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ENERGY AND EXERGY ANALYSIS OF A 75MW STEAM POWER PLANT IN SAPELE (NIGERIA)

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Abstract— This research deals with Energy and Exergy analysis of Sapele steam power plant in Nigeria. The key point in this paper is to identify areas where energy losses are occurring and develop a model that will ensure efficient and effective improvement in a thermal power station. This was accomplished by conducting energy analysis of the overall plant and determination of the efficiencies and energy losses of all the major parts on the power plant in light of experimental data collected from Sapele power plant in Nigeria. Areas where energy losses are being experienced in the plant were pinpointed. It was deduced that energy losses occurred fundamentally in the boiler where 105KW was lost to the surrounding while just 15.7 KW was lost from the condenser system. The rate proportion of the exergy destruction was discovered to be greatest in the boiler system (105.9%) trailed by the turbine (86.53%), and after that the condenser (62.5%). Moreover, the exergy efficiency of the power plant was 11.003% for boiler, 30.315% for turbine and 59.8% for condenser. For a moderate change in the reference environment state temperature, no exceptional change was seen in the execution of major components and the principle conclusion continued as before; the boiler is the significant wellspring of irreversibilities in the power plant. Synthetic response is the most noteworthy wellspring of exergy destruction.

Keywords— Energy analysis, exergy analysis, power plant, exergy destruction, exergy efficiency, mass balance, energy balance, thermodynamic second law.

I INTRODUCTION

The twenty- first century is forming into a perfect energy storm. This is evidence from rising energy prices, diminishing energy availability, and growing environmental concern. All these factors are quickly changing the global energy panorama. Energy and water are the key to modern life and they provide the basic necessities for sustained economic development. Industrialized Nations have become increasingly dependent on fossil fuel for myriad uses. Modern appliances, and machines are sustained through the exploration of expensive fossil fuels. Securing sustainable and future energy supplies will be the greatest challenge faced by all Nations in this century [1].

Power generation in Nigeria fluctuates between 2000 and 35000 megawatts forcing the citizens to rely on generators, which gulp N3.5tn annually and a whopping N1.75tn in the past five years. Despite the huge government investment in the power sector in the last 16 years, Nigeria has only succeeded in mustering an installed electricity generation capacity of 10000 megawatts. Yet the country operates at about 30% of this capacity with generation fluctuating between 2000 and 35000MW. Painfully, per capita electricity usage in the country remains 136 kilowatt. This is one of the lowest electricity consumption on a per capita basis in the world when compared with the average per capita electricity usage in Libya, which is 4270KWH; India, 616KWH; China, 2944KWH, South Africa, 4803KWH, Singapore, 8307KWH; and the United State of America, 13,394KWH.

It is important that fossil fuel plants reduce their negative environmental impact by operating more efficiently. However, with the increasing demand for one of the world essential commodity the need for the optimization, and increasing the efficiency of power plant performance arises. Generally, the performance of thermal power plant is evaluated through energetic performance criteria based on first law of thermodynamics, including electrical power and thermal efficiency. In recent decades, the energetic performance based on the second law of thermodynamics has found a useful method in the design, evaluation, optimization and improvement in thermal power plants. Sarang j et al, 2013 [2] defined exergy as the useful work potential of a system is the amount of energy we extract as useful work. The useful work potential of a system at the specified state is called exergy. Exergy is a property and is associated with the state of the system and the environment. Exergy analysis is an effective means, to pinpoint losses due to irreversibility in a real situation [3].

Exergy is a generic term for a group of concepts that define the maximum possible work potential of a system, a stream of matter or heat interaction; the state of the environment being used as the datum state. In an open flow system there are three types of energy transfer across the control surface namely working transfer, heat transfer, and energy associated with mass transfer or flow [4]. The work transfer is equivalent to the maximum work, which can be obtained from that form of energy. The exergetic performance analysis cannot only determine magnitudes, location and causes of irreversibility in the plants, but also provides more meaningful assessment of plants' individual component's efficiency, these points of the energetic performance analysis are the basic differences from exergetic performance analysis [5]. Therefore it can be said that performing energetic and exergetic analysis together can give a complete depiction of system characteristics.

Such a comprehensive analysis will be a more convenient approach for the performance evaluation and determination of the steps towards improvement. Exergy of a thermodynamic process shows efficiency and inefficiency of that process. Exergy provides us with a better understanding of processes for qualifying energy. Therefore, it would be better to use exergy to locate, qualify and quantify energy destruction. Exergy can play an important role in strategic development of power plants and provision of use of instruction in existing power plant. As energy analysis is based on the first law of thermodynamics, it has some inherent limitations such as accountability for the properties of the systemic degradation of energy quality through dissipative processes [6]. An energy analysis does not characterize the irreversibility of processes within a system. In contrast, exergy analysis will characterize the work potential from a system. Exergy is the maximum work that can be obtained from the system, when its state is brought to the reference or ‘’dead state (standard atmospheric condition). Exergy analysis is based on the second law of thermodynamics [7].

This research deals with exergetic and energetic performance analysis of each component of steam power plant, in order to determine the needed improvement and identify the methods of reducing the energy losses in the power plant.

II METHODOLOGY

A. Plant Description

Sapele power plc, Sapele is a thermal generating station located in Nigeria’s gas-rich Delta State. Sapele has an installed capacity of 1020MW. It powers six, 120MWsteam turbines which generate a daily average of 86.72MWH/H or approximately 2500GW/H annually. Sapele power plant currently operates at peak capacity of 972MW.

Sapele power plan is strategically located in Niger Delta region close to sources of both natural gas feed stock and a river for cooling its steam turbine generators. Sapele power plant includes an updated control room, a switch gear room, a staff training school and medical and recreation facilities. It began operations in 1978. Figure 3.1 displays a schematic diagram for a 70MW unit of a power plant.

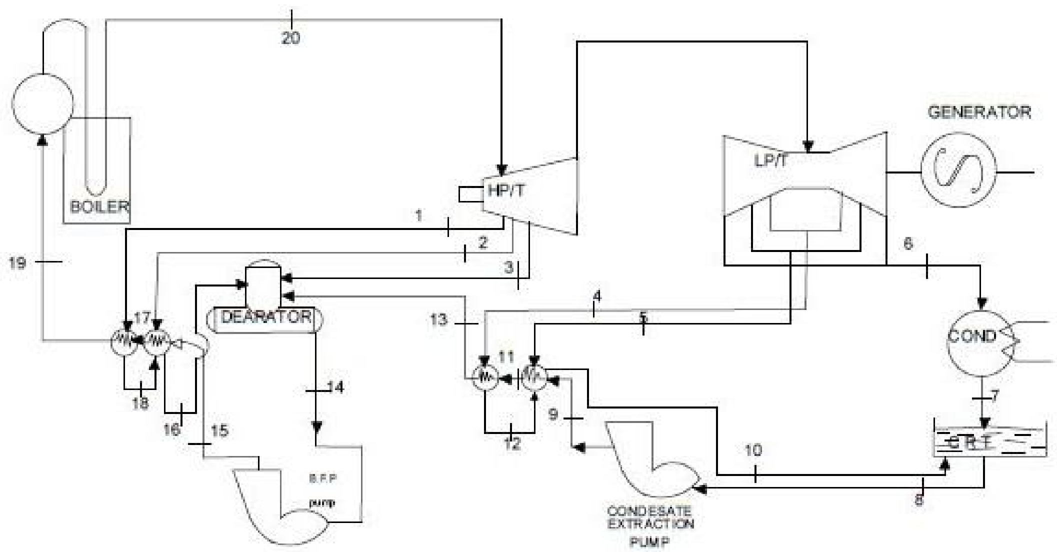

Fig. 1 Schematic diagram of the power plant, [8].

TABLE 1
OPERATING CONDITION OF THE POWER PLANT, Sapele 1978

Operating condition	Value
Acting Power	70MW
Reacting Power @ generator	15MVAR
Frequency	50.9
Turbine Power Output	120
Feed Water Pressure	200Kg/cm^2
Extraction Steam Pressure	5Kg/cm^2
Extraction Steam mass flow rate	103.438Kg/s
Thermal Efficiency	35%

TABLE 2
PROPERTIES OF HEAVY OIL USED IN SAPELE POWER PLANT FOR MARCH 2015

Property	Value
Flash point	210°C
Kinematic Viscosity @ 40°C	65.69cSt
Boiling point	316°C
Specific gravity	0.87
Density @15°C	869kg/m^3
vapour pressure@20°C	0.1mmHg
Vapour density	1

B. *Energy Analysis Of Component In The Power Plant*

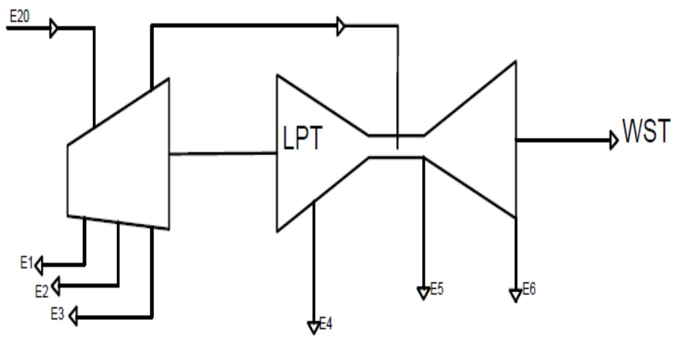

Fig. 2 Steam turbine

- Mass balance

$$M_{20} = M_1 + M_2 + M_3 + M_4 + M_5 + M_6 \quad [1a]$$

- Energy Balance

$$M_{20}h_{20} = M_1h_1 + M_2h_2 + M_3h_3 + M_4h_4 + M_5h_5 + M_6h_6 + W_{turbine} \quad [1b]$$

- Exergy Destruction

$$E_{in} - E_{out} + W_{turbine} \quad [1c]$$
$$E_{in} = E_{20}$$
$$E_{out} = E_1 + E_2 + E_3 + E_4 + E_5 + E_6$$

- Work Output (W) = $W_{turbine}$ = 16.78KW

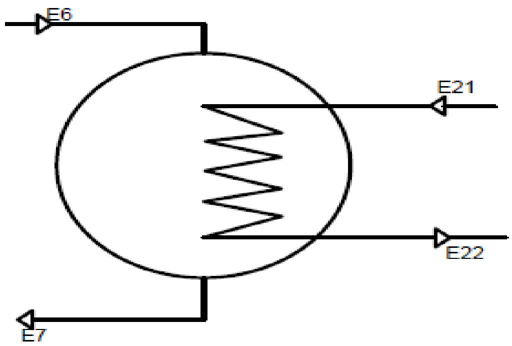

Fig. 3 Condenser

- Mass Balance

$$M_6 + M_{21} = M_7 + M_{22} \quad [2a]$$

- Energy Balance

$$M_6h_6 + M_{21}h_{21} = M_7h_7 + M_{22}h_{22} \quad [2b]$$
$$E_{in} = E_6 + E_{21}$$
$$E_{out} = E_7 + E_{22}$$

- Exergy Destruction.

$$E_{in} - E_{out} \quad [2c]$$

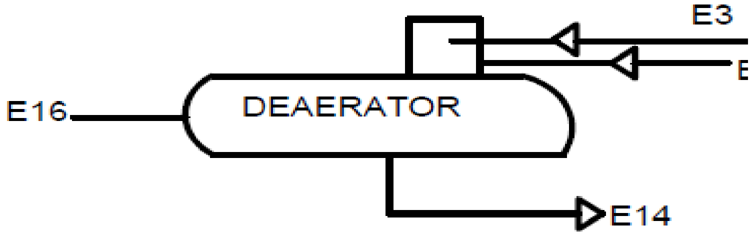

Fig. 4 Deaerator

- Mass Balance

$$M_3 + M_{13} + M_{16} = M_{14} \quad [3a]$$

- Energy Balance

$$M_3 h_3 + M_{13} h_{13} + M_{16} h_{16} = M_{14} h_{14} \quad [3b]$$

- Exergy Destruction

$$E_{in} - E_{out} \quad [3c]$$
$$E_{in} = E_3 + E_{13} + E_{16}$$
$$E_{out} = E_{14}$$

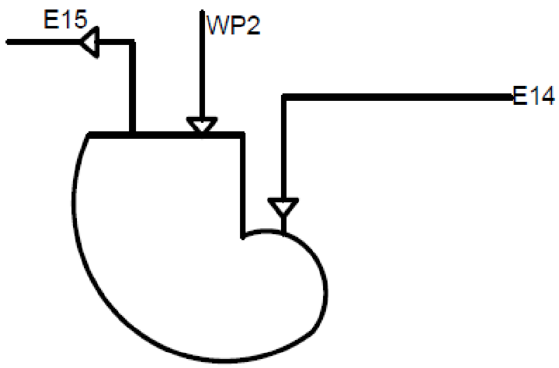

Fig. 5 Boiler feed pump

- Mass Balance

$$M_{14} = M_{15} \quad [4a]$$

- Energy Balance

$$M_{14} h_{14} = M_{15} h_{15} \quad [4b]$$

- Exergy Destruction.

$$E_{in} - E_{out} + W_{PZ} \quad [4c]$$
$$E_{in} = E_{14}$$
$$E_{out} = E_{15}$$

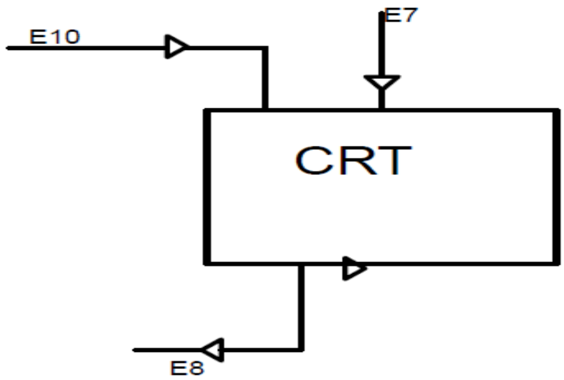

Fig. 6 Condensate receive tank (C.R.T)

- Mass Balance

$$M_7 + M_{10} = M_8 \quad [5a]$$

- Energy Balance

$$M_7 h_7 + M_{10} h_{10} = M_8 h_8 \quad [5b]$$

- Exergy Destruction.

$$E_{in} - E_{out} \quad [5c]$$
$$E_{in} = E_7 + E_{10}$$
$$E_{out} = E_8$$

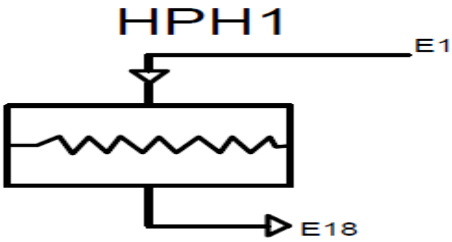

Fig. 7 High pressure heater 1

- Mass Balance

$$M_1 + M_7 = M_{18} \quad [6a]$$

- Energy Balance

$$M_1 h_1 + M_{17} h_{17} = M_{18} h_{18} \quad [6b]$$

- Exergy Destruction

$$E_{in} - E_{out} \quad [6c]$$
$$E_{in} = E_1 + E_{17}$$
$$E_{out} = E_{18}$$

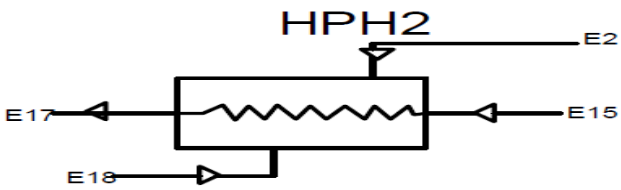

Fig. 8 High pressure heater 2

- Mass Balance

$$M_2 + M_{15} + M_{18} = M_{17} \quad [7a]$$

- Energy Balance

$$M_2 h_2 + M_{15} h_{15} + M_{18} h_{18} = M_{17} h_{17} \quad [7b]$$

- Exergy Destruction

$$E_{in} - E_{out} \quad [7c]$$
$$E_{in} = E_2 + E_{15} + E_{18}$$
$$E_{out} = E_{17}$$

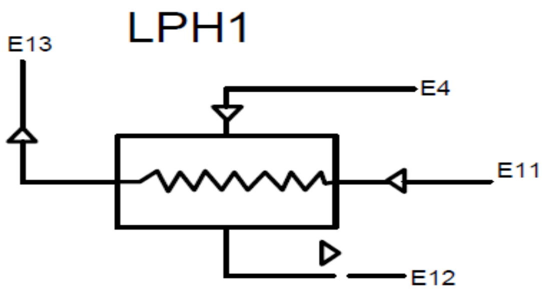

Fig. 9 Low pressure heater 1

- Mass Balance

$$M_4 + M_{11} = M_{12} + M_{13} \quad [8a]$$

- Energy Balance

$$M_4h_4 + M_{11}h_{11} = M_{12}h_{12} + M_{13}h_{13} \quad [8b]$$

- Exergy Destruction

$$E_{in} - E_{out} \quad [8c]$$
$$E_{in} = E_4 + E_{11}$$
$$E_{out} = E_{12} + E_{13}$$

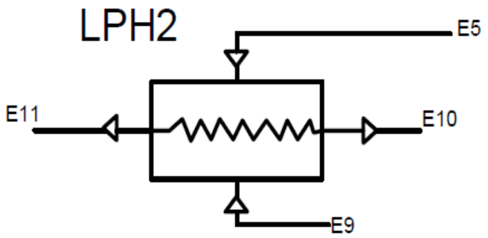

Fig. 10 Low pressure heater 2

- Mass Balance

$$M_5 + M_9 = M_{10} + M_{11} \quad [9a]$$

- Energy Balance

$$M_5h_5 + M_9h_9 = M_{10}h_{10} + M_{11}h_{11} \quad [9b]$$

- Exergy Destruction

$$E_{in} - E_{out} \quad [9c]$$
$$E_{in} = E_5 + E_9$$
$$E_{out} = E_{10} + E_{11}$$

III. RESULT AND DISCUSSION

A. Analysis With A Full Load Operation Condition

Energy and exergy analysis has been performed in details in accordance with theoretical expression parameter and assumptions mentioned in chapter 3 and 4 all of the important components, subsystems and the entire system had been covered in analysis with full load operation condition.

The power plant was analyzed using the above relation nothing that the environment reference temperature and pressure are 298K and 1.013bar respectively.

The distribution of energy addition exergy losses and exergy consumption for different components has been worked out on the basis of analysis exergetic efficiency for boiler; turbine and other components have been calculated.

TABLE 3
THE EXERGY DESTRUCTION RATE AND EXERGY EFFICIENCY EQUATION FOR PLANT COMPONENTS

	Exergy destruction rate	Exergy efficiency
Boiler	$\dot{I} = X_{FUEL} + X_{in} - X_{out}$	$\eta_{II,boiler} = \frac{\dot{X}_{out} - \dot{X}_{in}}{\dot{W}_{fuel}}$
Pump	$\dot{I}_{PUMP} = X_{IN} - X_{OUT} + W_{PUMP}$	$\eta_{II,PUMP} = 1 - \frac{\dot{I}_{PUMP}}{\dot{W}_{PUMP}}$
Heater	$\dot{I}_{heater} = X_{IN} - X_{OUT}$	$\eta_{II\ heater} = 1 - \frac{\dot{I}_{heater}}{\dot{X}_{in}}$
Turbine	$\dot{I}_{Turbine} = X_{in} - X_{out} - \overline{W}_{el}$	$\eta_{II\ turbine} = 1 - \frac{\dot{I}_{Turbine}}{\dot{X}_{in} - \dot{X}_{out}}$
Condenser	$\dot{I}_{Condenser} = X_{IN} - X_{out} - W_F$	$\eta_{II\ condenser} = \frac{\dot{X}_{out}}{\dot{X}_{in} + \dot{W}_f}$
Cycle	$\dot{I}_{Cycle} = \sum_{all\ componet} \bar{I}_i$	$\eta_{II\ cycle} = \frac{\dot{W}_{net,out}}{\dot{X}_{fuel}}$

Mass, energy, and exergy balances for any control volume at steady state with negligible potential and kinetic energy changes can be expressed, respectively, by

$$\sum \dot{m}_i = \sum \dot{m}_e$$

$$\dot{Q} - \dot{W} = \sum \dot{m}_e \dot{h}_e - \sum \dot{m}_i \dot{h}_i \qquad [10]$$

$$X_{heat} - w = \sum \dot{m}_e \Psi_e - \sum \dot{m}_i \Psi_i + \dot{I} \qquad [11]$$

where the net exergy transfer by ($\dot{X}_{heat}$) at temperature T is given by

$$\dot{X}_{heat} = \sum \left(1 - {}^{T_o}/_{T}\right) Q \qquad [12]$$

and the specific exergy is given by

$$\Psi = h - h_o - T_o(s - s_o) \qquad [13]$$

Then the total exergy rate associated with a fluid stream becomes

$$\dot{X} = \dot{m}\Psi = m[h - h_o - T_o(s - s_o)] \qquad [14]$$

TABLE 4
ENERGY ANALYSIS OF THE POWER PLANT WHEN T = 298.15K, P= 101.3KPA

POINT	T(K)	P(mpa)	M(ton/h)	h(kj/kg)	s(kj/kgk)	Ψ(kj/kg)	X(MW
1	628.4	3.0071	16.72	3128.6	6.7643	1117.434	5.189861
2	514.3	1.8713	13.82	2887.5	6.5614	936.7984	3.596265
3	439.9	0.4219	15.41	2789.33	7.01229	704.2632	3.014638
4	434.2	0.3131	12.73	2784.65	7.1316	664.0288	2.34808
5	375.7	0.0813	5.43	2687.68	7.7085	395.1426	0.596007
6	331.7	0.0118	198.62	2608.62	8.2219	163.089	16.998005
7	318.9	0.0118	198.62	192.202	0.7038	12.9348	0.71364
8	318.9	0.0113	211.00	191.362	0.70132	13.0358	0.76404
9	311.1	2.5170	211.00	190.42	0.7178	18.8888	1.10709
10	314.2	0.0113	19.15	197.39	0.6747	0.925	0.00492
11	320.2	0.0319	211.00	274.67	0.899	11.3636	0.666033
12	326.2	0.0843	12.73	301.15	0.9727	15.881	0.056157
13	430.9	0.3968	211.00	418.14	1.2832	40.342	2.364489
14	438.9	1.0020	265.00	580.94	1.6800	84.8956	6.249259
15	456.5	12.5859	265.00	596.55	1.6731	102.5618	7.549688
16	445.1	0.9700	42.71	615.58	1.7465	99.7186	1.18305
17	433.1	10.223	265.00	731.49	1.9796	146.1648	10.75935
18	436.1	1.9814	15.70	748.34	2.2127	93.551	0.407986
19	484.6	9.9280	265.00	877.52	2.4625	148.2906	10.91584
20	783.5	8.7280	265.00	2608.32	6.6669	626.1794	108.09376
Output air	318.15	0.1013	23.900	444.68	3.9468	726.871	4.82561

TABLE 5
TOTAL EXERGY TEMPERATURE RATE AT DIFFERENT REFERENCE ENVIRONMENT TEMPERATURE

	283	288	293	298	303
1	5.643	5.490	5.339	5.189	5.042
2	3.959	3.836	3.715	3.596	3.478
3	3.448	3.302	3.157	3.015	2.873
4	2.713	2.589	2.468	2.348	2.229
5	0.765	0.707	0.652	0.596	0.541
6	15.591	13.373	11.176	8.998	6.841
7	0.343	0.486	0.690	0.714	0.796
8	0.372	0.524	0.654	0.764	0.851
9	0.701	0.858	0.993	1.108	1.199
10	0.038	0.025	0.0142	0.005	0.002
11	1.232	1.022	0.833	0.666	0.521
12	0.094	0.080	0.067	0.056	0.046
13	3.268	2.945	2.646	2.364	2.106
14	7.822	7.271	6.747	6.249	5.779
15	9.115	8.566	8.045	7.549	7.082
16	1.448	1.355	1.267	1.183	1.1033
17	12.663	12.001	11.367	10.759	10.179
18	0.536	0.492	0.449	0.408	0.368
19	13.352	12.513	11.702	10.915	10.157
20	53.173	50.786	48.427	46.049	43.788
0utput air	4.458	4.583	4.705	4.826	4.943

TABLE 6
CALCULATED RESULT OF EXERGY EFFICIENCY AND EXERGY DESTRUCTION OF DIFFERENT COMPONENTS OF THE PLANT.

COMPONENTS	Ein (KW)	Eout (KW)	W (KW)	Ed (KW)	% ED	% EF	% OF TOTAL ED
TURBINE	108.094	31.743	16.78	93.1307	86.1574	29.3662	42.284547
HPH1	15.9494	14.363	0	1.5864	9.94646	2.55797	0.72028033
HPH2	11.5538	10.7594	0.7154	0.7944	6.87566	93.1243	0.36068497
LPH1	3.01408	2.4205	1.276	0.59358	19.6936	80.3064	0.26950577
LPH2	1.7031	0.6709	0.19	1.0322	60.6071	39.3929	0.46865437
CRT	0.7186	0.691	0	0.0276	3.84081	96.6135	0.01253135
BOILER FEED PUMP	6.2493	6.113	1.268	1.4043	22.4713	97.819	0.63760059
DEAERATOR	6.5621	6.2493	0.015	0.3128	4.76677	95.2332	0.14202198
CONDENSER	16.998	5.131	3.81	15.6776	62.8135	59.601	7.11817064
BOILER	108.092	10.9158	8.5123	105.688	89.9014	97.777	47.9859939

TABLE 7
REFERENCE TEMPERATURE AGAINST CALCULATED RESULT OF EXERGY EFFICIENCY OF DIFFERENT COMPONENTS OF THE PLANT.

Ref T	BOILER % EF	TURBINE % EF	CONDENSER % EF
283	11.003	30.315	58.719
288	10.72	30.001	59.001
293	10.411	29.781	59.301
298	10.099	29.366	59.601
303	9.79	28.913	59.813

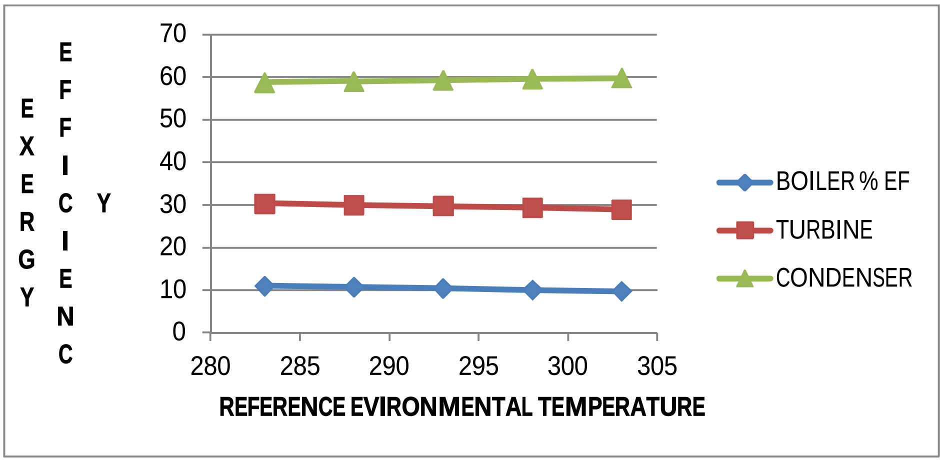

Fig. 11 Graph of reference temperature against exergy efficiency of different components

Fig. 11 shows results of reference temperature against exergy efficiency. It can be deduced that the exergy efficiency decreases considerably as the reference temperature increases. The boiler decreases from 11% to 9.79% as the temperature increases, the turbine reduces from 30% to 28.9% while the condenser increases from 58.7% to 59.8%. This decrease is due to the inability of the components to harness the exergy.

TABLE 8
EXERGY EFFICIENCY OF DIFFERENT COMPONENTS OF POWER PLANT.

COMPONENTS	**HPH1**	**TURBINE**	**HPH2**	**LPH1**	**LPH2**	**CRT**	**BOILER FP**	**DEAERATOR**	**CONDENSER**	**BOILER**
% EF	2.557965	2.557965	93.12434	80.30643	39.39287	96.6135	97.819	95.23323	59.601	10.09862

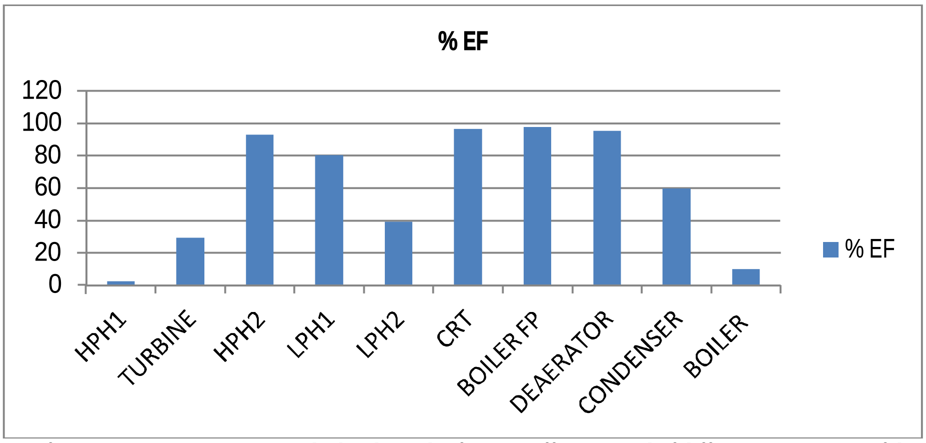

Fig. 12 Reference temperatures against calculated Result of exergy efficiency and of different components of the plant.

Fig. 12 Shows the graph of Reference temperature against Calculated Result of Exergy Efficiency and of different Components of the Plant. It can be deduced that the boiler feed pump has the highest exergy efficiency while the high pressure heater 1 has the lowest exergy efficiency.

TABLE 9
DIFFERENT REFERENCE ENVIRONMENT TEMPERATURES AGAINST CALCULATED RESULT OF EXERGY DESTRUCTION OF BOILER, TURBINE AND CONDENSER.

REF TEMP(K)	**BOILER % ED**	**TURBINE % ED**	**CONDENSER % ED**
283	104.00	85.391	63.631
288	104.31	85.613	63.519
293	104.93	85.993	63.101
298	105.58	86.157	62.813
303	105.931	86.531	62.493

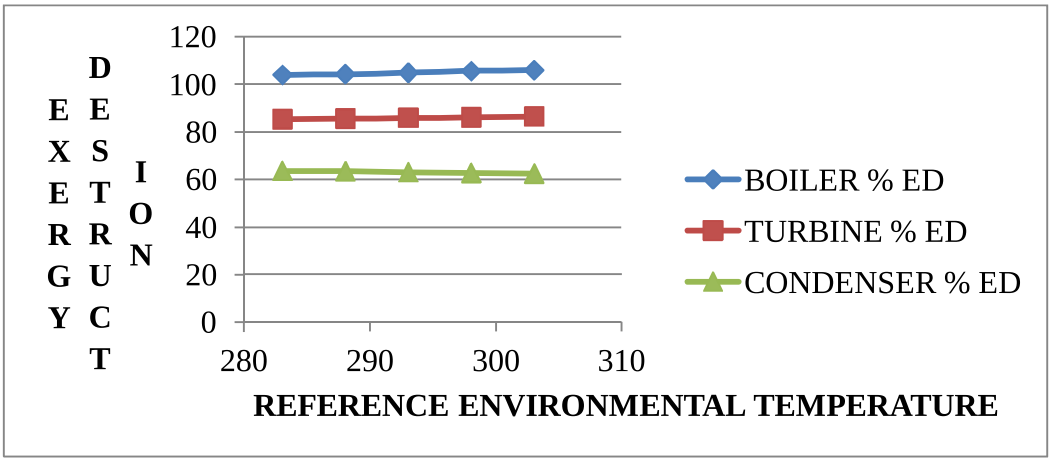

Fig. 13 Graph of Reference Environment Temperature against Boiler, Turbine and Condenser.

From the above figure, it is observe that the exergy destruction is very high and increase considerably as the reference temperature decreases. This increase in exergy destruction is due to irreversibility in the component, poor design and maintenance of the components which lead to decrease in power supply in Nigeria.

TABLE 10
EXERGY DESTRUCTION OF DIFFERENT COMPONENTS OF POWER PLANT.

COMPONENTS	HPH1	TURBINE	HPH2	LPH1	LPH2	CRT	BOILER FP	DEAERATOR	CONDENSER	BOILER
% ED	9.94646	86.1574	6.87566	19.69357	60.60713	3.84081	22.4713	4.766767	62.8135	89.9014

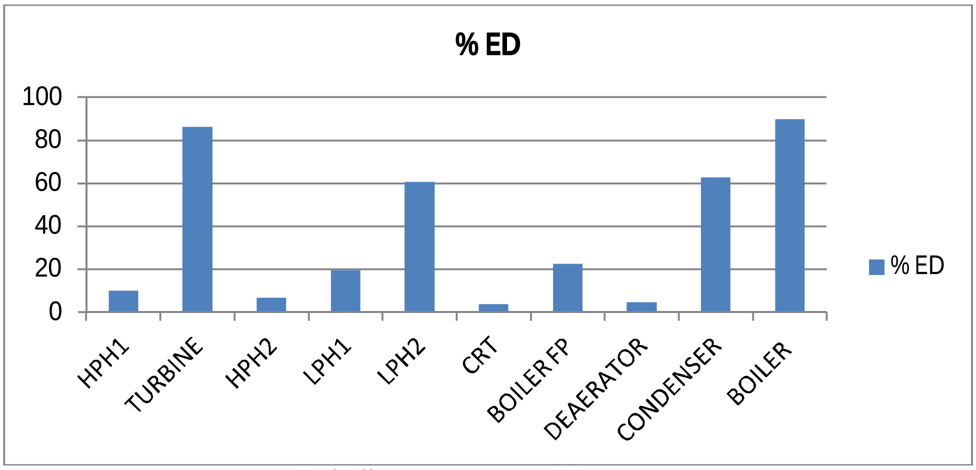

Fig. 14 Graph of different Components and their Exergy Destruction

Fig. 14 above shows percentage exergy destruction of the components of Sapele power plant. It is observed that the boiler and the turbine have a very high rate of destruction, this affect the rate of steam generation coming from the boiler, thus reducing the work done and efficiency of the steam power plant.

IV CONCLUSION

In this study, an energy and exergy analysis as well as the effect of varying the reference environment temperature on the exergy analysis of a steam power plant has been presented. Mass balance, energy balance and second law of efficiency were used to calculate the exergy efficiency and destruction of each components in the power plant using different environment temperature such as 283K, 288K, 293K, 298K, and 303K. From the result obtained, it can be deduced that maximum energy loss occurred at the boiler where by 87.3% was destroyed, thereby reducing the rate of steam generated in the boiler. This lead to decrease in the workdone and efficiency of the steam power plant because little amount of steam is transfer to the turbine. On the other hand, the exergy analysis of the plant showed that lost energy in the boiler thermodynamically significant due to its quality. In terms of exergy efficiency, it is generally low that is about 30.315%% for turbine, 11.003% for boiler and 59.8% for condenser. This affect the power output of the power plant, leading to epileptic power supply in south-south region in Nigeria..

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