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INVESTIGATION OF TECHNICAL PERFORMANCE OF UTILIZATION OF FLARE GAS IN TURBINE SYSTEMS FOR POWER GENERATION

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ABSTRACT

This study presents technical performance of the technology for power generation in turbines utilizing flare natural gas processed from Modular Gas Technology (MGT) system in the Niger Delta. It highlights two areas – first; natural flare gas capture and processing using MGT unit and second; performance of gas turbine for the actual electricity generation. The advantages of MGT over the conventional Joule-Thompson (JT) technology for gas operations are cheapness, portability, scalability and transferability. The MGT unit separates the associated natural gas from wellheads into dry gas and the NGLs. The market prices of NGLs is considered in deciding whether to separate NGL into propane, butane, LPG and plant condensates. The analyses of the modular technology shows that it has a conversion efficiency of 95% and a thermal efficiency of 80%. The dry gas (methane) from MGT is utilized in gas turbines for on-site electricity generation, thereby saving fuel cost, while the power generated could be sent to the national grid and to consumers, thus adding to the total power generation in the country. The study shows that Combined Cycle Gas Turbine (CCGT) is preferred to the Conventional Turbine (CT) system in terms of efficiency and megawatts of power generated.

KEYWORDS: **Flared gas, Turbine, Modular, Technology, CCGT, Power generation**.

1. INTRODUCTION

Access to consistent and stable supply of electricity is a major challenge for both the urban and rural dwellers in Nigeria. This problem however, is more prevalent in the rural areas where only about 10% of the population have access to electricity (Adramola etal, 2012). An analysis of Nigeria's electricity supply problems and prospects found that the electricity demand in Nigeria far exceeds the supply, which is epileptic in nature. The acute electricity supply hinders the country's development and not only restricts socio-economic activities to basic human needs; it adversely affects quality of life (Sule etal, 2011).

The goal of the electric energy system is to provide the needed energy services (Masjuki and Mahlia, 2001). Energy services are the desired and useful products, processes or indeed services that result from the use of electricity, such as for lighting, provision of air-conditioned indoor climate, refrigerated storage, and appropriate temperatures for cooking (Sambo, 2005). In this regard, power plants play a key role in producing electricity. Among different kinds of power plants, gas turbine power plants have gained a lot of attention because they are attractive in power generation field due to a feature of low capital cost to power ratio, high flexibility, high reliability without complexity, compactness, early commissioning and commercial operation, fast starting-acceleration and quick shut down. The gas turbine is further recognized for its good environmental performance, manifested in the low environmental pollution (Kaviri etal, 2012).

The main objective of any power utility in the new competitive environment would be to supply customers with electrical energy as economically as possible with a higher degree of reliability and quality. The performance of a power plant by way of its efficiency and reliability, and other operating factors has definite socio-economic significance both on the company operating the plant as well as the nation at large (Gujba and Mulugetta, 2010). However, without adequate and reliable electricity supply, socioeconomic transformation would remain a mirage. Improving the availability of existing units is as important as

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improving the reliability expectation of units during the planning phase. Power plant availability and the causes of unavailability constitute essential performance indicator for assessing services rendered by generating power plants.

In this paper, we discuss the technical performance of utilization of Modular Gas Technology (MGT) unit processed flared natural gas in Gas turbines for electricity production. The electrical power generated serves two major purpose; one being that it can be used onsite to power drilling and production equipment or it can be sent to the grid where it can be utilized for industrial, commercial or residential uses. In this case the host community benefit from the operation.

2. MATERIALS AND METHOD

The Modular Gas Technology (MGT)

The modular gas processing technology is utilized in this work for the natural gas processing prior to gas turbine activity for power generation. The feed gas from the well undergoes several steps in which liquid hydrocarbons, water acid gases and solids impurities are removed. This processed flare gas yields dry gas suitable for use in gas turbine plants for electricity generation. Note that sales gas specification is given by the electricity generator on the composition of the sales gas to be delivered to them for use in the turbine plants.

The processing route for the well-stream natural gas take the path provided in the figure below.

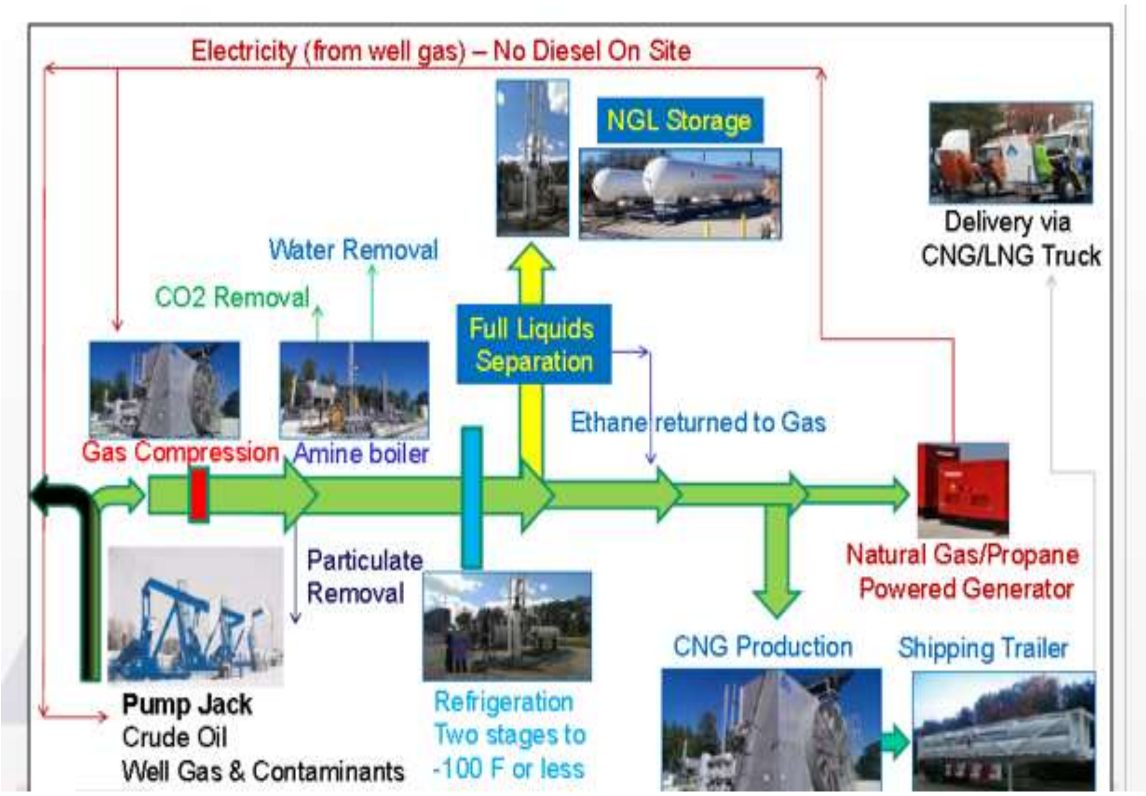

Figure 1: Flare gas capture and usage route

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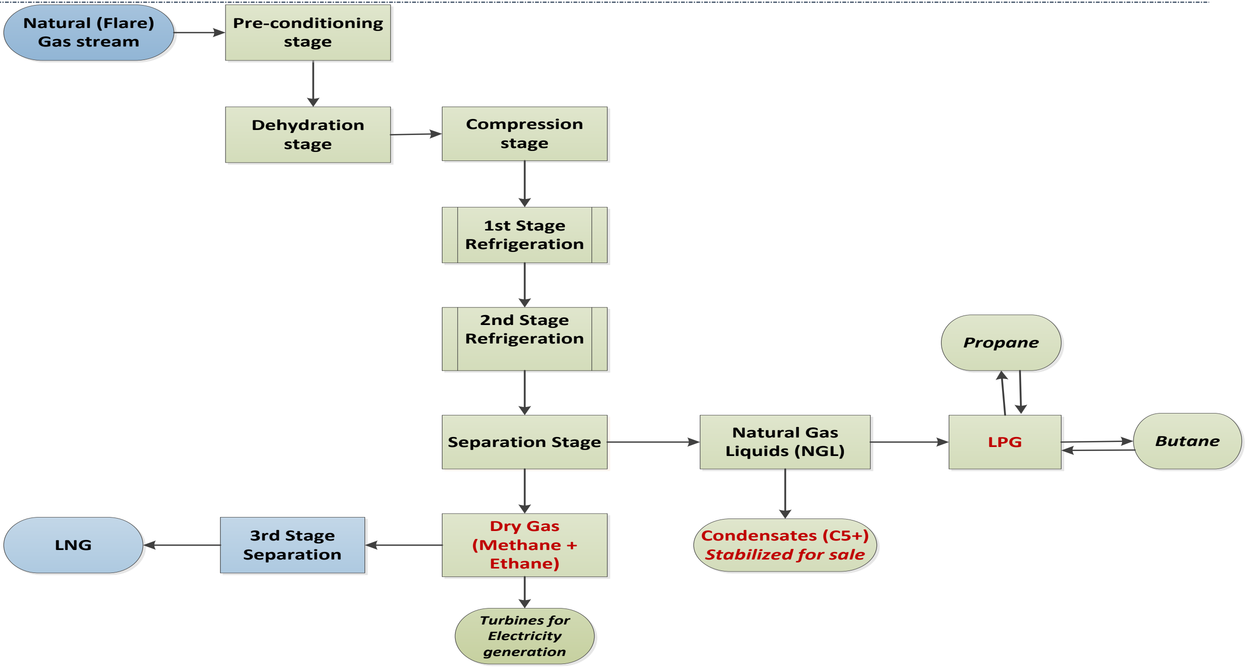

Figure 2: Modular Gas Processing System- Process

The feedstream natural gas must undergo some processing before the products useful for power generation is gotten. From the above diagrams it is seen that the major products of the flare gas processing are the dry gas and the natural gas liquids (NGLs). The NGLs are further broken down into constituents and sold either as LPG and plant condensates (gasoline) while the dry gas composed predominantly of methane with very little ethane and is routed for use in power generation. In some cases as required by sales gas specification, there could be ethanizer unit that knocks out the ethane thereby reducing its composition in the sales gas. The ethane removed could be sold and used as petrochemical feedstock.

Indicators of Technical Performance

In performance, we talk about how the technology works and its effect to both humans and the environment at large. Here several parameters are used to analyze the performance of the system. A technology must show good and desirable performance before further analyses can be done to determine its economic feasibility.

Efficiency

Efficiency is the ratio of useful work done to the overall work input. For any machine to be recommended for use, its efficiency must be known. If the efficiency is low, then more energy would be wasted in the process of conversion which will generally result to low performance of the unit.

$$conversion\ efficiency(\%) = \frac{plant\ capacity}{volume\ of\ gas\ at\ inlet} x100 \quad (1)$$

From the above, if the conversion efficiency is already known from literatures, then we can change subject formula to determine the volume of gas required at inlet that will yield the volume of gas necessary for the plant capacity. Then,

$$Volume\ of\ gas\ at\ inlet = \frac{plant\ capacity}{conversion\ efficiency} \quad (2)$$

Note: conversion efficiency here is expressed as a decimal.

Recovered Gas Shrinkage Factor

Not all the gas can be recovered even while in the processing unit. The shrinkage factor is a measure of the volume of gas recovered to the volume loss due to shrinkage.

$$shrinkage\ volume = capacity\ range\ x\ shrinkage\ factor \quad (3)$$

Thermal Losses

Because of high temperature of processes, some of the gases would be dissipated as heat. This must also be calculated.

The Resulting Pollutions and Associated Pollutants

In many plants, due to incomplete combustion, there is pollution resulting from the incomplete combustion of major impurities contained in the fuel mixture. Analyses of the level of pollutions throws more light into the technical performance of the plant.

In this work the main technical performance parameters to be analyzed are the efficiencies of the flare gas capture and the gas processing technology; the shrinkage factor of the gas and volume of gas on safe delivery after emissions.

Description of Gas Turbine System

Gas turbines are mechanical devices for the conversion of chemical energy in the form of gas to electrical energy via power generation. There are two main types, the single cycle or the conventional gas turbine and two-cycle or combined cycle gas turbine system.

The system runs on natural gas. The ethane (C_2) component of the captured gas is used to power the system thereby eliminating additional cost on the system. The emissions of the system is a function of the degree of processing of the captured natural gas. Since the system runs on clean natural gas, i.e. one with less sulphur contaminants, the degree of attendant pollution is minimized.

Combined Cycle Gas Turbine (CCGT)

In electric power generation, a **combined cycle** is an assembly of heat engines that work in tandem from the same source of heat, converting it into mechanical energy, which in turn usually drives electrical generators. The principle is that after completing its cycle (in the first engine), the working fluid of the first heat engine is still low enough in its entropy that a second subsequent heat engine may extract energy from the waste heat (energy) of the working fluid of the first engine. By combining these multiple streams of work upon a single mechanical shaft turning an electric generator, the overall net efficiency of the system may be increased by 50–60%. That is, from an overall efficiency of say 34% (in a single cycle) to possibly an overall efficiency of 51% (in a mechanical combination of two cycles) in net Carnot thermodynamic efficiency. This can be done because heat engines are only able to use a portion of the energy their fuel generates (usually less than 50%). In an ordinary (non-combined cycle) heat engine, the remaining heat (e.g., hot exhaust fumes) from combustion is generally wasted (Jean and Francoise, 2009).

Combined cycle plants are usually powered by natural gas, although fuel oil, synthesis gas or other fuels can be used. The supplementary fuel may be natural gas, fuel oil, or coal. Biofuels can also be used

A combined-cycle power plant uses both a gas and a steam turbine together to produce up to 50 percent more electricity from the same fuel than a traditional simple-cycle plant. The waste heat from the gas turbine is routed to the nearby steam turbine, which generates extra power.

A Combined Cycle Power Plant produces high power outputs at high efficiencies (up to 55%) and with low emissions. In a Conventional power plant, we are getting **33% electricity only** and remaining 67% **as waste**.

Working Principles of CCGT

A combined cycle gas turbine power plants having Brayton cycle based topping cycle and Rankine cycle based bottoming cycle has been considered for the present study and analysis. Gas turbine power plants consist of four components; compressor, combustion chamber, turbine and generator. Air is drawn in by the compressor and delivered to the combustion chamber. Liquid or gaseous fuel is commonly used to increase the temperature of compressed air through a combustion process. Hot gases leaving the combustion chamber expands in the turbine which produces work and finally discharges to the atmosphere (state 1, 2, 3 in Figure 3) (Al-Ibrahim and Varnham, 2010).

The waste exhaust gas temperature from gas turbine decreases as it flows into the heat recovery steam generator (HRSG), which consists of super-heater, evaporator and economizer. Then the HRSG supplies a steam for the steam turbine in producing electricity. In the later, the waste condensate from the steam turbine will be flowed

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into a condenser, where cooling water transfers waste heat to the cooling tower. In the final stage, feed water is the output from a condenser, which is suctioned by the feed water pump and sent to the heat recovery steam generator (Hosseini, 2007).

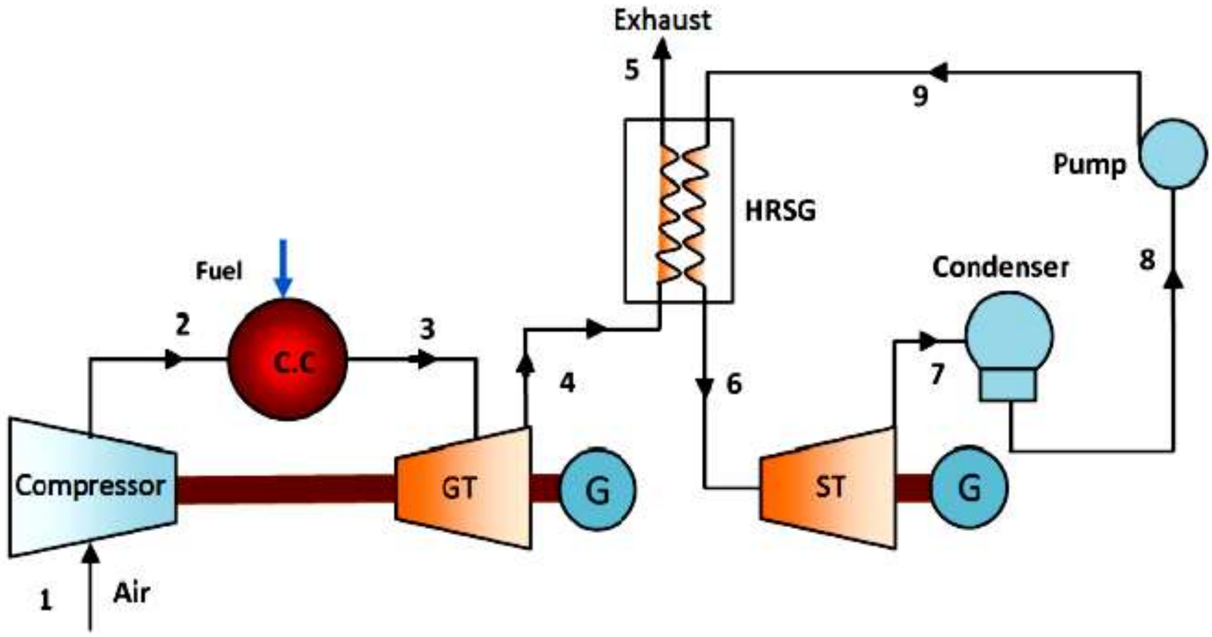

Figure 3. The schematic diagram of combined cycle gas turbine power plant. (Kim etal, 2011)

How a CCGT plant produces electricity

This is how a combined-cycle plant works to produce electricity

1. Gas turbine burns fuel.
    - The gas turbine compresses air and mixes it with fuel that is heated to a very high temperature. The hot air-fuel mixture moves through the gas turbine blades, making them spin.
    - The fast-spinning turbine drives a generator that converts a portion of the spinning energy into electricity.
2. Heat recovery system captures exhaust.
    - A Heat Recovery Steam Generator (HRSG) captures exhaust heat from the gas turbine that would otherwise escape through the exhaust stack.
    - The HRSG creates steam from the gas turbine exhaust heat and delivers it to the steam turbine.
3. Steam turbine delivers additional electricity.
    - The steam turbine sends its energy to the generator drive shaft, where it is converted into additional electricity.

In discussing the performance of the turbine, we shall first understand the parameters for the evaluation.
The amount of fuel used to generate electricity depends on the efficiency or heat rate of the generator (or power plant) and the heat content of the fuel. Power plant efficiencies (heat rates) vary by types of generators, power plant emission controls, and other factors. Fuel heat contents also vary.

Efficiency of CCGT Plant

Roughly the steam turbine cycle produces **one third of the power** and gas turbine cycle produces **two thirds of the power output** of a Combined Cycle Power Plant (CCGT). By combining both gas and steam cycles, high input temperatures and low output temperatures can be achieved. The efficiency of the cycles adds, because they are powered by the same fuel source.

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To increase the power system efficiency, it is necessary to optimize the HRSG, which serves as the critical link between the gas turbine cycle and the steam turbine cycle with the objective of increasing the steam turbine output. HRSG performance has a large impact on the overall performance of the combined cycle power plant. A Combined Cycle Power Plant produces high power outputs at high efficiencies (up to 58%) and with low emissions. In a Conventional power plant we are getting **33% electricity only** and remaining 67% **as waste**.
The electric efficiency of a combined cycle power station may be as high as 58 percent when operating new and at continuous output which are ideal conditions. As with single cycle thermal units, combined cycle units may also deliver low temperature heat energy for industrial processes, district heating and other uses. This is called cogeneration and such power plants are often referred to as a Combined Heat and Power (CHP) plant.

METHODOLOGY

Here, the mathematical equation is given. The interest is in the generation of electrical power from a given volume of natural gas and the efficiency of the generation system. The emission gases are also highlighted and the power usage ratio is also outlined. The turbine technology employed here is the CCGT. It operates with natural gas as the inlet fuel which is converted to electrical energy.

Heat Rates

The heat rate is the amount of energy used by an electrical generator or power plant to generate one kilowatt hour (kWh) of electricity. Heat rate is a term commonly used in power stations to indicate the power plant efficiency. The heat rate is the inverse of the efficiency: a lower heat rate is better. While efficiency is a dimensionless measure (sometimes quoted in %), heat rate is typically expressed as GJ/GWh. This is because Watt-hours are more commonly used when referring to electrical energy and Joule is more commonly used when referring to thermal energy.

$$\text{Heat rate} = \frac{\text{Thermal energy in}}{\text{Electrical energy out}} \quad (4)$$

1KWh = 3.6MJ = 3412Btu
1MWh = 3600MJ

Heat Content

Heat content is the amount of heat energy available to be released by the transformation or use of a specified physical unit of an energy form (e.g., a ton of coal, a barrel of oil, a Kilowatt-hour of electricity, a cubic foot of natural gas, or a pound of steam). The amount of heat energy is commonly expressed in British thermal units (Btu). Note: heat content of combustible energy forms can be expressed in terms of either gross heat content (higher or upper heating value) or net heat content (lower heating value), depending upon whether or not the available heat energy includes or excludes the energy used to vaporize water (contained in the original energy form or created during the combustion process).

Table 1: Heat content range of some product fuels

Product	**Gross Heating Value**	
	(Btu/ft^3)	**(Btu/lb)**
Natural Gas (typical)	950 - 1150	19500 - 22500
Octane saturated with water	6239	20542
Pentane	3981	20908

For the sake of this work, a natural gas heat content of 1029Btu/cft shall be used

Turbine Efficiency

For a conventional gas turbine plant, the efficiencies are in the range (31-34%) i.e. single cycle turbines. The efficiency of turbine is the inverse of heat rates. According to conversion of units, 1 kWh = 3412 Btu. But if you actually convert some fuel to electricity, some energy will be lost due to the inefficiency of the generating process. We refer to this inefficiency by using the heat rate, which is the actual amount of fuel required to produce 1 kWh. For example, if the heat rate is 8400 Btu, then the efficiency is 3412 ÷ 8400 = 40.6%

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Fuel Usage

This is the volume of natural gas needed to produce 1kwh of electricity. The fuel usage varies for different turbine and fuels used. It is also affected by the efficiency of the plant

Two formulas can be used to calculate the amount of fuel used to generate a Kilowatt-hour (kWh) of electricity (Polyzakis etal, 2008):

1. Amount of fuel used per kWh = Heat rate (in Btu per kWh) / Fuel heat content (in Btu per physical unit)
2. Kilowatt-hour generated per unit of fuel used = Fuel heat content (in Btu per physical unit) / Heat rate (in Btu per kWh)

Calculation examples using these two formulas and the assumptions below (Hosseini etal, 2007):

1. Amount of fuel used to generate 1 kWh:
    - Coal = 0.00052 short tons or 1.04 pounds
    - Natural gas = 0.01011 Mcf (an Mcf equals 1,000 cubic feet)
    - Petroleum = 0.00173 barrels (or 0.07 gallons)
2. Kilowatt-hour generated per unit of fuel used:
    - 1,927 kWh per ton, or 0.96 kWh per pound, of coal
    - 99 kWh per Mcf (1,000 cubic feet) of natural gas
    - 578 kWh per barrel, or 13.76 kWh per gallon, of petroleum

Assumptions:

Power plant heat rates (for steam electric generators in 2014)
Coal = 10,080 Btu/kWh
Natural gas = 10,408 Btu/kWh
Petroleum = 10,156 Btu/kWh
Fuel heat contents (for fuels received by electric power industry in 2014)
Coal = 19,420,000 Btu per short ton (2,000 pounds) Note: Heat contents of coal vary widely by types of coal.
Natural gas = 1,029,000 Btu per 1,000 cubic feet (Mcf)
Petroleum = 5,867,946 Btu per Barrel (42 gallons) Note: Heat contents vary by type of petroleum product.

3. RESULTS AND DISCUSSION

The Modular Gas Technology

This configuration consist of the technology for the flare gas capture and the flare gas processing and transportation technology.

Parameters given

Conversion efficiency of plant: 95% (from literatures)
Thermal efficiency of plant: 80% (from literatures)
Shrinkage volume: 6% (from literatures)
Heat rate for 20mmscf/d of gas: 7171MJ/MWh

$$\text{Volume of gas at inlet} = \frac{\text{plant capacity}}{\text{conversion efficiency}}$$

$$\text{Volume of gas at inlet} = \frac{20\text{mmscf/d}}{0.95} = 21\text{mmscf/d}$$

Shrinkage volume = capacity range x shrinkage factor
Shrinkage volume = 20mmscf x 6% =1.2mmscf

$$\text{Heat rate} = \frac{\text{thermal energy in}}{\text{electrical energy out}}$$

1KWh=3.6MJ, 1MWh=3600MJ

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A 100% efficiency implies equal input and output: for 1 MWh of output, the input must be 1 MWh. This thermal energy input of 1 MWh = 3600MJ
Therefore, the heat rate of a 100% efficient plant is simply 3600 MJ/kWh
For a thermal efficiency of 80%, the heat rate would be (3600/0.8)MJ/MWh = 4500MJ/MWh

Table 2 was developed from these parameters given above.

Table 2: Technical performance of modular gas technology (both flare gas capture and processing)

Capacity range	Conversion efficiency	Volume of inlet gas	Shrinkage factor	Shrinkage volume	Heat rate (MJ/MWh)	Thermal efficiency
20mmscf/d	95%	21mmscf/d	6%	1.2mmscf	4500	80%
50mmscf/d	95%	52.5mmscf/d	6%	3mmscf	4500	80%
100mmscf/d	95%	105mmscf/d	6%	6mmscf	4500	80%
200mmscf/d	95%	210mmscf/d	6%	12mmscf	4500	80%

Combine – Cycle Gas Turbine (CCGT)
Parameters given
Heat content of natural gas = 1029Btu/Cft (from literatures)
Heat rate of natural gas = 10408 Btu/Kwh
1 kWh = 3412 Btu
Efficiency for conventional turbine (CT) = 1Kwh/heat rate
Efficiency for conventional turbine (CT) = 3412/10408 = 0.32782475 $\approx$ 32.78%
Efficiency for combined cycle Gas turbine (CCGT) = 55% (from literatures)
Table 3 was developed from these parameters given above.

Table 3: Performance Parameters Turbine Plants

Natural Gas Feed Rate(MMscfd)	Heat Content(Btu/Cuft)	Heat Rate(Btu/Kwh)	CT Efficiency	CCGT Efficiency
20	1029	10,408	32.78%	55%
40	1029	10,408	32.78%	55%
60	1029	10,408	32.78%	55%
80	1029	10,408	32.78%	55%
100	1029	10,408	32.78%	55%

From the parameters given above
Kilowatt-hour generated per unit of fuel used = Fuel heat content (in Btu per physical unit) / Heat rate (in Btu per kWh)
Kilowatt-hour generated per unit of fuel used = 1029/10408 = 0.098866257Kwh/scf or 98.87Kwh/Mcf
Daily allowable energy generated(Kwh) = Feedrate(MMSCF/D) x 0.098866257Kwh/Scf

For 20mmscf/d,
Daily allowable energy generated (Kwh) = 20000000 x x 0.09887Kwh/Scf= 1977325.2Kwh
Noting that,

$$\text{Power} = \frac{\text{Energy}}{\text{Time}}$$

$$\text{Optimum power generated} = \frac{\text{Daily available energy generated}}{\text{Time}}$$

For 20mmscf/d
Optimum power generated = 1977325.2/ 24 = 82388.55KW
Power generated for both CT and CCGT in MW = optimum power generated x efficiency of plant/1000
For 20mmscf/d using CT plant power generated = 82388.55x 0.32782475/1000 = 27.00900582MW
For 20mmscf/d using CCGT plant, power generated = 82388.55x 0.55/1000 = 45.3137025MW

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Table 4 was computed using the information and formulas above

Table 4: Results for Calculations on Performance Parameters for Turbine Plants

Natural Gas Feed Rate (MMscfd)	Available Gas Volume(Scf)	Daily Available Energy Generated(Kwh/Scf)	Optimum Power Generated (KW)	CT Power Generated (MW)	CCGT Power Generated (MW)
20	20000000	1977325.2	82388.55	27.00900582	45.3137025
40	40000000	3954650.4	164777.1	54.01801164	90.627405
60	60000000	5931975.6	247165.65	81.02701747	135.9411075
80	80000000	7909300.8	329554.2	108.0360233	181.25481
100	100000000	9886626	411942.75	135.0450291	226.5685125

Below is the MATLAB program calculator designed for the computation of performance variables as it concerns both the modular gas technology and the gas turbine system for electricity generation.

Figure 5: MATLAB Calculator Program for Calculation of Technical Performance Parameters

The plots below are those gotten when certain variables are varied to see the degree of relationship between them.

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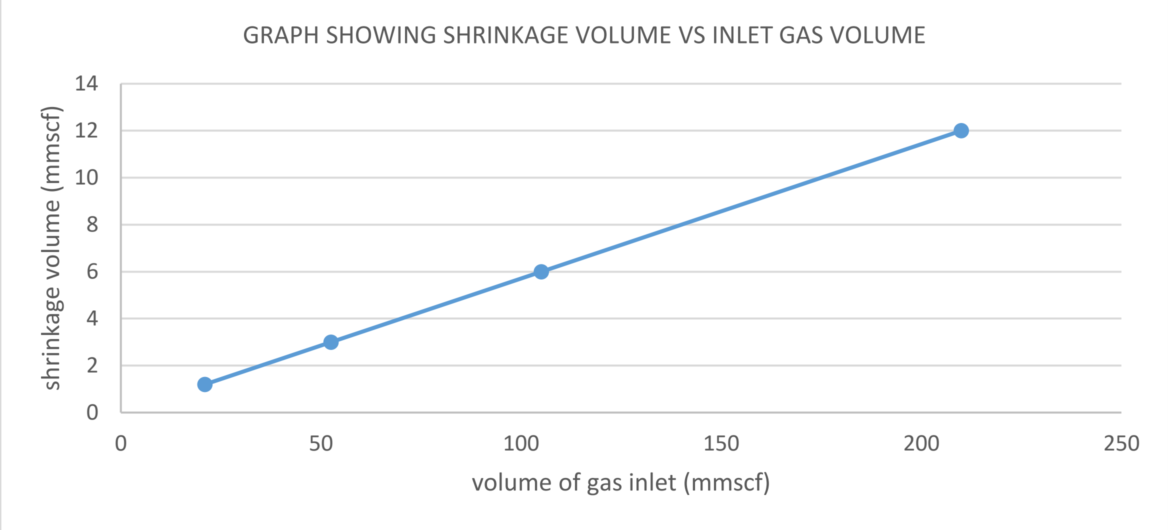

Figure 6: Graph of shrinkage volume and volume in initial place

Figure 6 shows that gas shrinkage volume increases as the volume of inlet gas (feed stream) increases

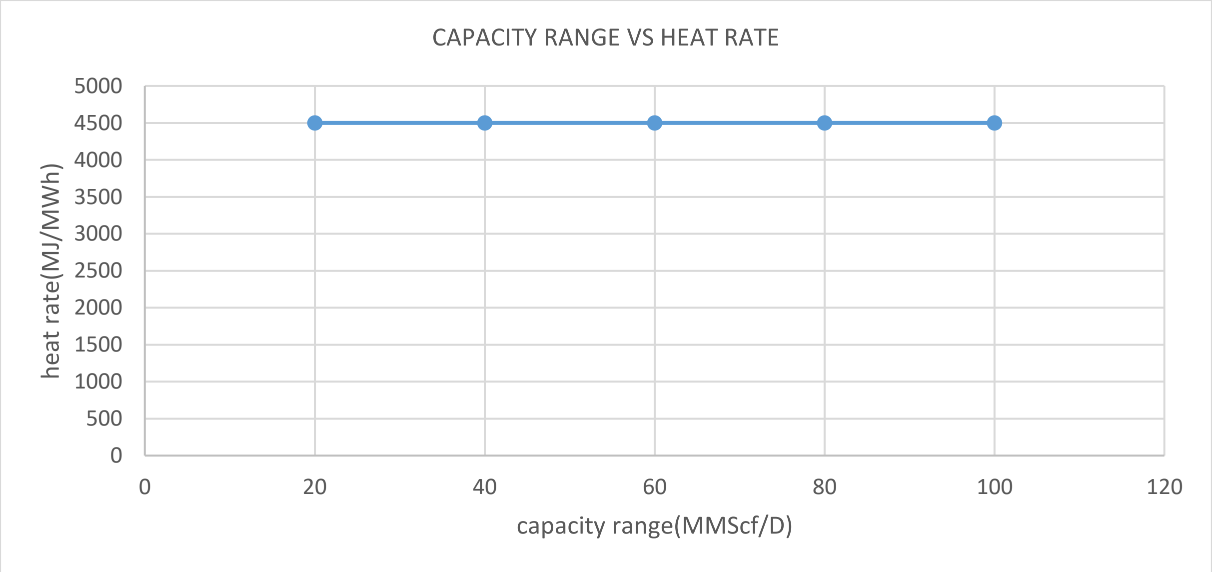

Figure 7: Graph plant capacity and heat rate

Figure 7 shows that the heat rate is constant for all capacities for a particular type of plant or turbine used.

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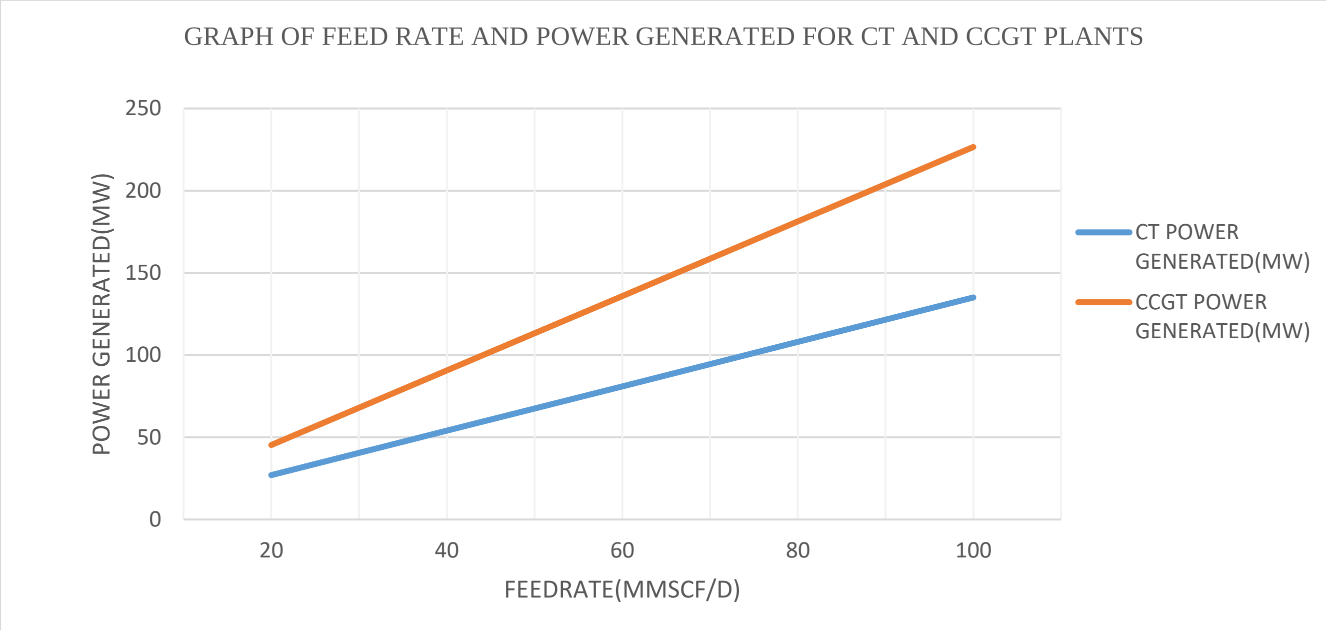

Figure 8: Graph Indicating Relationship Between Feed Rate and Power Generated.

In the figure 8 above, it is seen that there is a positive linear relationship between the feed rate of natural gas to the gas turbine and the electrical power generated. Note here that the plant efficiency is accommodated in the power generated. The optimum power generated is an idealized power generated if the plant were to be 100% efficient.

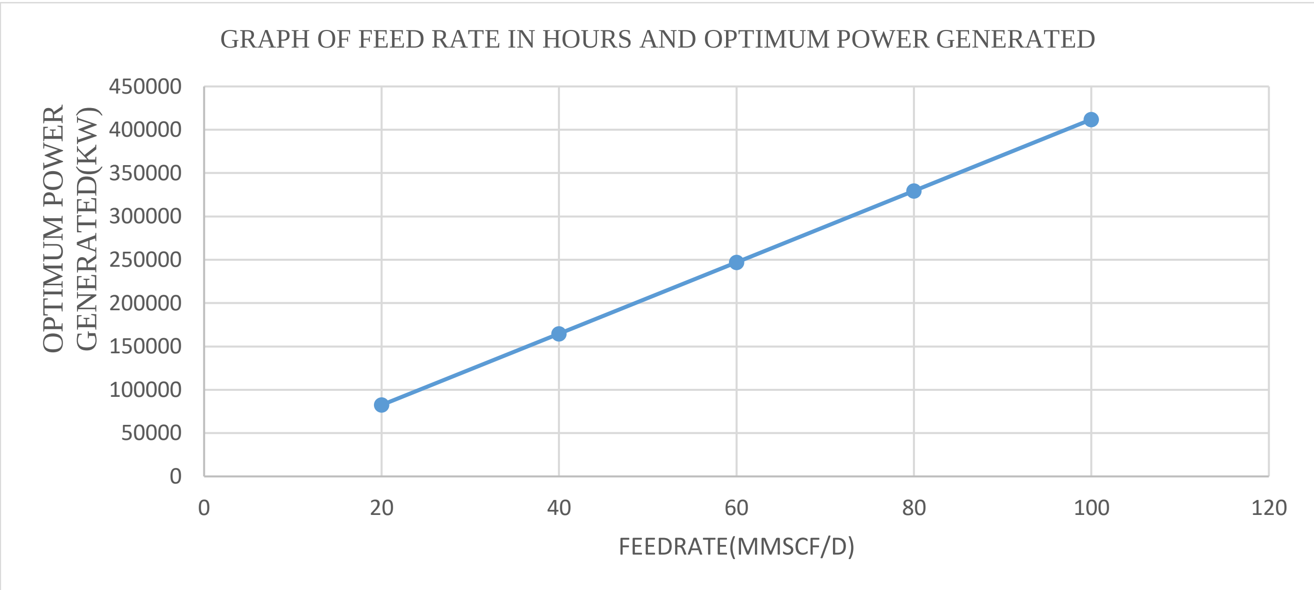

Figure 9: graph indicating relationship between feed rate in scf/hr and optimum power generated.

Figure 9 shows that there is linear relationship between gas feed rate and optimum power generated. Since no plant can give us a 100% efficiency. The optimum power that the plant can generate is a basis for the power achievable in case of improvement in machine performance.

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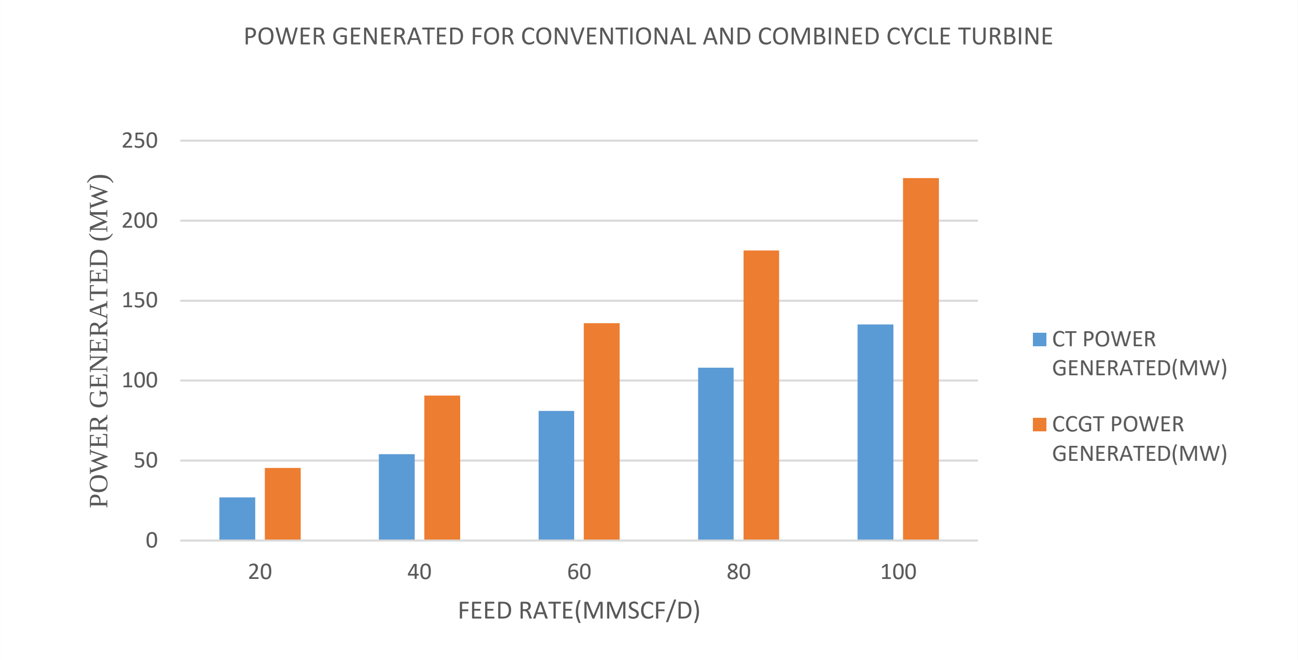

Figure 10: Column Chart Comparison of Power Generated tor The CT and CCGT Plants

From figures 8 and 10, it is seen that the CCGT plant yielded more MW of electricity than the conventional turbine (CT). This is because of its combined system where waste heat resulting from the conversion process is recaptured for electricity generation thereby increasing the efficiency of the overall process.

PLANT EMMISIONS AND CONTRIBUTION TO GREENHOUSE GASES

Modular gas technology operates with a very high environmental friendliness. It is designed in such a manner that its emission is within the acceptable standards.

Major pollutants such as CO_2, NO_x and SO_2 are produced only sparingly. The modular gas technology ensures that the major pollutants in the natural gas stream such as has been mentioned above have been minimally reduced to the acceptable environmental standards. The pollutions encountered in plants operations results from the oxidation of impurities in the fuel used. Purer fuels give less pollutions.

Table 5: Emissions of Different Inlet Fuels

Fuel source	SO_2	NO_X	CO_2
Coal (incorporating fuel emission control)	0.10	0.60	1.05
Heavy Fuel-Oil	1.20	0.75	0.85
Natural Gas	0.00	0.25	0.50

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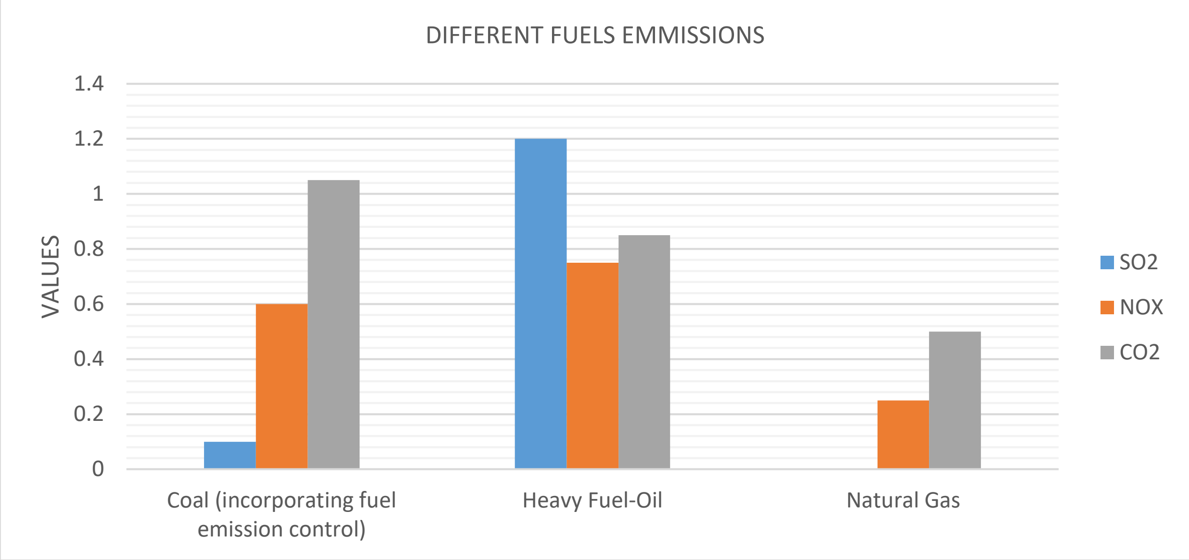

Figure 11: graph indicating emissions of conventional fuels

From figure 11 it is seen that natural gas has the least emissions as compared to other fuels. Its SO_2 emission is zero

4. CONCLUSION

The technical performance of the use of flare natural gas in turbines systems for electricity generation gas has been discussed. It is seen that the dry gas component of the flare gas stream could actually be used for power site fuel for electricity generation and save cost accruing to power. Furthermore the electrical energy could be monetized in the case where it is contracted by power generation companies and monetized by sending it to the national grid and to consumers. This will further add to the total power generation in the country and help address areas close to production sites where power generation is epileptic.

From the results tabulated, it is seen that using the CCGT yields more electrical power than the conventional turbine type. For a base 20mmscf capacity of plant, the CT generates 27MW while the CCGT generates 45.3MW of electricity. The efficiency of the CT and CCGT are 32.78% and 55% respectively.

From the result we get a high plant conversion efficiency of 95% and a thermal efficiency of 80% for the modular gas technology. The result also shows that the gaseous emission are only sparingly, making the generation process an environmentally friendly one.

This work highlights the possibility of investors investing in power generation from the flare gases. The materials are readily available at very low cost, i.e. cost of acquiring the gas form the operating companies.

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