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(Review Article)

# Gas turbine modification: A review

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## Abstract

Energy is a vital part of life today and it is utilized by humans to carry out work. Energy is required in different forms e.g. chemical, mechanical, electrical etc. Electricity is a secondary energy resource due to its dependence on other primary energy resources like coal, natural gas, wind, solar, hydro etc. and it is one of the most important energy source needed today because man relies on it for a lot of processes and activities. Electricity generated by renewable means have zero effect on the environment while electricity generated by non-renewable means generate pollution to the atmosphere and deplete energy resources. 51% of the electricity generated in the world today is derived from fossil fuel which is a nonrenewable energy resource. Natural gas power plants account for 23.1% of electricity generation in the world while gas turbines makes up a large percentage for natural gas plants in power generation. Gas turbines can be modified to increase their generation capacities with the aim of reducing pollution associated with combustion of fossil fuel. Nigeria relies mainly on gas turbine to supply electricity to the grid. 81% of power plants in Nigeria are thermal power plants while 17.59% are hydro-power plants. Gas turbine power plants make up 89% of the thermal plants in Nigeria today and they mostly operate using simple cycle. This data shows that there is a lot of potential to increase gas turbine efficiency in the Nigerian electricity space while reducing pollution and reducing fuel consumption.

**Keywords:** Efficiency; Gas Turbine; Nigeria; Electricity; Thermodynamics; Modified Cycles

## 1. Introduction

Energy can generally be defined as the ability to do work. Energy can also be defined as a quantitative property which must be transferred to a body or a system to perform work or heat the body [1]. According to the law of conservation of energy, energy can neither be created nor destroyed but converted from one form to another therefore it is a conserved quantity. Energy can be divided into two types which are kinetic energy and potential energy. Kinetic energy is the energy an object possesses due to its motion while potential energy is the energy a body possesses due to its position relative to ground, its chemical properties, stresses within itself, electrical charges etc. There are several forms of energy; Sound energy, mechanical energy, electrical energy, gravitational energy, chemical energy, nuclear energy etc. Energy has been available since the beginning of time. The term energy was possibly used first by Thomas Young in 1807 to replace 'vis viva' which was used by Gottfried Leibniz to describe a living force [2]. Electricity is a form of energy and was invented by several scientists. However, the most notable of the discoveries was done by Michael faraday and joseph henry who invented the electric motor in 1931. They documented that electric current can be produced in a wire when a magnet is move near it [3].

The world today depends on energy to meet its needs like heating, transportation, electricity etc. Among the energy resources needed by man today, electrical energy stands out the most. Man relies on electricity for a lot of processes and activities. Electricity is a secondary energy resource due to its dependence on other primary energy resources like coal, natural gas, wind, solar, hydro etc. Primary resources are converted to electrical energy by using energy conversion machines which transforms the chemical energy in fossil fuel energy resources into electricity. The combustion of fossil

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fuel generates by-products like carbon dioxide and nitrous oxide and many other pollutants which are dangerous to our environment. Sustainable development goals (SDG) also known as global goals are a group of sustainable goals adopted by the united nations in 2015 as a universal call to protect, preserve the environment, and end poverty by the year 2030 [4]. The two sustainable development goals relevant to this study are 7th and 13th goal. The 7th Goal addresses affordable and clean energy which directly impacts on the worlds' energy resources and their utilization. Currently, humans rely majorly on non-renewable energy resources to meet growing energy needs. The main sources of non-renewable energy are petroleum, hydrocarbon gas liquids, natural gas, coal and nuclear energy. The 13th sustainable development goal is climate action which specifically addresses the effect of greenhouse gas emissions in the atmosphere. Greenhouse gases are gases that when they are released into the atmosphere, they cause heat to be trapped in the atmosphere and warm up the planet. The main gases responsible for greenhouse effect are carbon dioxide, methane, nitrous oxide, water vapor and fluorinated gases. The first 4 gases mentioned are generated naturally while the fifth is manmade. Combustion process has carbon dioxide as its by-product and this process is contained in most technological solutions which require an independent power source e.g. automobiles, ships, airplanes etc.

To give a perspective of the greenhouse gases emission in the world today, consider countries with the largest consumption of primary energy in the world today. In 2020, china consumed about 145.46exajoules of energy followed by united states at 87.79 exajoules and India at 31.98exajoules. Carbon dioxide ($CO_2$) is a major driver of climate change. From data obtained from Union of concerned scientists, UCSUSA [5] which collates $CO_2$ emission from 1750 – 2020, United states accounted form 416,738MT of $CO_2$. In 2019 alone, china accounted for 9.90GT of carbon dioxide followed by United states, India and Russia. Figure 1 below shows a breakdown of greenhouse gasses in the united states.

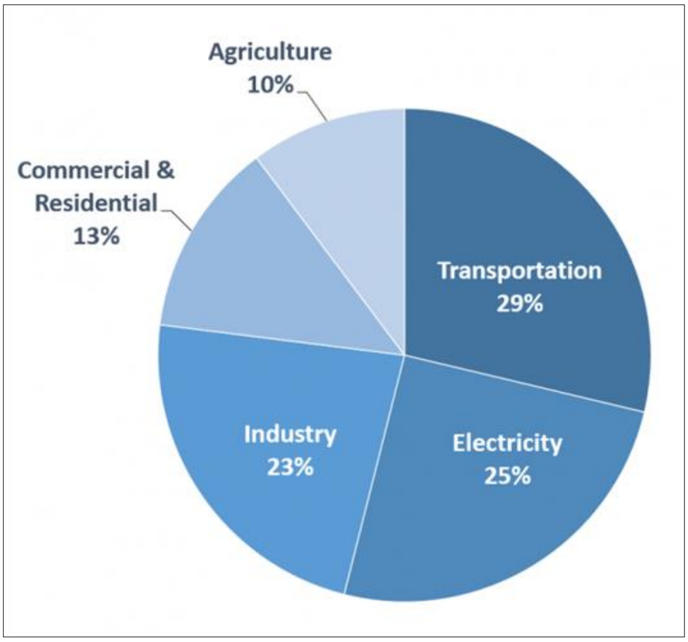

**Figure 1** Total United States Greenhouse Gas Emissions in 2019 = 6,558 Million Metric Tons of CO2 equivalent

According to United states environment protection agency (EPA) [6] in 2019, 6,588MMT of $CO_2$ equivalent was generated by the United states alone. The primary sources of greenhouse gas emissions in the united states are from transportation accounting for 29% of greenhouse emissions. Greenhouse gases are released by combustion of fossil fuel for motor vehicles, ships, trains and planes. 25% of greenhouse emission was from electricity generation and approximately 60% of the greenhouse gases generated for electricity was the result of combustion of fossil fuel i.e. coal and natural gas, 23% generated by industry processes which are mainly from chemical reactions which are required for the production of goods, 13% was generated by commercial and residential processes including fossil fuels used for heat, handling of waste and other processes which generate greenhouse gasses, agriculture amounted to 10% of greenhouse gas emission mainly from the production of livestock, rice production and agricultural soils and finally 12% resulted from land usage and forestry.

There are many factors which affect the consumption of electricity; According to a study conducted by Chen [7] gross domestic product (GDP), employment rates, residential space and the implementation of energy labeling schemes affects residential consumption today. Gross domestic product (GDP) is a measure of all the goods and services produced by a country in a specific time period. Measuring both the GDP and population of a country, the country's standard of living can be measured i.e. the spending power of citizens in a country. This is known as the GDP per capita. The more spending power people have the higher they consume electricity and this is directly proportional to the population of a country and the GDP of the country. All these are factors which affect the electricity consumption in a country which needs to be factored into when planning for electricity supply in a country. Global consumption of electricity amounted to 22,848 terawatt-hour (TWh) in 2019 according to IEA [8] which is 135% above the global consumption of electricity in 1990. China, United States and India accounted for more than 50% of the global electricity consumption with china alone consuming 6,523TWh of electricity, United States 3,830TWh and India 1,311TWh of electricity.

**Table 1** Energy Resources used to Generate Electricity[9]

| **Year** | **1990** | **1995** | **2000** | **2005** | **2010** | **2015** | **2019** |
|---|---|---|---|---|---|---|---|
| Coal (GWh) | 4,429,513.00 | 4,993,305.00 | 5,995,467.00 | 7,325,951.00 | 8,670,586.00 | 9,535,705.00 | 9,914,448.00 |
| Oil (GWh) | 1,324,040.00 | 1,230,339.00 | 1,188,490.00 | 1,128,488.00 | 966,573.00 | 1,023,393.00 | 747,171.00 |
| Natural gas (GWh) | 1,747,827.00 | 2,017,942.00 | 2,771,466.00 | 3,702,259.00 | 4,843,606.00 | 5,535,167.00 | 6,346,009.00 |
| Biofuels (GWh) | 105,260.00 | 94,925.00 | 112,383.00 | 169,384.00 | 275,160.00 | 409,619.00 | 542,567.00 |
| Waste (GWh) | 24,142.00 | 35,010.00 | 49,740.00 | 58,149.00 | 86,950.00 | 99,554.00 | 112,742.00 |
| Nuclear (GWh) | 2,012,902.00 | 2,331,951.00 | 2,590,624.00 | 2,767,952.00 | 2,756,289.00 | 2,570,071.00 | 2,789,694.00 |
| Hydro (GWh) | 2,190,975.00 | 2,545,911.00 | 2,695,584.00 | 3,019,330.00 | 3,535,864.00 | 3,981,698.00 | 4,328,966.00 |
| Geo thermal (GWh) | 36,426.00 | 39,895.00 | 52,171.00 | 58,284.00 | 68,119.00 | 80,714.00 | 91,091.00 |
| Solar PV (GWh) | 91.00 | 197.00 | 800.00 | 3,734.00 | 32,047.00 | 244,867.00 | 680,952.00 |
| Solar thermal (GWh) | 663.00 | 824.00 | 526.00 | 597.00 | 1,645.00 | 9,607.00 | 13,367.00 |
| Wind (GWh) | 3,880.00 | 7,959.00 | 31,347.00 | 104,465.00 | 342,203.00 | 833,993.00 | 1,427,413.00 |
| Tide(GWh) | 536.00 | 547.00 | 546.00 | 516.00 | 513.00 | 1,006.00 | 1,000.00 |
| Other sources (GWh) | 19,939.00 | 23,864.00 | 22,049.00 | 32,983.00 | 33,715.00 | 37,293.00 | 48,770.00 |

The data in the table above shows the electricity generation by source from 1990 to 2019.

According to IEA [9], more than 51% of the electricity generated in the world today is derived from fossil fuel as a primary energy resource. Coal, Oil, Natural gas make up the fossil fuel energy resources which is used in the production of electricity. Figure 2 breaks down electricity generation by different sources shown in a pie chart. From the chart, it is evident that despite the drive for sustainable energy sources, that the world still relies heavily on fossil fuel for electricity generation. Coal fired thermal plants produce about 900 $gCO_2/kWh_e$ while gas fired thermal plants produce 400 $gCO_2/kWh_e$ [10]. When compared with wind turbines which produces between 10 – 30 $gCO_2/kWh_e$, thermal and gas fired power plants produce higher pollution. Despite this, the world still depends greatly on thermal plants for electricity generation.

A gas turbine is a type of internal combustion engine which produces mechanical energy by combustion of a fuel (chemical energy) and operates on Brayton cycle or Joules cycle. The Brayton cycle is made up of 4 processes having two adiabatic processes and two isobaric processes. The average efficiency of a gas turbine operating in an open simple cycle gas turbine is about 30.4% [11]. A gas turbine operating in simple cycle configuration can be modified or the performance of the gas turbine can be optimized to increase its power and efficiency. Some methods of modification of the gas turbine are; addition of a reheating process to the cycle to increase the power output, combining water injection to gas turbine to increase the mass-flow inside the compressor and increase the output power significantly, introducing an intercooler to the cycle, and including a recuperator also increases the efficiency of the gas turbine. Some ways of increasing gas turbine efficiency are by increasing the pressure ratio of the Brayton cycle and turbine inlet temperature.

Although increasing the pressure ratio of a gas turbine increases the temperature of the air exiting the compressor significantly, the method is applicable within the limit the materials used in the hot gas paths can withstand.

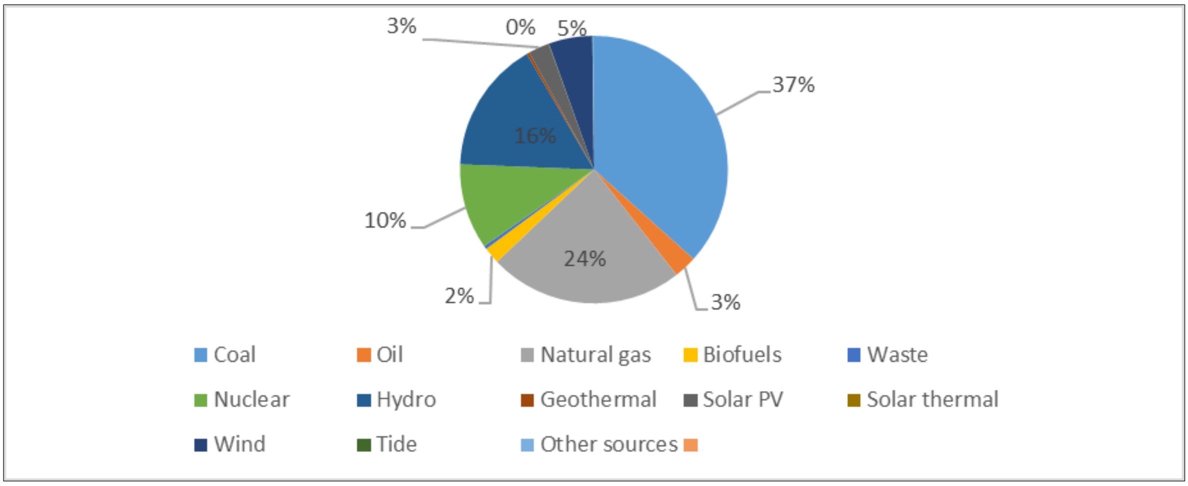

**Figure 2** Electricity generation by source

## 2. Gas Turbine Modification

Sustainability of energy resources is very important in the society today. According to Dincer and Rosen [12] improving the efficiency of utilizing an energy resource reduces the environmental impact of emissions. Also increasing the efficiency also helps to conserve the natural resources thereby increasing the lifetime of the resources reserve. Since Gas turbine is a widely used energy conversion technology, improving the efficiency of the gas turbine guarantees the sustainability of natural gas, reduces the impact to the environment while increasing the electricity generation output to meet growing demand. The thermal efficiency of a gas turbine increases with any increase of the turbine inlet temperature. This however is limited due to the metallurgical limits imposed by the materials which the turbine parts are built [13]. Modification of the gas turbine cycle to include intercooling, reheating and regeneration is another way to improve the efficiency of the gas turbine. Intercooling requires the use of an intercooler in between two compressors to reduce the temperature of the compressed air before it is introduced into the combustion chamber. This would reduce the work input for the compressor thereby increasing the net-work output. In a reheat cycle, the gas turbine has two combustion chambers and two turbines; high pressure and low pressure turbines. When the hot gases leave the first combustion chamber, energy is extracted from the hot gases at the first turbine then the exhaust gases from the first turbine is heated and reintroduced into the second low pressure turbine where more work is extracted from the exhaust gases. In a reheat gas turbine cycle, the heat from the exhaust of the gas turbine is used to heat the air leaving the compressor before it is introduced into the combustion. This extra heat added reduces the amount of fuel which is required to increase the temperature of gas before it enters into turbine inlet temperature. Alfellag [14] carried out a parametric study on the intercooled reheat and regenerative gas turbine power plant to evaluate the influence of different parameters in the performance of the plant. They were able to deduce that the thermal efficiency of the plant increased when the effectiveness of the regenerative and intercooler effectiveness is increased. Also, increasing turbine and compressor efficiency increases the thermal efficiency of the gas turbine. Peak efficiency was observed to have occurred when the compression ratio was at 2.2, then it decreased with further increase in compression ratio.

Different approaches have been proposed to increase gas turbine plant efficiency and some are currently in use today. Increasing the turbine inlet temperature is one way if increasing the efficiency of a gas turbine. However, this would translate to improving the thermal barrier coatings in the gas turbine to accommodate the higher temperature. Heat recovery methods can also be used to increase efficiency for power generation output especially the commercial process. The exhaust of a gas turbine is around 500$^{o}$c and this makes up about 60% of the total energy output of an open cycle gas turbine [15]. Many configurations of gas turbine cycles have been developed to cater for environmental and economic concerns regarding the use of natural gas for power generation. There are two heat recovery arrangements used for recovering heat from a gas turbine: recuperation and bottoming cycles. Recuperation is a configuration where heat is recovered and utilized in the same gas turbine cycle while a bottoming cycle is a configuration whereby the heat recovered from the exhaust of the gas turbine is used as the heat source in an independent power cycle. There are different types of recuperation; gas to gas recuperation, steam injection, evaporation cycle, chemical recuperation. In a gas to gas recuperation, the exhaust gas from the gas turbine is used to heat up the compressed air before it enters into the combustion chamber. This reduces the amount of fuel which is burnt to achieve turbine inlet temperature. One of the main limitation for this configuration is the metallurgical problems which arises from the high temperature in the heat exchanger. When the pressure ratio of a compressor is increased, the exit temperature of the air from the compressor also increases but the exhaust temperature reduces in modern higher efficiency turbines. Introducing an intercooler in compressing the air helps to reduce the compressor exit temperature and this allows recuperation in higher efficiency turbines. Therefore combining intercooler and recuperation produces the best combination resulting in an efficiency as high as 42% [16].

Steam injection gas turbine cycle is also a type of gas turbine recuperation. In this configuration, the exhaust heat is used to generate saturated steam which is then introduced into the turbine to increase the mas flow rate and power output of the turbine. Saturated steam can be achieved in temperatures less than 200°C at a pressure which is higher than the pressure at the compressor outlet. This configuration requires water with high purity which is consumed to generate power in the form of steam. Although steam injection increases the power output of a gas turbine, it requires additional investment to generate very pure water for stream injection. Bolland and Stadaas [17] investigated the combination of a combined cycle gas turbine plant with water injection, steam injection and recuperation to be able to ascertain the best combination which gave the highest efficiency. A model of a gas turbine was designed for this study and was applied to calculated the performance of combined cycle, simple cycle, steam injected cycle and dual recuperated intercooled and after-cooled steam injected cycle. they compared the models with standard gas turbines in four groups; large industrial (123 – 158MW), medium industrial (38 – 60 MW), aero derivatives (21 – 41MW) and small industrial (4 – 6MW). When comparing the efficiency of a simple cycle and a steam injected cycle, the steam injected cycle produces a higher efficiency due to reduced cycle energy rejection temperature and a high specific work. However, the increase in efficiency of a steam injected cycle is thermodynamically limited by the pinch point of the exhaust gas heat recovery process. Also in recuperation gas turbine, there is an increase in the efficiency of the cycle, however the increase is thermodynamically limited by the effectiveness of the recuperator heat exchanger. A combined steam injection, recuperation and water injection cycle into an exhaust heat recovery system is also known as the DRIASI (Dual Recuperated Intercooled After-cooled Steam Injected) cycle. in the DRIASI cycle, water is injected into the compressor and after the compressor to reduce the stack temperature thereby reducing the temperature of cycle heat rejection, the water and steam injection increases the loss of latent heat from the exhaust stack. By adding water injection to recuperation, aa reduced temperature of heat of addition to the cycle is avoided. the result obtained from their study showed that for the smaller turbines, the DRIASI cycle proved to have higher efficiency than the other cycles.

For the medium industrial gas turbines, combined cycle produced the highest efficiency although the DRIASI cycle also performed very well while for the large gas turbine cycles, combined cycle was found to be more efficiency than the other cycles [18]. Evaporation cycles are also a type of recuperation cycle. In an evaporation cycle, water is injected into the exit of the compressor. The heat generated by compressing air will then evaporate the water which will result in a single phase mixture, then it goes into a recuperator where is further heated by exhaust gases before it is introduced into the combustion chamber. The best known evaporation cycle is the humid air turbine (HAT) or the integrated gasification humid air turbine (IGHAT). The IGHAT is designed to work with coal gasification plant. The last type of recuperation is the chemical recuperation cycle. the exhaust gases from steam injection plants are high in water content. The amounts to significant heat loses from the heat recovered from the exhaust to the atmosphere in the form of latent heat. Chemical recuperation is a proposed system which would use the exhaust heat to manufacture hydrogen rich fuel from methane feedstock. The hydrogen rich fuel is manufactured in a steam reformer where the exhaust of an intercooled, reheated turbine with steam injected is channeled into and is used as the heat source.

Bottoming cycles as mentionedearlier is a type of heat recovery cycle which makes use of the exhaust heat from a gas turbine as the heat source for an independent power system. A combined cycle configuration is an example of a bottoming cycle which makes use of the heat from the exhaust of the gas turbine to heat steam in a steam turbine cycle. A combined cycle configuration has numerous advantages over conventional coal fired steam turbines likehigher thermal efficiencies over 55% in current designs, relatively lower capital cost i.e. it costs less than half the cost of a coal fired plant, it requires lesser construction times, its configuration is flexible, it can be used with various types of fuel and its emission levels are relatively lower. The Kalina cycle is another type of bottoming cycle which uses heat recovered from the exhaust to heat up a zeotropic mixture of water and ammonia as a working fluid. The Kalina cycle is claimed to have plant efficiency of 58.8% which is higher than the most efficient Rankine cycle [19]. Kalina cycle also cost about 2/3 of the cost to implement a conventional combined cycle (using steam turbine). Cogeneration power plants and combine cycle power plants are examples of modified gas turbine cycle. While a conventional gas turbine produces about 28-31% efficiency, a cogeneration power plant can produce as much as 85% efficiency [20]. This shows how much gain can be achieved in improving the efficiency of a conventional gas turbine. Inlet air cooling is another way of increasing gas turbine efficiency. By cooling the inlet air, the mass flow rate of the air increases and this increases the power output. For this work, we would review some of the studies which have been done to improve turbine efficiency in the past. Efekemo and Saturday [11] carried out a study to compare the a simple and modified gas turbine cycle. Their study aimed to establish the gains made when a simple Brayton cycle is modified and applied in a gas turbine. A simple gas turbine cycle was modelled for their study and then modified to include an intercooler, reheat and a regenerator. The modification was done to increase the power and efficiency of the gas turbine. Their study revealed that the modified cycle had an energy efficiency of 48% which was 18% higher than the simple gas turbine cycle which was used in the study.

An inverse Brayton cycle is a potential exhaust-gas heat recovery technology which is an inverse of the Brayton cycle. In an inverse Brayton cycle, the exhaust gas from a Brayton cycle is further expanded in a turbine to a pressure below the atmospheric pressure. Power which is extracted from the turbine is used to drive the compressor in the process. Next the gas enters the heat exchanger where it is cooled further. gas and this reduces the work done by the compressor. The cooler gas is channeled into the compressor where its pressure is increased back to the atmospheric pressure. The inverse Brayton cycle was applied by Zhu et al [21] to a turbocharged diesel engine as a waste heat recovery solution. Results from their study showed that there was a 6.1% increment in engine exhaust recovery. Although they recommended further study should be done on the heat exchanger. Zhang et al [22] evaluated the power and efficiency of a combined Brayton and inverse Brayton cycle. Their study also included optimization of the efficiency for the combined Brayton and inverse cycle. The combined cycle includes a top cycle and a bottom cycle. The top cycle consists of the high pressure compressor, high pressure turbine and combustion chamber while the bottom cycle consists of the low pressure turbine, heat exchanger and the low pressure compressor. The aim of their study was to achieve the optimal bottom cycle pressure ratio and optimal flow rate that will ensure the plant produces at maximum power output. They concluded that the net power output was maximum with respect to the air mass flow rate. The net power was maximum with respect to the compressor ratio of the top cycle. Goodarzi et al [23] carried out a performance analysis on a regenerative and inverse Brayton cycle. The study modeled the airflow for exhaust of the 1st turbine divided into two streams which supplied the regenerator and the inverse Brayton cycle. Their results showed that the thermal efficiency of the cycle and net power output increases with the increase of the pressure ratios of the first compressor which is the top cycle.

A gas turbine operates as operates as a control volume which means a fixed volume. Temperature is inversely proportional to density and increasing the ambient temperature of the inlet air of a gas turbine lowers the density of air entering the gas turbine which translates to less air admitted into the gas turbine. Whereas lowering temperature of the air entering the gas turbine increases the density which means the at the same speed the mass flow will increase with a lower temperature. Habib et al [24] researched on an application of a reversed Brayton cycle to cool the intake air into a gas turbine which combines an intercooler with regenerative reheat gas turbine cycle and evaporative cooling to evaluate output energy. In the proposed design for the study the air passes through a refrigeration cycle (reversed Brayton cycle) then enters an evaporative air cooling before it enters the combustion chamber. They aimed to reduce the inlet air temperature to a low as possible to ensure more mass flow rate. They also applied a recuperator and reheater to their model to ensure more energy is extracted from the process. They concluded that a reduction in temperature from 299k to 287k resulted in a 2.18% increase in power output. Also, the configuration reduced the amount of NOx (Nitrous Oxide gases) from 1000ppm to 100ppm. More work was done by Elwekel and Abdala [25] to evaluate the effect of mist cooling on a steam injected gas turbine cycle. Mist cooling is a method by which the inlet air into the gas turbine is cooled below the ambient temperature before it is admitted into the turbine. A steam injected gas turbine is a modification of the Brayton cycle which introduces steam into the cycle in order to boost the output capacity of the turbine as well as reduce the NOx emission. This modification includes the addition of a heat recovery steam generator where the steam will be produced also a constant supply of demineralized water which will mean additional equipment.

Kayadelen and Ust [26] compared a simple cycle, intercooled, steam injected cycle and a intercooled steam injected cycle to evaluate the efficiency, net output and economic and pollutant emissions. Intercooled steam injected gas turbine cycle incorporates an intercooler to the steam injected cycle to increase the efficiency of the gas turbine. Their study showed that incorporating steam injection cycle to a simple cycle and an intercooled cycle increases the net-work output by 22% for the simple cycle and 14% for the intercooled cycle. Further studies carried out revealed that specific fuel consumption of the gas turbine decreases with the addition of steam injection by 6.7% and 4.5% for the simple cycle and the intercooled cycle respectively. They also recorded a 67% NOx decrease in the simple cycle and a 65% decrease in the intercooled cycle. Likewise, Elwekel and Abdala's [25] research concluded that having a saturated steam coolant temperature of 433K combined with a pressure ratio of 10 resulted in an efficiency of 47.2%. Further study on reduction of inlet cooling to increase air mass flow was carried out by Mohaptra and Sanjay [27] which analyzed different types of inlet air cooling for gas turbines. The two methods compared were vapor compression and evaporative cooling applied to a gas turbine which incorporates air film cooling of turbine buckets. Based on the results obtained from their study, they concluded that the inlet cooling improved the work output and efficiency of the gas turbine cycle which showed a higher improvement in higher ambient temperature and lower humidity. Also their work showed that the efficiency of the gas turbine was improved by 4.18% and work output by 18.41% when vapor compression air cooling was applied compared to using evaporative cooling. Bassily [28] studied the effect of evaporative inlet cooling and after cooling of a recuperated gas turbine cycle. the study used four different configurations of a recuperated gas turbine cycle combined with evaporative inlet and after cooling. The following configurations of the recuperative gas turbine cycle was studied; recuperated cycle having both evaporative inlet cooling and after cooling (RDECEA), recuperated gas turbine cycle with evaporative after cooling (REA), recuperative gas turbine cycle with evaporative inlet air cooling (RDEC) and the final cycle was a standard recuperative gas turbine cycle (R). the study also included the effect of the turbine inlet temperature, ambient temperature and relative humidity on the compressor performance of the different configurations. The study concluded that the recuperated gas turbine with evaporative cooling (REA) had higher power values and obtained efficiencies close to optimum efficiency. Evaporative after cooling (water injected at the outlet of the compressor) could increase power by about 10% and efficiency of the cycle by up to 16% at the same pressure ratio.

Combining intercooling with other gas turbine modification methods have been shown to further improve the efficiency and power output of a gas turbine. Bassily [29] investigated the addition of absorption inlet cooling to a gas turbine with intercooling, reheat and recuperation. Also the study explored the combination of absorption inlet cooling and evaporative cooling also the effect of ambient temperature, relative humidity, the effectiveness of the recuperation heat exchanger and other variables on the absorption inlet cooling. The gas turbine design used for this study has an air cooler which is used to cool the air before it enters the low pressure compressor. Afterwards the air leaves the low pressure compressor and is further cooled in an air cooler in two stages in the air intercooler. After the air intercooler it enters the high pressure compressor where it is further compressed. At the exit of the high pressure compressor, the air is cooled with the after cooler using water injection which injects water warmed using a heat exchanger at the exit of the recuperated heat exchanger. The results from their study showed that the use of two stages of cooling boosted the efficiency gain; the addition of evaporative inlet cooling increased the efficiency by 1.55%. Applying the absorption inlet cooling could lead to an increase of 6.6% compared to an increase of 3.9% in the ace of evaporative cooling. Shukla and Singh [30] carried out performance evaluation on a steam injected gas turbine power plant with inlet evaporative cooling to check the effect of steam injection, inlet cooling and film cooling on a simple gas turbine cycle. Inlet air cooling is a cost effective means to improve the efficiency of a gas turbine especially when the ambient temperature is high during hot seasons. By cooling the inlet air, the density of air increases when entering the compressor. This increases the performance of the compressor. Steam injection increases the mass flow rate of the gas turbines. According to the study carried out by Bahrami et al [31] single shaft gas turbines are very sensitive to frequency drops because the sudden drop in load and frequency causes a reduction in mas flow of the air passing through the turbine. Steam injected gas turbine cycle performs better in sudden large drops of frequency due to the amount of available power and higher specific heat capacities of the working fluid. The study conducted by Shukla and Singh [30] showed that modified gas turbine cycle with inlet air cooling, steam injection and film cooling is a configuration that increases power and efficiency. Further studies carried out by Chakartegui et al [32] with respect to turbine inlet air cooling showed that a gas turbine loses about 7% of its power output with an increase of air temperature by 15$^{o}$C. Cooling the air inlet temperature is one way of increasing the performance of a gas turbine power plant. Another method is to increase the turbine inlet temperature above 800$^{o}$C. This can only be achieved by improving the cooling of the turbine buckets because an increased temperature will melt the hot gas components of the gas turbine. This metallurgical restriction must be overcome by cooling to achieve a higher turbine inlet temperature.

Data et al [33] studied the energy analysis of an externally fired gas turbine cycle. An externally fired gas turbine adds heat to the gas turbine cycle by combusting solid, liquid or gaseous fuel in a configuration that heats up the working fluid (air) in a heat exchanger. The externally fired gas turbine has two advantages which are; it can reuse heat from the exhauster in a recuperative process in the combustion chamber. Also it can use biogas and other sources of energy which are not usable in the conventional gas turbine design. The study applied an integrated biomass gasifier to analyze the effect of different operating parameters on the thermal efficiency and specific air flow. The thermal efficiency of the externally fired gas turbine was found to be between 16-34% for the ranges of operating parameters which were investigated. Haseli et al [34] modelled a gas turbine cycle combined with solid oxide fuel cell. The studied a gas turbine with recuperator combined with a high temperature solid oxide fuel cell (GT-SOFC) to ascertain the performance and irreversibility's within the system. In this configuration, compressed air is passed through the recuperator where it gains heat which increases the total efficiency. Then it exits the recuperator into the solid oxide fuel cell(SOFC) along with natural gas to produce direct current electricity. Heat is also produced in the SOFC during the process of electricity generation before it enters the combustion chamber. Previous works have shown that the efficiency of this system can achieve up to 60%. The result from their study showed that the GT-SOFC combination achieved a thermal efficiency as much as 27.8% more than the conventional gas turbine. Efficiency of the cycle studied was at 60.55%. Researchers have studied other gas turbine combinations in order to improve efficiency and reduce emission levels. SOFC is increasingly being studied as a hybrid with gas turbine to produce cleaner energy. [35] carried out a thermodynamic modelling of a solid oxide fuel cell hybrid with a gas turbine combined with an organic Rankine cycle as a bottoming cycle to improve the efficiency. They used different working fluids for the organic Rankine cycle (ORC) to carry out their study. Their results showed that adding the organic Rankine cycle to SOFC-GT increased the efficiency from around 63.17% to 75.81%.

Mehrpooya et al [36] combined ammonia-water single effect absorption cycle as a bottoming cycle to a solid oxide fuel cell gas turbine hybrid system. The efficiency of the system was found to be 62.4%. Carcasci and Winchler [37] studied the heat recovery of an aero derivative gas turbine which is used as heat source in a combined cycle configuration. The organic Rankine cycle was further analyzed using different organic fluids as its working fluids. Working fluids are a critical component of a thermodynamic system. They have thermodynamic properties which make them suitable for the system which they are applied. In the case of an organic Rankine cycle, the working fluid converts thermal energy into mechanical energy by changing phases, or heat of compression/expansion. Working fluids have different boiling points. For this study, toluene, benzene, cyclopentane and cyclohexane were tested. For the work, two power plant configurations were used; the waste heat was recovered from the exhaust gases while in the second configuration, waste heat was recovered from the intercooler. Their study showed that using benzene and cyclohexane, an efficiency of 54.4% can be reached for the combined plant while toluene and cyclopentane did not yield good results. for the configuration using the recovery heat from the intercooler, the efficiency increased by 2.2 percent. The recovery heat from a combined cycle power plant can be used to get more energy by adding another bottoming cycle. Balanescu and Homutescu [38] analyzed the performance of a gas turbine combined cycle which had attached an organic Rankine cycle to recover the waste heat. Combined cycle power plants are one of the most advanced and efficient systems operating in the world today. Although in a combined cycle, a steam cycle is already used as a bottoming cycle to recover waste heat from the gas turbine exhaust, the remaining heat being released into the atmosphere is still quite significant and can yield extra power. The main aim of the study is to improve the performance further by extracting more power from the waste heat. In the configuration studied, a heat recovery steam generator (HRSG) extracts heat for the steam Rankine cycle while downstream to the HRSG, a heat recovery boiler extracts heat for the organic Rankine cycle. two working fluids were tested in the organic Rankine cycle; R134a and R123 respectively. Their study concluded that the configuration effectively increased the overall efficiency by 1.10% when R134a was the working fluid of the organic Rankine cycle and 1.19% when R123 was used.

A maisotsenko cycle is a thermodynamic system designed to capture energy from the air by using the psychometric renewable energy from latent heat of water evaporation into the air [39]. A Maisotsenko gas turbine cycle can be described as an evaporative gas turbine cycle and it consists of an air saturator, humidification tower, after cooler, recuperator and economizer as one component. As with steam injected gas turbines, water addition into the maisotsenko cycle reduces the formation of NOx and increases the power generated. Saghafifar and Gadalla [40] have carried out extensive study on the maisotsenko cycle on the analysis of the Maisotsenko open gas turbine power cycle using an air saturator instead of a heat exchanger. They also performed an analysis of gas turbine combined with a Maisotsenko cycle as a bottoming cycle. The proposed configuration consisted of a topping gas turbine cycle and a bottoming Maisotsenko gas turbine cycle. The exhaust flue gas from the topping gas turbine cycle was used to generate humidity and heat up the air in the bottoming cycle. The proposed model including the use of an air saturator instead of a heat exchanger when analyzed performed at an efficiency improvement of 3.7%. Sayyaadi et al [41] did further studies on extraction of low grade thermal energy from a gas turbine plant equipped with a bottoming cycle. the study compared the different bottoming cycles after modelling and optimization while considering cost, efficiency and useful energy extracted. The cycles which were exploited for low grade thermal energy in the study were Organic Rankine cycle, super critical Rankine cycle, kalian cycle, Goswami cycle and trilateral flash cycle. A gas turbine cycle model with a first bottoming cycle (absorption chiller) was modified by directing the exhaust gas from the outlet of the absorption chillers generator to the different bottoming cycles in the study. The absorption chiller was used to cool the inlet air to the compressor of the gas turbine. The results from their study revealed that the Goswami cycle presented the highest values of mechanical and cooling power. It also achieved the highest thermal and exergetic efficiency at the lowest cost of production and investment.

Bhagava et al [42] explored the use of gas turbine bottoming cycles in cogenerative applications. The study compared the inverted Brayton cycle, Brayton bottoming cycle and the organic Rankine cycle in a cogenerative combined heat and power application. The results obtained from the study showed that the organic Rankine cycle produced a better result compared to the two other cycles analyzed in the study. The organic Rankine cycle produced a better efficiency and primary energy savings. Chacartegui et al [43] studied the application of low temperature organic Rankine cycle in a medium and large scale combined cycle power plant. Their study incorporated the ORC bottoming cycles into gas turbines with low exhaust temperatures like recuperated or very high pressure gas turbines having very high efficiency. Maheshwari and Singh [44] carried out the thermodynamic analysis of different gas turbine cycles. They compared combined cycle with a simple gas turbine and steam turbine with steam applied to cool the gas turbine blades, combined cycle gas turbine with ammonia water used to cool the gas turbine blades, combined cycle with both steam and ammonia water turbine while using the steam to cool the gas turbine blades, combined cycle with steam and ammonia water turbine with ammonia water cooling the blades, combined cycle with reheat steam and ammonia water turbine using steam for blade cooling, combined cycle with reheat steam turbine and ammonia water turbine using ammonia water for blade cooling and simple gas turbine cycle. Results from their study showed that the combined gas turbine cycle with reheat ammonia water turbine steam turbine with ammonia water cooling the blades gave a better maximum cycle efficiency and work power output. Chazikhani et al [45] modelled a gas turbine with air bottoming cycle combined with steam injection and carried out analysis on the model. Two air bottoming cycles were used for this study; the evaporative gas turbine with air bottoming cycle and the steam injection gas turbine with air bottoming cycle. They concluded from the result that in both cycles more energy recovery and a higher inlet mass flow rate resulted in an increased efficiency. The evaporative gas turbine with air bottoming cycle showed a higher work output when compared with the steam injection gas turbine with air bottoming cycle.

Gas turbines greatly contribute to the worlds electricity pool and using cleaner energy sources like biomass fuel is encouraged to ensure a cleaner environment. Athari et al [46] analyzed the incorporation of fogging inlet air cooling and steam injection to a biomass fired gas turbine power plant. The biomass integrated fog cooling steam injected gas turbine cycle is analyzed and compared with biomass integrated fogging combined cycle and corresponding cycle with no fog cooling system present to establish the benefits of fogging in the system. The results from their study showed that the energy and exergy efficiencies are high for low pressure ratios for the biomass with combined cycle with cooling and high pressure ratios for biomass integrated steam injection gas turbine with fog cooling. Also raising the gas turbine inlet temperature increases the efficiency of both plants. Kayadelen et al [47] carried out thermodynamic comparison between simple, reheat, steam injected and reheat steam injected gas turbine cycles. The aim of the study was to analyze the effects of reheat as well as steam injection on the performance of the gas turbine. A simple gas turbine with reheat but without regeneration decreases the overall thermal efficiency of the cycle because more fuel is combusted in the reheat process and the extra fuel is usually higher than the network output achieved. The study introduced steam injection to the simple cycle with reheat in order to minimize the effect of extra heat addition. Results from their study showed that steam injection in a steam injection gas turbine cycle produced a higher net-work output and thermal efficiency than in a reheat steam injection gas turbine cycle.

Barelli et al [48] proposed a modified gas turbine cycle with the aim of improving the flexibility of plant operation and improving efficiency in part load operation named supercharged natural gas combined cycle (SNGCC). The reference cycle used in this study is a combined cycle power plant which comprises of simple cycle components; compressor, combustion chamber and turbine combined with a heat recovery steam generator and steam turbine which is used to extract the waste heat from the exhaust of the simple cycle turbine and it is converted to extra work. There are issues relating to a gas turbine operation in part load. these issues are drop in inlet temperature, drop in turbine and compressor isentropic efficiency, which all negatively affect the efficiency of the combined cycle gas turbine during operation. The proposed the introduction of an extra compressor at the inlet of the main air compressor. The additional compressor introduces a variable inlet pressure to the main air compressor. This enables the air mass flow rate entering the main air compressor to be varied allowing the main air compressor receive design point air mass flow rate even at part load. The additional compressor which is placed upstream to the simple cycle gas turbine is not powered by the gas turbine shaft, as such its speed can be varied. The conventional design and the proposed design were simulated and the result showed that the conventional combined cycle gas turbine could achieved an efficiency of 48% only above 70%-part load while the proposed design achieved an efficiency of 49% at a part load of 47.8%. This shows that a SNGCC can be implemented to improve the efficiency of conventional combined cycle plants. Kalina cycle is a thermodynamic power cycle which uses ammonia-water as its working flue upgrade low temperature heat to higher efficiency power [49]. The simplified Kalina cycle adopted from the work carried out by El-sayed and Tribus [50], Wall et al [51] is a bottoming cycle which gets heat from the exhaust gas of a gas turbine. The low grade heat is used in the boiler to heat up ammonia water to superheated temperature before it is admitted into the turbine where work is extracted from it. the simple kalian cycle is made up of the distiller, separator, absorber, condensate pump, throttle, boiler feed pump, feed water heater, boiler and turbine which makes it different from the Rankine cycle which uses just the boiler, turbine, feed water pump, feed heaters and condensers. The Kalina cycle has a better energy and exergy efficiency than the Rankine cycle and organic Rankine cycle and it can be used in different fields [52].

Kalina cycle can be used to replace the Rankine cycle in a combined cycle gas turbine system as its bottoming cycle. the kalian cycle has a better thermodynamic performance than the Rankine and organic Rankine cycle using both the first and second laws of thermodynamics. Kalina cycle has the advantage of having different configurations which can be used in various applications most especially in geothermal power generation. In a gas turbine combined cycle configuration, kalian cycle has been used by Wang et al [53] in the recovery of waste heat from a compressor intercooler. The system modeled was also compared with an organic Rankine cycle used to recovery the waste heart intercooler. In their study, natural gas is compressed in two stages with an intercooler in between. Natural gas in first pumped into the first compressor where it is compressed then it passes through an intercooler where it is cooled before it is passed on to a second compressor. The heat released in the intercooler is then extracted by the working fluid of either the Kalina cycle or the vapor compressor. They concluded that the net power consumption shown in the optimization results was lower in the Kalina cycle when compared with the organic Rankine cycle. Ogriseck [54] analyzed a combined heat and power plant integrated with Kalina cycle to harvest the low grade heat from the exhaust. The steam from the system us used for the purpose of heating mostly and the waste heat is usually not enough for generate steam for a steam cycle. Integrating the Kalina cycle to the combined heat and power plant recovers the low grade heat and maximizes the generated electricity without addition of extra fuel. This increases the overall efficiency of the combined heat and power plant. Kalina cycle was compared with triple pressure steam cycle both used as a bottoming cycle in a gas turbine combined cycle power plant. The study carried out by Marston and Hyre [55] compared a triple pressure steam cycle with a single stage kalian cycle and an optimized three stage kalian cycle. the results from the study carried out showed that the both kalian cycles outperformed the triple pressure steam turbine cycle. The single staged kalian cycle generated more power than the triple pressure steam cycle. The optimized three stage kalian cycle produced an output of 9MWe from a plant of 240MWe. Kalina and Leibowitz [56] also carried out a similar study to compare the performance of a kalian cycle as a bottoming cycle and a triple pressure steam plant. The combined cycle used in this study contained 3 units of gas turbines and a kalian cycle as the bottoming cycle in a combined cycle arrangement. The kalian cycle has three turbines; the high pressure turbine, a reheating process before entry into the intermediate pressure turbine then a re-cooling process before entry into the low pressure turbine. The re-cooler heats up the vapor from the intermediate pressure turbine. Kalina cycle uses an ammonia and water as its working fluid which creates variable boiling processes. The advantage of this is that it narrows the gaps between the temperature of the steam generated and the hot gases from the exhaust of the gas turbine. The condenser in the kalian cycle uses a vapor absorption principle whereby the working fluid is separated then absorbed, condensed and recombined before it enters the boiler. Their results showed that a 16 – 32% increment in the bottoming cycle output compared to the triple pressure steam cycle. they also concluded that there are no technological barriers in the application of kalian cycle because the temperatures required are within the range found in power plants.

Josson and Yan [57] compared a gas turbine which uses Kalina cycle as its bottoming cycle and an evaporative gas turbine cycle. the Kalina cycle used ammonia water mixture as its working fluid due to the advantage it has over steam Rankine cycle. evaporative gas turbine cycle used a mixture of air and water as its working fluid whereby the heat from the exhaust gases in the gas turbine cycle is used to humidify compressed air with the aim of increasing the mass flow through the turbine to raise the power output. Their study showed that the evaporative gas turbine cycle gave a higher efficiency than the single pressure kalian cycle. However, the triple pressure kalian cycle produced a higher efficiency than the evaporative gas turbine cycle. Du et al [58] combined inlet air precooling with kalian cycle and ejector refrigeration study. They proposed an integrated system used the evaporator from the ejector refrigeration cycle to cool the inlet air in order to increase mass flow rate in through the gas turbine. The proposed Gas turbine, Kalina cycle system, ejector refrigeration cycle (GT-KCS-ERC) used the boiler outlet flue gas in the Kalina cycle and the Kalina cycle separator outlet low concentration ammonia and water liquid waste heat to drive the ejector refrigeration cycle. The results from their study showed that the optimal saturation evaporator temperature and the pressure ratio of vapor generator to condenser in the ejector refrigeration cycle is 0$^{o}$C and 4$^{o}$C. also under optimal conditions, the integrated system produced 219.4kW and 764.2kW more power and cooling than a standard gas turbine with Kalina cycle system (GT-KCS). The total energy efficiency of the GT-KCS-ERC integrated system improved by 5.347% compared to the stand alone GT-KCS integrated system. The cooling system generated in the GT-KCS-ERC system has an efficiency of 54.187%.

Jonsson and Yan [59] studied humidified gas turbines as a gas turbine working fluid. There are different air-water mixtures which have been proposed for use in gas turbines; direct water injected cycles and steam injected cycles, evaporative cycles with humidification towers. Although the commercial applications of these designs are limited. The study concluded that the humidified gas turbines have thermodynamic potentials, evaporative gas turbines which included humidification towers have the highest efficiency when compared to other types of air-water gas turbines, and humidified gas turbines have high specific output compared to conventional gas turbines. Currently only steam injected gas turbines are commercially available today although they have lower efficiencies compared to the evaporative gas turbines while water injected cycle is the least investigated from the three. Micro gas turbines a beginning to gain prominence in recent times. Micro gas turbines are small gas turbines having a power output ranging from 30kW to over 200kW [60]. They have very high shaft speeds and are usually equipped with a recuperator which will be used to preheat the compressed air in order to increase the efficiency of the system. Micro gas turbines have lower efficiency than its larger counterparts, however they have the advantages of compact sizes, multiple fuel capability, low weight per unit power and ease of emission control. Micro gas turbines achieve efficiencies of up to between 15 to 30%. Due to their small sizes, they can be used in off grid installations to provide both electricity and heat in a combined heat and power configuration. Paepe et al [61] studied the use of water to increase the output power of a micro gas turbine. There are various means by which water can be introduced into the micro gas turbine; by the injection of steam or preheated water, by use of a saturation turbine to introduce humidity into the gas turbine. The study conducted evaluated the use of more advanced techniques to introduce water into the system. The different water injection techniques in this study are; inlet air cooling with air inlet fogging, direct injection of preheated water, Regenerative evaporation (REVAP) cycle with a combination of liquid water injection and after cooling, injection of steam, micro humidity air turbine, micro humidity air turbine plus. Some features of these techniques are; The regenerative evaporation cycle uses an after cooler and an economizer, injection of steam technique injects the steam both in the compressor outlet or in the combustion chamber in addition to using a humidification tower, Micro humidity air turbine plus makes use of an after cooler. The results obtained from their study showed that the cycle with the most heat recovery from exhaust gases showed resulted in the highest electrical efficiency. Regenerative evaporation cycle had a stack temperature of 55.3°C which was the best stack temperature from all the techniques tested. Application of this technique resulted in an increase in efficiency from 32.8% to 37.5%. Nemati et al [62] carried out a comparative thermodynamic analysis of an organic Rankine cycle (ORC) and Kalina cycle for waste heat recovery of gas turbine cogeneration system (combined heat and power generation). They used the CGAM system CHP in carrying out this study. The CGAM is a cogeneration plant which produces 30MW power and 14kg/s of saturated steam which was named after the first initials of the researchers who proposed methods to solve the problem of optimization of the system [63]. Organic Rankine cycle is a well-known bottoming cycle which converts waste heat to mechanical power. The organic Rankine cycle has a simple configuration and has the advantage of simple, reliable and flexible design. However, Kalina cycle does the recovery of waste heat with a high performance. Some of the conclusions from this study are; by varying the air compressor ratio, the first and second law efficiency is optimized although the output power and turbine size parameter are minimized. Also increasing the superheat temperature has a negative effect on the performance of the CGAM/ORC. A 15°C increase on the superheat temperature will decrease the ORC output by about 60kW.

## 3. Gas Turbine Modification in Nigeria

Nigeria has abundant reserve of crude oil and natural gas and is a major exporter of these resources. Also, Nigeria depends on its natural resources for its supply of energy including for electricity generation. According to statistics from national population commission , the current population of Nigeria is approximately 215 million people [64]. Nigeria has a total installed capacity of 13,014.14MW, generation capacity of 7,652.6MW and a peak generation of 5801.6MW [65]. Hydro power plants and thermal power plants are the two main types of power plants are used for electricity generation in Nigeria. According to Wikipedia, 81 percent of power plants in Nigeria are thermal power plants while 17.59% makes up the percentage of electricity generation using hydro-electric sources [66]. The Table 2 shows a list of power plants in Nigeria indicating their cycles, status and capacity.

**Table 2** Power plants in Nigeria, their cycles and capacities [66]

| S/N | Power station | Type | Capacity | Status |
|---|---|---|---|---|
| 1 | AES Barge (IPP) | Simple cycle gas turbine | 270 MW | Non-operational |
| 2 | Aba Power Station (IPP) | Simple cycle gas turbine | 140 MW | Non-operational |
| 3 | Afam VI Power Station (IPP) | Combined cycle gas turbine | 624 MW | Partially operational |
| 4 | Alaoji Power Station (NIPP) | Combined cycle gas turbine | 1074 MW | Partially operational |
| 5 | Calabar Power Station (NIPP) | Simple cycle gas turbine | 561 MW | Non-operational |
| 6 | Egbema Power Station (NIPP) | Simple cycle gas turbine | 338 MW | Non-operational |
| 7 | Egbin Thermal Power Station (FGN but Privatized) | Gas-fired steam turbine | 1320 MW | Partially operational (1000 MW) |
| 8 | Geregu I Power Station-Privatized | Simple cycle gas turbine | 414 MW | Partially operational |
| 9 | Geregu II Power Station (NIPP) | Simple cycle gas turbine | 434 MW | Partially operational |
| 10 | Ibom Power Station (IPP) | Simple cycle gas turbine | 190 MW | Partially operational (90 MW) |
| 11 | Ihovbor Power Station (NIPP) | Simple cycle gas turbine | 450 MW | Partially operational |

| | | | | |
|---|---|---|---|---|
| 12 | Okpai Power Station (IPP) | Combined cycle gas turbine | 480 MW | Operational |
| 13 | Olorunsogo Power Station | Simple cycle gas turbine | 336 MW | Partially operational |
| 14 | Olorunsogo II Power Station (NIPP) | Combined cycle gas turbine | 675 MW | Partially operational |
| 15 | Omoku Power Station (IPP) | Simple cycle gas turbine | 150 MW | operational |
| 16 | Omoku II Power Station (NIPP) | Simple cycle gas turbine | 225 MW | Non-operational |
| 17 | Omotosho I Power Station (FGN-Privatized) | Simple cycle gas turbine | 336 MW | Partially operational |
| 18 | Omotosho II Power Station (NIPP) | Simple cycle gas turbine | 450 MW | Partially operational |
| 19 | Sapele Power Station-Privatized | Gas-fired steam turbine and Simple cycle gas turbine | 1020 MW | Partially operational (135 MW) |
| 20 | Sapele Power Station (NIPP) | Simple cycle gas turbine | 450 MW | Partially operational |
| 21 | Transcorp Ughelli Power Station (privatised) | Simple cycle gas turbine | 900 MW | Partially Operational (465 MW) |
| 22 | Ibom Power Plant (AKSG) | Simple cycle gas turbine | 191MW | Operational Since 2009 |
| 23 | Azura Power Station (IPP) | Simple cycle gas turbine | 461 MW | Fully operational |
| 24 | Trans Afam Power Limited | Simple cycle gas turbine | 966MW | Partially perational (340MW) [67] [68] |
| 25 | Trans Amadi Power Plant | Simple cycle gas turbine | 136MW | Partially Operational (100MW) [69] |
| Coal Fired Power Plants | | | | |
| 26 | Itobe Power Plant | Circulating Fluidized Bed technology | 1200 MW | Under construction |
| Hydroelectric stations | | | | |
| 27 | Kainji Power Station | Reservoir(Niger River) | 800 | Fully operational |
| 28 | Jebba Power Station | Reservoir (Niger River) | 540 | Fully operational |
| 29 | Shiroro Power Station | Reservoir (Kaduna River) | 600 | Fully operational |
| 30 | Zamfara Power Station | Reservoir (Bunsuru River) | 100 | Fully operational |
| Hydroelectric station (Still under construction) | | | | |
| 31 | Kano Power Station | Reservoir (Hadejia River) | 100 | Not yet completed |
| 32 | Zamfara Power Station | Reservoir (Bunsuru River) | 100 | Not yet completed |
| 33 | Dadin Kowa Power Station | Reservoir (Benue River) | 40 | Not yet completed |
| 34 | Mambilla Power Station | Reservoir (Donga River) | 3050 | Not yet completed |

Among the 25 thermal power plants in Nigeria, 24 of these stations operate gas turbine power plants and 4 are designed in combined cycle configuration while the rest are simple cycle gas turbines. Aggregating the data from table 2, Figure 3 shows a bar chart representing the plant technologies and their configurations with respect to the power generated by each technologies. Figure 4 breaks shows the different thermal power plant technologies currently installed in Nigeria.

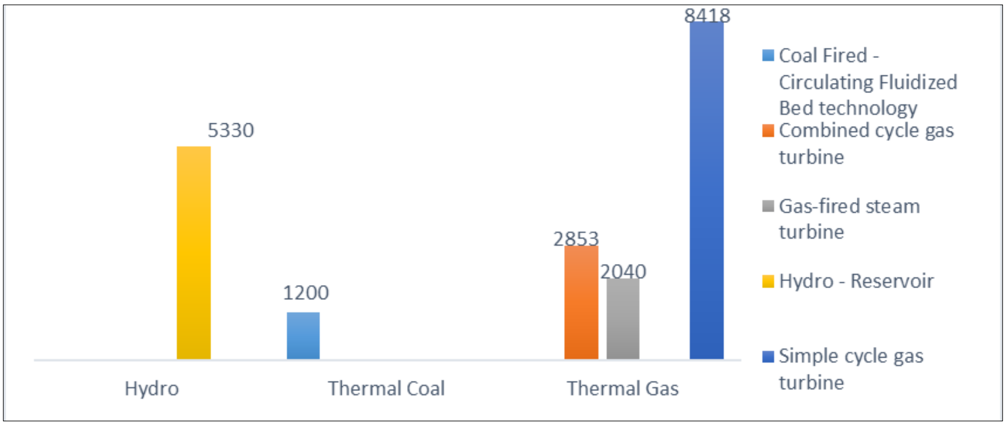

**Figure 3** Power plants grouped by MW into technologies and configurations (Installed Capacity)

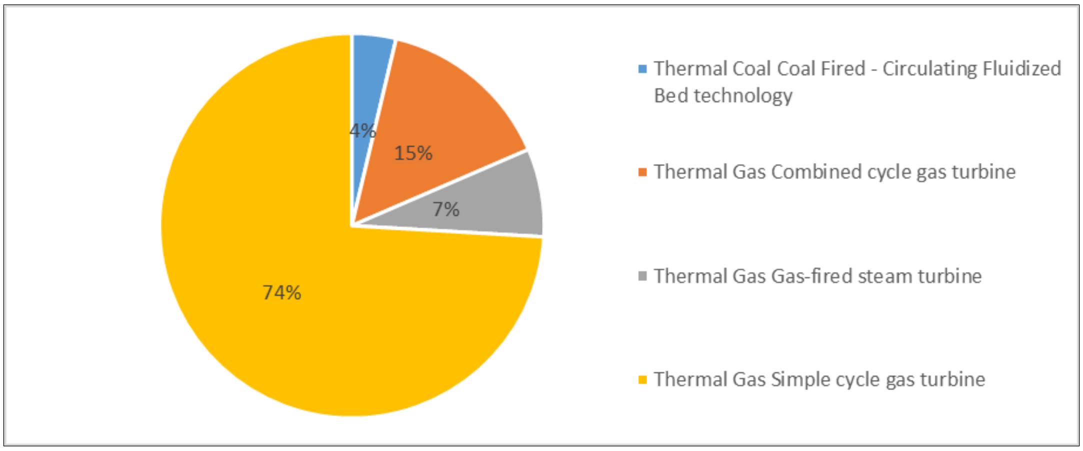

**Figure 4** Thermal Power plants grouped by technologies

13,311MW of all the power plants in Nigeria are thermal power plants and this represents 67% of total number. Figure 4 shows that a total of 89% of the thermal plants in Nigeria are gas turbines. 74% of thermal power generating plants operate using simple cycle configuration while 15% use combined cycle technology. From Figure 3, combined cycle combined cycle power plants are generating 2853MW while the simple cycle power plants generate a total of 8,418MW. The capacity of power plants using simple cycle configuration makes up 42% of all the power plants in Nigeria today. Since simple cycle power plants are operates at minimum efficiency, this means that some there is significant room for efficiency improvement in Nigeria.

Studies have been done by researchers to increase the generating capacities of power plants in Nigeria. Saturday and Ebieto [70] investigated a comparative economic analysis of a power plant located in the niger delta area of Nigeria. The gas turbine was modeled as a simple cycle and a modified cycle with intercooler, reheater and regenerator. The study was aimed at carrying out an economic analysis the simple cycle and then the modification of the simple cycle to ascertain the costs associated producing electricity with both cycles. The results showed that although the net present value for the simple cycle was far less than the modified cycle, the modified cycle produced lower cost of electricity than the simple cycle due to the higher efficiency of the modified cycle. Also the cost of electricity produced by the modified cycle decreases further as the effectiveness of the regenerator increases, although the net present value of the modified cycle increases with the increase in the regenerator effectiveness. Lebele-Alawa and Le-Ol [71] performed a study to improve an already existing 25MW gas turbine located in Omoku, Nigeria. The study was aimed at extracting the exhaust heat was carried out. A performance analysis was carried out on the gas turbine and a simple cycle gas turbine model was developed using the data extracted. A bottoming cycle (steam cycle) was then added to the simple cycle to extract the exhaust heat which will be used to generate more energy. Steam turbines requires a source of cooling for the steam at the condenser. Water is usually used as a cooling medium for the condenser. The water flows through the condenser to extract the latent heat of condensation in the steam which then causes it to condense to form liquid droplets. The water can be obtained from flowing rivers in an open cycle cooling system or a closed cycle cooling system where a cooling tower releases the heat extracted from the working fluid into the atmosphere. For the design of the combined cycle plant, cooling water was derived from a flowing river for cooling the steam at the condenser. The study resulted in an increase in overall efficiency of the plant from 26.60% to 48.81% and an increase in power output from the machine by 51%.

According to Saturday and Efekemo [11], a simple cycle gas turbine can be improved by modification of the gas turbine cycle. Modification of a simple cycle 26.9MW gas turbine plant located in Trans Amadi, Nigeria was carried out with the aim of carrying out exergo-economic analysis. Performance analysis was carried out on the gas turbine and the operating parameters were obtained to develop a model of its gas turbine cycle. The simple cycle developed was then modified to improve its efficiency by including an intercooler, a reheater and a regenerator. The result showed that the plant efficiency improved from 30.4% to 48% with an increase in overall power output to 44.67MW. It also showed that the cost of generating electricity for the simple cycle gas turbine was higher compared to the cost of generating electricity in the modified cycle gas turbine. The difference in cost arising due to the reduced equipment cost in the modified cycle owing to lower pressure ratios of the compressors in the modified cycle.

## 4. Conclusion

Electricity is a very important commodity in the present world. Many developing countries are faced with the problem of meeting electricity demand of their population and this is affected by many factors. Some of these factors include GDP, population, available technology etc. Among the methods of generating electricity, gas turbines generators have gained widespread usage because of the advantages it has over the other methods. As world leaders grapple increasing effect of global warming and sustainability concerns, there is a need to use more sustainable energy resources to reduces greenhouse gases and conserve the energy resources available. While research is being done on newer and more sustainable means of generating electricity, it is important to improve the current technologies relied on for generating electricity. Gas turbines technology can be improved by increasing their efficiencies by applying different method. Modification of gas turbine cycles and optimizing performance of already installed systems is one of the ways this can be achieved

Nigeria depends mostly on gas turbines to generate electricity. Nigeria has a population of about 213 million people and an installed capacity of 13,014.14MW with generation capacity of 7,652.6MW. By benchmarking Nigeria's population with other countries, it is evident that there is a huge deficit in meeting the electricity demand of its population. Nigeria's electric power consumption (kWh per capita) was 144.53kWh/capita in 2014 [72]. This ranks very low amongst other countries in the world. Iceland has the highest electric consumption in the worlds with an electric consumption per capita of 53,832.48 kWh/capita in the same time period. While Egypt with a population of about 102million people [73] has an electric consumption of 1683.21kWh/capita in the same time period. Comparing the electricity consumption and population between Egypt and Nigerian, Egypt consumes1,064.61% more electricity per capita than the electric consumed in Nigeria and the Nigeria has a 108.8% higher population difference than Egypt. It is clearly evident that there is a huge deficit in electricity generation in Nigeria. Nigeria can bridge the generation deficit and also meet its sustainability goals by modification of its installed power plants. This has the has both thermodynamic and economic advantages. Also Nigeria relies on mostly thermal gas power plants (i.e 89% of thermal plants are gas turbines). Improving on the efficiency of the installed power plants would significantly increase the electricity generation output thereby meeting the electricity demand of the country.

## Compliance with ethical standards

### *Disclosure of conflict of interest*

No conflict of interest to be disclosed.

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