OPTIMAL FRAMEWORK FOR ALLOCATING NATURAL GAS TO DIFFERENT PROCESSING AND UTILIZATION ALTERNATIVES

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ABSTRACT

Optimal framework for allocating crude natural gas to its processing options and production of end-user products at Nigerian Liquefied Natural Gas Company, Bonny was determined using mathematical programming to aid revenue maximization and consumers' satisfaction in this sector. This investigation involved formulation of a crude gas allocation model of this company with revenue maximization as the objective function subject to the constraints of its plant parameters as well as other technical, environmental and market factors of the company/sector. Results revealed 3:1:2:6:17:8:1:2:2:2:1 as the optimal ratio by which the raw gas should be allocated for the production of methane, ethane, propane, gasoline, ethylene, propylene, butylene, gas oil, naphtha, kerosene and diesel respectively. Contrary to the general view that conversion of the gas to ethylene will yield more revenue due to its high demand. The optimization result also indicated a revenue of NGN10 billion (USD 48.1million) from processing of crude natural gas based on this optimal ratio over the existing production schedule of the company which has the raw gas processing options in the ratio of 1:1:1:2:5:2:1:1:1:1:1. In addition to this revenue improvement, allocation of crude natural gas for the production of these end-user products in this ratio also raise the availability of these products to rally with their ever increasing domestic and industrial applications thereby reducing the bottleneck which other sector that depend on these feedstocks are facing due to the shortfall in their supply from the company.

Keywords: Mathematical programming, natural gas, processing framework, utilization alternatives, revenue maximization

1.0 INTRODUCTION

The continuous increasing importance of natural gas in the world at large cannot be over emphasized. This is as a result of the increase in its utilization alternatives and the advancement in the related technologies globally. Natural gas is a hydrocarbon gas. In its raw form/state it is a complex mixture of hydrocarbon gases, hydrogen sulphide, carbon dioxide, mercury, helium, nitrogen, oxygen and traces of rare gases (Ozgirgin, 2004; Rios-Mercados and Borraz-Sanchez, 2014). In addition, it contains some traces of water molecules, liquid hydrocarbon and dust particles (though depending on the source). Younger (2004), noted that the major components of natural gas are paraffin hydrocarbons with traces of olefin hydrocarbons, naphthenic hydrocarbons, aromatic hydrocarbons, mercaptans, and non-hydrocarbon compounds. The paraffin hydrocarbons are the alkane series which are saturated hydrocarbons with general molecular formula $C_nH_{(2n+2)}$, the olefin hydrocarbons are the alkene series which are unsaturated hydrocarbons with the general molecular formula C_nH_{2n}, the naphthenic hydrocarbons are the cyclic saturated hydrocarbons with general molecular formula C_nH_{2n}, mercaptans are represented with the general formula XSH (where X represents an alkyl group) and the non-hydrocarbons include nitrogen, carbon dioxide, hydrogen sulphide, helium, water vapour, carbonyl sulphide, carbon disulphide and sulphur (Younger, 2004). It is highly flammable, has about 70% - 90% of methane and energy efficiency of about 91% from source to end-user (Ozgirgin, 2004). Natural gas has a wide range of applications: it is used domestically as fuel for cooking and residential heating, industrially as raw material for chemical synthesis, production of low emission combustion fuel through gas-to-liquid (GTL) process, electric power generation (Lee *et al.*, 2012). These diverse utilization alternatives have given natural gas very prominent stake in recent times among the global sources of energy supply. Rios-Mercado and Borraz-Sanchez (2014), asserted that the importance of natural gas in meeting the energy demand of many countries will continue to increase because of its multiple applications across all sectors. In the U. S., it accounted for up to 26% source of primary energy consumption in the transportation, industrial, residential, commercial and electric power generation sectors (Lee *et al.*, 2012). While Allison (2014), reported that in Nigeria natural gas utilization increased by 36.59% from 1999 to 2008. The increasing awareness of the importance of this valuable resource that was formerly stranded in Nigeria has shown that utilization of natural gas may be surpassing that of crude oil globally soon. This is because natural gas can last for over 170 years after crude oil has depleted globally (Allison, 2014). The world natural gas reserve amounted to 6606.4 trillion cubic feet in 2014 with Nigeria having up to 180.1 trillion cubic feet and its reserve-to-production ratio (r/p) is 54.1 years (Ogbe, 2010; Otombosoba and Dosunmu, 2016).

Natural gas is sourced in its raw state as associated gas from crude oil wells, non-associated gas from gas wells and condensate wells with little or no crude oil or as coal bed gas pores or coal seams. Processing of extracted raw natural gas using Nigerian Liquefied natural gas (NLNG) plant of Nigerian Liquefied Natural Gas Company involves purification that takes different phases ranging from filtration, dehydration, desulphurization, and other processes to remove all impurities leaving methane and other useful by-products (Fig. 1). The methane (or simply natural or sales gas) can be sold as residential, commercial and industrial fuel by transporting it directly to end-user market or volumetrically reducing it to liquefied natural gas (LNG) before transportation using special LNG tankers which will be later gasified at the end users terminus. During liquefaction, natural gas is cooled to about -160ºC to produce liquefied natural gas (LNG) which takes about 1/600th the volume of natural gas (Wordu, 2013). The acid gases removed by amine treatment are then routed into a sulphur recovery unit (Claus process) which converts the hydrogen sulphide in the acid gas into elemental sulphur with a capacity of less than 2000 barrel per day. Rejection of impurities takes place in the cryogenic unit (Nitrogen rejection) before the purified natural gas is condensed into the natural gas liquid (NGL) recovery plant with a capacity of 300MMSCFD from which the liquid hydrocarbon (ethane, propane, butane, pentane) is compressed through heat exchangers to the hydrocracker (thermal cracker) where complex hydrocarbon molecules are processed into ethylene, propylene, gasoline, and fuel oil. The capacities to run gas feeds through the cracker is 600,000Ib/stream hour with 50% ethane, 35% propane feed, 5% butanes feed and 10% gas oil feed. The recovered NGL stream is processed through a fractionation train consisting of three distillation towers in series – a de-ethanizer, a de-propanizer and a de-butanizer.

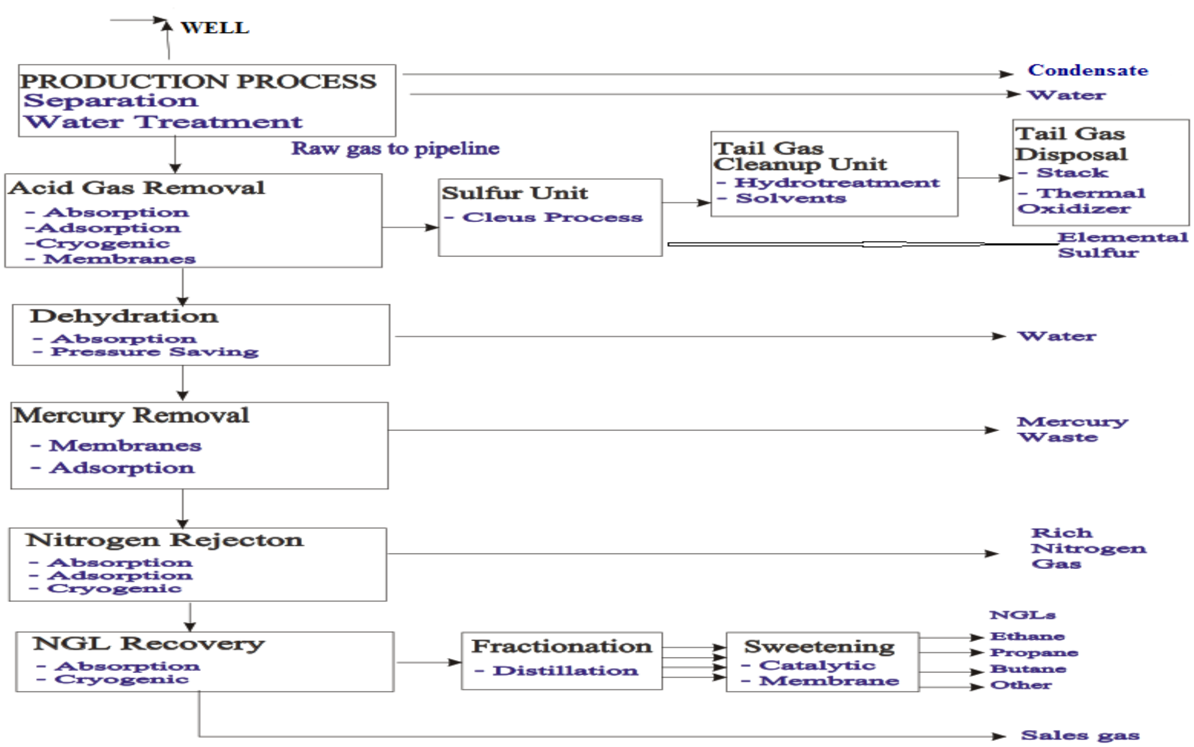

Figure 1: Schematic flow diagram of a typical gas plant

Source: Harvard (2013)

The NLNG plant fractionates a full range of natural gas liquid feed into ethane, propane, butanes and natural gasoline. Both the feed and product are transported via major pipeline system. The overhead product from the de-ethanizer is ethane with de-ethanizer column showing a capacity of more than 80,000b/d and the bottoms are fed to the depropanizer. The overhead product from the depropanizer is propane in a natural gas liquid feed with a capacity of more than 90,000b/d and the bottoms are fed to the debutanizer, the feed capacity of the tower can be increase to 105,000kg/h with a capacity of more than 200,000b/d. The overhead product from the debutanizer is a mixture of normal and iso-butane, and the bottoms product is a C_5+ mixture. The recovered streams of propane, butanes and C_5+ are each "sweetened" in a Merox process unit to convert undesirable mercaptans into disulphides along with the recovered ethane, and are the NGL by-products and the purified sales gas are pipelined to the end-user market. The pentane+ is further processed using Gas to Liquid (GTL) plant to Naphtha, kerosene, diesel, lubricant. This Fischer-Tropsch gas-to- liquid process vary from small (5 to 15,000 B/D) to large (> 50,000 B/D). Since the returns and constraints of converting crude natural gas into these processing/utilization alternatives at Nigerian Liquefied Natural Gas Company differ per unit gas processed, an optimal framework for allocating/processing crude natural gas to different utilization alternatives for maximum revenue generation and consumer satisfaction is paramount.

The search for optimal frame work for processing, transmission and utilization of natural gas is not new in this energy sector (O'Neil *et al.,* 1979). Huang and Shao (1994), applied the pattern recognition method to solve the problem of ethylene production optimization by focusing basically on the technological parameters. Guldmann and Wang (1999), defined the theory and methodology for optimizing natural gas supply mix of local distribution utilities. However, direct practical implementation of these works in Nigerian Liquefied Natural Gas Company suffered some set back because most of the optimization models from which the authors' conclusions were derived were data/system dependent. Thus, the inadequacy of the framework presently used for allocating raw natural gas to its different processing options in this company. Since, most of these works applied mathematical programming approach in the development of optimization models used, there is need to develop similar model determining an implementable framework for optimal allocation of crude natural gas to different processing options in Nigerian Liquefied Natural Gas Company. Mathematical programming is one of the operations research techniques used in industrial and scientific investigations that involve selection of the best among a set of alternatives to satisfy most or all interests, and it is mainly used in the optimal allocation of resources (O'Neilet al., 1979; Offiong, 2000). It is most appropriate for problems involving the challenge of the best allocation option for scarce resources among competing alternative uses with well-defined objectives and constraints on the extent of resources available for satisfying the objective(s). The objective can be cost minimization or product/profit maximization while the constraints may be limitations due to availability of raw materials and power, product demand plant and storage capacities (Offiong, 2000). Since NLNG (2015), showed that the company was established basically to produce and market/deliver liquefied natural gas and other natural gas liquids/feedstock to buyers safely, reliably and profitably, this work therefore established an optimal framework for allocating natural gas to different processing and utilization alternatives in Nigerian Liquefied Natural Gas Company, Bonny.

2. METHODOLOGY

The optimization model used in this investigation was developed from the production data and operational/ process parameters of Nigerian Liquefied Natural Gas Company obtained from the company's local statistical office as well as prevailing average demand and market prices of the company's inputs and outputs between 2013 and 2016. Revenue maximization constitutes the model's objective function, subject to constraints of parameters of production facilities as well as other technical, environmental and market factors of the company/sector. Methane, x_1 Ethane, x_2 Propane, x_3 Butane, x_4 Gasoline, x_5 Ethylene, x_6 Propylene, x_7 Gas oil, x_8 Butylene, x_9 Fuel oil, x_{10} Naphtha, x_{11} Kerosene, x_{12} Diesel Fuel, x_{13} Lubricant, x_{14} Helium, x_{15} Sulphur, x_{16} constitutes the decision variables of this study. The prevailing mean selling price as per these products (decision variables) per barrel within this study period are 151.55, 126.38, 88.90, 105.64, 108.55, 220.96, 215.26 89.31, 84.10, 39.92, 76.75, 88.18, 185.64, 33.20, 13.50, 14.80 US dollars respectively. Thus, the objective function, Z was derived as follows:

$$Z = 151.55x_1 + 126.38x_2 + 88.90x_3 + 105.\,64x_4 + 108.55x_5 + 220.96x_6\; 215.26x_7 + 89.31x_8 + 84.10x_9 + 39.92x_{10} + 76.75x_{11} + 88.18x_{12} + 185.64x_{13} + 33.20x_{14} + 13.50x_{15} + 14.80x_{16} \quad (1)$$

This objective is subject to the following constraints:

Fischer-Tropsch Capacity: The gas-to- liquid process uses Fischer-Tropsch (FT).The size of GTL plants can vary from small (5 to 15,000 B/D) to large (> 50,000 B/D). GTL plants produce petroleum products like Naphtha, kerosene, Diesel, and lubricant which are sold in a commodity market. Thus;

$$x_{11} + x_{12} + x_{13} + x_{14} \leq 50{,}000 \quad (2)$$

Cracker Capacity: The capacity to run gas feeds through the cracker is 600,000Ib/stream hour with 50% ethane feed, 35% propane feed, 5% butanes and feed 10% gas oil feed. Thus;

$$0.50x_2 + 0.35x_3 + 0.05x_5 + 0.10x_8 \leq 600{,}000 \quad (3)$$

Ethane/Propane Temperature: Fresh natural gas and recycle hydrocarbons (ethane and propane) temperature to reformer is kept at 455°C. Thus;

$$0.50x_2 + 0.35x_3 = 455 \quad (4)$$

Natural Gas Liquid Recovery: This unit will recover 99.26% of the ethane and 100% of the other heavier components (propane, butane and condensates) of the feed gas with a capacity of 300MMSCFD of feed gas taken from the pipelines network and sent to the Plant. Thus;

$$0.9926x_2 + x_3 + x_4 + x_5 \leq 300 \quad (5)$$

Refrigeration Cycle: This unit uses a two stage refrigerant cooling powered by 85 MW compressors. The two cooling stages, held in a heat exchanger tower, use mixed refrigerants (MR) of about 27% methane, 50% ethane, 20% propane, 2% Butane and 1% nitrogen to cool and condense the natural gas. Thus;

$$0.27x_1 + 0.50x_2 + 0.20x_3 + 0.02x_4 \leq 85 \quad (6)$$

Processing Plant Capacity: Typical blended in market reports is 85% methane, 11% ethane, 3.5% propane and 0.5% of other hydrocarbons and undesirable compounds with a capacity of 200 million barrel per day. Thus;

$$0.85x_1 + 0.11x_2 + 0.035x_3 \leq 200 \times 10^6 \quad (7)$$

Claus Process Capacity: Claus process is usually able to recover 97% of the Sulphur that has been removed from the natural gas stream with a capacity of less than 2000 barrel per day. Thus;

$$0.97x_{16} \leq 2000 \quad (8)$$

Liquefied Petroleum Gas Capacity: Four LPG refrigerated storage tanks, each with a capacity of 65,000 cubic metres (2 each for propane & butane). Thus;

$$2x_3 + 2x_4 \leq 65000 \quad (9)$$

Fractionation Unit: The common fractionation unit has 800,000 ton per year LPG capacity and is designed to process approximately 70% of the overall LPGs with the remainder processed by the in-train fractionation units. Thus;

$$0.70x_3 + 0.70x_4 \leq 800{,}000 \quad (10)$$

Flow Rate: At the present conditions, 9974.6kg/h was the optimal flow rate which has refrigerant composition of 82% methane, 10% ethane, 4% propane and 4% butane. Thus;

$$0.82x_1 + 0.10x_2 + 0.04x_3 + 0.04x_4 \leq 9974.6 \quad (11)$$

Gas Well Capacity: At most 500,000 barrels per day of natural gas can be recovered from gas well with 82.62% methane, 9.84% ethane, 4.78% propane, 2.06% butane and 0.7% heavy hydrocarbon. Thus;

$$0.0984x_2 + 0.0478x_3 + 0.0206x_4 + 0.007x_5 \leq 500{,}000 \quad (12)$$

Propylene Refrigeration Cycle: In the propylene refrigeration cycle, 400kg/s of propylene are compressed at the expense of 80.90x10^{6}w of energy. Thus;

$$400x_7 \leq 80.90 \times 10^6 \quad (13)$$

Storage Tanks Capacity: More than 180 metric tons of storage tank capacity. This is to enable the gas plant stock and provide liquefied petroleum gas to customers in the operation area. Thus;

$$x_2 + x_3 + x_4 + x_5 + x_8 + x_{10} + x_{11} + x_{12} + x_{13} + x_{14} \geq 180 \quad (14)$$

Capacity of Refinery Capacity: Because of limited refinery capacity, at most 14, 000 barrels per day of diesel fuel can be produced daily. Thus;

$$x_{13} \leq 14000 \quad (15)$$

Ethylene Production Capacity: Ethylene is produced by thermal cracking of hydrocarbon in the presence of steam plant with capacity up to 1.5million tons per year ethylene. Thus;

$$x_{16} \leq 1.5 \times 10^6 \quad (16)$$

Generator Capacity: The maximum output that the generating equipment can supply load, adjusted for ambient conditions is 50Mw. Thus;

$$x_1 + x_2 + x_3 + x_4 + x_5 + x_6 + x_7 + x_8 + x_9 + x_{10} + x_{11} + x_{12} + x_{13} + x_{14} + x_{16} \geq 50 X 10^6 \quad (17)$$

The non-negativity of the decision variables was accounted for as;

$$x_1 + x_{16} \geq 0 \quad (18)$$

3. RESULTS AND DISCUSSION

The mathematical programming model used for this analysis was formulated from the derived functions (Equation 1-18) as follows;

Maximize $Z = 151.55x_1 + 126.38x_2 + 88.90x_3 + 105.64x_4 + 108.55x_5 + 220.96x_6 + 215.26x_7 + 89.31x_8 + 84.10x_9 + 39.92x_{10} + 76.75x_{11} + 88.18x_{12} + 185.64x_{13} + 33.20x_{14} + 13.50x_{15} + 14.80x_{16}$

Subject to:

$$x_{11} + x_{12} + x_{13} + x_{14} \leq 50{,}000$$
$$0.50x_2 + 0.35x_3 + 0.05x_5 + 0.10x_8 \leq 200{,}000$$
$$0.50x_2 + 0.35x_3 = 455$$
$$0.95x_2 \leq 1000$$
$$0.27x_1 + 0.50x_2 + 0.20x_3 + 0.02x_4 \leq 85$$
$$0.80x_2 + 0.20x_3 \leq 200 \times 10^6$$
$$0.97x_{16} \leq 2000$$
$$2x_3 + 2x_4 \leq 65000$$
$$0.70x_3 + 0.70x_4 \leq 800{,}000$$
$$0.49x_1 + 0.41x_2 + 0.05x_3 + 0.05x_4 \leq 20000$$
$$0.8262x_1 + 0.0984x_2 + 0.0478x_3 + 0.0206x_4 + 0.007x_5 \leq 500{,}000$$
$$400x_7 \leq 80.90 \times 10^6$$
$$x_2 + x_3 + x_4 + x_5 + x_8 + x_{10} + x_{11} + x_{12} + x_{13} + x_{14} \geq 180$$
$$x_{13} \leq 14000$$
$$x_{16} \leq 1.5 \times 10^6$$
$$x_1 + x_2 + x_3 + x_4 + x_5 + x_6 + x_7 + x_8 + x_9 + x_{10} + x_{11} + x_{12} + x_{13} + x_{14} + x_{16} \geq 50\ X10^6$$
$$x_1 \text{ to } x_{16} \geq 0$$

The optimal solution of this model was evaluated as $x_1 = 535$, $x_2 = 269$, $x_3 = 413.85$, $x_5 = 1328.30$, $x_6 = 3535.05 x_7 = 1734.55 x_9 = 210.05$, $x_{10} = 370$, $x_{14} = 350.50 x_{15} = 40.35 x_{16} = 27.75$ and Z = USD48108504.5 using MATLAB software. The other variables not stated in the above solutions are economically insignificant; therefore, they will add no value to the production schedules of the natural gas plants. Thus, methane:ethane:propane:gasoline:ethylene:propylene:butylene:gasoil:naphtha:kerosene: diesel ratio is given as: 535:269:413.85:1328.30:3535.05:1734.55:210.05:370:350.5:430:277.75 (3:1:2:6:17:8:1:2:2:2:1). This is required for optimal performance of the natural gas sector and other sectors that depend on it. Apart from that this end users natural gas products ratio will make more natural gas products available to other sectors of our economy, it is even obvious that the predicted objective function(revenue) of USD48108504.5 associated with this optimal ratio is higher than the derivable revenue of a natural gas product of the same quantity(in barrel). In other words, methane, ethane, propane, gasoline, ethylene, propylene, butylene, gas oil, naphtha, kerosene, and diesel must be combined in this ratio in the processing plant in order to achieve maximum revenue and minimum running cost in the natural gas processing plant.

4. CONCLUSION

This study revealed 3:1:2:6:17:8:1:2:2:2:1 as the optimal ratio by which the raw gas should be allocated for the production of methane, ethane, propane, gasoline, ethylene, propylene, butylene, gas oil, naphtha, kerosene and diesel respectively. Contrary to the general view that conversion of the natural gas to ethylene will yield more revenue due to its high demand and its uses for variety other products. Also indicated is a revenue of NGN10billion (USD48.1million) from processing of crude natural gas per day in this optimal ratio over the existing production schedule of the company which has the raw gas processing options in the ratio of 1:1:1:2:5:2:1:1:1:1:1. In addition to this revenue improvement, allocation of crude natural gas for the production of these end users products in this ratio also raise the availability of these products to tally with their ever increasing domestic and industrial applications, thereby reducing the bottleneck which other sectors that depend on these feed stocks are facing due to the shortfall in their supply from this gas company.

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