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# TECHNO-ECONOMIC ANALYSIS OF PAPALANTO GAS TURBINE POWER STATION, OGUN STATE, NIGERIA

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## ABSTRACT

*The persistent inadequacy of electricity supply in Nigeria has created the need to improve the operational efficiency and economic sustainability of gas turbine power plants. This study investigates the techno-economic performance of the Papalanto Gas Turbine Power Station (PGTPS), Ogun State, Nigeria, with emphasis on the effects of ambient temperature and compressor pressure ratio on turbine performance and electricity generation cost. Operational data collected between 2018 and 2020 were analyzed using the Brayton cycle thermodynamic model and regression analysis, while the economic feasibility was evaluated using the Levelized Cost of Electricity (LCOE) approach. The results showed that increasing ambient temperature from 296 K to 306 K reduced thermal efficiency from 0.1354 to 0.0938 and power output from 22.69 MW to 19.05 MW. Conversely, increasing the compressor pressure ratio from 7 to 13 improved thermal efficiency from 0.04 to 0.40 and increased power output from 22.5 MW to 42 MW. The estimated LCOE values were $0.0424/kWh, $0.0431/kWh, and $0.0436/kWh for 2018, 2019, and 2020 respectively, with variations mainly influenced by fuel cost and turbine performance. The study recommends the adoption of inlet air cooling systems, optimized compressor pressure ratios, and effective fuel management strategies to improve efficiency, reduce generation costs, and enhance sustainable electricity supply.*

**Keywords**: Gas turbine, Techno-economic analysis, Brayton cycle, Power generation, Ambient temperature, Levelized Cost of Electricity

## 1 INTRODUCTION

Reliable and efficient electricity supply is essential for socio-economic development, industrialization, and improved quality of life. Unfortunately, in many developing nations such as Nigeria, the electricity sector has remained unstable despite abundant energy resources. Nigeria possesses vast hydro resources and natural gas reserves, yet power generation remains insufficient, erratic, and unable to meet the rising demand [1]. Seasonal variations significantly affect hydropower generation, particularly during dry seasons when water levels decline, thereby limiting generation capacity. Consequently, the nation has increasingly turned to thermal power generation, with gas turbines emerging as a vital alternative. Gas turbines (GTs) are gaining prominence worldwide as a reliable technology for electricity production due to their relatively fast start-up time, controllability, and ability to respond to fluctuations in electricity demand [2]. They have found widespread applications in power generation, particularly in the oil and gas sector, where operational flexibility and efficiency are critical. Research and development in gas turbine technology have improved performance, extended operational life, and enhanced economic viability, making them a competitive option for thermal power generation [3]. However, gas turbines are not without limitations. Their performance is highly sensitive to ambient conditions such as air temperature, humidity, and compressor pressure ratio, all of which directly affect efficiency, power output, and fuel consumption. Additionally, rising fuel costs and environmental considerations associated with gas turbine operations demand careful techno-economic analysis to ensure sustainability. The Nigerian electricity sector exemplifies the urgency of such evaluations. Industrial and residential consumers in urban centers are often compelled to rely on backup generators due to unreliable grid supply, which increases operational costs and hinders productivity. Thermal power plants, particularly gas turbine systems, therefore play a crucial role in bridging the energy deficit. The Papalanto Gas Turbine Power Station (PGTPS), located in Ogun State and commissioned in 2006 with an installed capacity of 335 MW, is one of the key thermal plants feeding into the national grid. Its operational performance, however, is strongly influenced by varying environmental conditions and fuel-related constraints, highlighting the importance of a rigorous assessment of its efficiency and economic viability. Techno-economic analysis provides a structured framework for evaluating the technical performance and economic feasibility of energy systems. It integrates cost–benefit assessments with performance modeling, enabling a holistic evaluation of efficiency, fuel consumption, levelized cost of electricity (LCOE), and environmental impacts [4]. Such an approach is especially relevant for Nigeria, where fuel availability, fluctuating operating conditions, and sustainability concerns must be balanced against the growing electricity demand. This study, therefore, focuses on conducting a techno-economic analysis of PGTPS to assess its performance under varying environmental conditions. By analyzing power output, efficiency, fuel cost, and environmental risks, the research seeks to provide insights into the optimal operating conditions of gas turbines in Nigeria. The findings are expected to contribute to policy formulation, operational improvements, and sustainable energy planning for the country's thermal power sector.

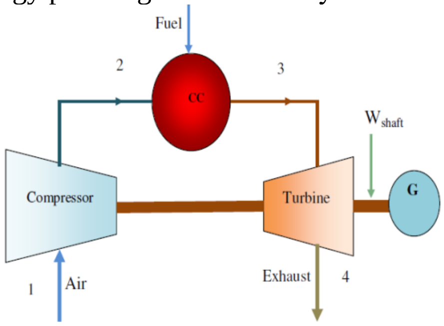

Figure 1. The schematic diagram for a simple gas turbine [5]

## 2 MATERIALS AND METHODS

### 2.1 Data Collection

Operational data from the PG6581B gas turbine units at PGTPS were collected between 2018 and 2020. Data included ambient temperature, compressor pressure ratio, turbine inlet temperature, and power output. Daily averages were computed to minimize random fluctuations.

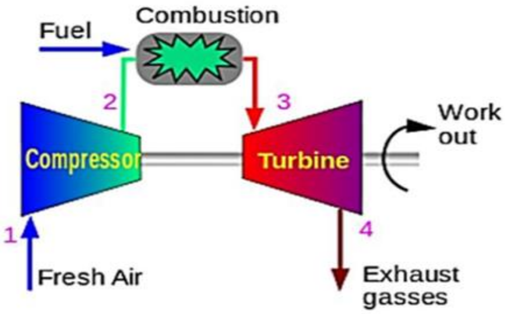

Figure 2. Representation of a simple cycle gas turbine [6]

### *2.1.1 Papalanto Gas Turbine Power Station*

The plant consists of eight independent gas turbine units, each rated at 42 MW, giving a total installed capacity of 335MW.The station operates with the PG6581B gas turbine manufactured by Nanjing Turbine Works. The turbine is a heavy-duty, single-shaft, simple-cycle gas turbine designed for outdoor operation. Natural gas used for combustion is supplied by the Nigerian Gas Company. The plant also includes a water treatment facility that produces demineralized water for cooling and other auxiliary operations. Key design parameters of the PG6581B gas turbine installed at the station are presented in Table 1.

Table 1. Parameters of Papalanto Gas Turbine Power Station

| Description | Values |
|---|---|
| Gas Turbine Model | PG6581B |
| Average Atmospheric Pressure | 0.1013 MPa |
| Max. Ambient Temperature | 35.6°C |
| Power Factor | 0.8 |
| Overall Pressure Ratio | 12.2 |
| Exhaust Temperature | 548°C |
| Exhaust Pressure Drop | 500 Pa |
| Compressor Stages | 17 |
| Turbine Stages | 3 |
| Power Output | 42 MW |
| Turbine Speed | 5163 rpm |
| Gross Thermal Efficiency | 31.17% |

## 2.2 Thermodynamic Modeling

The Brayton cycle model was applied to determine compressor efficiency, turbine efficiency, network output, heat input, and overall thermal efficiency [6] Equations based on the first and second laws of thermodynamics were used to evaluate turbine performance. The T-S diagram for Brayton cycle is demonstrated in Figure 1, Figure 2 and Figure 3. The pressure loss in the $P_3 - P_3'$ and pressure loss in the exhaust is represented by $P_4' - P_4$.

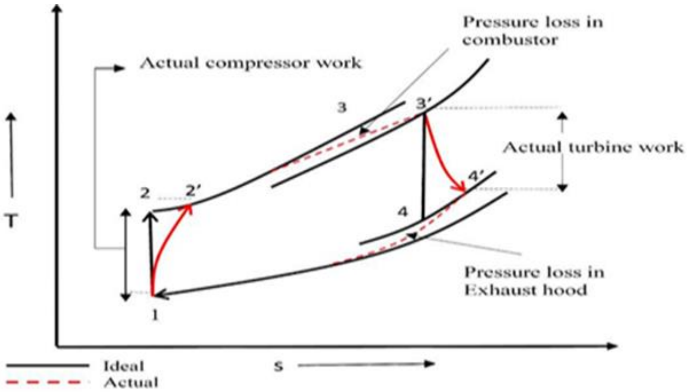

Figure 3. Actual gas turbine cycle presentation on T-S diagram [7]

In this cycle: $1 - 2$ is isentropic compression, $3 - 4$ is isentropic expansion, $1 - 2'$ is actual compression, $3' - 4'$ is actual expansion [8]. The first law of thermodynamics states that energy can neither be created nor destroyed but can only be converted from one form to another.

$$\frac{dE_{ev}}{dt} = \dot{Q} - W_{shaft} + \sum_{in} \dot{m} \left(h + \frac{v^2}{2} + gt\right)_{in} - \sum_{out} \dot{m} \left(h + \frac{v^2}{2} + gt\right)_{out} \tag{1}$$

The left-hand side of the equation represents the change in energy within the control volume over time. For the steady flow processes of the Brayton cycle and the gas turbine, the system inside the control volume is the same from one point in time to another and so the change in energy is zero. The heat transfers in and out of the system is characterized by $\dot{Q}$, and the shaft work transfer is $W_{shaft}$. The third and fourth terms on the righthand side of the equation represent the energy that is converted out of the control volume by the mass flowing across the control surface. The enthalpy of the flow is represented by h, the velocity term represents the kinetic energy of the flow, and the final term, $gt$, represents the gravitational potential energy [8]. For the purposes of this analysis, the kinetic and gravitational energy are not significant factors and can be neglected. The first law becomes:

$$0 = \dot{Q} - \dot{m}(h_{in} - h_{out}) \tag{2}$$

The first process of the Brayton cycle is an adiabatic compression from $P_1$ to $P_2$. Because the compression is adiabatic, there is no heat transfer and the work required to run the compressor can be given as shown in equation (3):

$$\dot{W}_{1-2} = \dot{m}(h_1 - h_2) == W_{1-2} = C_p(T_2 - T_1) \tag{3}$$

The second process is an addition of heat at constant pressure. There is no shaft work transfer so the heat addition is in equation (4):

$$\dot{Q}_{2-3} = \dot{m}(h_3 - h_2) == W_{2-3} = C_p(T_3 - T_2) \tag{4}$$

Then the gas is expanded through an adiabatic isentropic turbine. As in the first process, there is no heat transfer. The work transfer is obtained from equation (3) yielding equation (5):

$$\dot{W}_{3-4} = \dot{m}(h_3 - h_4) == W_{3-4} = C_p(T_3 - T_4) \tag{5}$$

Finally, heat is rejected using a heat exchanger to return the gas to its inlet state. There is no shaft work transfer so the heat transfer is shown in equation (6).

$$\dot{Q}_{4-1} = \dot{m}(h_1 - h_4) == W_{2-3} = C_p(T_3 - T_2) \tag{6}$$

Mathematically;

$$Q_{net} = P_{net} \tag{7}$$

$$Q_{in} - Q_{out} = P_{out} - P_{in} \tag{8}$$

Dividing all through by $Q_{in}$, equation (9) becomes;

$$1 - \frac{Q_{out}}{Q_{in}} = \frac{P_{net}}{Q_{in}} \tag{9}$$

The thermal efficiency of the ideal Brayton Cycle,

$$n_{th} = \frac{P_{net}}{Q_{in}} = 1 - \frac{Q_{out}}{Q_{in}} == 1 - \frac{m_{cpg}(T_4 - T_1)}{m_{cpg}(T_3 - T_2)} == 1 - \frac{T_4 - T_1}{T_3 - T_2} \tag{10}$$

Where; $Q_{net}$= net heat energy from fuel, $Q_{in}$ and $Q_{out}$ represent heat supplied and heat exhaust respectively, $P_{net}$= Net Power generated, $P_{out}$and $P_{in}$ = power output and input respectively. Assuming $m_{cpg} = m_{cpa}$, $C_{pg}$ and $C_{pa}$ represent: Specific heat capacity of gas and air respectively. Therefore; thermal efficiency is equal to$1 - \frac{T_4 - T_1}{T_3 - T_2}$. The energy balance for steady flow process can be expressed on a unit mass basis, For combustion process (2 – 3) in Figure 3.

$$T_3 = \frac{C_v + \eta_{comb} + C_{pg} + A/F \times T_2}{(C_v A/F) + C_{pg}} \tag{11}$$

## 2.3 Regression Analysis

Regression models were developed to predict power, work ratio, heat input, and thermal efficiency as functions of ambient temperature and pressure ratio. From regression analysis, the power, work ratio, heat input and thermal efficiency are governed by the following equations:

$$\text{Power} == P = -0.363736\ T_1 + 3.17859057 P_r + 108.1051374 \tag{12}$$

Work ratio == $W_r$ = -0.000953824 $T_1$ + 0.003468215 $P_r$ + 0.647433 (13)

Heat Input == $H_i$= -0.127491 $T_1$ -1.017316802 $P_r$ + 820.07153 (14)

Thermal Efficiency ==$\eta_{th}$ = -0.006935$T_1$ + 0.045 $P_r$ +1.87315916 (15)

## 2.4 Economic Analysis

Fuel consumption and cost data, were analyzed to estimate the LCOE; considering fuel as the main operational cost [9]. Exchange rate fluctuations were included to determine local currency values.

## 3 RESULTS AND DISCUSSION

Considering the operational data 2018 to 2020 as obtained from Papalanto power station; regression analysis was used to predict Generator Power at different ambient temperature inlet to compressor and compressor pressure ratio. Table 1 shows the different values of Power at different ambient Temperature and Compression ratio.

Table 2. The variation of power with ambient temperature

**$P_r$** =

| $P_r$=7 | | $P_r$=10 | | $P_r$=13 | |
|---|---|---|---|---|---|
| Power (MWh) | $T_1$ (K) | Power (MWh) | $T_1$ (K) | Power (MWh) | $T_1$ (K) |
| 22.6894 | 296 | 32.2252 | 296 | 41.7610 | 296 |
| 22.3257 | 297 | 31.8615 | 297 | 41.3972 | 297 |
| 21.9619 | 298 | 31.4977 | 298 | 41.0335 | 298 |
| 21.5982 | 299 | 31.1340 | 299 | 40.6698 | 299 |
| 21.2345 | 300 | 30.7702 | 300 | 40.3060 | 300 |
| 20.8707 | 301 | 30.4065 | 301 | 39.9423 | 301 |
| 20.5070 | 302 | 30.0428 | 302 | 39.5785 | 302 |
| 20.1433 | 303 | 29.6790 | 303 | 39.2148 | 303 |
| 19.7795 | 304 | 29.3153 | 304 | 38.8511 | 304 |
| 19.4158 | 305 | 28.9516 | 305 | 38.4873 | 305 |
| 19.0521 | 306 | 28.5878 | 306 | 38.1236 | 306 |

*Pressure Ratio, $T_1$= Ambient Temperature*

## 3.1 Effect of Ambient Temperature

Performance decreases with rising ambient temperatures. At a pressure ratio of 7, power output dropped by 16% when ambient temperature increased from 296 K to 306 K. Thermal efficiency decreased by 50% over the same range just like in the work of [6].

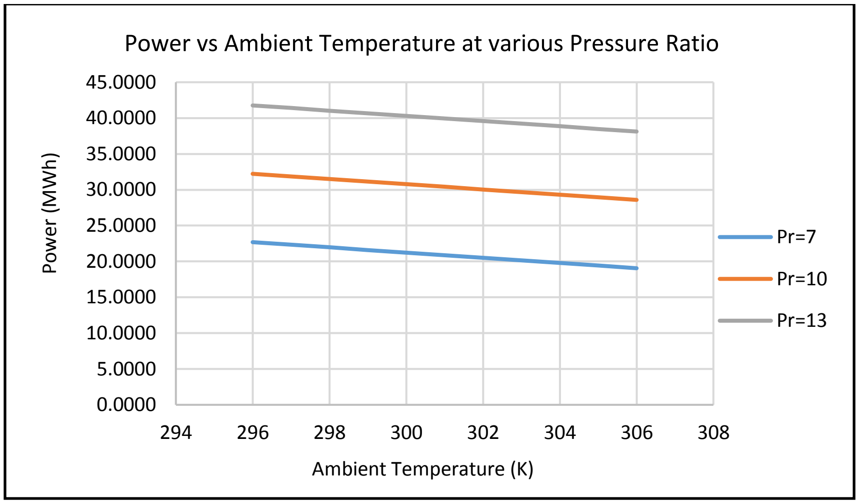

Figure 4. Power against ambient temperature at various pressure ratio.

### 3.2 Thermal Efficiency and Ambient Temperature

Since the gas turbine is an air-breathing engine, its performance is changed by anything that affects the density and/or mass flow of the air intake to the compressor [6]. The chart in Figure 5 presents a relation between the gas turbine ambient temperatures and Thermal efficiency for different turbine Pressure ratio. It shows that the Gas Turbine Power Output is affected by Ambient Temperature due to the change of Air Density and Compressor Work. The thermal efficiency is equal to the ratio of Net work and heat input.

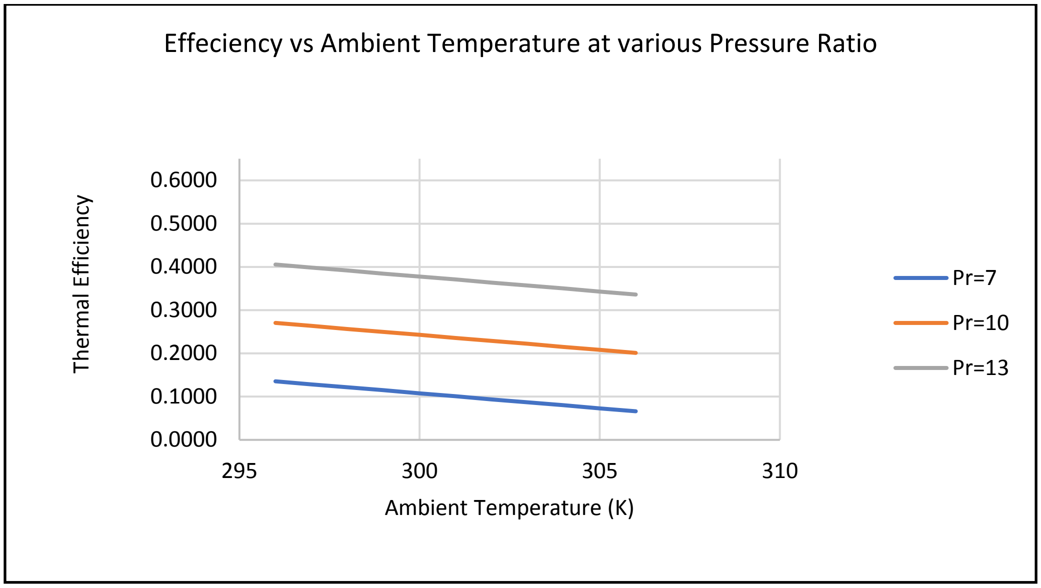

Figure 5. Variation of thermal efficiency with ambient temperature at various pressure ratio.

### 3.3 Effect of Pressure Ratio

Increasing the pressure ratio improved turbine efficiency and power output [10]. At a ratio of 13, efficiency increased four times and power nearly doubled compared to a ratio of 7.

### 3.3 Economic Findings

The calculation of Levelized Cost of Electricity (LCOE), is done based on the cost of fuel used in generation of electricity only in contrast with the work of [11]. Using \$0.009/ SCF (Price of natural gas per Standard Cubic Feet), The LCOE was estimated at \$0.0424/kWh (₦14.83) in 2018, \$0.0431/kWh (₦16.38) in 2019, and \$0.0436/kWh (₦17.45) in 2020. Fuel price and exchange rates were the dominant factors influencing generation costs.

### 3.4 Comparison with Design Efficiency

The company design thermal efficiency of the PG6581B unit was 31.17% from Table1, while operational efficiency averaged 27.18% in 2018, 26.98% in 2019, and 26.83% in 2020 as calculated. The decline is attributed to environmental conditions and turbine degradation [7].

## 4 CONCLUSIONS

This study demonstrates that ambient temperature and pressure ratio significantly influence gas turbine performance and economic viability. Higher ambient temperatures reduce efficiency and power output, whereas higher pressure ratios enhance both. The LCOE findings highlight the importance of fuel cost management and stable exchange rates in reducing electricity generation costs. Optimizing turbine operation under Nigerian environmental conditions and ensuring favorable natural gas pricing could improve efficiency and affordability of electricity supply.

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