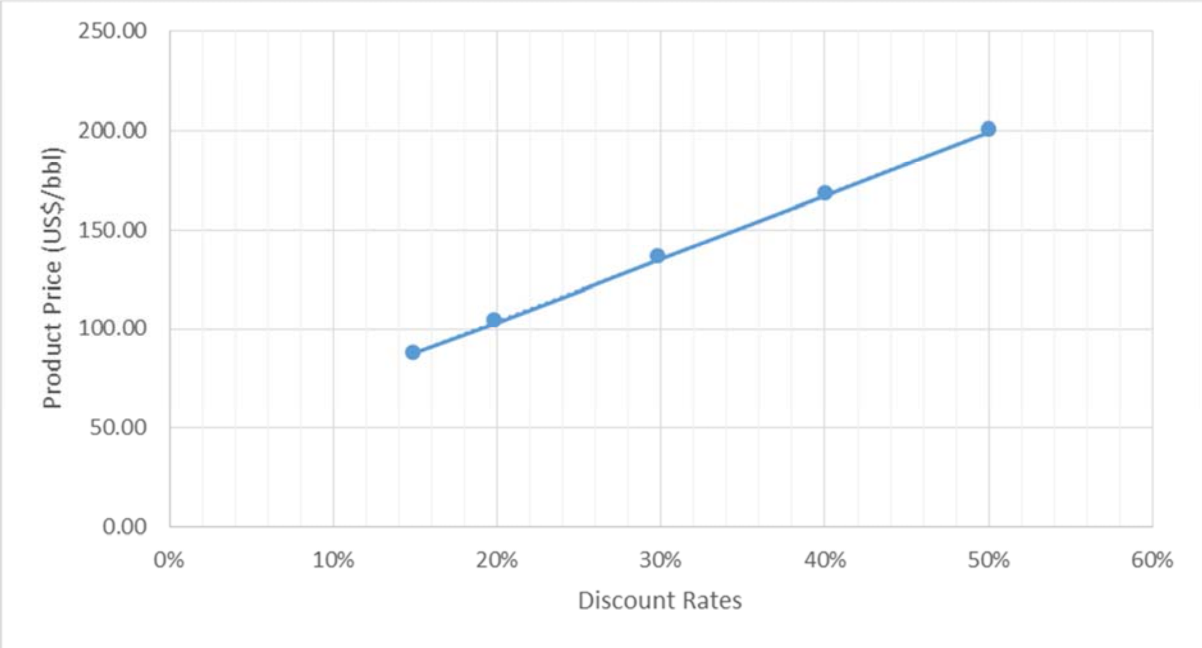

Figure 5. *Graph of critical product price of diesel for different discount rates.*

From figure 5, the intercept on the y-axis is $39.73/bbl. This means that for a 0% discount rate the project is profitable for $39.73/bbl. It is important to determine the natural gas price for which the NPV will be positive for a profitable project at varied operating conditions. The figure below gives the natural gas price for positive NPV.

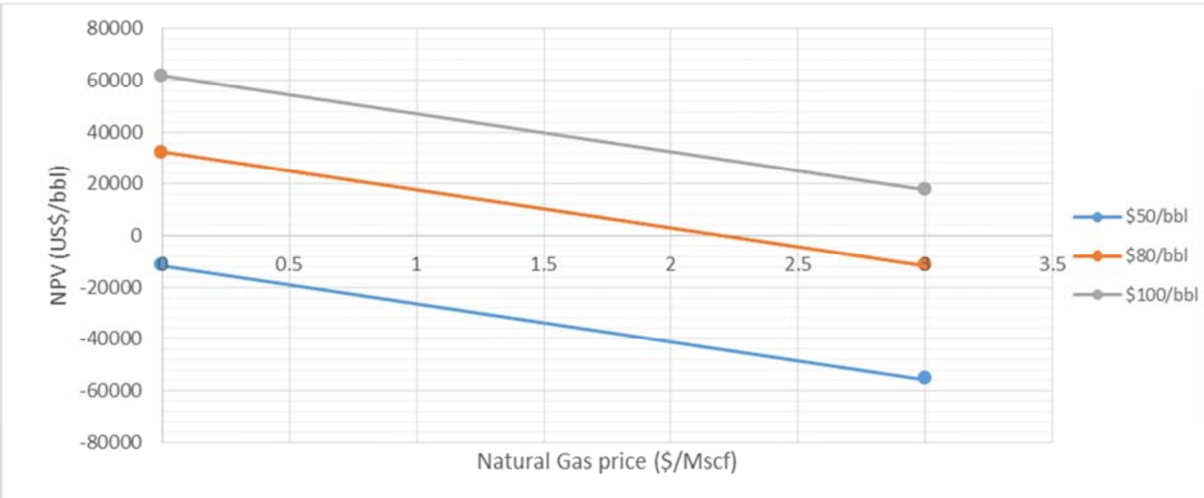

Figure 6. *NPV and natural gas price for 15% discount rate and base CAPEX and OPEX.*

From figure 6, the project is not profitable for product prices of $50/bbl for all the natural gas prices considered. For diesel price of $80/bbl the critical natural gas price is $2.2/Mscf. When the diesel price is $100/bbl, the NPV is positive for natural gas price of $3/Mscf and below.

2. Varying the OPEX and CAPEX

Both the OPEX and CAPEX are varied to determine their effects on the NPV. Sensitivities are performed for CAPEX of $25000/BLPD, $90000/BPLD, and $120000/PBLD. Similarly, the base OPEX is 6%, sensitivities are performed for OPEX of 5% and 7%.

Table 8. *Full economic analysis results for natural gas price $0/Mscf.*

Discount Rates	CAPEX: $73370/BLPD			CAPEX: $25000/BLPD			CAPEX: $90000/BLPD			CAPEX: $120000/BLPD		
	OPEX (% OF CAPEX)											
	5%	6%	7%	5%	6%	7%	5%	6%	7%	5%	6%	7%
15%	35503	32421	29338	89658	88607	87557	16885	13103	9321.7	-16703	-21745	-26787
20%	9960.5	7601	5241.4	62758	61954	61150	-8191.6	-11086	-13980	-40938	-44797	-48656
30%	-17307	-18895	-20482	34041	33500	32959	-34961	-36909	-38856	-66809	-69405	-72001
40%	-31273	-32465	-33657	19334	18928	18522	-48672	-50134	-51596	-80059	-82008	-83958
50%	-39686	-40640	-41594	10474	10149	9823.6	-56931	-58101	-59271	-88041	-89601	-91161
NCR, US$	16843	16366	15889	17738	17575	17413	16535	15950	15365	15980	15200	14420
IRR,%	22.8	22.2	21.5	70.9	70.3	69.6	18.1	17.4	16.7	12.6	11.9	11.2
POT,%	4.37	4.48	4.62	1.41	1.42	1.44	5.44	5.64	5.86	7.51	7.89	8.32

Table 8 gives the full economic analyses results for the project at a natural gas price of US$0/Mscf. It can be observed from table 8 that the project is profitable for a wider range of discount factors for CAPEX below the base CAPEX.

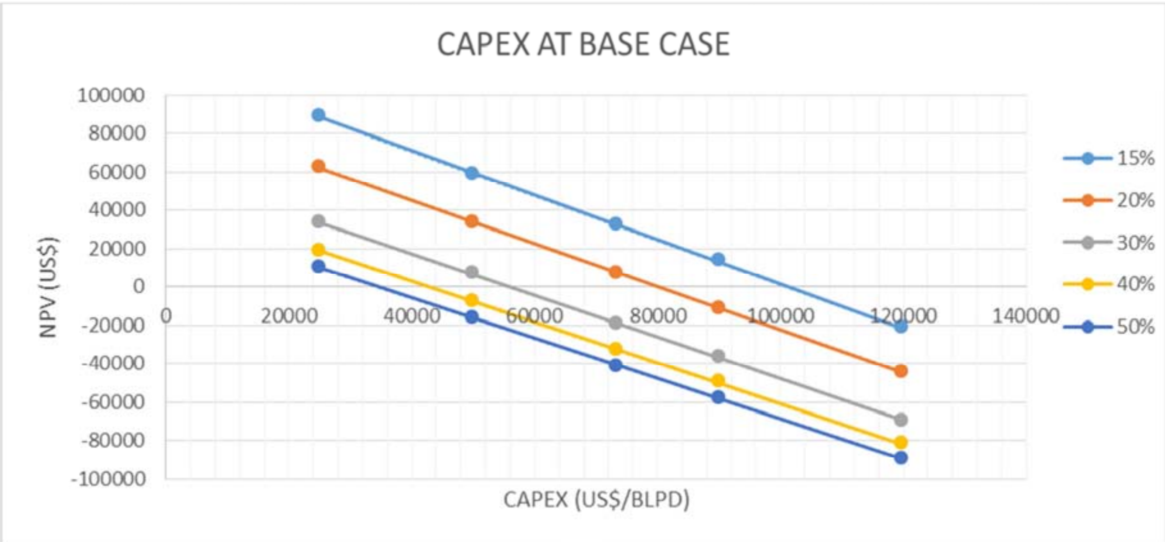

Figure 7. *Graph of NPV and CAPEX for $0/Mscf natural gas and OPEX of 6%.*

Figure 8. *Graph of NPV and CAPEX for $3/Mscf natural gas and OPEX of 6%.*

Table 9 summarizes the table for the critical CAPEX for both prices of natural gas considered.

Table 9. *Critical CAPEX at different natural gas prices and discount rates.*

DISCOUNT RATE	CRITICAL CAPEX (US$/bbl)	
	$0/Mscf	$3/Mscf
15%	101280.1	63300.62
20%	80134.38	50083.65
30%	55926.88	34954.76
40%	42814.12	26758.59
50%	34665.71	20587.33

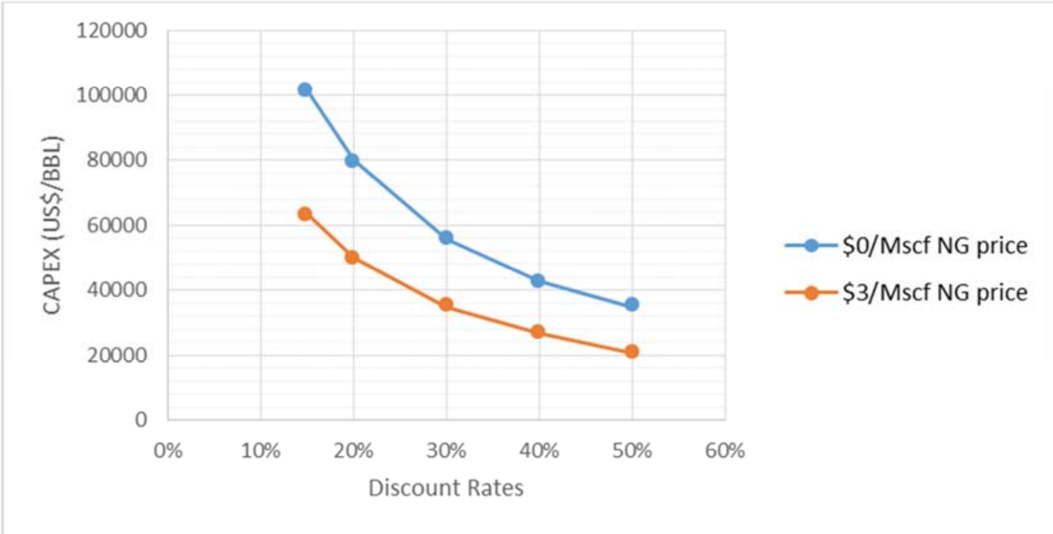

Figure 9. *Graph of critical CAPEX at various discount rates.*

Figure 9 describes the relationship of the CAPEX at several discount rates. It is evident from figure 9 that an increase in natural gas price substantially decreases the project profitability.

From the economic evaluation, it can be observed that the GTL project is profitable for base case conditions of $73370/bbl CAPEX. Generally, changes in operating cost had minimal effect on the NPV of the project. Natural gas price above $3/Mscf is only profitable for GTL product price above $100/bbl.

The use of modular technology further reduced the capital and operating costs of GTL technology. GTL diesel was selected because of its demand as a transport fuel within the locale of production. Analyses of the GTL diesel with conventional diesel reveal that GTL diesel gives better performance when used in cars and leaves comparatively lower emissions and carbon footprints in the atmosphere when used.

In general, it can be seen from the analyses that GTL project NPV depends on three major parameters.

i. The price of product and
ii. The CAPEX,
iii. The natural gas price.

The OPEX has little effect on the NPV of the project.

5. Conclusions

The economic attractiveness of mini-GTL plant utilization for stranded gas monetization in the Niger Delta, Nigeria has been extensively evaluated. From the research study, the following conclusion were reached.

i. The vast stranded associated gas in the Niger Delta region of Nigeria has economic potentials to be monetized.
ii. Modular gas-to-liquids technology shows great potentials for monetization of the stranded associated gas, the GTL diesel produced is in high demand around the locale of production.
iii. The price of GTL products has the most influence on the NPV of GTL project. This is followed by the capital cost of the plant and then the price of natural gas.
iv. The operating expenditure (OPEX) has the least effect on the NPV of the GTL project.
v. For GTL diesel price of US$80/bbl, the GTL project is profitable at natural gas prices below US$2.2/Mscf. Any price of natural gas above this value translates to an unprofitable project for base CAPEX, OPEX, and at 15% discount rates.

6. Recommendations

The Government should provide laws that will lead to more gas penetration in the energy mix in Nigeria. This can be achieved by lowering the price of gas products and providing investment environments like subsidies, tax holidays, and security in the country.

Nomenclature

bbl: barrels
CAPEX: Capital expenditure
F-T: Fischer-Tropsch
GTL: Gas-to-Liquids
IRR: Internal rate of return
MMscfd: Million standard cubic feet
Mscf: Thousand standard cubic feet
NPV: Net present value
OPEX: Operating expenditure
POT: Pay-out time

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