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Performance evaluation and economic analysis of a gas turbine power plant in Nigeria

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A B S T R A C T

In this study, performance evaluation and economic analysis (in terms of power outage cost due to system downtime) of a gas turbine power plant in Nigeria have been carried out for the period 2001–2010. The thermal power station consists of nine gas turbine units with total capacity of 301 MW (9×31.5 MW). The study reveals that 64.3% of the installed capacity was available in the period. The percentage of shortfall of energy generated in the period ranged from 4.18% to 14.53% as against the acceptable value of 5–10%. The load factor of the plant is between 20.8% and 78.2% as against international best practice of 80%. The average availability of the plant for the period was about 64% as against industry best practice of 95%, while the average use factor was about 92%. The capacity factor of the plant ranged from 20.8% to 78.23% while the utilization factor ranged from 85.47% to 95.82%. For the ten years under review, there was energy generation loss of about 35.7% of expected energy generation of 26.411 TW h with consequent plant performance of 64.3%. The study further reveals that the 35.7% of generation loss resulted in revenue loss of about M$251 (approximately b₦40). The simple performance indicator developed to evaluate the performance indices and outage cost for the station can also be applicable to other power stations in Nigeria and elsewhere. Measures to improve the performance indices of the plant have been suggested such as training of operation and maintenance (O & M) personnel regularly, improvement in O & M practices, proper spare parts inventory and improvement in general housekeeping of the plant. From technical point of view, performance of the plant can be improved by retrofitting with a gas turbine air inlet cooling system, heat recovery system or adding modifications (inter-cooling or regeneration) to the simple gas turbine units.

1. Introduction

Substantial expansion in quantity, quality and access to infrastructure services, especially electricity, is fundamental to rapid and sustained economic growth, and poverty reduction [1,2]. Yet, for the past three decades, inadequate quantity and quality and access to electricity services have been a regular feature in Nigeria [3,2].

In Nigeria, access to reliable and stable supply of electricity is a major challenge for both the urban and rural dwellers. The challenge, however, is more significant in the rural areas where only about 10% of the population have access to electricity [4]. An analysis of Nigeria's electricity supply problems and prospects found that the electricity demand in Nigeria far outstrips the supply, which is epileptic in nature. The acute electricity supply hinders the country's development and not only restricts socio-economic activities to basic human needs; it adversely affects quality of life [5].

The objective of the electric energy system is to provide the needed energy services [6]. Energy services are the desired and useful products, processes or indeed services that result from the use of electricity, such as for lighting, provision of air-conditioned indoor climate, refrigerated storage, and appropriate temperatures for cooking [7,8]. In this regard, power plants play a key role in producing electricity. Among different kinds of power plants, gas turbine power plants have gained a lot of attention because they are attractive in power generation field due to feature low capital cost to power ratio, high flexibility, high reliability without complexity, compactness, early commissioning and commercial operation and fast starting–accelerating and quick shut down. The gas turbine is further recognized for its good environmental performance, manifested in the low environmental pollution [7,9,10].

Notwithstanding, Gas turbine (GT) performance is critically limited by the predominating ambient temperature, especially in hot and dry regions. The increase in inlet air temperature, especially

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Nomenclature

Symbol

E_p	total energy generated (GW h)
C_{in}	power plant installed capacity (GW)
T_h	total hours of the year (h)
T_{oh}	total number of operating hours in one year (h)
L_{av}	average load generated (GW h)
L_{md}	maximum load generated (GW h)
P_T	total power outage cost due to downtime for n number of years ($)
P_A	annual power outage cost for m number of units ($)
P_R	annual power generation reduction for n number of units (GW)
P_r	annual power generation reduction for individual unit (GW)
C_U	unit cost of power (NGN, ₦)
P_{IC}	annual installed energy capacity for individual unit (GW h)
P_{GG}	annual generated energy capacity for individual unit (GW h)
P_F	annual power factor for m number of units
G_C	generated power capacity for individual unit (GW)
I_C	installed power capacity for individual unit (GW)
M	mean time between failure (h)

Greek symbol

ζ	mean time to repair (h)
ψ	availability
λ	expected failure rate
β_t	total operating time between maintenance (h)
Ψ_t	total outage hours per year (h)
μ	expected repair rate
Φ_n	number of failure per year
φ_n	number of failure between maintenance

pronounced in summer, causes a significant decrease in gas turbine power output. It occurs because the power output is inversely proportional to the ambient temperature and because of the high specific volume of air drawn by the compressor. Cooling the air intake to the compressor has been widely used to mitigate this shortcoming [11–14].

Efficiency and electric-power output of gas turbines vary according to the ambient conditions. The amount of these variations greatly affects electricity production, fuel consumption and plant incomes. The amount of electricity production is much more important for electricity production companies during peak demands. Because, due to the high sale prices during peak periods, incomes and profit raise. However, the amount of electricity production is not constant in power plants and is affected by ambient conditions (temperature, pressure and relative humidity) dependent on the plant type and characteristics. Because the ambient air is used directly as working fluid in the system, gas turbines are the mostly affected ones in all conventional power generation systems [15–17].

The main objective of any power utility in the new competitive environment would be to supply customers with electrical energy as economically as possible with a higher degree of reliability and quality.

The performance of a power plant by way of its efficiency and reliability, and other operating factors has definite socio-economic significance both on the company operating the plant as well as the nation at large [18]. However, without adequate and reliable electricity supply, socioeconomic transformation would remain a mirage.

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

Power generation in Nigeria is mainly from two sources: hydroelectric power stations and thermal (steam and gas) stations. Most of these facilities are being managed by Power Holding Company Nigeria Plc (PHCN), a public sector charged by law for the generation, transmission, distribution, or marketing and sales of electricity to the public in Nigeria [19]. Since inception of the PHCN, its services have tended to expand annually in order to meet the ever-increasing demand. Unfortunately, the majority of Nigerians have no access to electricity and the supply to those provided is not regular. Only about 40% of the nation's over 130 million has access to grid electricity and at the rural level, where about 70% of the population live, the availability of electricity drops to 15% [20,21].

As at 2012, the installed capacity of grid electricity was about 82% thermal and 18% hydropower [22]. In 2005 Nigeria produced 23.5 billion kW h from about 6 GWe (giga watts electric) of plant and had final consumption of 17 billion GW h, giving per capita consumption of only 113 kW h/yr [23–25]. The electric energy output was very low, with installed capacity for energy generation put at 10.9 GW, while actual generating capacity was between 4420 MW and 6020 MW [22]. Available statistics indicating the percentage utilization of the installed capacity of electricity supply and index of industrial production shows that for example, in the decade of 1970s, the installed capacity of electricity generation averaged 1097.79 MW, while the average capacity utilization was 35.58 percent. Installed capacity improved marginally in the following decade to about 3318.83 MW and only an average of 33.43 percent was actually utilized in 1980s [26]. The period from 1990 to 2003, saw average installed electricity generating capacity increasing to about 6000 MW, whereas the utilization rate was on the average below 40% [27]. The low and unstable capacity utilization, evident in the average capacity utilization of less than 40% in more than three decades, shows the large gap between installed and actual operational capacity. This large gap is indicative of the level of technical inefficiency in the power-generating sector in Nigeria. Furthermore, because of the depleting nature of the fossil energy resources used, their climate change effects due to their carbon emission, and other health and environmental issues associated with their prospecting and processing, there is a need for efficiency of utilization of energy resources and of energy generation in Nigeria.

On the other hand, a large amount of money is invested annually on improving energy generation. It is estimated that as much as ten billion dollars ($10 bn) has been invested over the course of seven years, without any discernible positive effect on the availability of electricity in Nigeria [28]. Similarly Ibitoye and Adenikinju [23], in their report on future demand for electricity in Nigeria, projected that an annual investment of $10 billion per annum would be required over the next 20 years to achieve optimum power availability at optimum industrial and human capacity growth by the year 2030. There are twenty-one electricity generating installations servicing the national energy grid in Nigeria, with

Table 1
Installed capacity of electricity power stations in Nigeria as at February, 2012. *Source:* Ref. [22].

S/No.	Power station	Type (MW)	Installed capacity (MW)
1	Kainji	Hydro	800
2	Jebba	Hydro	540
3	Shiroro	Hydro	600
4	Egbin	Steam	1320
5	Sapele I	Steam	1020
6	Sapele II	Gas	450
7	Afam (IV–V)	Gas	726
8	Afam (VI) (IPP)	Gas	624
9	Delta	Gas	900
10	AES (IPP)	Gas	270
11	Okpai (IPP)	Gas	480
12	Omoku (IPP)	Gas	150
13	Ajaokuta (IPP)	Gas	110
14	Ibom (IPP)	Gas	60
15	Geregu I	Gas	414
16	Geregu II	Gas	434
17	Omotosho I	Gas	336
18	Omotosho II	Gas	375
19	Olorunsogo I	Gas	336
20	Olorunsogo II	Gas/steam	675
21	Alaoji	Gas/steam	277
	Total		10,897

a combined power outlay of about 10,897 MW as at February, 2012 (see Table 1). However, the stations do not generate at maximum output on account of infrastructure failure, unsustainable management practices, and in some cases, economic sabotage [29,30].

Other reasons have also been suggested as being responsible for the sub-optimal energy production from Nigeria's power stations but hardly has any of these reasons considered the issue from the perspective of actual plant performance. One method PHCN has used to beef up its actual power output from time to time has been the commissioning of new stations [31,32]. Experience has shown that new power plants merely solve the problem in the short run. The technical problems that confronted the older units no sooner than later affect the new ones and they also get run down.

In a bid to improve the electricity generation in Nigeria, the Electric Power Sector Reform (EPSR) Act has made it possible for Independent Power Producers (IPPs) to obtain licence from the National Electricity Regulatory Commission (NERC) to generate electricity.

The power sector over the years has been in a deplorable state due to inadequate maintenance of equipment, poor funding and inadequate infrastructural development. For over ten years prior to 1999, the sector did not have any substantial investments in infrastructure development and installation of new generation plants. The involvement of IPPs in power generation in Nigeria was expected to create efficient, transparent and goal-driven institutions that can achieve the desired performance expected from a power industry as obtainable in the developed countries [33].

It is unfortunate that neither the state-owned nor private-owned IPPs are operating effectively in Nigeria. The IPPs have not met their mandates successfully – (short- and medium-term) expectations of providing quality and reliability in power [34]. The problems of IPPs are similar to that of the public owned power utility (i.e. PHCN) in Nigeria as they are also faced with enormous technical, management and economic problems. In order to find solutions to power system problems in the IPPs, it is necessary to carry out technical and management analysis of interrelated factors that affect their smooth operation of the IPPs in Nigeria. Hence, one of the first IPPs in Nigeria – AES gas power station (Lagos state owned IPP), is considered in this study. The objectives of this study therefore include: (1) to evaluate the performance of AES barges gas turbine power station over a period of ten years (2001–2010); (2) to evaluate the outage cost due to system downtime of the station over the period of ten years (2001–2010) and (3) to proffer recommendations to improve electric power generation in AES barges in particular, with the hope that other IPPs (state-owned and private-owned) would benefit from the outcome of this study.

2. Electricity generation and consumption in Nigeria

The historical installed capacity, generation capacity and capacity utilization in Nigeria over the period of 1980–2009 are presented in Table 2. A close look at the table shows that the Nigeria's electricity industry is operating far below its installed capacity and the optimal level of production. This reflects the extent of inefficiency in the sector.

Total generation capacity over the period of 1980–2009 ranged from 783.9 to 4076.2 MW, while the installed capacity ranged from 2507 to 8702.25 MW. There is a wide gap between generation capacity and installed capacity. For over two decades (1980s to 2000s), the generation capacity by PHCN was less than half installed capacity.

The fluctuation of capacity utilization at different times in Table 2 is due to huge energy losses as a result of poor power plant maintenance, fluctuations in water levels powering the hydro plants, resistive and other losses (e.g. unmetered consumption, theft, etc.) in transmission grid and distribution lines, and more importantly, lack of spinning reserve inbuilt in PHCN power short and long term plans. The above reasons among others account for the increasing gap between demand and supply of electricity in addition to about 30–47% losses of electricity generated in transmission due to old transmission infrastructure of the Power Holding Company of Nigeria (PHCN) [35].

Among other factors which could be stated as responsible for the underutilization of the PHCN power plants are the following: (i) frequent major breakdowns, arising from the use of outdated and heavily overloaded equipments; (ii) lack of co-ordination between town planning authorities and PHCN, resulting in poor overall power system planning which in turn leads to over-loading of PHCN equipments; (iii) inadequate generation due to operational/technical problems arising from machine breakdown and low gas pressure; (iv) poor funding of the organization (PHCN's sole source of revenue is from tariffs which are the lowest in Africa [23]; (v) inadequate budgetary provision and undue delay in release of funds to PHCN; (vi) PHCN's inefficient billing and collection system; (vii) high indebtedness to PHCN especially by public sector consumers who are reluctant to pay for electricity consumed as and at when due; (viii) vandalization and pilfering of PHCN equipments; (ix) inability to convert gas flares to a source of electricity; (x) scarcity of relevant manpower for adequate maintenance and general consumer indiscipline; (xi) lack of essential spare parts for maintenance of the plants; (xii) absence of local manufacturing capabilities and (xiii) lack of systematic studies of distribution networks to reduce extraordinary losses that usually accompany haphazard system expansion [35,36].

The electricity consumption in Nigeria is very low due to inadequate supply. As at 2011, electricity consumption stood at just 149 kW h per head [37]. At 149 kW h per capita, electricity consumption is one of the lowest in the world. Nigeria's per capita electricity consumption is about 4 times less than the African average (563 kW h per capita) and about 17 times less than the world's average (2596 kW h per capita) [22].

In spite of Nigeria's huge resource endowment in energy and enormous investment in the provision of energy infrastructure, the performance of the power sector has remained poor in compar-

Table 2
Electricity generation, utilization and distribution losses in Nigeria from 1980 to 2009. *Source:* Ref. [40,41].

Year	Installed capacity (MW)	Generation capacity (MW)	Capacity utilized (%)
1980	2507	783.9	31.3
1981	2755	895.0	32.5
1982	2872	929.2	32.4
1983	3192	945.5	29.6
1984	3572	978.7	27.4
1985	4192	1133.4	27.0
1986	4574	1300.9	28.4
1987	4574	1227.5	26.8
1988	4574	1273.4	27.8
1989	4960	1398.5	28.2
1990	4548	1536.9	33.8
1991	4548	1647.2	36.2
1992	4548	1693.4	37.2
1993	4548.6	1655.8	36.4
1994	4548.6	1772.9	39.0
1995	4548.6	1810.1	39.8
1996	4548.6	1854.2	40.8
1997	4548.6	1839.8	40.4
1998	4548.6	1724.9	37.9
1999	5580	1859.8	33.3
2000	5580	1738.3	31.2
2001	6180	1689.9	27.3
2002	6180	2237.3	36.2
2003	6130	2378.4	38.8
2004	6130	2763.6	45.1
2005	6538.3	2494.4	38.2
2006	5898	2523.9	42.8
2007	5898	2623.1	44.5
2008	8351.4	4076.2	48.8
2009	8702.25	4035.5	46.4

ison with other developing economies [38]. As at 2010, Nigeria's electricity sector contributed only 0.32% and 0.22% to economic value added and economic growth respectively [39]. This reflects the poor state of infrastructural development in the country.

Notwithstanding the above factors that had rendered public electricity supply in Nigeria unreliable and inefficient, the trend of its utilization has grown significantly over the past years. Fig. 1 shows total electricity consumption in MW h and the various sectoral consumptions. Public sector electricity utilization by the industrial sector has been fairly static because of the unreliability nature of the public electric supply system in the country. Thus, many companies had resolved in providing their own power generating sets for more reliable self generation of electricity leading to high costs of their products and services [42]. Okafor [26] observed that power distribution to the industrial sector in Nigeria also remains abysmally irregular. The effect of irregular power on the cost of production by manufacturing industries was assessed

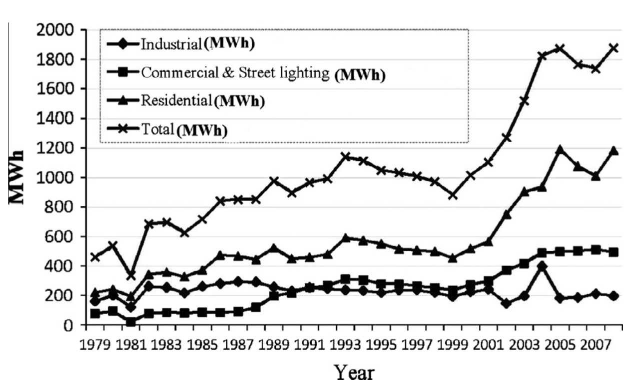

Fig. 1. Electricity consumption pattern in Nigeria. *Source:* Ref. [20].

Table 3
A comparative analysis of energy use per person in Africa. *Source:* Ref. [44].

Countries	Energy use per person (kW h/cap/year)
Cameroon	184
Nigeria	85
Ethiopia	21
Kenya	126
Tanzania	55
Uganda	38
Burkina Faso	29
Ghana	204
Senegal	114
Algeria	581
Egypt	900
Morocco	430
World average	2108

by Adebayo and Alake [43]. The study observed that cost of operating on self power generating sets is 50 times cost of operating on power supply from national grid by PHCN.

The per capita electricity consumption is, on the other hand, still very low as remarked earlier. Table 3 shows that Nigeria's per capita energy use per year (kW h) fall far below world average [42,44].

3. Materials and methods

3.1. Case study – AES barges gas turbine plant

AES barges gas turbine plant is one of the first Independent Power Producers (IPPs) established in Nigeria. AES Nigeria Barge Operation Ltd. is a subsidiary of AES Corporation headquartered in Virginia, USA and has been operating the 301.5 MW power station in Lagos state since 2001. The station consists of nine (9) barge (9×31.5 MW) mounted frame-6B gas turbine (three Alsthom, four John Brown, and two Iuka) which are connected to the national grid via two (2) 132 kV circuits. The plant has three desalination units to produce de-mineralized water for water injection to the gas turbines to control NOx emission and to conduct Compressor wash. The units, though fitted with dual fuel nozzle, operate on gas fuel only. The units are situated on the lagoon jetty, at the PHCN Egbin Thermal Station premise, in Ijede, a suburb of Ikorodu Town in Lagos.

Figs. 2 and 3 show the energy generated and running hours of the plant from 2001 to 2010 respectively. The total energy generated from 2001 to 2010 varies from 549.21 to 2066.24 GW h, while the average running hours vary from 1905.20 to 7490.44 h. The highest total energy generated of 2066.24 GW h was obtained in 2010, and the highest running hours of the plant also occurred in 2010. There has been variability in the total energy generation and the running hours from 2001 to 2010.

3.2. Methodology

Performance and outage costs analyses were carried out on each plant unit. Several trips were made to the plant during which empirical data were collected from plant records from 2001 to 2010 prepared by the Efficiency Department of the utility. Information on the following parameters was used in this work.

i. Gross energy generated (GW h).
ii. Energy used in the plant (GW h).
iii. Energy sent out (GW h).
iv. Installed capacity (GW) for individual unit.
v. Running hours (h).

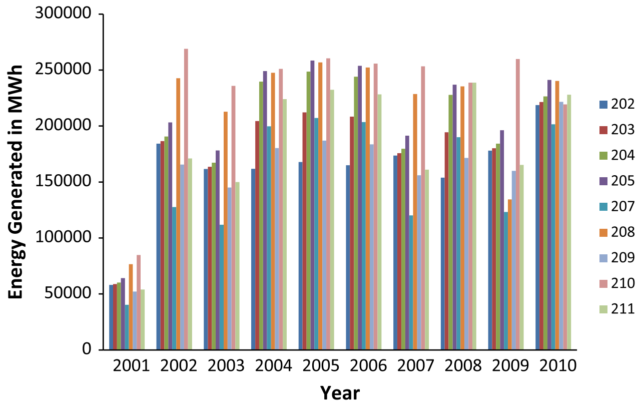

Fig. 2. Unit by unit energy generation in MW h per year.

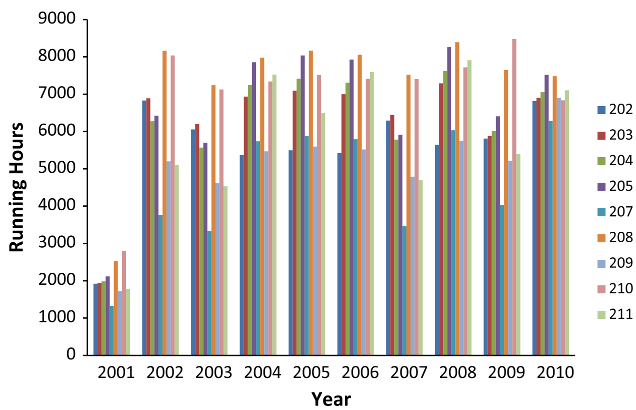

Fig. 3. Unit by unit running hours per year.

3.3. Data presentation

Data for this study were obtained from AES barge gas turbine power station's logbook with the assistance of the company's Efficiency Department. These are inventory records of monthly energy generation between 2001 and 2010 and operational statistics showing the period when each of the plant units had major outages and the time of maintenance. The summary of data collected is presented in Table 4. Table 4 shows the total energy generated and running hours for the period under consideration (2001–2010). In processing the data, percentage shortfall from target energy, load factor, capacity factor and utilization factor were evaluated.

3.3.1. Plant performance indices

Power plant performance depends on several indices and the five (5) most important of these are [45]:

i. Thermal (and overall) efficiency.
ii. Reliability indices.
iii. Capacity of plant.
iv. Plant factors (load factor, capacity factor, utilization factor, etc.).
v. Availability of water for condensate.

Other indices used in evaluating a plant's performance are: generation unit cost, fuel volume utilization efficiency, fuel cost per unit generation, staff productivity, breakdown maintenance, etc. [46]. In this paper, the following parameters and factors for a period of ten (10) years (2001–2010) were determined as key performance indicators of the plant. These include: plant capacity, capacity factor, plant use factor, load factor, utilization factor, and plant reliability. The economic factor considered in this work is outage cost for the plant.

The plant performance indices used in this work are given as follow:

3.3.1.1. Plant Capacity (PC). This refers to both the total amount of power (GW) and energy (GW h) the plant is capable of producing, where the energy plant capacity (EPC) equals the power plant capacity (PPC) multiplied by the expected running hours.

$$\mathrm{EPC} = \mathrm{PPC}\ (\mathrm{GW}) \times \text{Running Hours}\ (\mathrm{H}) \tag{1}$$

where EPC is the energy plant capacity and PPC is the power plant capacity.

3.3.1.2. Capacity Factor (CF). The extent of use of the generating plant is measured by the Capacity Factor (CF) which is the ratio of the average energy output of the plant for a given period of time to the plant capacity. This is the ratio of the average load to the rated capacity of the plant.

$$\mathrm{CF} = \frac{E_P}{C_{in} \times T_h} \tag{2}$$

where E_p is the total energy generated (GW h) in a given period, C_{in} the installed (rated) capacity of the plant, and T_h is the total hours of the year.

3.3.1.3. Plant Use Factor (PUF). This is the ratio of actual energy generated during a given period to the product of capacity of the plant and the number of hours the plant has been in operation during the period. This is a modification of plant capacity factor in that only the actual number of hours that the plant was in operation is used.

Table 4
Energy generated in GW h and running hours from 2001 to 2010.

Year	Energy generation (GW h)		Energy used		Energy sent out		Average running hours	Capacity factor
	Target	Actual	(GW h)	(%)	(GW h)	(%)		
2001	607.17	549.21	17.71	3.22	531.50	96.78	1905.20	0.208
2002	1902.28	1740.45	56.18	3.23	1684.27	96.77	6309.39	0.659
2003	1687.20	1525.85	42.64	2.79	1483.21	97.21	5596.03	0.578
2004	2058.62	1945.57	54.81	2.82	1900.16	97.18	6827.92	0.737
2005	2106.43	2018.36	51.95	2.57	1966.42	97.43	6986.51	0.764
2006	2077.46	1982.19	65.16	3.29	1917.03	96.71	6890.41	0.751
2007	1752.41	1639.50	52.31	3.57	1580.50	96.43	5812.31	0.634
2008	2164.86	1850.25	50.96	2.75	1799.29	97.25	7180.28	0.699
2009	1837.80	1681.45	55.27	3.29	1626.18	96.71	6095.52	0.637
2010	2254.37	2066.24	67.92	3.29	1998.32	96.71	7490.44	0.782
Avg	1844.86	1699.91	51.49	3.08	1648.69	96.92	6109.40	0.645

$$\mathrm{PUF} = \frac{E_P}{C_{in} \times T_{oh}} \tag{3}$$

where E_p is the total energy generated (GW h) in a given period (one year), C_{in} the installed (rated) capacity of the plant, and T_{oh} is the total number of operating hours in the given period (one year).

3.3.1.4. Load Factor (LF). This is the ratio of the average load to the maximum demand for a particular period of time. Since the average load is always less than the maximum demand, load factor is always less than unity.

$$\mathrm{LF} = \frac{L_{av}}{L_{md}} \tag{4}$$

where L_{av} is the average (demand) load generated and L_{md} is the maximum (demand) load generated in a given period (one year).

3.3.1.5. Utilization Factor (UF). This is the ratio of the maximum demand to the rated capacity of the power plant. The utilization factor measures the use made of the total installed capacity of the plant.

$$\mathrm{UF} = \frac{L_{md}}{C_{in}} \tag{5}$$

where L_{md} is the maximum (demand) load generated in a given period and C_{in} is the installed (rated) capacity of the plant.

3.3.2. Outage cost

Power plant outage cost is determined by the following equations [19]:

$$P_T = \sum_{i=1}^{n} P_{Ai} \tag{6}$$

where P_T is the total power outage cost due to system downtime for n number of years and P_A is the annual power outage cost for m number of units.

But

$$P_A = P_R \times P_F \times C_U \tag{7}$$

$$P_R = \sum_{j=1}^{M} P_r \tag{8}$$

$$P_r = P_{IC} - P_{GC} \tag{9}$$

$$P_F = \frac{\sum G_C}{\sum I_C} \tag{10}$$

where P_R is the annual power generation reduction for m number of units, P_r the annual power generation reduction for individual unit, P_{IC} the annual installed energy capacity in GW h for individual unit, P_{GC} the annual generated energy capacity in GW h for individual unit, P_F the annual power factor for m number of units, G_C the generated power capacity in GW for individual unit, I_C the installed power capacity in GW for individual unit, C_U the unit cost of energy, and its value is given as 4.7 US cent/kWh (N 7.40/kWh) (as at 2011) [46].

The total power outage cost (P_T) due to system down time from 2001 to 2010 is calculated as follows:

The annual power outage cost (P_A) for the year 2004 is computed as example using data in Table 4. In this case, each unit of the plant is considered. Annual power generation reduction for the nine units for the year 2004 is computed and result is as shown in Table 5.

If unit cost of energy C_u is 4.7 US cent/kWh. Substituting values of P_F, P_R and C_u into equation (7), we have:

$$P_A(2004) = 695.57 \times 4.7 \times 0.737 \times 10^6 = \$24{,}093{,}849.23$$

The same procedure is used to obtain cost of power outage for other years. Table 6 shows the total power outage cost for the period under review.

3.3.3. Plant reliability indices

The availability and reliability analysis of AES barge gas turbine plant was based on available data over a period of six year (2005–2010). The records of failure frequency of installations, containing the description and analysis of the failure and other materials filed by the company Efficiency Department constitute the basic source of information on the failure frequency and range of repairs of the plant. In processing the available data, mean time between failure (m), mean time to repair (ζ) and availability (ψ) were obtained.

3.3.3.1. Mean Time Between Failure (MTBF).

$$m = \frac{1}{\lambda} = \frac{\beta_t}{\varphi_n} \tag{11}$$

where λ is the expected failure rate, φ_n the number of failure between maintenance, and β_t is the total operating time between maintenance.

3.3.3.2. Mean time to repair (ζ).

$$\zeta = \frac{1}{\mu} = \frac{\psi_t}{\varphi_n} \tag{12}$$

where ψ_t is the total outage hours per year, φ_n the number of failure per year, and μ is the expected repair rate.When these two factors are known (Eqs. (11) and (12)) for any given system or component, then the availability (Ψ) is expressed as:

3.3.3.3. Availability (Ψ).

$$\psi = \frac{\mu}{\lambda + \mu} \tag{13a}$$

Table 5
Annual power generation reduction for the year 2004.

Unit	Energy plant capacity (P_{IC}, GW h)	Power plant capacity (P_{IC}, GW)	Energy generated capacity (P_{GC}, GW h)	Power generated capacity (P_{GC}, GW)	Energy generation reduction (GW h)	Running hours
PB202	293.46	0.034	171.85	0.032	121.61	5369.25
PB203	293.46	0.034	214.47	0.031	78.99	6934.07
PB204	293.46	0.034	239.59	0.033	53.87	7243.64
PB205	293.46	0.034	249.13	0.032	44.33	7856.39
PB207	293.46	0.034	174.22	0.030	119.24	5739.01
PB208	293.46	0.034	247.59	0.031	45.87	7979.92
PB209	293.46	0.034	180.27	0.033	113.19	5467.90
PB210	293.46	0.034	221.26	0.030	72.20	7340.88
PB211	293.46	0.034	247.19	0.033	46.27	7520.20
	2641.14	0.306	1945.57	0.285	695.57	61451.27

Table 6
Power outage cost due to system downtime.

Year	Energy plant capacity (GW h)	Energy generation reduction (GW h)	Cost of power outage (M$)	% Power reduction	% Power available
2001	2641.14	2091.93	20.25	79	21
2002	2641.14	900.69	29.13	34	66
2003	2641.14	1115.02	30.00	42	58
2004	2641.14	695.57	24.09	31	69
2005	2641.14	610.19	21.70	23	77
2006	2641.14	658.96	23.03	25	75
2007	2641.14	1001.64	29.55	38	62
2008	2641.14	725.36	23.60	27	73
2009	2641.14	959.69	28.45	36	64
2010	2641.14	574.90	20.92	22	78
Total	26411.40	9333.95	250.72	Avg = 35.7	Avg = 64.3

or

$$\psi = \frac{m}{m + \zeta} \quad (13b)$$

4. Results and discussion

The expected full load installed capacity of the plant under study is 0.3015 GW, but the generated capacity for the period under review ranges from around 0.257 GW and 0.288 GW. From Table 4, the station targets are far from installed capacity of 2641.14 GW h. The average energy generating of the plant from data obtained is 1699.91 GW h. Hence, about 64.3% on average of installed capacity was available. This shows gap between installed capacity and actual operational capacity of the plant which may be due to aging generating facilities that are poorly maintained.

Percentage shortfall from the target energy for the period under review is shown in Fig. 4. A reduction in shortfall signifies better performance of the plant and this may be as a result of concerted efforts made by the management in carrying out preventive maintenance in the plant. A decrease in shortfall occurred from 2004 to 2005. The shortfall rises from 2006 to 2008 with the highest value of 14.5%. For the period under review the shortfall ranges from 4.18% to 14.53%. This value is not far from average acceptable value of between 5% and 10% [44]. The percentage shortfall in energy in the plant is far better than that obtained by Obodeh and Isaac [28] for Sapele thermal plant (ranged from 27.4% to 49.1%) within the period of 1997–2006. This might be as a result of long years of operation of Sapele plant (commissioned in 1978) while AES plant was commissioned in 2001.

The plant's capacity factor for period under review is presented in Fig. 5. The average capacity factor of the plant is 64.49% with a minimum value of 20.8% in 2001 and a maximum value of 78.23% in 2010 as against industry best practice of between 50% and 80% [27]. Thus, the characteristic behavior of generating plant depends substantially on the capacity factor and utilization factor. High capacity factor is desired for economic operation of the plant [45].

The low capacity factor (20.8%) of the plant in 2001 signifies that the average energy generation is low. This is due to late commencement of generation of energy in the year as the plant was commissioned middle of 2001. In general, low capacity factor indicates excessive plant failure which implies capacity of the plant remains unutilized for major part of the year, so the cost would be high. High capacity factor is desired for economic operation of the plant [29]. If scheduled routine maintenance of the plant is significantly improved, the frequency of failure will reduce, high capacity factor will be attained.

Fig. 6 shows the plant use factor. The average plant use factor for the period under review is 92.01% with a minimum of 85.47% in 2008 and maximum value of 95.82% in 2005. High plant use factor indicates high ratio of actual generation to expected generation, while low plant use factor is an indication of low ratio of actual generation to expected generation. Low use factor also indicates excessive plant failure and hence plant's generation below rated capacity.

The variation of plant load factor with year is similar to variation of capacity factor depicted in Fig. 5. The load factor varies from 20.81% to 78.24% with an average value of 64.48%. This is low compare to international best practice of 80% [47]. The load factor is indication of the utilization of power plant capacity.

A high load factor means that the total plant capacity is utilized for most of the time and is desirable from point of view of reducing cost of generation per unit of energy produced. After 2003, the load factor increases to value as high as 76.42% in 2005. This may be attributed to possibility of the management to carry out

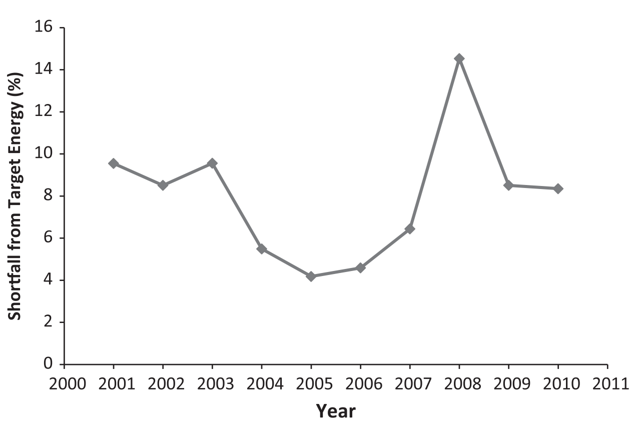

Fig. 4. Shortfall from target energy with year.

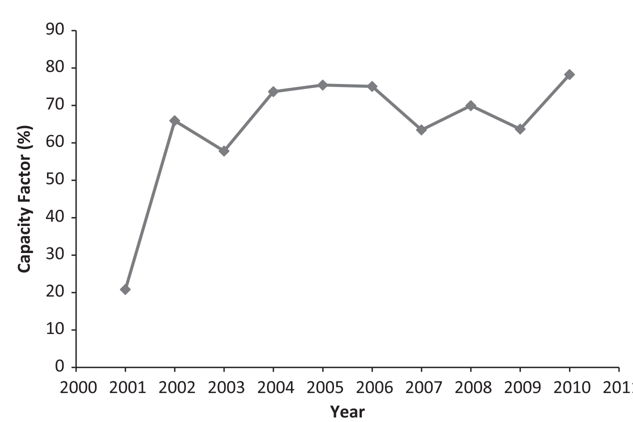

Fig. 5. Variation of capacity factor with year.

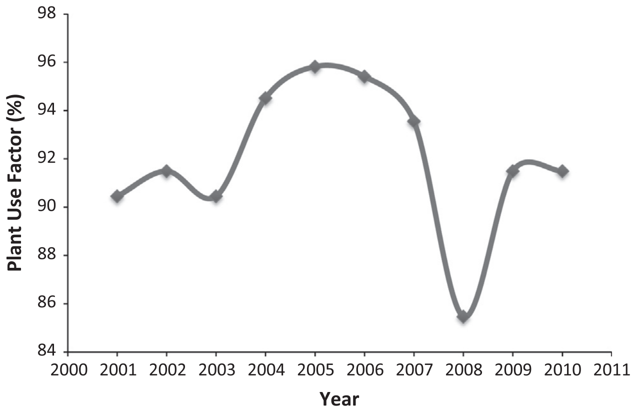

Fig. 6. Variation of plant use factor with year.

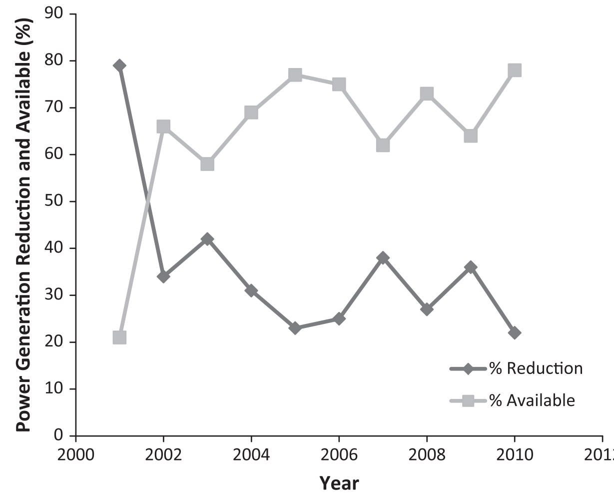

Fig. 7. Variation power generation reduction and available with year.

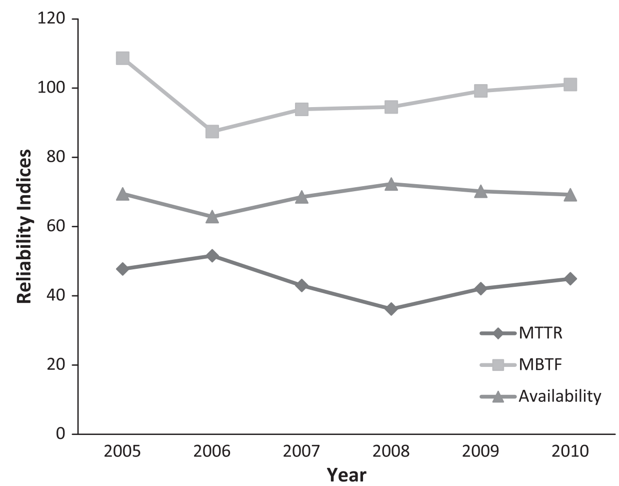

Fig. 8. Reliability indices of AES barge gas turbine plant over the period 2005–2010.

turn-around maintenance on the plant. Effective management and political will are required to ensure adequate, reliable and cost effective operation of electric power generation plant.

The plant variation of utilization factor with year is similar to variation of plant use factor shown in Fig. 6. The utilization factor has been rising and falling and not consistent. The value of utilization factor ranges from 85.47% to 95.82% for the period under review. The utilization factor for the plant is not too far from best practice (over 95%) [28,48,49].

The trend of utilization factor reflects how effectively managed the station is in terms of downtime. This result shows that there was no generating equipment in the plant that was utilized for less than their normal hours of utilization all year round. However, as the plant's operation year is below half of its life span (i.e. 12th year in operation) additional gains can be achieved by replacement of warn-out essential parts, undergoing planned and routine maintenance regularly.

The total power generation reduction due to down time of the plant for the period under review (2001–2010) is 9333.95 GW h. The plant was expected to generate 26411.40 GW h of electricity from the year 2001 to 2010. The generation reduction amounting to 35.7% of the total installed capacity of the plant. This put the availability of the plant for the period under review at 64.3%. Fig. 7 shows the variation of power generation reduction and available with year. The power generation reduction ranges from 22% to 79% while the power available ranges from 21% to 78% from 2001 to 2010. There is continuous decrease in power generation reduction while power generation available increases. This indicates improvement in the performance of the plant.

Considering the loss of revenue in dollars based on the power generation reduction of 35.7%, this amount to the tune of about M$250 (M₦39,827). This is no mean amount. As the operation period of the plant is still far from its life span (i.e. 25 years), the management and stakeholder of the power station should see this study as an eye opener and to invest adequately on preventive maintenance of the plant. This will enable them to get good return on the investment.

Fig. 8 presents reliability indices of the AES plant over the period of 2005–2010. The Mean Time Between Failure (MTBF) of the plant varies from 87.46 h (2006) to 108.66 h (2005). The mean time to repair (MTTR) varies from 36.20 h (2008) to 51.59 h (2006). This shows that time spent on the plant in 2006 in order to put it to operation was more than other years (2005, 2007–2010). From this it can be concluded that there is inverse relationship between the component/ equipment availability and failure rate. The operational consequences of failure can be reduced by taking steps to shorten the downtime, most often by reducing the time to get hold of spare parts.

Considering the plant availability with the available data over the period 2005–2010, it was found that the plant availability varies from 0.6290 (2006) to 0.7231 (2008). These values of availability for the gas turbine station are lower than the IEEE recommended standard of ASAI which is 0.999 [50]. The plant availability can be improved significantly by reviewing maintenance practices by (i) devoting more attention to planned or scheduled maintenance as directed by the unit manufacturer's operation and maintenance manual package. In other words, routine preventive maintenance must be well planned and more regular, (ii) by training and retraining of technical personnel on the major equipment being used. This will improve their skill and knowledge on the current information and communication technology (ICT) as well as improve their manpower quality, (iii) effective maintenance management is essential in reducing the adverse effect of equipment failure to operation and (iv) failure rates in the plant can be reduced if the maintenance procedure tasks involve periodical inspection and replacement of parts that were subjected to very high temperature and located in the hot gas paths (combustion chamber and turbine).

Gas turbines are designed for standard air conditions. However, operating periods at off-design conditions are much greater than that at design conditions. The difference between the actual power generated by a gas turbine and the design rated power tagged on the gas turbine is observed whenever a gas turbine operates at site ambient conditions that vary from the stipulated ISO conditions.

Gas turbine power plants operating in Nigeria are simple gas turbines, there is a tremendous de-rating factor due to higher ambient temperatures. Coupled with this, these gas turbines are made to operate without the application of gas turbine inlet air cooling equipment and technology applications. The average efficiency of gas turbine plants in the Nigerian energy utility sector over the past two decades was in the range 27–30% [51].

It is generally understood that efficiency improvement that is consistent with high plant reliability and low cost of electricity is economically beneficial. Possible economical methods and technologies to improve performance of AES gas turbine power plant are:

- Retrofitting with a gas turbine air inlet cooling system (evaporative cooling or inlet chilling method) is a useful option for increasing power output of the plant. Inlet air cooling increases output by taking advantage of the gas turbine's characteristic of higher mass flow rate and, thus, output as the compressor inlet temperature decreases. Because the cooled air is denser, it gives the machine a higher air mass flow rate and pressure ratio, resulting in an increase in output. As the plant is very close to lagoon area, the source of cooling water can be obtained from lagoon. The inlet air cooling system is cost effective and can be implemented in the basic system without major modification to the original system integration.
- Heat recovery from hot exhaust gases can be used to augment the performance of the gas turbine plant. Combined cycle is a common way to recover thermal energy from the exhaust gases; it is suitable for this plant as it operates as base loading plant.
- Furthermore, with the rapid increase in electricity demand in Nigeria and the expected shortages in power supply due to delays in implementation of the major power projects, retrofitting the plant with inter-cooling between two compressors and regenerator cycle would be an attractive investment opportunity for the stakeholder of the plant.

5. Conclusion

In this study, performance evaluation and economic analysis on AES barge gas turbine power plant have been investigated. Emphasis has been on key performance indices (plant capacity, capacity factor, plant use factor, load factor, and utilization factor), reliability indices and cost of power outage.

The study revealed that 64.3% of the plant installed capacity was available between 2001 and 2010. Also, the percentage shortfall of energy generated within the period under review ranges from 4.18% to 14.53% as against the average acceptable value between 5% and 10%. The average capacity factor was 64.49% with 20.8% minimum value in 2001 and 78.23% maximum in 2010 as against international best practice standard of 50–80%. The plant use factor ranged from 85.47% to 95.82% and the average value is 92.01%. The load factor varied from 20.8% to 78.2% with average value of 64.5% as against the international best practice standards of 80% and above. The utilization factor of the plant varied from 85.5% to 95.8% with the average value of 92.01% while international best practice standard is 95% and above. The above parameters evaluated for the plant are not too low to the international best practice standard. Notwithstanding, there is still opportunity for improvement of the performance indices as the analysis carried out revealed that the station was expected to generate a total of 26411.40 GW h of electricity from the year 2001 to 2010, but there was a reduction of 9333.95 GW h. The study also shows that the 35.7% loss of power generation resulted in revenue loss of about M$251 (about b₦ 40). This is no mean amount. The plant availability over the period of six years (2005–2010) was found to vary from 0.6290 to 0.7321. These values of availability for the gas turbine station are lower than the IEEE recommended standard of ASAI which is 0.999.

This study shows that the performance of the plant can be greatly improved. As earlier suggested, the power generation reduction and revenue loss can be reduced through improvement in operational and management (O & M) practices, proper spare parts inventory, improvement in general housekeeping of the plant and regular training of O & M personnel.

From technical point of view, possible economical methods and technologies to improve performance of AES gas turbine power plant are: Retrofitting with a gas turbine air inlet cooling system, heat recovery system or inter-cooling between two compressors and regenerator cycle.

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