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Power Generation Systems Assessment: A New Approach

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ABSTRACT: Power generation systems have become useful for grid base and off grid electric power generation. Hence, its performance has become critical for sustainable growth and development. Performance evaluation of power generation systems has always been carried out using the independent assessment approach (IAA) whose models are: the reliability, availability, emission characteristics, energy and exergy efficiency. The IAA approach only assesses the system performance in part without recur to other indexes, hence, limiting a holistic view of the true plant state. In this paper, the development of a new performance index using the combined assessment approach (CAA) is explored. This approach (CAA) seeks to combine two relatable traditional measures for the assessment of power generation system. The model combines exergy efficiency and reliability measures for analysis. First Independent Power Limited (FIPL) gas turbine power plant was used to test the model. The plant reliability and availability were evaluated along with its thermal efficiency using the exergy model. The analysis of plant thermal efficiency was carried out using the steady state model. Results of the traditional indexes of the plant were compared with the proposed (Bassy-II index) index. It was seen that the new index provided a new assessment criteria. The exergy efficiency, reliability and availability measures indicated a fairly rated plant state. However, the new index defined a new plant state which is unique and represents the true status of the system in whole. Hence, the proposed index (Bassy-II index) is recommended for use in the holistic assessment of power generation systems.

KEYWORDS: Combined assessment approach (CAA), gas turbine, thermal efficiency, Reliability and availability.

1.0 INTRODUCTION

Power generation systems come in different forms and sizes, depending on the technology and areas of application. They may be classified into conventional and non-conventional types. Among the conventional type are hydroelectric power plants, nuclear power stations, spark ignition engines, compression ignition engines, gas turbine power plants, steam turbine power plant and combined cycle power plant [1]. Among the non-conventional power generation systems are wind power plant, solar power plant and geothermal power plant. A common characteristic of the conventional power generation systems is that they produce mechanical work in the form of shaft power which is transferred to do useful work in the form of propulsion, pumping, electricity generation etc, and to drive auxiliary systems. For example, the shaft power developed by vehicle engines is transferred to traction for propulsion while for stationary power plants, the developed shaft power is used to drive alternator which converts the rotational mechanical power to electrical power [1].

For electric power utility companies, the conventional power generation system is an ideal choice for used in power generation because of many of its advantages such as: easy availability of raw materials, high efficiency of the energy source, low production expenses, ease in transportation of its raw materials, it does not require any specific place for its installation, and it can generate energy at instant [1, 2].

Electricity consumers (both domestic and industrial) long for uninterrupted, reliable and affordable electric power supply. In most cases, they are willing to pay more for guaranteed electric supply. Hence, optimal performance of power generation system is key for prompt service delivery and profit maximization [3].

Several performance measures have been used in the evaluation of power generation systems. Among the measures used are: thermodynamic performance measures (i.e., energy and exergy efficiency measures), reliability, availability, maintainability, environmental characteristics, and sustainability measures [2]. The thermodynamic performance focuses on energy and exergy efficiency of the system. However, in gas turbine power plant and combined cycle power plant, the exergy efficiency model of the thermodynamic performance is preferable for use in its assessment because, it captures both available and unavailable energies of the system [2]. A common feature of the above mentioned performance measures is that their assessment approach is independent. That is, each measure is used independently in the assessment of a system without recur to another [2]. Thus, for this type of assessment approach, we classify it under the “Independent Assessment

Approach”. It is important to clarify that the Independent Assessment Approach (IAA) have not completely yield an optimal solution i.e., allows the plant state to be seen as a whole, but rather in parts. Hence, an approach that allows power generation system’s state to be evaluated and viewed as a whole is envisaged.

According to [4], reliability, availability, maintainability, environmental characteristics and sustainability measures are considered as technical characteristics of power generation system. These measures relate with one another in one form or the other. For instant, both availability and maintainability measure have significant effects on system reliability [2, 3, 5]. Also, a system is considered sustainable when environmental impacts of such a system are negligible. Hence, an improvement of one measure can lead to an improvement of the other and vice versa [2, 4]. Thus, on the bases of the proposed concept of [4], a combined assessment model encapsulating exergy efficiency and availability measures was developed and called Bassy-I index. This index was used in the assessment of First Independent Power Limited (FIPL) gas turbine power plant in Afam, Nigeria [2]. Consequently, this paper further explores the combined assessment approach (CAA) technique for the development of a new model for use in the evaluation of power generation systems. Here, the exergy efficiency and the reliability measures are harnessed using the combined assessment approach for the development of a new assessment model that will define a new plant state.

2.0 MATERIALS AND METHODS

2.1 Materials

A gas turbine power plant in the Niger Delta region of Nigeria is used as a case study to test the developed model. The plant is situated in Afam, in Oyigbo Local Government Area of Rivers State. It has a capacity of 180 MW and is owned by the First Independent Power Limited (FIPL) group.

2.2 Methodology

2.2.1 Data collection

The Plant operational data was collected from the operational log sheet. Quantities like mass flow rate, temperature and pressure at different sections of the plant (i.e., compressor, combustion chamber, turbine, exhaust and fuel line section) were collected. These data where obtained across the study period from year 2013 to 2019. Outage frequency and plant duration information on planned and forced outages for the periods were also collated.

2.2.2 Structure of the analysis

Exergy analysis method being a component of the thermodynamic assessment was used in the evaluation of the plant. The First law and Second law of thermodynamics were brought to bear. A comparative analysis of the exergy efficiency of the plant at base load of 80, 120 and 140 MW at year 2013, 2014, 2018 and 2019 were carried out. The power plant availability and reliability for the study period were determined. A model that combines exergy efficiency and reliability was developed and proposed.

2.3 System specification

The plant has four main component which are: an air compressor (AC), a combustion chamber (CC), a turbine (GT) and exhaust (EH). The ISO input temperature and pressure are 25°C and 1.0135 bar, respectively. The compressor isentropic efficiency is 83% and amplifies the pressure up to 18.2 bar. The turbine isentropic efficiency is 88%, with turbine inlet temperature of 1046°C. Table 1 present technical information of the pant.

Table 1: Technical Data of GT13E2, FIPL Afam [2]

GT13E2 performance Parameters	Specification	GT13E2 performance Parameters	Specification
Fuel	Natural gas	Number of turbine Stages	5
Frequency	50 Hz	Number of Compressor stages	16
Gross Electrical Output	180 MW	GT Generator cooling medium/fluid	Air
Net Thermal Efficiency (LHV)	39.0%	Number of Combustor Cans	48 (AEV burners)
Gross Heat rate	8980 Btu/kWh	Exhaust gas temperature	515 ºC or 959 ºF
Turbine speed	3000 rpm	Exhaust Energy (MM kJ/hr)	1219
Compressor pressure ratio	18.2:1	Exhaust gas flow	537 /s

2.4 Thermodynamic model for the gas turbine power plant

The gas turbine power plant in consideration is assumed to operate under the following conditions: (i) the flow is of steady state, (ii) the fuel used is natural gas with Lower Heating Value (LHV) of 7141kJ/kg, (iii) the working fluid/medium for the system is air, and (iv) the working fluid obeys the ideal gas law. Figure 1 shows the flow diagram of the simple gas turbine. The cycle diagram in which the plant operates on is shown in Figure 2.

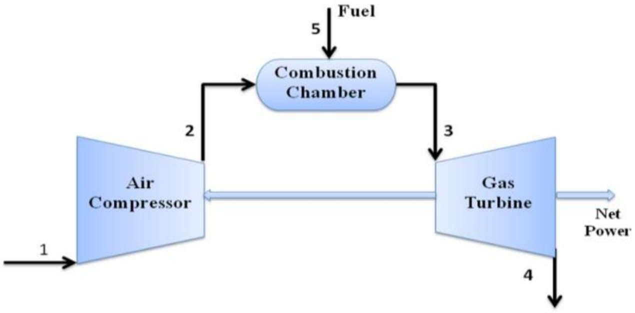

Fig. 1. Flow diagram of simple gas turbine [2]

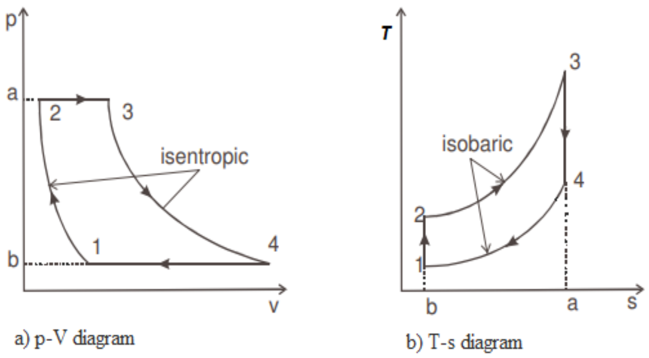

Fig. 2. Gas power cycle diagram [2]

For a system that interacts with the environment to produce work, the maximum theoretical work that can be extracted from such a system may be analyse from the exergy point of view. Since a system that passes from its initial state to a state of equilibrium with the environment possesses an amount of exergy [6, 7]. The total exergy (Ex) of such a system may be expressed as a function of the component exergy. Hence,

$$Ex = Ex_{ph} + Ex_{ch} + Ex_{kn} + Ex_{pt} \quad (1)$$

Where,
Ex_{ph} is exergy physical, Ex_{ch} is exergy chemical exergy, Ex_{kn} is exergy kinetic and Ex_{pt} is exergy potential.

For a system at rest, and relative to the environment, the exergy potential and kinetic values are assumed to be zero ($Ex_{kn} = Ex_{pt} = 0$). Thus under this condition, the total exergy of the plant is given as [7]:

$$Ex = Ex_{ph} + Ex_{ch} \quad (2)$$

for a mass specific exergy of the plant, we have

$$ex = ex_{ph} + ex_{ch} \quad (3)$$

Physical Exergy:
Considering an ideal gas scenario, the physical exergy can be expressed as a function of enthalpy (h) and entropy (s).

The relationship between the enthalpy (h) and entropy (s) is presented in equation (4).

$$Ex_{ph} = m\left[C_p(T_1 - T_0) - T_0(s_1 - s_0)\right] \quad (4)$$

Specific physical exergy (ex_{ph}) can be written as:

$$ex_{ph} = \left[(h_1 - h_0) - T_0(s_1 - s_0)\right] \quad (5)$$

where, T represent the absolute temperature, subscript o represent ambient condition, subscript 1 represent state 1 of the system. While h and s denote the specific enthalpy and entropy respectively.

The change in the system entropy may be expressed as:

$$(s_1 - s_0) = C_p\text{In}\left(\frac{T_1}{T_0}\right) - R\text{In}\left(\frac{P_1}{P_0}\right) \quad (6)$$

where, C_p = specific heat at constant pressure and R = gas constant

Putting equation (6) into (4) we have:

$$Ex_{ph} = m\left[C_p(T_1 - T_o) - T_o\left[C_p\text{In}\left(\frac{T_1}{T_o}\right) - R\text{In}\left(\frac{P_1}{P_o}\right)\right]\right] \quad (7)$$

The heat capacity (C_p) is obtained by polynomial form as a function of temperature as given by equation (8) [8]:

$$C_p = a + bT + cT^2 + dT^3 \quad (8)$$

It should be noted that no chemical reaction or combustion takes place in the turbine and compressor. Hence, the chemical exergy value of both components will be considered to be zero.

Chemical Exergy:
For many fuels, the chemical exergy can be estimated on the basic of the lower heating value (LHV). The relation between the LHV and the chemical exergy for gaseous fuel with formular C_nH_m based on the atomic composition is given by [6, 7] as:

$$\varphi = \frac{e_f^{-ch}}{LHV} \cong 1.033 + 0.0169\frac{m}{n} - \frac{0.0698}{n} \quad (9)$$

where, φ is the ratio of fuel exergy and the lower heating value of the fuel and e_f^{-ch} is the fuel exergy. For the majority of gaseous fuel, the value of φ is normally close to 1. For fuel like methane, φ_{CH4} = 1.06 and for hydrogen fuel, φ_{H2} = 0.985 [9, 10].

The rate of chemical exergy flow can be expressed as:

$$Ex_{ch} = \dot{m}\, e_f^{-ch} \quad (10)$$

Exergy destruction overall (E_D) and overall exergy efficiency (η_{Π})
Exergy destruction of each component of gas turbine engine is given as [6, 7]:

$$E_D = Ex_{in} + Ex_{out} \quad (11)$$

The exergetic efficiency (η_{Π}) of each component of the gas turbine power plant is defined by [11]:

$$\eta_{\Pi} = \frac{Ex_{out}}{Ex_{in}} \quad (12)$$

Exergy-in (Ex_{in}), exergy-out (Ex_{out}), exergy destruction (E_D) and exergy efficiency (η_{Π}) on component bases are presented in Table 2.

Table 2: Exergy existing equilibrium of each component [2, 6]

Components	Ex_{in} (MW)	Ex_{out} (MW)	E_D (MW)	η_{Π} (%)
Compressor	$W_c + Ex_1$	Ex_2	$W_c + Ex_1 - Ex_2$	$\frac{Ex_2}{W_c + Ex_1}$
Combustion C.	$Ex_2 + Ex_5$	Ex_3	$Ex_2 + Ex_5 - Ex_3$	$\frac{Ex_3}{Ex_2 + Ex_3}$
Gas Turbine	Ex_3	$Ex_4 + W_{gt}$	$Ex_3 - (Ex_4 + W_{gt})$	$\frac{Ex_4 + W_{gt}}{Ex_3}$

Overall plant exergetic efficiency ($\eta_{II,Power\ plant}$)
The exergy efficiency of the entire power plant may be expressed as [12, 13]:

$$\eta_{\Pi,Power\ plant} = \frac{W_{net}}{Ex_5} \quad (13)$$

Where, W_{net} is the turbine Net-work and Ex_5 is the fuel (natural gas) entering the combustion chamber.

Average performance data of a-four-year period (2013, 2014, 2018 and 2019) from the operational log sheet is presented in Tables 3 at 80, 120 and 140 MW base loads, respectively. This information was used in computing the exergy efficiency of the plant.

Table 3: Thermodynamics performance parameters of the plant at 80, 120 and 140 MW base loads

Date	@ 80 MW base load							
	T_1 (K)	T_3 (K)	T_4 (K)	P_1 (Bar)	M_f (kg/s)	η_c %	η_t %	γ_a
2013	297	1289.85	432.0667	1.012	5	0.83	0.88	1.4
2014	304	1449.495	483.8495	1.007	6.1	0.83	0.88	1.4
2018	301	1420.551	450.385	1.006	5.9	0.83	0.88	1.4
2019	300	1406.065	456.1205	1.005	5.8	0.83	0.88	1.4

Date	@ 120 MW base load							
	T_1	T_3	T_4	P_1	M_f	η_c	η_t	γ_a
	(K)	(K)	(K)	(Bar)	(kg/s)	%	%	
2013	300	1483.638	497.1405	1.009	7.9	0.83	0.88	1.4
2014	298	1448.863	485.1829	1.007	7.6	0.83	0.88	1.4
2018	298	1448.863	486.4903	1.006	7.6	0.83	0.88	1.4
2019	300	1529.924	513.6623	1.007	8.3	0.83	0.88	1.4
Date	@ 140 MW base load							
	T_1	T_3	T_4	P_1	M_f	η_c	η_t	γ_a
	(K)	(K)	(K)	(Bar)	(kg/s)	%	%	
2013	299	1549.494	519.5146	1.01	8.6	0.83	0.88	1.4
2014	299	1572.231	526.6058	1.006	8.8	0.83	0.88	1.4
2018	302	1560.865	525.8094	1.012	8.7	0.83	0.88	1.4
2019	302	1515.345	489.1299	1.01	8.3	0.83	0.88	1.4

Source: FIPL Log Book, 2013-2019

where, T_1 is the compressor inlet temperature, P_1 is the compressor inlet pressure, T_3 is the flue gas temperature, T_4 is the turbine outlet temperature M_f is the mass of fuel, η_c is the compressor efficiency, η_t is the turbine efficiency, and γ_a is the specific heat ratio of air.

2.5 Formulation of reliability model for power plant assessment

Several models that are based on reliability function have been formulated and used in performing various types of reliability analysis. These models include:

2.5.1 Failure Density Model

This is defined by [14] as:

$$f(t) = -\frac{dR(t)}{dt} \quad (14)$$

Where t is time, f(t) is the failure (or probability) density function, and R(t) is the item reliability at time t.

2.5.2 Hazard Rate Model

This is expressed by [14] as:

$$\lambda(t) = \frac{f(t)}{R(t)} \quad (15)$$

where λ(t) is the item hazard rate or time-dependent failure rate.

By putting Equation (14) into Equation (15) we have,

$$\lambda(t) = -\frac{1}{R(t)}\frac{dR(t)}{dt} \quad (16)$$

2.6 General Reliability Model

The general reliability function can be obtained by using Equation (16). Thus, rearranging Equation (16), we have,

$$-\lambda(t)dt = \frac{1}{R(t)}\,dR(t) \quad (17)$$

Integrating both sides of Equation (17) over the time interval [0, t], we have

$$-\int_0^t \lambda(t)dt = \int_1^{R(t)} \frac{1}{R(t)}\,dR(t) \quad (18)$$

because at t = 0, R(t) = 1

Evaluating the right-hand side of Equation (18) yields

$$\text{In } R(t) = -\int_0^t \lambda(t)dt \quad (19)$$

Thus, from Equation (19), we have the following general expression for reliability function:

$$R(t) = e^{-\int_0^t \lambda(t)dt} \quad (20)$$

Equation (20) can be used to determine the reliability of an item when its time to failure follow any time-continuous probability distribution.

2.6.1 Mean Time to Failure Model

Mean time to failure is an important reliability measure and it can be obtained by using any of the following three formulas [15, 16]:

$$MTTF = \int_0^\infty R(t)\,dt \quad (21)$$

or

$$MTTF = \int_0^\infty t\,f(t)\,dt \quad (22)$$

or

$$MTTF = \lim_{s\to 0} R(s) \quad (23)$$

where s is the Laplace transform variable, MTTF is the mean time to failure, and R(s) is the Laplace transform of the reliability function R(t).

Substituting Equation (20) into Equation (14) yields

$$f(t) = -\frac{de^{-\lambda t}}{dt} = \lambda e^{-\lambda t}$$

(24)

Thus, substituting Equation (24) into Equation (22) yields

$$MTTF = \int_0^\infty t\lambda e^{-\lambda t}\,dt$$

$$= [-te^{-\lambda t}]_0^\infty - [-\frac{e^{-\lambda t}}{\lambda}]_0^\infty$$

$$= \frac{1}{\lambda}$$

(25)

Taking the Laplace transform of Equation (20), we get

$$R(s) = \int_0^\infty e^{-st}.e^{-\lambda t}.dt$$

$$= \frac{1}{s+\lambda}$$

(26)

Substituting Equation (26) into Equation (23) yields

$$MTTF = \lim_{s\to 0}\frac{1}{(s+\lambda)} = \frac{1}{\lambda}$$

(27)

Equation (23), Equation (25), and Equation (27) are identical, proving that Equations (21) - (23) give the same result. It should be noted that MTTF is used for non-repairable systems (i.e., systems with only one life). An example of this is a bulb. Alternative to MTTF is Mean time between failures (MTBF).

2.6.2 Mean Time between Failures Model

Mean time between failures (MTBF) measures the time between system failures. With MTBF, it is easier to understand than a probability number. For exponentially distributed failure modes, MTBF is a basic figure-of-merit for reliability (failure rate λ, is the reciprocal of MTBF). It is used for repairable systems; it is also applicable to this work. Thus, for a given mission time where high reliability is targeted, a long MTBF is required, mathematically [17]:

$$MTBF = 1/\lambda$$

(28)

where

λ - is the expected failure rate

and

$$\lambda = \frac{\beta_n}{\varphi_t}$$

(29)

where

β_n - number of failure between maintenance

φ_t - total operating time between maintenance

2.6.3 Mean Time to Repair Model

MTTR is defined as an arithmetic average of how fast a system is repaired. It is easier to visualize than a probability value. Mathematically,

$$MTTR = 1/\mu$$

(30)

where

μ – expected repair rate

2.7 Availability Model

Availability (ψ) is a measure of the percentage of time that an equipment is capable of producing its end product at some specified acceptable level. Mathematically, availability may be expresses as [14]:

$$\psi = \frac{\mu}{(\mu+\lambda)}$$

(31)

Alternatively,

$$\psi = \frac{MTBF}{MTBF+MTTR}$$

(32)

where,

MTBF - mean time between failures and,

MTTR - mean time to repair.

Hence,

$$MTTR = \frac{\sum_{i=1}^{n}\lambda_i M_i}{\sum_{i=1}^{n}\lambda_i}$$

(33)

where,

M_i The time needed to repair when component i fails (the maintenance time for preventive maintenance activity i)

n - Number of repaired components in the system

λ_i Failure rate of the i^{th} repairable component in the system ($\lambda_i = 1/MTBF_i$)

2.8 Reliability R(t)

Reliability refers to the probability of failure-free operations within a given time interval. It deals with reducing the failure frequency over a time interval. It is a measure of success for a failure-free operation. According to [17], it is expressed as:

$$R(t) = e^{-\left(\frac{t}{MTBF}\right)} = e^{-\lambda t} \quad (34)$$

where

R(t) – reliability at time t (in hours)

λ - Constant failure rate and

Reliability and availability data of the power plant for a-four-year period (2013, 2014, 2018 and 2019) is presented in Table 4. Operational data of year 2015 and 2016 were not available because the plant was not in operation at that time.

Table 4: Four-year outage frequency data for FIPL Afam [2]

	FIPL AFAM										
Year	Outages due to grid disturbances		Outages due to gas constraint		Outages due to system failure		Total outages		Period hours	Service hours	Active period
	Freq.	Dur. (hrs)	Freq.	Dur. (hrs)	Freq.	Dur. (hrs)	Freq.	Dur. (hrs)	(hrs)	(hrs)	
2013	53	332.78	16	1208.63	11	423.37	80	1964.78	8760	6795.22	Jan-Dec
2014	32	1088.8	11	2755.53	20	403.56	63	4247.90	8760	6720.10	Jan-Dec
2015	-	-	-	-	-	-	-	-	-	-	Nil
2016	-	-	-	-	-	-	-	-	-	-	Nil
2018	55	645.2	21	858.17	24	1421.45	100	2924.82	8760	5835.18	Jan-Dec
2019	10	204.3	8	280.15	10	339.72	28	824.17	2160	1335.83	Jan-Mar.

Note: Plant reliability was computed using the failure frequency □, at t = 100 hours (Source: FIPL Log Book, 2013-2019)

2.9 Computation of reliability parameters for year 2013

Mean time between failures (MTB)

MTBF (grid) = Period hours/number of failures = 8760/53=165.28

MTBF (gas) = Period hours /number of failures = 8760/16 =547.50

MTBF (sub-system) = Period hours /number of failures = 8760/11=796.36

MTBF (entire system) = Period hours /number of failures = 8760/80=109.50

Mean time to repair (MTTR)

MTTR (grid) = Downtime/number of failures = 332.78/53 = 6.2789

MTTR (gas) = Downtime/number of failures = 1208.63/16 = 75.5394

MTTR (sub-system) = Downtime/number of failures = 423.37/11= 38.4882

MTTR (entire system) = Downtime/number of failures = 1964.78/80 = 24.5598

Failure rate, λ

Failure rate (grid) = 1/MTBF = 1/165.28 = 0.006050 fault/hour

Failure rate (gas) = 1/MTBF = 1/547.50 = 0.001826fault/hour

Failure rate (sub-system) = 1/MTBF = 1/796.36 = 0001256 fault/hour

Failure rate (entire system) = 1/MTBF = 1/109.50 = 0.009132 fault/hour

Repair rate, μ

Repair rate (grid) = 1/MTTR = 1/6.2789 = 0.159264 fault/hour

Repair rate (gas) = 1/MTTR = 1/75.5394 = 0.013238 fault/hour

Repair rate (sub-system) = 1/MTTR = 1/38.4882 = 0.025982 fault/hour

Repair rate (entire system) = 1/MTTR = 1/24.5598 = 0.040717 fault/hour

Availability, Ψ

Availability (grid) = MTBF/(MTBF+MTTR) = 165.28/(165.28+6.279) = 0.9634

Availability (gas) = MTBF/(MTBF+MTTR) = 547.50/(547.50+75.54) = 0.8788

Availability (sub-system) = MTBF/(MTBF+MTTR) = 165.28/(165.28+6.279) = 0.9539

Availability (entire system) = MTBF/(MTBF+MTTR) = 165.28/(165.28+6.279) = 0.8168

Reliability, R(t)

Reliability (grid) = exp(-t/MTBF) = exp(-100/165.28) = 0.5461

Reliability (gas) = exp(-t/MTBF) = exp(-100/547.50) = 0.8331

Reliability (sub-system) = exp(-t/MTBF) = exp(-100/796.36) = 0.8820

Reliability (entire system) = exp(-t/MTBF) = exp(-100/109.50) = 0.4012

Table 5: Computed reliability parameters of the entire system for year 2013 to 2019

Reliability parameters	Years of operation			
	2013	2014	2018	2019
Number of Failures	80	63	100	28
Downtime (h)	1964.78	4247.90	2924.82	824.17
MTBF (h/fault)	109.50	139.05	87.60	77.14
MTTR (h/fault)	24.56	67.43	29.25	29.44
Failure rate, λ (fault/h)	0.0091	0.0072	0.0114	0.0129
Repair rate, μ (fault/h)	0.0407	0.0148	0.0342	0.0340
Availability, Ψ	0.8168	0.6734	0.7497	0.7238
Reliability, R(t)	0.881993	0.795877	0.760353	0.629415

2.10 Formulation of Bassy-II Model (Exergy efficiency and reliability relation)

The thermal efficiency of power generation system may be analysed based on energy or exergy analysis. For gas turbine system efficiency, exergy analysis is an ideal approach because of it ability to capture all possible energies of the system. The thermal efficiency (i.e, exergy efficiency) of gas turbine ranges between 0.25 to 0.40 depending on the made and size. Original equipment manufacturers (OEM) do specify the actual design efficiency for each plant type. It is important to note that the operating efficiency of gas turbine power plant may differ from (i.e., be lower, equal or a little higher than) the design efficiency. These changes in operating efficiency values is attributed to certain operational conditions the plant may be subjected to.

Hence, the analysis here expresses a modified exergy efficiency concept which is expressed as the ratio of operating exergy efficiency to the design exergy efficiency. With this concept, a common base of measurement is attained in comparing exergy performance index [2].

Mathematically, the modified plant exergetic efficiency (E) is expressed as:

$$E = E_o / E_d = \left(\frac{\text{Plant thermal efficiency}}{\text{Design efficiency}} \times 100\right) \quad (35)$$

Where,

E_o- Operating exergetic efficiency in percentage

E_d- Plant designed exergetic efficiency in percentage

Where,

$E_o = \eta_{II,\text{Power plant}}$ (the exergy efficiency of the entire power plant)

Since exergy efficiency and reliability indexes of power generation systems deteriorate with time, they are viewed as time derivative functions. Hence the combination of these two functions sees the development of a new measure called the Bassy-II index. Thus,

Let, R, be denoted as the plant reliability, and B, the proposed index (Bassy-II index).

Thus, B may be expressed mathematically as:

$$B = \left(1 - \frac{\left(\frac{(1-E)+(1-R)}{2}\right)}{(E+R)}\right) \quad (36)$$

Hence, B expresses a new plant state in dimensionless form.

It should be noted that the range of values of "B" is 0 to 1, and "B" is possible where $0.667 \geq (E+R) \leq 2$.

Further simplification of B shows that:

$$E(3 - 2B) + R(3 - 2B) = 2 \quad (37)$$

Thus;

$$E = (2/(3 - 2B)) - R \quad (38)$$

or

$$R = (2/(3 - 2B)) - E \quad (39)$$

For a fixed value of B, the values of E and R may vary.

Tables 6 shows the averagely computed values of E_o and E at base loads of 80, 120 and 140 MW for year 2013, 2014, 2018 and 2019. Also presented are the computed reliability and availability state of the plant for year 2013, 2014, 2018 and 2019. This information is used in the computation of the new plant state using the Bassy-II index.

Table 6: Performance measures at 80, 120 and 140 MW base load

Year	Performance Measures @ 80 MW Base Load			
	E_O (yearly average)	E (yearly average)	R	Ψ
2013	0.2806	0.7195	0.881993	0.81680
2014	0.2929	0.7510	0.795877	0.67344
2018	0.3045	0.7808	0.760353	0.74969
2019	0.2882	0.7389	0.629415	0.72382

Year	Performance Measures @ 120 MW Base Load			
	E_O (yearly average)	E (yearly average)	R	Ψ
2013	0.3087	0.7916	0.881993	0.81680
2014	0.3063	0.7854	0.795877	0.67344
2018	0.3032	0.7774	0.760353	0.74969
2019	0.3071	0.7875	0.629415	0.72382
Year	Performance Measures @ 140 MW Base Load			
	E_O (yearly average)	E (yearly average)	R	Ψ
2013	0.3389	0.8691	0.881993	0.81680
2014	0.3422	0.8775	0.795877	0.67344
2018	0.3355	0.8602	0.760353	0.74969
2019	0.32935	0.8445	0.629415	0.72382

Note: E_o and E values presented here are the computed yearly average values and not the values at any instant of the year.

3.0 RESULTS AND DISCUSSION

Four years operational data were sought from the operational data sheet and analysed. Reliability and availability state of the plant were computed from the failure frequency data as obtained from the plant (See Tables 4). Reliability analysis was performed at hundred (100) hours. Total available hours for operations in the years under study were 8760, 8760, 8760 and 2160 hours for year 2014, 2018 and 2019, respectively. Reliability and availability analysis were performed for each unit (Grid, gas and sub system) of the plant and also for the entire generation system.

Figure 3 presents the failure rate information of the plant. According to [18] and [5], higher failure rate indicates low reliability and availability values. The grid unit recorded a higher failure rate compared to the gas supply unit and the sub-system unit. The high values of failure rate for grid unit caused significant rise in the failure rate of the power generation system. In Figure 4, the sub-system and generation system availability showed a downward trend, corroborating [19]. Grid system availability decreased in year 2014 and peaked in the year 2018. There was a significant difference between the availability of the sub-system and that of the generation system. This difference was greatly caused by the availability of the grid system, indicating that the grid failed more often. The subsystem and grid availability were found to be slightly stable across the years.

According to [14, 18 and 20], system reliability decreases over a long period of time due to continuous wear and tear. This is evident in Figure 5, which shows a downward trend of the generation system reliability. The gas and the subsystem units were greatly responsible for the reliability state of the generation system. The generation system reliability deteriorated in 2018 and 2019 despite showing improvement in 2014. Generally, the gas supply system and sub-system reliability deteriorated over the years, indicating a poor gas service delivery and subsystem malfunctioning. However, the sub-system reliability expresses the true state of the power plant and not that of the entire generation system. Hence, the subsystem reliability is used in further analysis as the plant system reliability.

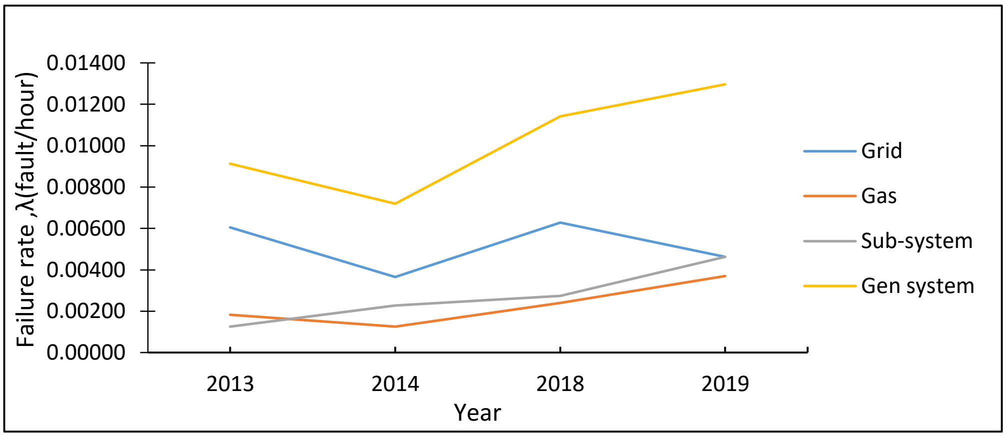

Fig 3: Failure rate of FIPL Afam for the years under study [2]

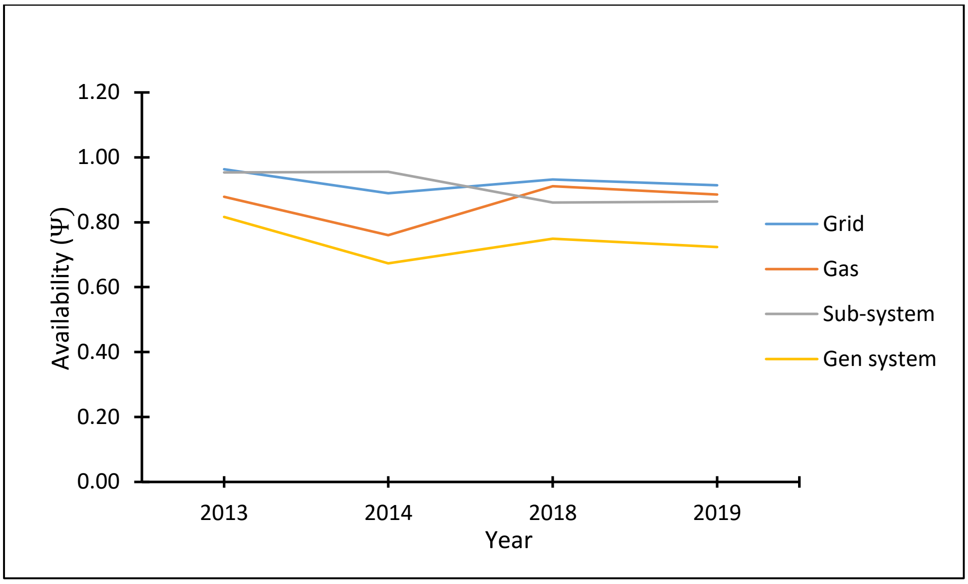

Fig 4: Availability of FIPL Afam for the years under study [2]

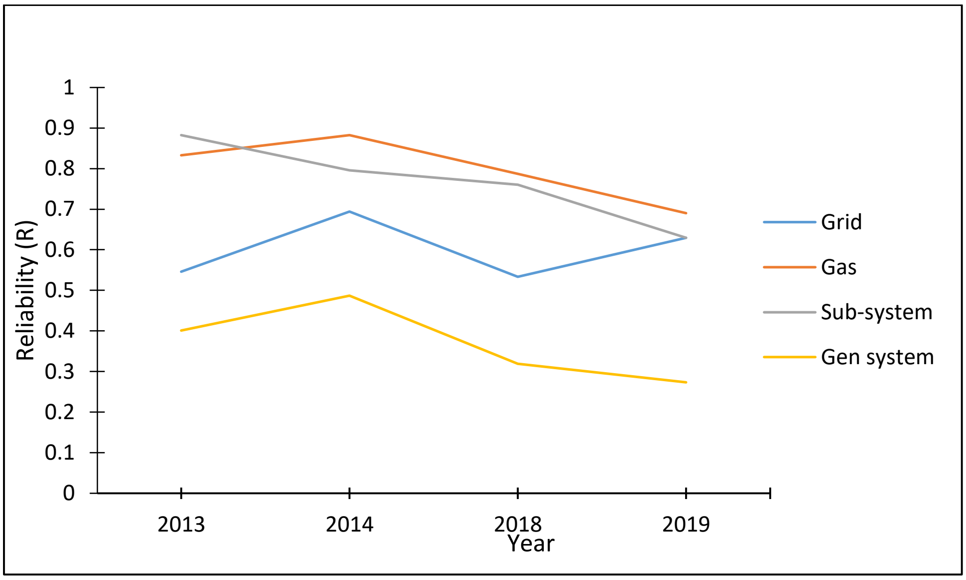

Fig. 5: Reliability of FIPL Afam for the years under study

The thermal efficiency of the plant which is also called the operating exergy efficiency is presented in Fig 6. This efficiency is compared at base load of 80, 120 and 140 MW. The result showed that the operating exergy efficiency increases with increase in base load thus signifying that gas turbine operations at higher base load are more efficient than at lower base load [21, 22, 25]. However, a decreasing trend of thermal efficiency was observed across the years for all base load corroborating with the time derivative theory [2, 23].

Result of Average operating exergy efficiency (E_o) and average exergy efficiency (E) of the plant at base loads of 80, 120 and 140 MW for the period under review (2013, 2014, 2018 and 2019) are presented in Figure 7 and 8 respectively.

The plant's performance with respect to Bassy-II Index is presented in Figure 9. At 140MW, the plant exhibited better performance compared to 80 and 120 MW base load. This is an indication that Bassy-II Index increases with increase in base loads. This behavior tallies with that of the exergetic performance [24]. Also, the downward trend effect of the plant reliability and exergy efficiency performance was also reflected in the plant performance based on the Bassy-II Index. The comparative performance of the plant with respect to other performance measures is also presented in Figure 10, 11 and 12 at base loads of 80, 120 and 140 MW respectively.

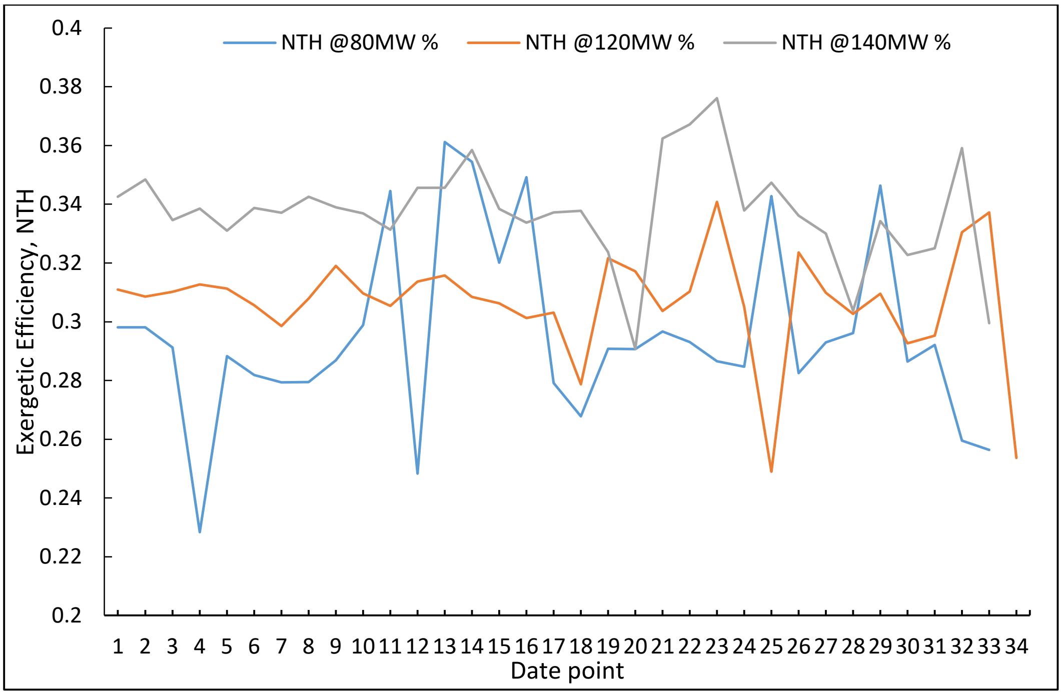

Fig. 6: Thermal efficiency (E_o) variation at base loads of 80, 120 and 140 MW [2]

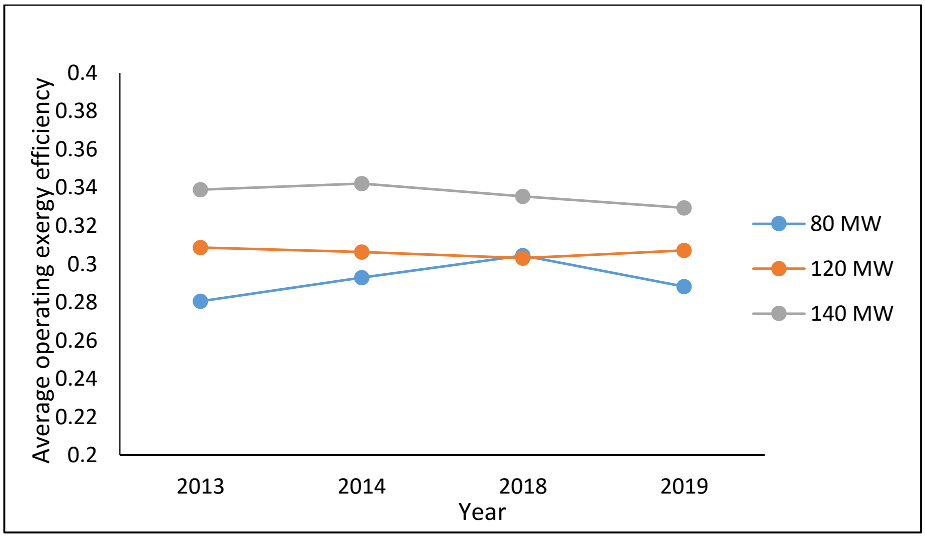

Fig. 7: Average operating exergy efficiency, Eo [2]

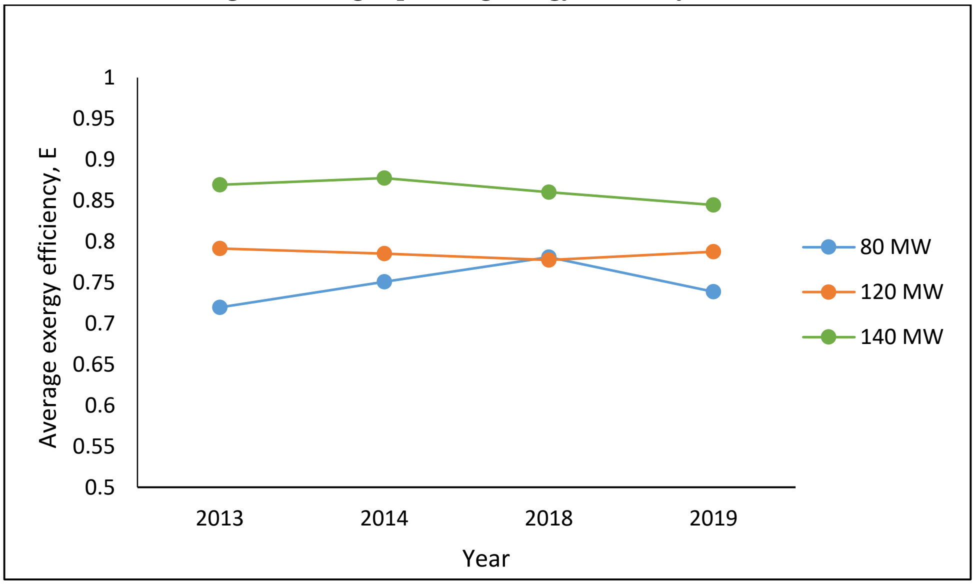

Fig. 8: Average Exergy efficiency, E at base load of 80, 120 and 140 MW [2]

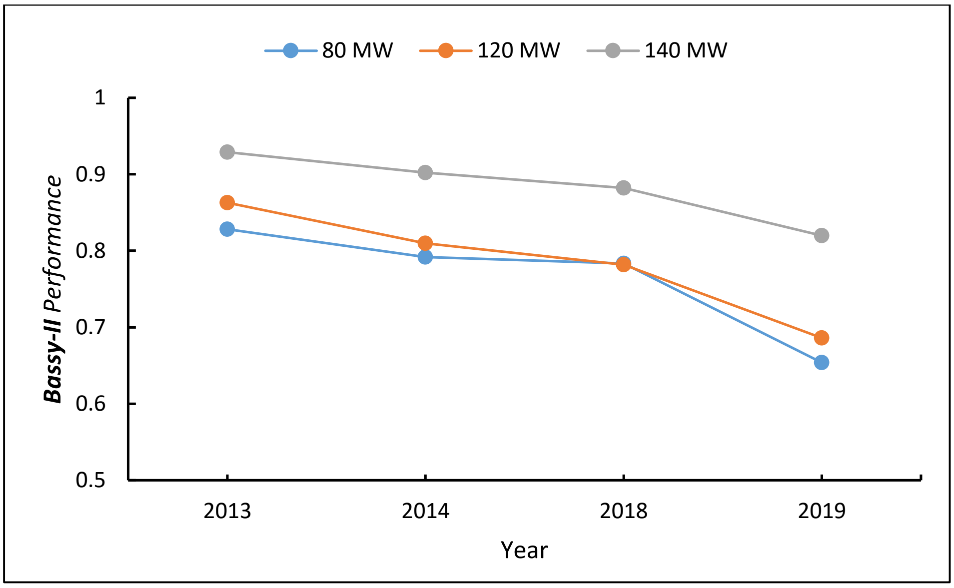

Fig. 9: Bassy-II performance measure at 80, 120 and 140 MW base loads

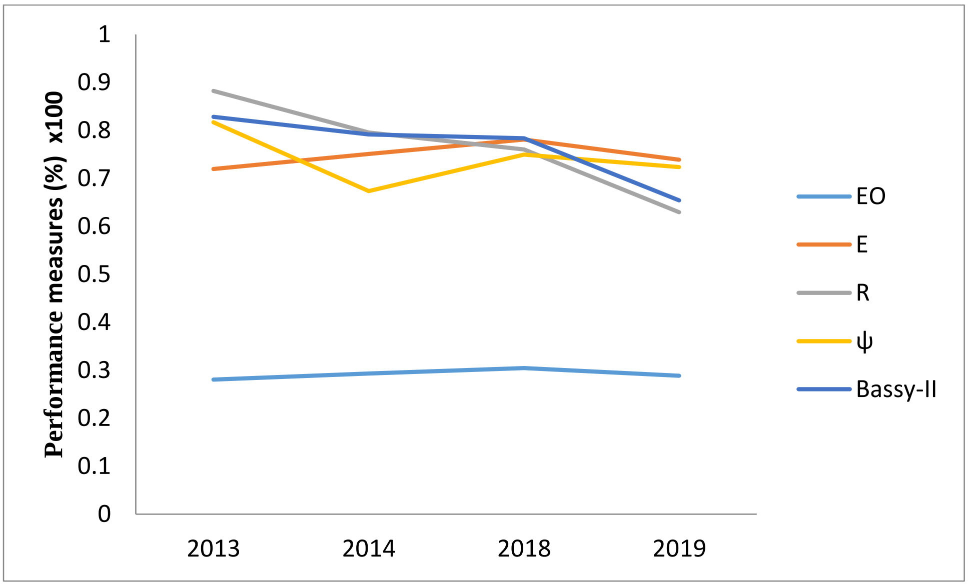

Fig. 10: Bassy-II performance with traditional measures at 80 MW base load

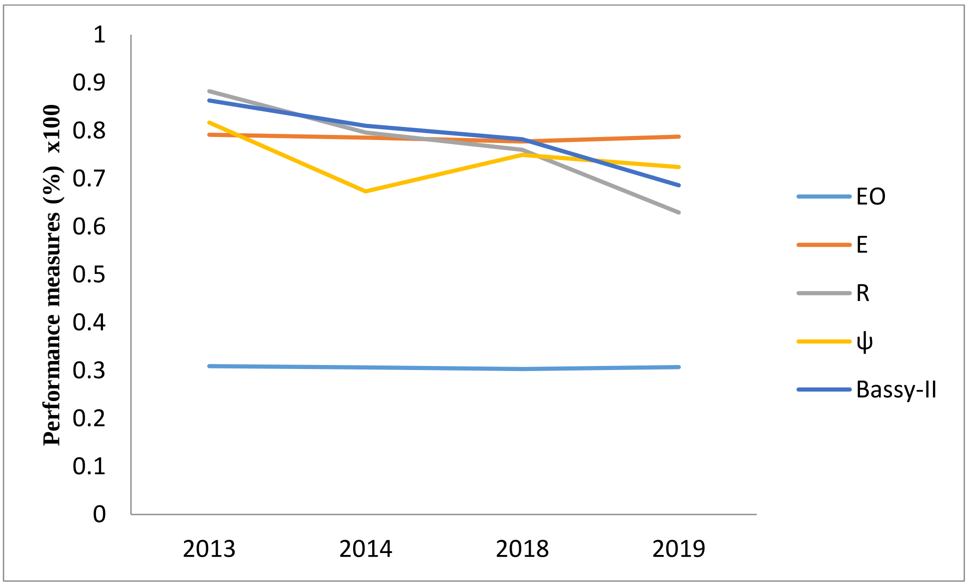

Fig. 11: Bassy-II performance with traditional measures at 120 MW base load

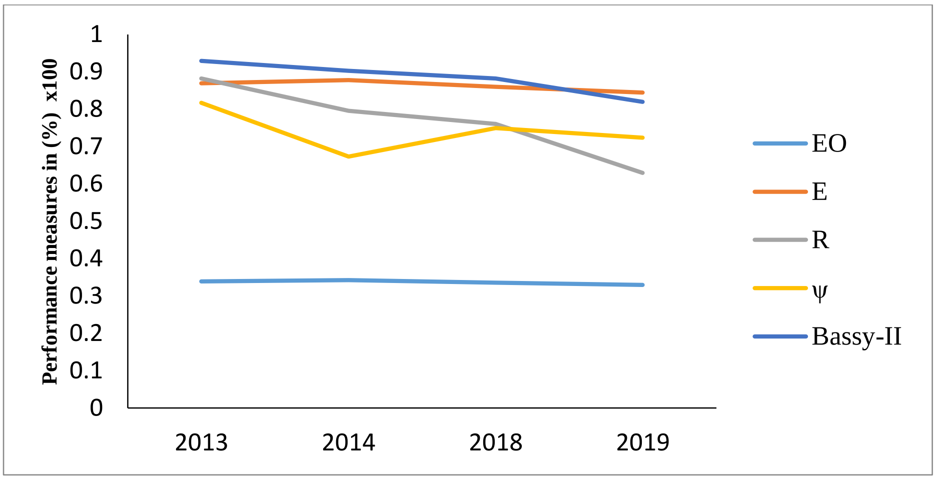

Fig. 12: Bassy-II performance with traditional measures at 140 MW base load

4.0 CONCLUSION

The performance of power generation systems have over the years been analysed using the Independent Assessment Approach (IAA). The IAA approach only assesses the system performance in part without recur to other indexes. Among the IAA measures are exergy efficiency, reliability and availability measures etc. In this study, the combined assessment approach (CAA) is explored, hence, giving rise to the development of a new measure called "Bassy-II index". The Bassy-II index combines two traditional indexes (reliability and exergy efficiency measure) hence, providing a new assessment criteria. The proposed Bassy-II index was used along with the traditional assessment measures such as reliability, availability, and exergy efficiency in the evaluation of FIPL power plant and the results of the IAA models were compared with Bassy-II index. Thus, exergy efficiency, reliability and availability measure showed the plant to be fairly rated. However, Bassy-II index defines a new plant state which is unique and represent the true status of the system in whole. Hence, this new measure (Bassy-II index) is recommended for use in heat driven power generation systems for holistic assessment of power generation systems.

5.0 COMPETING INTEREST

Authors have declared that no competing interest exists.

REFERENCES

1. Ibrahim Dincer and Calin Zamfirescu 2014. Advanced Power generation systems. Elsevier, Pg. 199-310;https://doi.org/10.1016/B978-0-12 383860-5.00005-5. https://www.sciencedirect.com/science/article/pii/B9780123838605000055.
2. Bassey, J.B. and Odesola, I.F. 2024. Performance Measures of Power Generation Systems. International Journal of Research in Engineering and Science (IJRES). Vol. 12(6), Pp: 139-151.
3. Bassey, J. B. and Odesola, I. F. 2020a. Effect of grid instability on power generation system's reliability. Journal of Engineering Research and Reports 11(1), 27-37. https://doi.org/10.9734/jerr/2020/v11i117053
4. Boroumandjazi, G.; Saidur, R.; Rismanchi, B. and Mekhilef, S. 2012. A review on the relation between the energy and exergy efficiency analysis and the technical characteristic of the renewable energy systems. Renewable and Sustainable Energy reviews 16: 3131-3135.
5. Oyedepo, S. O.; Fagbenle, Richard O. and Adefila, Samuel S. 2015a. Assessment of performance indices of selected gas turbine power plants in Nigeria. Energy Science and Engineering; 3(3): 239–256, doi: 10.1002/ese3.61
6. Bassey, J.B.; Odesola, I.F. and Asobinonwu, D.A. 2020b. Estimation of maximum cycle temperature and pressure ratio for optimum design and operations of gas turbine power plant. Asian Journal of Advanced Research and Reports 9(4): 40-51. https://doi.org/10.9734/ajarr/2020/v9i430230.
7. Moran, M.J. and Shapiro, H. N. 2010. Fundamentals of engineering thermodynamics. 6th edition, John Wiley & Sons.
8. Cengel, A.Y. and Boles, M.A. 2006. Thermodynamics engineering approach, Fifth Edition, McGraw Hill Companies, New York, USA.
9. Kotas, T.J. The Exergy Method of Thermal Plant Analysis, Butterworths, Essex, UK. 1985.
10. Oladiran, M. and Meyer, J. 2007.Energyand exergy analyses of energyconsumptions in the industrial sector in South Africa.South Afr.,Elsevier publisherVol. 84: pp.1056-1067.
11. Bejan, A.; Tsatsaronis, G. and Moran, M. 1996. Thermal Design and Optimization. J. Wiley & Sons Edition.
12. Eke, M.N., Okoroigwe, E.C., Umeh, S.I. and Okonkwo, P. 2020. Performance improvement of a gas turbine power plant in Nigeria by exergy analysis: a case of Geregu 1. Open Access Library Journal Vol. 7: e6617.

https://doi.org/10.4236/oalib.1106617

13. Eke, M.N., Onyejekwe, D.C., Iloeje, C.O., Ezekwe, C.I. and Akpan, P.U. 2018. Energy and exergy evaluation of a 220 mw thermal power plant. Nigerian Journal of Technology (NIJOTECH) Vol. 37(1): pp. 115-123.
14. Dhillon, B. S. 2006. Maintainability, maintenance, and reliability for engineers. CRC Press, Taylor & Francis Group, 6000 Broken Sound Parkway NW, Suite 300 Boca Raton, FL 33487-2742. ISBN 0-8493-7243-7.
15. Stevenson, C. 1995. Software engineering productivity, Chapman and Hall, London.
16. Martin, J. 1985. Fourth-generation languages, Vol. 1, Englewood Cliffs, NJ. : Prentice Hall.
17. Stapelberg, R.F.2009. Handbook of reliability, availability, maintainability and safety in engineering design. Springer, London. https://doi.org/10.1007/978-1-84800-175-6_4.
18. Kapur, K. C. and Pecht, M. 2014. Reliability engineering: wiley series in systems engineering and management. New Jersey, John Wiley and Sons Inc.
19. Eti, M.C.; Ogaji, S.O.T. and Probert, S.D. 2007. Integrating reliability, availability, maintainability and supportability with risk analysis for improved operation of the Afam thermal power-station. Applied Energy Vol. 84(2): pp. 202-221, https://doi.org/10.1016/j.apenergy.2006.05.001.
20. Morrow, L.C., Ed. 1957. Maintenance engineering handbook.New York, McGraw-Hill.
21. Egware, H.; Obanor, A. and Itoje, H. 2014. Thermodynamic evaluation of a 42 MW gas turbine power plant. International Journal of Engineering Research in Africa Vol. 12: pp. 83-94
22. Bassey, J.B., Ekpo, D.D. and Gentle, V.U. 2024. Computational Fluid Dynamics Analysis of Flow Characteristics in Convergent and Divergent Sections. International Journal of Science, Engineering and Technology. Vol. 12(2). Pp.1-7
23. Martin, A.; Miswandi, P.; Kurniawan, I. and Romy 2016. Exergy analysis of gas turbine power plant 20 MW in Pekanbaru-Indonesia. International Journal of Technology. Vol. 5. Pp. 921-927.
24. Abam, F.I.; Ugot, I.U. and Igbong, D.I. 2012. Components irreversiblities of a (25 MW) gas turbine power plant modeled with a spray cooler. American J. of Engineering and Applied SciencesVol. 5(1): pp. 35-41.
25. Bassey, J.B and Okposin, W.A. 2024. Design and Development of A Dual Powered Air Compressor for Tyre Inflation. International Journal of Recent Research in Civil and Mechanical Engineering (IJRRCME). Vol. 11(1). Pp. 19-29. Paper publisation.
26. First Independent Power Limited (FIPL) Log sheet, 2013-2019. Accessed on: January, 2020