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Energy analysis of 3 x 2.5 MW centaur 40 terminal gas turbine generators

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ABSTRACT

The temperature of the surrounding air affects a gas turbine's (GT) performance and sustainability. Besides, to prolong the active life of a GT and thus its sustainability, the energy analysis of the operating parameters of the GT should be well understood. A power augmentation technique for GTs, turbine inlet air cooling lowers the temperature of the turbine's incoming air, increasing the machine's power output, heat rate (HR), and sustainability. For two years (2021 and 2022), the energy analysis of the three 2.5 MW GT generators was carried out utilizing mean values calculated monthly and a daily average data operational variable. The total efficiency, thermal efficiency, thermal power, HR, specific fuel consumption, and work ratio (WR) were all statistically evaluated using thermodynamic equations. The average overall efficiency, average thermal efficiency, average HR, average thermal power, average specific consumption, and average WR of a three-unit 2.5 MW GT generator were 15.99%, 16.68%, 22,620 kW, 5,185 kW, 0.4714 kg/kW-h, and 0.4598, respectively, based on the GT results. The WR decreases as the compressor inlet temperature increases, demonstrating that GT generators are vulnerable to significant irreversibility at high compressor inlet temperatures.

Keywords: energy analysis, turbine efficiency, gas turbine, compressor, inlet temperature

INTRODUCTION

Production facilities can use gas turbines (GTs) for a variety of industrial purposes. These consist of cogeneration systems, compressed air production, process heating, and power generation. GTs provide several benefits, such as quick startup times, great energy efficiency, reduced carbon emissions, and inexpensive maintenance. Additionally, they lessen their influence on the environment while maintaining energy supply by employing clean fuels like natural gas. As power generation shifts to sustainable fuels and renewable energy sources, contemporary GTs can also play a significant role in maximizing the efficiency of natural gas as a transition fuel. This will reduce fuel consumption and greenhouse gas emissions. At the same time, CO_2 capture and other flue gas purification technologies can be used to drastically reduce any remaining emissions. Furthermore, even though GTs have been used to generate electricity for many decades worldwide, different climates might cause variations in their performance efficiency. In particular, because ambient temperature has a detrimental effect on the air compression process, GT operation is frequently adversely affected by dry seasons. Compressor intake air cooling has been shown to be a successful solution to the problem of power instability in such severe weather circumstances and in nations with high ambient air temperatures (Ameri et al., 2005). One of the numerous commercially available techniques to increase existing GT's efficiency and, consequently, its sustainability for future uses is to monitored its performance under the usage ambient temperature (Egware & Obanor, 2013; Farzaneh-Gord & Deymi-Dashtebayaz, 2011).

Due to their high power-to-mass ratios and fuel selection flexibility, GT power plants are a mainstay of the electrical generation industry (Elwardany et al., 2023a, 2023b, 2024a, 2024b; Khaleel et al., 2022). However, environmental temperatures have a major effect on their effectiveness (Elwardany et al., 2024a). Thermodynamic constraints cause efficiency to decline in hotter regions, such as the Niger Delta in Nigeria (Ibrahim et al., 2019). Energy analysis is used in this work to address this issue. Examining how different ambient temperatures affect the plant's performance is the main goal of this research. Our goal is to measure the effect on variables like average specific consumption, average work ratio (WR), average heat rate (HR), average thermal power, average overall efficiency, and average thermal efficiency. We can find ways to enhance the plant's performance, especially in hot weather, by comprehending these relationships. To further understand the factors affecting a GT power plant's efficiency, an energy analysis of the GT and its constituent parts is required (Ibrahim et al., 2010; Madu, 2018g, 2018i; Ukwamba et al., 2018). When operating outside of the design performance restrictions, Nigeria's GT performance sharply declines, as it does in all sub-Saharan African countries. This is due to the fact that GTs are designed to endure harsh weather conditions and topography (Sigler & Erickson, 2001; Orhorhoro & Orhorhoro, 2016; Orhorhoro et al., 2017). During the design stage, the thermodynamic properties that influence GT's performance are tuned. The main objective is to supply the energy industry with more reliable, highly efficient machinery. However, when providing GTs to clients, manufacturers only include the interface data; they do not include information regarding thermodynamic properties or any intermediate thermodynamic qualities. The design and operation of GT are only briefly comprehended by this (Madu, 2018f; Hosseini et al., 2007; Ibrahim et al., 2010, 2015). In their catalogs, turbine manufacturers frequently include five key features that are sufficient for installation requirements. These consist of GT electrical output, exhaust temperature, exhaust mass flow rate, pressure ratio, and overall efficiency (Bhargava et al., 2001; Chaker & Meher-Homji, 2011; Egware, 2013; El Hadik , 1993; Jaber et al., 2007; Madu, 2018f). Even though the information supplied is adequate from an operational standpoint, without knowing more operation data, such as specific fuel consumption (SFC), ambient inlet temperature, HR, thermal efficiency, WR, etc., it is impossible to perform a comprehensive thermodynamic analysis of the specific GT in order to fully comprehend it for possible situation-based modifications (Orhorhoro et al., 2017). Moreover, energy analysis evolved throughout the 20^{th} century and is currently recognized as a trustworthy technique for evaluating thermal systems, such as GTs (Abam et al., 2011). To optimize the thermal efficiency of the system, energy analysis is employed (Madu, 2018b, 2018e, 2018j; Rahman et al., 2010).

Furthermore, under certain operating conditions, GTs outperform piston engines in terms of cycle efficiency (Madu, 2018c, 2018d; Mahmood & Mahdi, 2009; Srinivas, 2008). When rapid startup and shutdown are required, GTs have historically been used by the power generation sector. In order to counteract peak demands during the day, this is very important. However, steam cycles, used for coal and oil fire or nuclear power, are base-load machines since they start and stop much more slowly due to their massive heat capacity (Dawaud, 2005). Because they can be quickly started and stopped, GTs are ideal for this application and can be used to address sudden increases in energy demand (Bhargava et al., 2001; Cjaker & Meher-Homji, 2011; Shi et al., 2010). However, many countries, like Nigeria, use huge traditional generators (GTs) as base load units since natural gas is less expensive than distillate fuel. To compensate for any disruptions in the energy supply that may arise during emergencies or periods of peak demand, smaller ones are used (Ahmed et al., 2020; Babaei Jamnani & Kardgar, 2020; Madu, 2018a, 2018h; Salah et al., 2022). These traditional generators (GTs) require inlet temperature cooling and this is mainly to enhance the efficiency and thus the sustainability of the turbine. In recent years, the pursuit of enhancing thermal power generation efficiency and sustainability garnered significant attention, reflecting the pivotal role of thermal power plants in meeting global energy demands. presented a comprehensive synthesis of energy and exergy studies across various plant types, including coal, gas, biomass, oil, and combined cycle plants. Their review underscored the importance of achieving a balance between performance, cost-effectiveness, and environmental responsibility, highlighting critical aspects such as optimizing operations, economic evaluations, and assessing environmental impacts. Key findings emphasized the primary sources of exergy destruction, with boilers accounting for over 50% of losses, while turbines and condensers also significantly contributed to energy losses. Their studies also identified optimization strategies crucial for improving efficiency, such as combustion air preheating and excess air ratios. Higher-pressure designs, particularly ultra-supercritical units, exhibited substantial reductions in exergy destruction. The review highlighting the importance of energy–exergy analysis in promoting sustainability and competitiveness in thermal power plants.

The performance degradation of GT power plants operating in high-temperature environments is the issue this study attempts to solve. The efficiency of these plants is adversely affected by hot temperatures, such as those found in Nigeria's Niger Delta, because of thermodynamic constraints. A thorough operational data set was used to assess the GT, considering both energy quantity and quality, in order to pinpoint regions of wasted potential within the GT cycle, even though this study suggests employing energy analysis. This study's uniqueness is its concentrated energy analysis of a GT power station operating in the Nigerian Niger Delta with high ambient temperatures. Additionally, increasing GT availability and dependability is essential to preventing unforeseen malfunctions and lowering operating expenses. Manufacturers and operators have taken notice of GTs' performance-based health monitoring, which collects real-time health-related data about the system and aids in creating a condition-based maintenance plan. Determining whether there is damage is the first step in describing the system's health condition, but it is crucial to comprehend the GT while it is operating by assessing its performance using energy analysis. Furthermore, the environmental circumstances of GT are essential for conducting energy analysis, and this work offers a dependable method for the real-time health monitoring of GT through GT's operational characteristics in the context of the usage area. More so, the study will evaluate the efficiency of the GT and thus determine the overall efficiency of the GT generators. Also, the condition of the compressor inlet air temperature, and the performance parameters for the GT plant will be evaluated.

MATERIALS AND METHODS

Description of the Gas Turbine

The twelve-stage, axial flow type compressor assembly for the three 2.5 MW centaur 40 GT generator engines includes an air inlet assembly, compressor variable vane assemblies, compressor case assembly, diffuser assembly, compressor bearing support housing, and compressor rotor assembly. An annular aperture on the air inlet assembly is shielded by a thick mesh screen. The air inlet housing supports the compressor rotor shaft front bearing and the accessory drive housing. The variable vane assemblies consist of the inlet guide vane assembly, the variable control actuator, and the first three stator assemblies. The gas producer turbine assembly consists of the combustor assembly, the gas producer bearing support housing, and the two-stage gas producer turbine rotor that drives the compressor. The compressor housing is attached to the forward flange of the turbine exhaust diffuser and the aft flange of the gas production bearing support housing. Twelve fuel injectors run through the combustor dome and end in the combustor chamber, mounted on bosses around the combustor housing. The turbine nozzles are housed in a nozzle casing that extends forward from the flange of the combustion housing. The gas producer's rotor bearings are supported by a bearing support assembly. To cool the turbine nozzles, more air is pumped into the engine. There are two primary sources of cooling air for turbines. The first source of cooling air is leakage between the compressor diffuser and the AFT compressor hub, and the second source is the compressor diffuser itself. The cooling air route from the diffuser is shared by the duct assembly (inner liner) and the convector (outer liner). After passing through the nozzle support housing screen, the air-cooling supply from the area around the convector (outer liner) is directed to the first-stage turbine nozzle via an annular duct. After passing through the outer impingement plate, which is positioned on each nozzle segment, cooling air entering the hollow first-stage nozzles escapes through a number of metering holes in the trailing edges of each first-stage nozzle vane. The schematic and TS diagram of the GT is shown in **Figure 1** and **Figure 2**, respectively.

Data Collection

The daily average operational variables and monthly mean values for the two-year period (2021 and 2022) are displayed in **Table 1**.

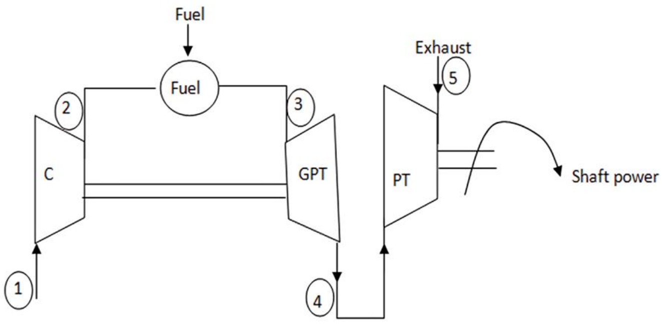

Figure 1. Schematic diagram of the GT generators (Source: Authors' own elaboration)

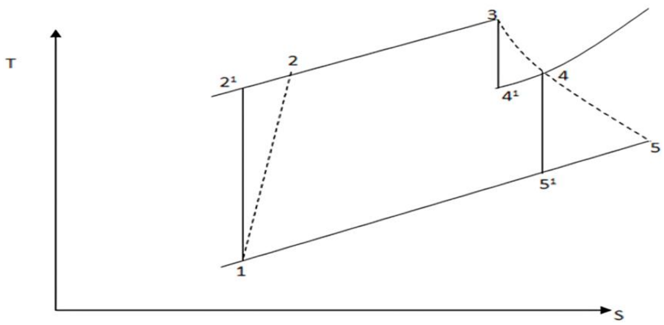

Figure 2. The TS diagram of the GT generators (Source: Authors' own elaboration)

Energy Analysis

Eq. (1)-Eq. (16) provide the energy analysis equation utilized in this study. Eq. (1) provides the work performed by the compressor, as follows:

$$W_c = m_a Cp_a (T_2 - T_1), \tag{1}$$

Table 1. Operating data for 2021 and 2022

Item	January	February	March	April	May	June	July	August	September	October	November	December
Year 2021												
T_{01} (°C)	53.93	53.80	52.70	54.95	53.05	54.82	53.90	53.70	55.82	54.81	53.00	54.70
T_{02} (°C)	73.72	73.83	72.95	73.65	74.82	74.70	74.95	74.95	74.80	75.13	74.93	75.70
T_{w1} (°C)	28.70	28.82	27.75	27.70	27.82	28.73	27.90	28.80	27.80	27.70	27.75	28.80
T_{w2} (°C)	34.80	35.80	35.71	35.25	34.80	35.73	34.70	34.80	35.35	35.24	35.80	34.70
T_1 (°C)	22.85	21.80	24.70	25.75	28.90	30.80	30.73	32.83	33.70	33.73	31.15	32.25
T_2 (°C)	359.85	361.15	360.70	354.80	362.47	355.80	366.70	354.82	357.95	369.48	358.05	373.25
T_3 (°C)	1,086.7	1,070.4	1,096.9	1,047.8	1,045.3	1,037.0	1,031.2	1,056.2	1,065.9	1,059.2	1,066.1	1,075.9
T_4 (°C)	546.95	538.10	555.90	540.25	537.82	525.65	525.80	558.00	565.80	555.90	526.85	540.91
P_1 (Bar)	102.90	101.89	101.70	101.81	101.81	101.70	102.25	102.70	101.80	102.90	102.13	102.90
P_2 (Bar)	964.70	956.10	955.25	955.34	955.34	954.55	963.40	964.70	955.35	965.45	958.37	964.70
Year 2022												
T_{01} (°C)	54.43	54.30	53.20	55.35	53.55	55.32	54.40	54.20	56.32	55.31	53.50	55.20
T_{02} (°C)	74.22	74.33	73.95	74.15	75.32	75.20	75.45	74.35	76.30	75.73	75.43	75.60
T_{w1} (°C)	28.90	29.32	28.35	28.10	28.12	29.73	28.40	29.30	28.40	28.30	28.85	29.40
T_{w2} (°C)	34.50	36.40	36.31	35.85	35.30	36.23	31.50	35.30	35.95	35.84	35.60	34520
T_1 (°C)	22.35	22.20	25.20	26.35	29.30	31.50	31.83	33.53	33.70	37.33	31.75	32.85
T_2 (°C)	360.35	361.65	361.30	355.50	362.97	356.40	367.30	355.32	358.35	369.98	359.25	374.35
T_3 (°C)	1,087.7	1,070.9	1,097.4	1,048.3	1,045.8	1,037.7	1,031.8	1,056.7	1,066.30	1,059.7	1,066.7	1,076.30
T_4 (°C)	547.25	539.70	556.30	541.65	538.32	526.25	526.30	558.50	566.30	556.40	527.35	541.01
P_1 (Bar)	103.50	102.49	102.20	102.31	102.31	102.20	102.55	102.90	101.30	103.20	102.73	103.20
P_2 (Bar)	965.30	956.60	955.75	955.74	955.84	955.05	963.90	965.40	955.85	965.95	958.87	965.20

where W_C is the work done by compressor, m_a is the mass flow rate of air through compressor, and Cp_a is the specific heat capacity of air.

Eq. (2) provides the work performed by the turbine:

$$W_T = m_{exh}Cp_{ezh}(T_3 - T_4), \tag{2}$$

where W_T is the work done by turbine, m_{exh} is the mass flow rate of exhaust, T_3 is the turbine temperature, and T_4 is the exhaust temperature.

Therefore,

$$P_{TH} = W_T - W_C, \tag{3}$$

where P_{TH} is the thermal power.

The heat generated by the friction losses at the bearings is extracted by the lubricating oil and released in the oil coolers.

Mass flow rate of lube oil, m_o is the lube oil volume flow rate × density of water. Heat removed from the bearing at the oil cooler, Q_o:

$$Q_o = m_o Cp_o(T_{o2} - T_{o1}). \tag{4}$$

Air extracts the heat produced by the generator losses:

$$M_w = \frac{Cooling\ water\ volume\ flow\ rate}{Specific\ volume}. \tag{5}$$

Generator losses:

$$Q_w = m_a Cp_w(T_{w2} - T_{w1}). \tag{6}$$

The flue gas losses is given by Eq. (7):

$$Q_{exh} = m_{exh}Cp_{exh}(T_4 - T_1). \tag{7}$$

The power consumed by auxiliaries is given by Eq. (8):

$$P_{max} = Total\ power\ consumed\ by\ auxiliary\ devices. \tag{8}$$

The electrical power generated is given by Eq. (9):

$$P_E = P_{TH} - P_{ML} - P_{GL} - P_{AUX}. \tag{9}$$

Mechanical efficiency ($л_m$) is given by Eq. (10):

$$л_m = \frac{P_{TH}-P_{ML}}{P_{TH}}. \tag{10}$$

The generator efficiency ($л_g$) is given by Eq. (11):

$$л_g = \frac{P_{TH}-P_{ML}-P_{GL}}{P_{TH}-P_{ML}}. \tag{11}$$

The thermal efficiency ($л_{TH}$) is given by Eq. (12):

$$л_{TH} = \frac{P_{TH}}{m_f \times LHV}. \tag{12}$$

The overall efficiency ($л_o$) is given by Eq. (13):

$$л_o = \frac{P_E}{m_f \times LHV}. \tag{13}$$

The SFC is given by Eq. (14):

Table 2. Results of performance evaluation of GTs

S/N	Parameter	3 × 2.5 MW GT generator
1	Average overall efficiency	15.99%
2	Average thermal efficiency	16.68%
3	Average HR	22,620 kW
4	Average thermal power	5,185 kW
5	Average specific fuel consumption	0.4714 kg/Kw-h
6	Average WR	0.4598

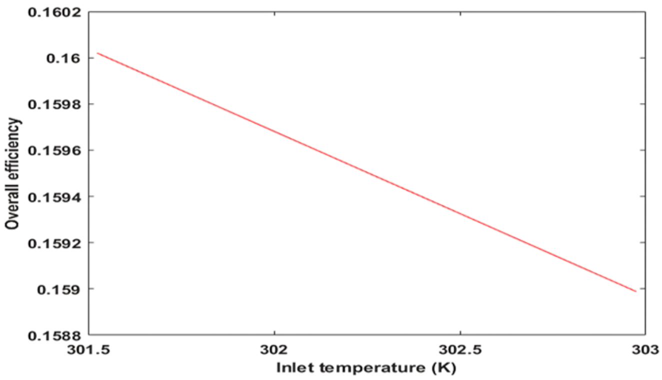

Figure 3. Outcome of compressor inlet temperature on the overall efficiency of 3 × 2.5 MW GT generator (Source: Authors' own elaboration)

$$SFC = \frac{m_f \times 3{,}600}{P_E}. \tag{14}$$

The HR and the WR is given by Eq. (15) and Eq. (16):

$$HR = SFC \times LHV. \tag{15}$$

$$WR = \frac{P_{TH}}{W_T}. \tag{16}$$

RESULTS AND DISCUSSION

Table 2 displays the findings for SFC, HR, net power, thermal efficiency, average compressor effort, and turbine work.

The average specific consumption, average WR, average HR, average thermal power, average overall efficiency, average thermal efficiency, and average specific consumption for a three-unit 2.5 MW GT generator were 15.99%, 16.68%, 22,620 kW, 5,185 kW, 0.4714 kg/Kw-h, and 0.4598, respectively. A 3 × 2.5 MW GT generator's overall efficiency is impacted by the compressor input temperature, as seen in **Figure 3**. It was found that the overall power efficiency drops as the compressor inlet temperature rises. This was in line with research by Orhorhoro and Orhorhoro (2016), Rahman et al. (2010), and Ukwamba et al. (2018), which found that raising the compressor inlet temperature reduced GT efficiency overall.

Figure 4 shows a 3 × 2.5 MW GT generator's compressor inlet temperature and thermal efficiency graph. The findings demonstrate that when the compressor inlet temperature rises, the thermal efficiency of both GT generators falls. The GT cycle's reduced net power output led to a drop in thermal

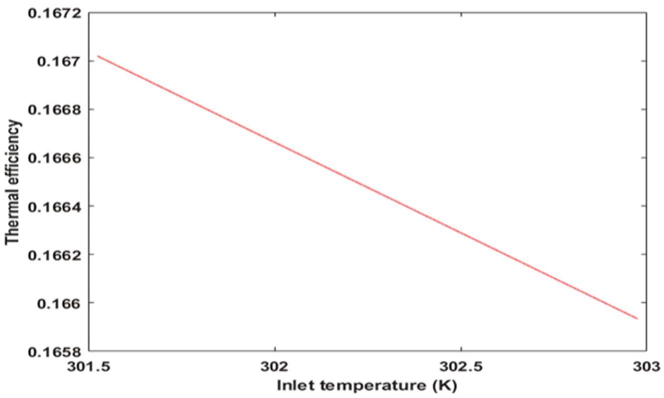

Figure 4. Outcome of compressor inlet temperature on the thermal efficiency of 3 × 2.5 MW GT generator (Source: Authors' own elaboration)

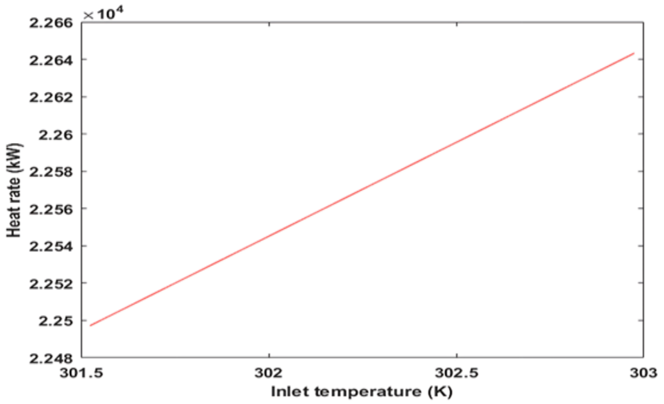

Figure 5. Outcome of compressor inlet temperature on the HR of 3 × 2.5 MW GT generator (Source: Authors' own elaboration)

efficiency, which in turn raised compressor power and lowered the mass flow rate of gases. These findings were consistent with those of Mahmood and Mahdi (2009), who found that a GT plant's thermal efficiency will fall when its thermal power output decreases due to an increase in the input temperature.

The compressor inlet temperature and HR for three 2.5 MW and three 4.2 MW GT generators are plotted in **Figure 5**.

It is evident from the performance analysis that the HR rises in tandem with the compressor inlet temperature. The cause of the decrease in thermal and overall efficiency is further supported by higher HR. A 3 × 2.5 MW GT generator's compressor inlet temperature and HR graph is displayed in **Figure 6**.

The quantity of thermal power generated was found to decrease as the compressor inlet temperature increased. In both of the GT generators employed in this study, the lowest compressor inlet temperature generated the maximum thermal power, while the highest compressor inlet temperature provided the lowest thermal power. A three-unit 2.5-megawatt GT generator's compressor inlet temperature and SFC graph are displayed in **Figure 7**.

It was shown that the SFC of both GT generators is significantly influenced by the compressor inlet temperature. SFC rises in proportion to an increase in compressor inlet temperature. A larger intake of ambient air temperature resulted in an increase in compressor power, which generated

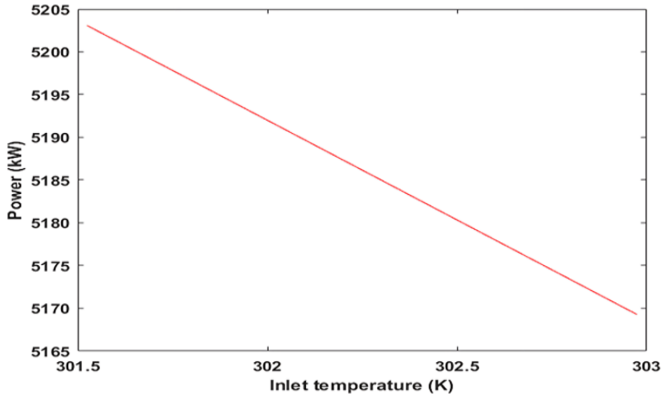

Figure 6. Outcome of compressor inlet temperature on the thermal power of 3 × 2.5 MW GT generator (Source: Authors' own elaboration)

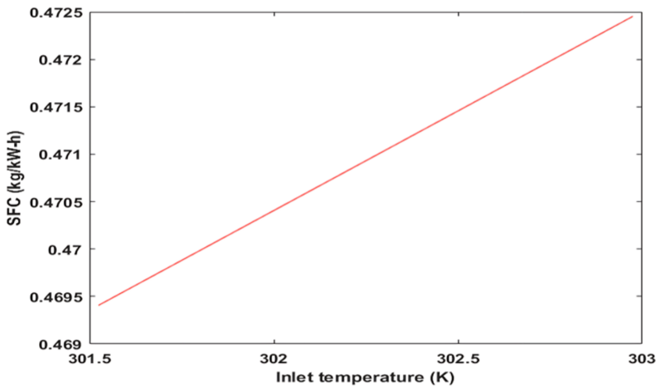

Figure 7. Effect of compressor inlet temperature on SFC of 3 × 2.5 MW GT generator (Source: Authors' own elaboration)

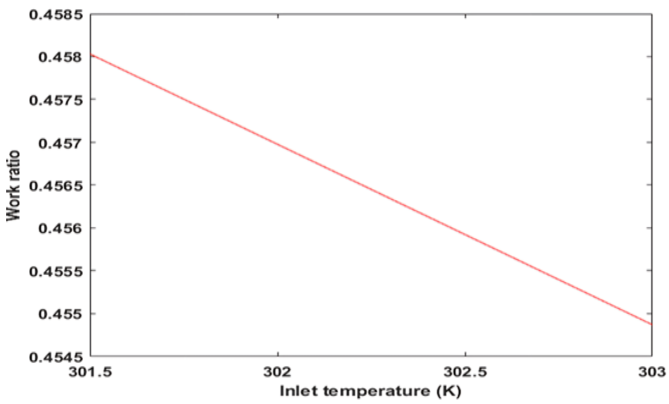

Figure 8. Effect of compressor inlet temperature on WR of 3 × 2.5 MW GT generator (Source: Authors' own elaboration)

a comparable rise. The decline in thermal efficiency, thermal power, and overall efficiency that occurred after the compressor inlet temperature increased was further reinforced by the rise in SFC.

Figure 8 illustrates how the WR drops as the compressor inlet temperature increases. The GT generator's efficiency is decreased by this decrease in WR. The GT generator's efficiency is decreased by this decrease in WR. This is because, in contrast to a low WR, a high WR lowers the probability of

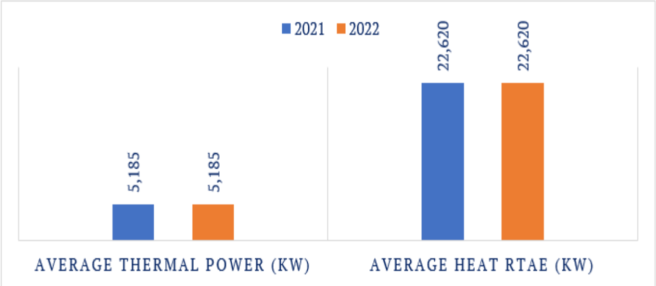

Figure 9. Analysis of average thermal power and HR for GT generators (Source: Authors' own elaboration)

irreversibility. This is consistent with research from Egware and Obanor (2013).

The thermal power and WR of three 2.5 MW GT generators during a two-year period is shown in a bar chart in **Figure 9**. Both thermal power and HR did not significantly vary, according to the chart.

CONCLUSION

In the field of industrial production, GTs are crucial to sustainability and energy efficiency. GTs remain a vital instrument for cutting energy expenses, minimizing environmental effects, and guaranteeing a sustainable future due to their constantly evolving technology and industrial uses. Since natural gas is more readily available and less expensive than distillate fuels, GT generators are typically employed in Nigeria to produce energy. Energy analysis is typically performed to identify potential performance-affecting factors and the sources of losses in GT generators during the conversion process. Overall efficiency, average thermal efficiency, average HR, average thermal power, average specific consumption, and average WR for the three 2.5 MW Centaur 40 GT generators were 15.95%, 16.64%, 22,574 kW, 5,185 kW, 0.4710 kg/kW-h, and 0.4598, respectively, according to the current study.

Author contributions: UN: results, data, and conceptual framework, writing – original draft; **KEM:** conceptualization, materials, procedures, supervision, project administration, formal analysis, validation, investigation, writing – review & editing. Both authors have agreed with the results and conclusions.

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Ethical statement: The authors stated that the study did not require permission from an ethical committee since it is based on existing literature.

Declaration of interest: No conflict of interest is declared by the authors.

Data sharing statement: Data supporting the findings and conclusions are available upon request from the corresponding author.

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