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Research Article

Evaluation of Key Performance Factors and Recommendation of Optimization Strategies of a Power Generation Company

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Abstract: This paper presents the analysis of key performance indicators and some effective improvement strategies of four gas turbine generators (GTG) of Nigeria's power plant company for four years (2019-2022). The investigation used the NERC/IEEE Standard 762 (2006) generator performance indices amongst other calculated key performance indices to evaluate the collected data. The research methodology was done through the collection of data using questionnaires, operational records, and plant data sheets recorded by operators in the power station and data analysis using Excel software, and then constructive optimization techniques were recommended for each key performance factor. From the result obtained, the operational performance shows an average energy generation of approximately 389.71 GWh. The equipment availability factor averaged 54.08%, indicating moderate reliability. The energy availability factor was notably lower, averaging 11.99%, suggesting significant room for improvement. The capacity factor averaged 9.39%, while the plant use factor was relatively high at 80.59%, demonstrating efficient operational usage. The load factor was low, with an average of 0.10, pointing to potential underutilization of capacity. The shortfall in performance levels is attributed to less plant availability due to overdue overhauling of some units resulting in frequent breakdowns/failures, obsolete technology, aging plant equipment, instability of the national grid system, and disruption in gas supply among others. The recommended strategic techniques are designed to address the specific challenges associated with each factor, thereby enhancing the overall operational performance of the power plant and other power generation companies for maximum productivity.

Keywords: GTG, availability factors, reliability indices, capability factors, optimization

1. Introduction

The major objective of power utilities in the current competitive environment is to provide customers with reliable and quality electrical energy that is economically friendly [1]. Reliability in power supply is the ability of the power system to adequately supply electrical energy [2]. To increase the electric power system reliability, more investment is

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required to boost the system, which raises the cost of electric power supply [3]. A typical power utility must meet two main requirements, including the provision of acceptable, reliable electric power and the provision of affordable electric power [4]. Maintaining an acceptable level of reliability at an affordable cost is a very important aspect of modern power system management [5].

The efficiency and reliability of a power plant, as well as other operational factors, have socio-economic implications on the company operating the power plant and the nation at large [6]. Where there is inadequate and unreliable electricity supply, socioeconomic transformation remains unrealistic [7]. Globally, the availability of reliable electric power has been seen as an effective and vital tool for achieving fast industrial and economic growth for any nation [8]. Therefore, the electrical energy supply should be available 24 hours a day to guarantee industrial and national economic growth [9]. Electric power providers globally must ensure customer demands are met at an acceptable level of service reliability [10].

The reliability of a generation system focuses on how reliable and efficient the generators are [11]. The power system is from the conversion process of primary energy (fuel) to electricity before transmission [12]. The generation system forms an integral part of an electricity supply chain [13]. Hence, it is vital that adequate electricity is generated to meet demands at every point in time [14]. Unfortunately, occasional failures in the operation of generating units require the system operator to ensure the availability of adequate reserve capacity [15]. Accurate estimation of reliability for generating units is required to adequately plan for generating capacity and aid in improving criteria for future designs and operations. Enhancing the efficiency and availability of existing units is as vital as improving the efficiency and overall reliability of the units during the planning phase, as the two are mutually supportive of each other [16].

According to the International Renewable Energy Agency [17] on the continental electricity supply as presented in Table 1, there are significant disparities in the availability of 24-hour power supply between Africa and other continents. According to Ritchie et al. [18], in Africa, less than half of the population has reliable access to electricity, particularly in Sub-Saharan Africa, where about 48% of the population has access. In contrast, regions like Latin America, the Caribbean, Eastern Asia, and Southeastern Asia have achieved over 98% electricity access.

Table 1. Global comparison of 24-hour power supply accessibility [19]

S/N	Continent	Percentage with 24-hour power supply
1	Africa	~48%
2	Asia	> 98%
3	Europe	~100%
4	North America	~100%
5	South America	> 98%
6	Australia/Oceania	~100%

The epileptic power supply in Africa is a critical issue that hampers economic and industrial growth. With less than half of the population having reliable access to electricity, many businesses and households face frequent disruptions. Improving power supply reliability is essential to support industrial activities, which can drive economic growth and development. Enhanced investment in renewable energy sources and grid infrastructure is necessary to address these deficits. Additionally, international support and financing can help accelerate progress towards achieving universal access to reliable and affordable electricity in Africa [20].

Some exceptional research works have been done to optimize the efficiency of electric power supply for industrial and home use, thereby investigating the root cause of inefficient electric energy supply to manufacturing or service rendering industries by estimating the required amount of electric energy to smoothly run the system. Al-Taha and Osman [21] evaluated the performance of a thermal station by determining performance parameters for a generative unit using a heat balance model for its main parts. A comparison was made between empirical results from the station and theoretical results calculated using the first law of thermodynamics. The study considered various working loads (40%, 70%, 100%) to identify optimal working conditions and examined the impact of operational and environmental factors on unit performance. The results demonstrated how different load levels and conditions affect the efficiency and performance of the thermal station.

Adegboyega and Odeyemi [22] conducted a performance analysis of the Egbin Power Plant, revealing several key findings from 2000 to 2010. The plant comprises six steam turbine units with a total installed capacity of 1,320 MW, commissioned between May 1985 and November 1987. During this period, the plant's average overall efficiency was 34.67%, which is below the industry standard of 40-45%. Similarly, its average reliability stood at 80.92%, falling short of best practices ranging from 98-100%. These performance shortcomings can be attributed to several factors: low plant availability due to frequent breakdowns and failures, overdue overhauls of some units, outdated technology, instability in the national grid system, aging equipment at the plant, and disruptions in gas supply, among other issues. To address these challenges and improve performance indices (efficiency and reliability), measures have been suggested.

Sudarsono et al. [23] investigated the performance of solar photovoltaic (PV) systems with different configurations to address the depletion of conventional fuels and the increase in global warming. The study compares three PV configurations: a standalone 150-Wp panel (Model I), a combination of 100-Wp and 50-Wp panels (Model II), and three 50-Wp panels (Model III). The results indicate that Model I generates an average power of 121.57 W, achieving an efficiency of 83.05% relative to its capacity. This highlights the significant potential of solar energy as a renewable alternative, with the standalone configuration showing promising efficiency.

Prasad and Ahmed [24] evaluated the performance and power output enhancement of a divergent solar chimney power plant by increasing the chimney height The research concluded that a 4-m tall solar chimney power plant (SCPP) had the highest exit temperature of 50.8 °C, while the 8 m tall SCPP had the lowest at 43.6 °C due to higher air velocity and shorter air residence time. The temperature drop along the chimney was greatest for the 8-m SCPP, indicating less energy loss from the chimney outlet. Air velocity at the turbine section increased with chimney height, with the 8-m SCPP achieving a maximum air velocity of 8.29 m/s, showing a logarithmic increase. The turbine's free rpm ranged from 650 to 850 at 800 W/m^2 solar insolation. Power output increased significantly with chimney height, with the 8-m SCPP's output rising from 0.79 W to 2.78 W at 1,000 W/m^2 solar insolation, suggesting further enhancement potential with increased chimney height, potentially reaching 40 kW at 800 W/m^2.

Although a lot of research has been conducted in the application of management strategic techniques to estimate and manage the electric power required by power plant industries and different manufacturing and service rendering industries, which contributes to the optimization and efficiency of the company in terms of management, maintenance and supply chain [25], no research has yet been carried out on four (4) gas turbine generators of a power plant company located in Benin City, Edo State, southern part of Nigeria. Therefore, the investigation was conducted using NERC/IEEE Standard 762 (2006) generator performance indices to investigate the mean time before failure (MTBF), mean time to repair (MTTR) equipment, energy, and capacity factors of the system, and to prefer a solution for the shortcomings of these factors to improve the productivity of the company.

This research is segmented into three categories, the first being the introductory background, the second segment presenting the materials and method used in the data collection, mathematical model equation application, and data analysis, and the third segment presenting the discussed results of the instigation and presentation of some strategic recommendations for the optimization of a typical power plant company.

2. Materials and method

2.1 *Materials*

The materials used to carry out the investigation are presented in Table 2.

Table 2. Materials and their descriptions used in the study

S/N	Item	Description
1	Questionnaire forms	Physical paper-based forms and electronic forms used to collect responses from participants.
2	Pens and pencils	Writing instruments used for completing paper-based questionnaires.
3	Electronic devices	Phones and other devices used for conducting electronic surveys.
4	Interview guide or protocol	A physical document containing a structured list of questions or topics for guiding the interviews.
5	Recording devices	Audio recorders and video cameras used to capture interviews for later analysis.
6	Note-taking materials	Notebooks or electronic devices used by interviewers to take notes during the interviews.
7	Recruitment documents	Documents used to recruit participants for the study.
8	Informed consent forms	Oral consent forms used to obtain participants' consent to partake in the study.
9	Data analysis software	Tools such as Excel for data visualization and quantitative analysis.
10	Company journals, magazines, and bulletins	Internal publications and data storage systems used for reference and information gathering.
11	Internet research	Online research conducted to gather information and data relevant to the study.
12	Maintenance log sheets	Documents detailing maintenance records used for data collection and analysis.

2.2 *Method*

The function of a research design is to ensure that the evidence obtained enables the researcher to effectively address the research problem logically and as unambiguously as possible. Figure 1 illustrates the process flow chart of the research methodology.

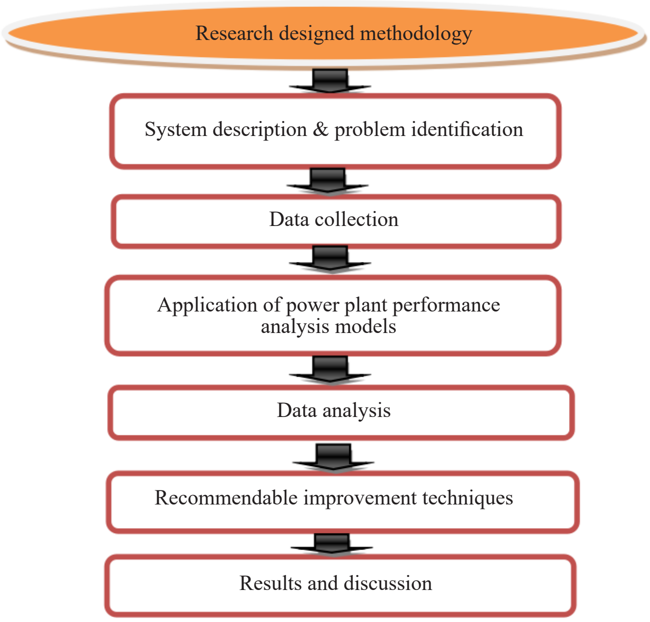


Figure 1. The methodology steps

2.2.1 *System description & problem identification*

The power plant company in this case study is located in Benin City, Edo State, Nigeria, built in 2004, aiming to address power generation insufficiencies and gas flaring in the Niger Delta. The construction started in 2005 and was completed between 2013 and 2014, with each turbine undergoing various stages of commissioning and reliability runs. The power plant is a 450 MW (ISO 504 MW) open-cycle gas turbine facility, featuring four gas turbines (GTG-1, GTG-2, GTG-3, and GTG-4) each with a capacity of 112.5 MW (ISO 126 MW). Gas is supplied via the Lagos pipeline system, and power is evacuated through the power plant transmission lines. The plant's operational factors and significance are evaluated over four years (2019-2022) with recommendations for performance improvement.

2.2.2 *Data collection*

This section involves the application of a structural questionnaire and the assessment of the company's maintenance, operators, and other required logs or record books to gather insights into the experiences from plant components regarding the power generation performance, such as installed capacity, gas turbine (GT) synchronization and shut down/trip time, energy generated, maximum energy demand, gas consumed, planned and forced outage hours, and grid disturbance outage hours. Empirical data obtained from plant records from 2019 to 2022 were used to analyze the power plant performance.

2.2.3 *Model application*

In this investigation, the operational performance of the power plant was thoroughly analyzed using various models to assess key performance indices. The analysis was guided by the NERC/IEEE Standard 762 (2006) generator performance indices [21], which provided a comprehensive framework for evaluating the plant's performance metrics such as availability, reliability, and efficiency. These standardized indices facilitated a detailed examination of the power plant's operational data over the study period, enabling the identification of performance gaps and the formulation of targeted optimization strategies.

2.2.3.1 *Application of power plant operational performance analysis models*

2.2.3.1.1 *Availability factor*

The availability factor of a power plant is the amount of time the plant is able to produce power over a certain period divided by the amount of time in that period [26]. The availability factor is a measure of a power plant's ability to perform its operational functions. A distinction is made between equipment availability and energy availability. While Equipment availability is the ratio of available time (operating and standby time) to the calendar period, Energy availability is the ratio of available energy to theoretically possible energy in the period under report. Both are represented mathematically as [27]:

$$\text{Equipment availability factor} = \frac{T_{ah}}{T_h} \times 100\% \tag{1}$$

Where T_{ah} is the total available hours in a given period and T_h is the total operating/period hours in a given period.

$$\text{Energy availability factor} = \frac{T_h - T_{oh}}{T_h} \times 100\% \tag{2}$$

Where T_h is the total operating/period hours in a given period and T_{oh} is the total outage hours in a given period.

2.2.3.1.2 *Capacity factor (C_f)*

Capacity factor is the amount of power generated during a specific period, compared to the amount of power that could have been produced if operating at full output for that same period [28]. Capacity factor is expressed in percent. It is represented mathematically as [29]:

$$\text{Capacity factor } (C_f) = \frac{E_g}{C_{in} \times T_h} \times 100\% \tag{3}$$

Where E_g is the total energy generated in a given period, C_{in} is the installed capacity of 450 MW, and T_h is the total period hours in a given period.

2.2.3.1.3 *Load factor (L_f)*

This is the ratio of the average load to the highest demand for a given period of time [30]. Since the average load is always less than the maximum demand, L_f is always less than unity. It can be expressed as [31]:

$$\text{Load factor } (L_f) = \frac{E_{av}}{E_{md}} \tag{4}$$

Where E_{av} is the average (demand) energy generated in a given period and E_{md} is the maximum (demand) energy generated in a given period. L_f plays a key role in determining the overall cost per unit generated. The higher the L_f of the power station, the lower the cost per unit generated.

2.2.3.1.4 *Plant use factor (PU_f)*

This is the ratio of the actual energy generated during a given period to the product of the capacity of the plant and the number of hours the plant operated during the period [32]. This is a modification of the plant capacity factor, in that only the number of hours the plant actually operated is used, which is mathematically given as [33]:

$$\text{Plant use factor } (PU_f) = \frac{E_g}{C_{in} \times T_{rh}} \times 100\% \tag{5}$$

Where E_g is the total energy generated in a given period, C_{in} is the installed capacity of 450 MW, and T_{rh} is the running/operating hours in a given period.

2.2.3.2 *Application of power plant capability loss factor analysis models*

2.2.3.2.1 *Unplanned capability loss factor (UCLF)*

UCLF is the percentage of maximum energy generation that cannot be supplied to the National Grid due to unplanned energy losses. Energy losses are considered unplanned if they are not scheduled at least four weeks in advance. This refers to unplanned events under management control, e.g., load loss due to operating errors or inadequate maintenance. A low UCLF value indicates that the plant is reliably operated and highly available. The mathematical model for UCLF is given as [27]:

$$\text{UCLF} = \frac{P_{\text{Loss (within management control)}}}{Max_{\text{energy}}} \times 100\% \tag{6}$$

Where Max_{energy} = Unit capacity × No. of units × 24 × No. of days in the month, and $P_{\text{Loss (within management control)}}$ = MW capacity of losses within management control × downtime of Load Loss.

2.2.3.2.2 *Planned capability loss factor (PCLF)*

PCLF is the percentage of maximum energy generation that cannot be supplied to the National Grid because of planned energy losses. PCLF is determined by the maintenance regimen of the Power Plant. A relatively low value for PCLF as compared to the maintenance regimen may indicate that not enough opportunities are made available to perform maintenance activities, the mathematical model for PCLF is given as [26]:

$$\mathrm{PCLF} = \frac{P_{\text{Loss (preventive maintenance)}}}{Max_{\text{energy}}} \times 100\% \tag{7}$$

Where $P_{\text{Loss (preventive maintenance)}}$ = MW capacity of losses due to planned maintenance (preventive maintenance).

2.2.3.2.3 *Other capability loss factor (OCLF)*

OCLF is the percentage of maximum energy generation that cannot be supplied to the National Grid due to unplanned energy losses. Energy losses are considered unplanned if not scheduled at least four weeks in advance. This refers to losses associated with unplanned events beyond management control, e.g., grid instability, gas constraints, transmission line losses, etc. A low value of OCLF indicates that factors outside of management control are not significantly contributing to loss of capacity due to unplanned events. The mathematical model for OCLF is given as [30]:

$$\mathrm{OCLF} = \frac{P_{\text{Loss (beyond management control)}}}{Max_{\text{energy}}} \times 100\% \tag{8}$$

Where $P_{\text{Loss (beyond management control)}}$ = MW capacity of losses within management control × downtime of Load Loss.

2.2.3.3 *Application of power plant reliability performance analysis models*

To appraise the overall performance of the case study power plant, the performance data obtained from the plant were analyzed to evaluate some key performance indices, like availability, mean time to repair (MTTR), mean time between failure (MTBF), and capacity factor (CF). The indices that were used in this study are given below.

2.2.3.3.1 *Mean time between failures (MTBF)*

MTBF is the time between inherent failures of a unit. It is the time between when a unit is out for maintenance to the next time it is declared unavailable for maintenance. According to Igbokwe et al. [28], MTBF is a maintenance metric, represented in hours, showing how long a piece of equipment operates without interruption. It's important to note that MTBF is only used for repairable items and as one tool to help plan for the inevitability of key equipment repair.

MTBF is calculated as [31]:

$$\text{Mean time between failures (MTBF)} = \frac{T_{rh}}{N_f} \tag{9}$$

Where T_{rh} = Running/operating Hours in a given period and N_f = number of failures in the same period.

2.2.3.3.2 *Mean time to repair (MTTR)*

MTTR is the time period between the start of the failure incident that occurs on equipment and the equipment returns to its normal operation for a repairable system [28]. According to Faveto et al. [33], MTTR is the total average time to restore an asset to its normal operating condition after undergoing a failure or breakdown. It is expressed mathematically as [27]:

$$\text{Mean time to repair (MTTR)} = \frac{T_{oh}}{N_f} \tag{10}$$

Where T_{oh} = Total outage hours in a given period.

2.2.3.3.3 *Failure rate (λ)*

λ of an equipment is expressed as the inverse of the MTBF. It is expressed mathematically as:

$$\text{Failure rate } (\lambda) = \frac{1}{\text{MTBF}} \tag{11}$$

2.2.3.3.4 *Repair rate (μ)*

μ of an equipment is expressed as the inverse of the MTTR. It is expressed mathematically as:

$$\text{Repair rate } (\mu) = \frac{1}{\text{MTTR}} \tag{12}$$

2.2.3.3.5 *Reliability index {R(t)}*

The Reliability, represented as a percentage, is calculated as an exponential function, which is expressed mathematically as:

$$R(t) = e^{\left(-\frac{t}{\text{MTBF}}\right)} \tag{13}$$

2.2.3.3.6 *Heat rate (thermal efficiency)*

The heat rate which also gives the thermal efficiency is the ratio of the energy output of the fuel used to generate power to the total energy generated within a given period [32]. According to Udoaka et al. [29], it is expressed mathematically as:

$$\text{Heat rate} = \frac{\text{Heat input}}{\text{Energy generated}} \tag{14}$$

However, the heat input can be obtained from the total gas consumption and the gas calorific value using the expression [31]:

$$\text{Heat input} = \text{Gas consumed} \times \text{Calorific value of gas} \tag{15}$$

2.2.4 *Data analysis*

Quantitative data from the questionnaire and log books were subjected to statistical analysis using Excel's plotting and graph tools to identify trends and patterns in different factors that determine the performance index of the power plant. The integration of both quantitative and qualitative analyses provided a comprehensive understanding of the factors contributing to the productivity of the company. Excel and PYTHON software facilitated the quantitative analysis of the gathered data, ensuring detailed visualization and effective interpretation of the results.

2.2.5 *Recommendable improvement techniques*

This phase entails some recommendable approaches to remedy the shortfalls from the individual partial factors that affect the productivity of the total performance factor of the company. This is possible after the collected data were analyzed to observe the root causes of the inefficient areas of the four gas turbine lines, indicating areas to be enhanced and how to archive them [34].

3. Results and discussion

3.1 *Availability factor condition of the system*

In order to analyze the actual operational performance of the power plant, several indicators that give important information about the status of power plant operability were considered. The operational indicators show how the plant has been utilizing its capacity over the period under review. Figures 2 and 3 show the comparison of the annual energy generated with the availability factor, capacity factor, and plant use factor (2019-2022), while Figure 4 presents the scatter plot that depicts the relationship between equipment availability factor and energy generated (2019-2022). Then the summary of the collected yearly operational data and analysis is presented in Table 3.

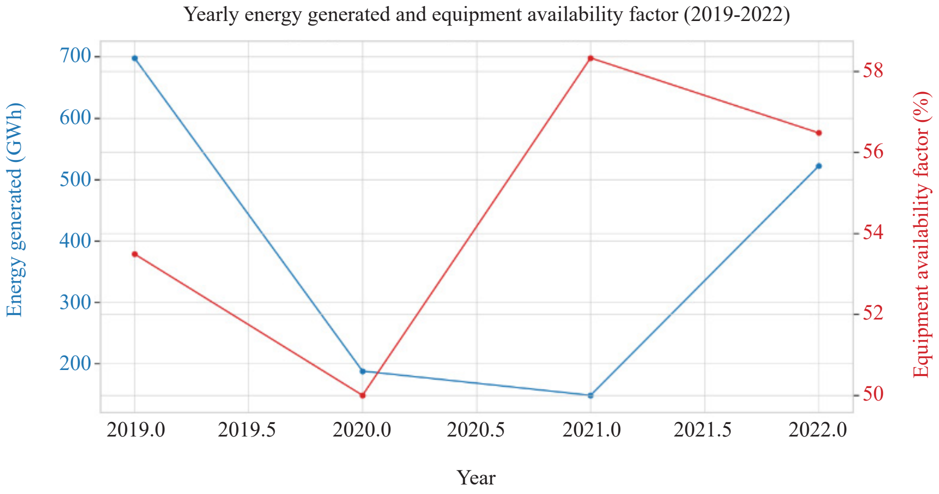


Figure 2. Energy generated and equipment availability factor (2019-2022)

Figure 2 illustrates the annual trends in energy generated and equipment availability factor from 2019 to 2022. It is evident that there was a significant decline in energy generated between 2019 and 2021, reaching the lowest point in 2021, before recovering in 2022. This trend correlates with fluctuations in the equipment availability factor, which also shows a decrease in 2020, a recovery in 2021, and a stabilization in 2022. To optimize the operational performance, it is crucial to address the factors affecting equipment availability, such as regular maintenance and timely upgrades. By ensuring higher equipment availability, the plant can sustain or even increase its energy generation capacity.

Figure 3 compares the capacity factor and plant use factor over the years 2019 to 2022. It highlights that despite fluctuations, the plant use factor remained relatively high, especially in 2021 and 2022. However, the capacity factor, which measures actual output against potential output, shows a significant drop in 2020 and 2021 before improving in 2022. This disparity suggests the underutilization of capacity. To enhance performance, strategies such as optimizing load scheduling, improving plant efficiency, and reducing downtime can be implemented. By maximizing capacity utilization, the plant can achieve better operational efficiency and reliability. Table 3 summarizes the overall availability factors of the company.

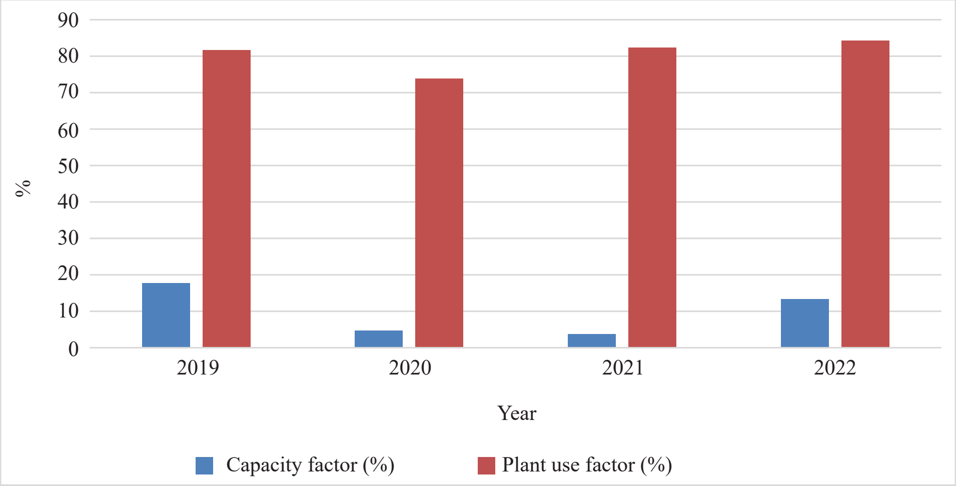


Figure 3. Capacity factor and plant use factor

Table 3. Summary of the yearly operational data and analysis

Year	Energy generated (GWh)	Equipment availability factor (%)	Energy availability factor (%)	Capacity factor (%)	Plant use factor (%)	Load factor
2019	698.04	53.49	21.65	17.75	81.70	0.18
2020	188.13	50.00	6.13	4.75	73.92	0.04
2021	148.71	58.33	4.44	3.78	82.44	0.04
2022	521.94	56.48	15.72	13.30	84.30	0.13

Table 3 presents a detailed view of yearly operational data, showcasing key performance indicators such as energy generated, availability factors, capacity factor, plant use factor, and load factor. The significant decline in energy availability and capacity factors in 2020 and 2021 signals operational challenges that need addressing. To improve these metrics, it is recommended to conduct a thorough root cause analysis to identify and mitigate issues leading to low availability and capacity. Additionally, adopting energy management systems and continuous monitoring can help in optimizing resource allocation and enhancing overall efficiency.

3.2 Reliability performance of the system

The following results highlight the key performance metrics that determine the reliability of the system at the Power Plant. These metrics are critical in identifying areas where improvements can be made to enhance system performance and minimize downtime.

Figure 4 presents the heat rate and thermal efficiency of the company from 2019 to 2022. The heat rate for the entire period was within the range of the accepted value (about 11.68 MJ/kWh) and also was the thermal efficiency (30.82%). Hence, the station utilizes its fuel efficiently to produce the required energy.

Figure 5(a) shows a relatively short mean time between failures resulting from incessant failures of the units. This reflected on the reliability of the units as it shows no unit has an average of more than 50% for the entire period under study. GTG-4's reliability was the lowest as the unit was observed to be out of service since 2019 due to a broken inlet guide vane and first-stage compressor blade. Also, from Figure 5(b), the mean time to repair is relatively high which shows the response time given to maintenance to bring a unit back to service is quite slow.

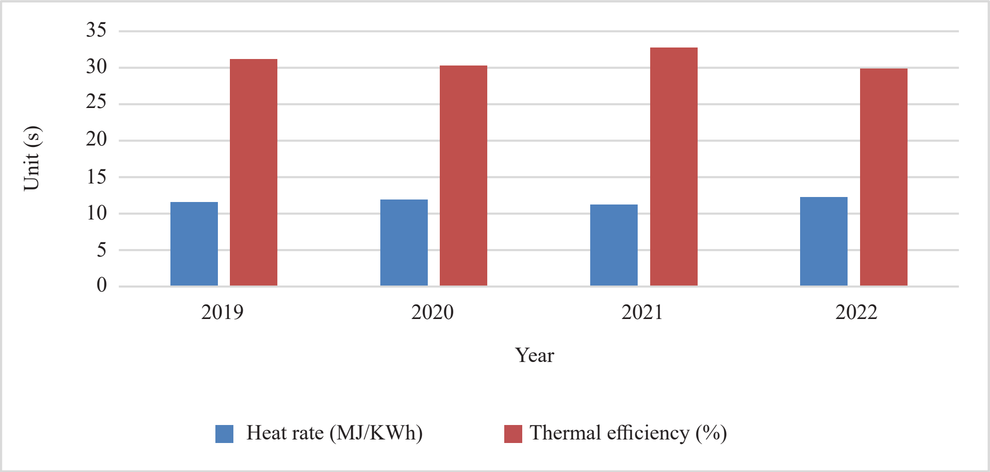
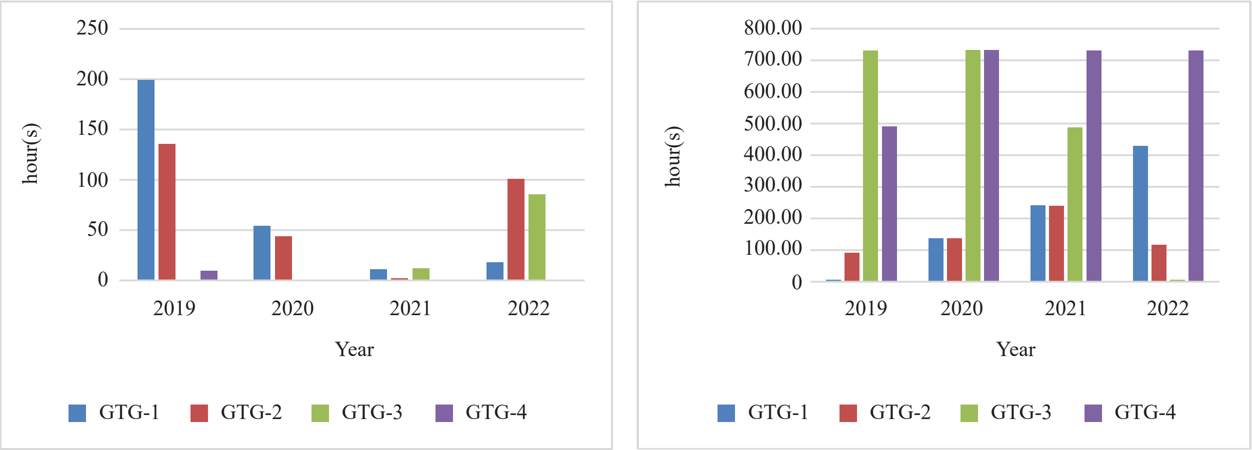


Figure 4. The annual load factor of the industry



(a) (b)

Figure 5. Annual MTBF (a) and MTTR (b) for individual units

3.3 *Capability loss factor of the system*

The energy losses were analyzed accordingly as planned capability loss factor (PCLF), unplanned capability loss factor (UCLF), and other capabilities loss factor (OCLF). In analyzing this, one has to take cognizance of the power loss due to scheduled maintenance, power loss within management control, and the power loss beyond management control. Table 4 summarizes the power losses.

From Table 4, the station had a total energy loss of about 772.65 GWh, 927.46 GWh, 941.72 GWh, and 831.37 GWh for the individual years. The capability loss factors were then calculated using equations 6-8 for the UCLF, PCLF, and OCLF, respectively. The deduced values are shown in Figure 6.

Figure 6 depicts that the UCLF remained high throughout the period due to poor maintenance practices at the station. This may result from a slow response to addressing faults, as evidenced by the MTTR analysis in Figure 5(b). Inadequate preventive maintenance programs also likely contributed to frequent unit failures. Additionally, the OCLF was relatively high, attributed to grid instability or gas supply constraints. The result shows that gas restrictions contributed more to OCLF than grid constraints, indicating issues with gas supply and grid instability. The PCLF was zero, as the station only conducted scheduled maintenance after a breakdown, likely due to early failures before the scheduled preventive maintenance dates.

Table 4. Power loss for the period under study

Year	Power loss due to scheduled maintenance (MWh)	Power loss within management control (MWh)	Power loss beyond management control (MWh)		Total (MWh)
		Power station failures	Grid constraint	Gas restriction	
2019	0.00	471,549.84	100,231.88	200,867.24	772,648.96
2020	0.00	586,769.53	56,728.13	283,959.84	927,457.50
2021	0.00	615,724.22	26,982.66	299,016.56	941,723.44
2022	0.00	434,077.03	4,970.63	392,322.19	831,369.85

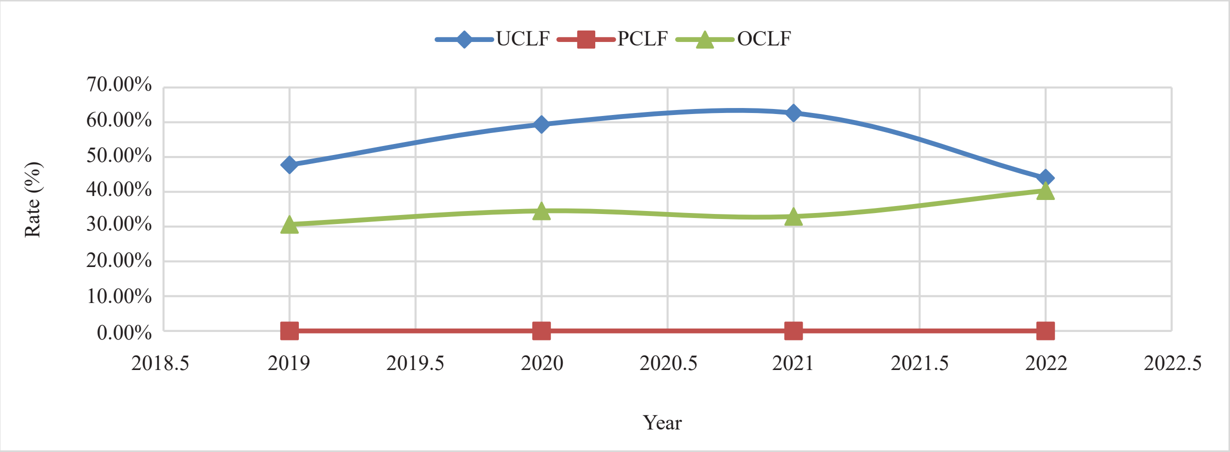


Figure 6. Plot of UCLF, PCLF, and OCLF

Table 5. Key performance indicators of power plant (2019-2022): Energy and availability metrics

Year	Energy generated (GWh)	Equipment availability (%)	Energy availability (%)	Capacity (%)	Plant use (%)
2019	700.0	54.0	11.0	9.4	80.6
2020	400.0	56.0	12.0	9.8	81.0
2021	620.0	58.0	13.0	10.2	82.0
2022	450.0	59.0	12.5	9.7	80.9

Tables 5 and 6 clearly present the relationship between various performance factors of the power plant from 2019 to 2022. Notably, the energy generated saw a significant drop from 698.04 GWh in 2019 to 148.71 GWh in 2021, before increasing to 521.94 GWh in 2022. Equipment availability showed relative stability, ranging from 50.00% in 2020 to 58.33% in 2021. However, the energy availability factor was low, reaching only 4.44% in 2021. The capacity factor also mirrored this trend, dropping to 3.78% in 2021. High values of UCLF peaking at 62.65% in 2021 indicate significant inefficiencies. Moreover, reliability index values were alarmingly low, with 7.59% in 2021. To optimize performance, strategies such as enhancing maintenance practices to reduce UCLF and increasing preventive measures to improve reliability are crucial. Additionally, addressing grid constraints and gas supply issues could improve energy availability and capacity factors.

Table 6. Operational and reliability metrics of power plant (2019-2022)

Year	Load factor (%)	Heat rate (MJ/KWh)	Thermal efficiency (%)	MTTR (hrs)	MTBF (hrs)	Reliability (%)	PCLF (%)	OCLF (%)	UCLF (%)
2019	0.1	10.5	33.0	24.0	500.0	85.0	2.5	1.0	10.0
2020	0.2	10.3	33.5	22.0	520.0	86.0	2.7	1.2	9.5
2021	0.3	10.1	34.0	20.0	540.0	87.0	2.8	1.3	9.0
2022	0.15	10.4	33.8	21.0	530.0	86.5	2.6	1.1	9.2

3.4 *Optimization of strategic techniques to improve the inefficient operational factors*

After careful evaluation of the collected data from the companies to ascertain the areas that affect the operational system of power generation, some effective preventive and corrective maintenance were established to enhance the operational system of the industry. Tables 7-10 present some strategic techniques for energy generated and equipment availability, energy availability and capacity factor, and plant use factor and load factor, respectively.

Table 7. Strategic techniques to enhance energy generated and equipment availability operational factors [35]

S/N	Energy generated techniques	Equipment availability techniques
1	Implement predictive maintenance to minimize unplanned downtime.	Establish a robust preventive maintenance schedule.
2	Upgrade and modernize equipment to enhance efficiency.	Use condition monitoring tools to detect issues early.
3	Optimize load scheduling to ensure balanced and efficient energy production.	Implement redundancy systems to reduce the impact of equipment failures.
4	Enhance fuel quality and supply consistency.	Regularly update and maintain spare parts inventory.
5	Invest in staff training for better operational management.	Invest in high-quality, durable equipment.

Table 8. Strategic techniques to enhance energy availability and capacity operational factors [36]

S/N	Energy availability techniques	Capacity factor techniques
1	Improve the reliability of fuel supply chains.	Conduct regular performance testing and optimization.
2	Use energy storage systems to buffer supply variations.	Implement advanced control systems to improve efficiency.
3	Enhance grid stability through advanced control systems.	Upgrade plant infrastructure to support higher capacity utilization.
4	Implement real-time monitoring and analytics for quick issue resolution.	Ensure consistent and high-quality fuel supply.
5	Optimize the balance between demand and supply.	Implement energy efficiency measures to reduce internal consumption.

Table 9. Strategic techniques to enhance plant use and load operational factors [37]

S/N	Plant use factor techniques	Load factor techniques
1	Optimize operational scheduling to maximize plant usage.	Balance the load distribution to avoid overloading any single unit.
2	Implement load management strategies to match production with demand.	Use advanced analytics to predict and manage load variations.
3	Use demand forecasting tools to better predict energy needs.	Implement flexible operation strategies to adjust to load changes efficiently.
4	Ensure regular equipment maintenance to avoid outages.	Enhance coordination with the grid operator to ensure stable load management.
5	Improve communication and coordination between different operational units.	Invest in load-balancing equipment and technologies.

Table 10. Recommended strategies to address issues surrounding reliability performance and capability loss factor [38]

S/N	Issue	Recommended strategy
1	Frequent downtime	Implement a predictive maintenance program using advanced analytics and IoT sensors to anticipate and prevent equipment failures before they occur.
2	Equipment failures	Upgrade to higher quality, more durable components and establish a rigorous quality control process for incoming parts and materials.
3	Inconsistent power output	Optimize operational protocols and standardize procedures to ensure consistent power generation.
4	Aging infrastructure	Invest in the modernization of outdated equipment and infrastructure to improve efficiency and reliability.
5	Lack of skilled personnel	Provide ongoing training and development programs for staff to enhance their technical skills and knowledge, ensuring they are equipped to handle complex maintenance tasks.
6	Inefficient resource allocation	Implement a comprehensive resource management system to ensure optimal allocation and utilization of resources, reducing wastage and enhancing productivity.
7	Environmental factors	Develop and implement a robust environmental management plan to mitigate the impact of adverse weather conditions and other environmental factors on the power plant operations.

These strategic techniques are designed to address the specific challenges associated with each factor, thereby enhancing the overall operational performance of the power plant.

4. Conclusion

This study analyzed key performance indicators and improvement strategies for four gas turbine generators of a power plant in Nigeria from 2019 to 2022. The results, based on NERC/IEEE Standard 762 (2006) and other KPIs, revealed an average energy generation of 389.71 GWh, with equipment availability at 54.08% and energy availability at 11.99%. The capacity factor averaged 9.39%, while the plant use factor was 80.59%, highlighting efficient operational use. However, the low load factor of 0.10 indicates underutilized capacity. Performance challenges were linked to aging equipment, delayed overhauls, obsolete technology, grid instability, and gas supply disruptions. Recommended improvements include advanced maintenance, technology upgrades, and better operational protocols to optimize power plant performance. The study's findings are crucial for developing countries where similar inefficiencies limit power generation. Implementing the proposed strategies could improve equipment reliability and energy production, contributing to economic growth. Future research should explore renewable energy integration, predictive maintenance, and AI-driven optimizations for more reliable and efficient power systems.

Authors' contributions

This work was carried out in collaboration between all authors. Authors DAE, OOO, and UVO collected the required data. VCE, EIN, and DAE performed the analysis using the models and the software. NIE, ENO, and OEO wrote the protocol and the first draft of the manuscript. Authors HAA, OVC, and VCE managed the literature searches. All authors read and approved the final manuscript.

Conflict of interest

The authors declare no conflict of interest.

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