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Energy and Exergy Analysis for Unit13E1 of Benghazi Combined Cycle Power Plant

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ABSTRACT

Presented in this paper, an exhaustive energy-exergy analysis of a 476 MW combined cycle power plant located in Benghazi-Libya, as an example to illustrate the utility and importance of exergy analysis compared with energy analysis. The proposed power plant cycle was simplified into sub-systems and modelled. These models of mass, energy and exergy balance equations were applied to each sub-system and farther validated by the manufacturer's data at design operating condition. The results indicate that, the power plant has an overall energy and exergy efficiencies of 55.0% and 52.0% respectively. The total exergy destruction rate is found to be 444.2 MW (48.3 % of fuel input exergy). Significant exergy destruction rate is found to occur in the combustion chamber which contributes a major share of 340.7 MW (37.06%), followed by heat recovery steam generator with 35.7MW (4. %). Moreover, the results of the exergy analysis are compared with those of energy analysis. The comparison is quite of interest. The exergy analysis is much more enlightening, because the dissipations and efficiencies measured with availability are true one, where as those measured with energy are erroneous and misleading. The benefit of this study has enabled us to identify sites where loss of useful energy (exergy) takes place in a power plant and its performance can be evaluated. The results presented here are of real practical value in many ways, they can be valuable for the academic research interest.

Keywords: *Combined Cycle Power Plant, Modelling, Energy, Exergy Analysis.*

1. Introduction

The availability of production electricity is essential to the economic strength of a nation. Electricity demand has therefore gained remarkable attention over the last few decades due to the higher standard of living and increasing number of consumers etc. Among the existing technologies, combined power plants dominate nowadays the electricity generation worldwide due to their high thermal efficiencies and power. In Libya, some of these plants are being installed [1]. Power plants where gas turbines are combined with steam cycles are particularly interesting for their higher overall efficiency (50 -60%) than either of the cycles executed individually [3, 4, 5].

The combination of the two kinds of cycles is possible due to the high exhaust heat temperature of gas turbines. The electricity generating companies are striving to improve the efficiency and performance of their power plants. To achieve this, the locations and causes of useful energy destruction and losses in the power plant components have to be investigated and found. Exergy analysis has increasingly attracted the interest of many researchers to achieve the above goal. The purpose of exergy analysis is generally to identify the location, the source and the magnitude of true thermodynamic inefficiencies in power plants. Moreover, the results provided by exergy analysis can be used as a guide for reducing the thermodynamic inefficiencies of power plants and improving their performance [6, 7, 8].

Exergy analysis has been widely used by many researchers in evaluation, optimization and improvement of thermal power plants. Many researchers, such as Ameri *et al.* [2], kotas [9], Moran [10], Rahim [11] Ersayin*et al* [12] have carried out exergy analysis on combined cycles power plant. According to their results, most of exergy is lost during the combustion process. Balli et al [13] carried out the exergy analysis of a gas turbine cogeneration power plant the results showed that 68% of the overall exergy destructed is occurring in the combustion chamber. The exergy concept has also play an important role in making an energy policy as elaborated by Rosen and Dancer [14]. According to them exergy does not only address the impact of energy resource use on the environment but prove to be a suitable technique for promoting the goal of improved energy conversion.

The exergy analysis is not so popular among industrial fraternity (friends) in Libya and it needs much more attention and application so that the irreversibility can be minimized and thus the systems can be operated at much higher efficiency and less emissions. There have been no enough studies on the exergy evaluation of power plants in Libya and it needs mulch more attention and application so that the useful energy destruction and losses can be minimized to the plants can be operated at higher efficiency.

The present work is one such effort to explain the application of energy-exergy analysis of a 476 MW combined cycle power plant located in Benghazi-Libya. The thermodynamic model and performance evaluation for the power plant by energy-exergy analysis using the design data at full load are presented.

2. Energy and Exergy Analysis

Energy analysis is based on the first law of thermodynamics, which is related to the conservation of energy. While exergy analysis is based on the second law of thermodynamics which state: the conservation of mass and degradation of the quality of energy along with the entropy generation in the analysis of energy systems [6]. The exergy analysis calculates the system performance based on exergy, which defined as the maximum possible reversible work obtainable in bringing the state of the system to equilibrium with the environment [6,7]. The loss of useful energy in power plants cannot be justified by the energy analysis, as it does not differentiate between the quality and quantity of energy [14]. Energy analysis presents only quantities results while exergy analysis presents qualitative results about actual energy consumption [6, 8, 9]. On the other hand, exergy analysis, based on the exergy analysis recognizes magnitudes and locations of the useful energy losses during any thermodynamic process. The primary objectives of exergy analysis are to analyze the energy system components separately and to identify and quantify the sites having the maximum energy and exergy losses.

3. Power Plant Process Description

The Benghazi-North combined cycle power plant was selected for the present work. The power plant was installed and commissioned by ABB in 1995, the design and arrangement of the plan was done in view later combined cycle conversion (1999) [1]. The plant consists of two gas turbines (GTs) units type 13E, 167 MW each, and one steam turbine (ST) unit with 142 MW. The detailed process flow-sheet of the plant is shown in Fig. 1. The gas turbine (Siemens, AG Germany) is shown as a topping plant cycle, whereas the steam turbines (HP and LP) forms the low temperature cycle. Each of GT-unit consists of compressor, combustion chamber and gas turbine. The ST-unit consists of condenser, Deaerator, feed-water heater, high-pressure drum, low and high pressure economizers, high pressure evaporator and super-heater. The connecting link between the two cycles is the heat recovery steam generator (HRSG).

The principle of the combined cycle considered in this study is that, air enters into compressor at state point ‘1’ and compressed at state ‘2’ and transferred to combustion chamber (CC) where combustion of fuel (natural gas injected at state point ‘5’) takes place and producing high-temperature flue gases (1142.0 °C). These high pressure-temperature gases are expanded in a GT unit from state point ‘3’ to state point ‘4’ and doing useful shaft work to drive an electrical generator for producing electricity. The exhaust gases (530.0°C) from the GT have still some energy which recovered in HRSG. In the steam cycle there are two levels of steam pressures on each evaporator. The superheated steam (515 °C, 80 bar) HP-E enters into HP-ST at state point ‘17’ for farther expansion. The superheated steam (288 °C, 5.5 bar) from LP-E before entering the LP-ST mixes with the exit steam coming from HP-ST turbine at state point ‘20’. The exit steam from LP-ST at state point ‘30’ is condensed into a condenser up to a pressure of 0.06 bar. The condensate steam is then directed to the FWH and DA. The BFWP circulates the feed-water to HRSG through the low pressure economizer and evaporator then the flow is divided into three streams to continue the cycle. The operational data at design condition was collected from the Ministry of electricity and the power plant manufacturer. This data includes the state of all streams and the power output at design condition. The design parameters of the power plant are presented in Table 1.

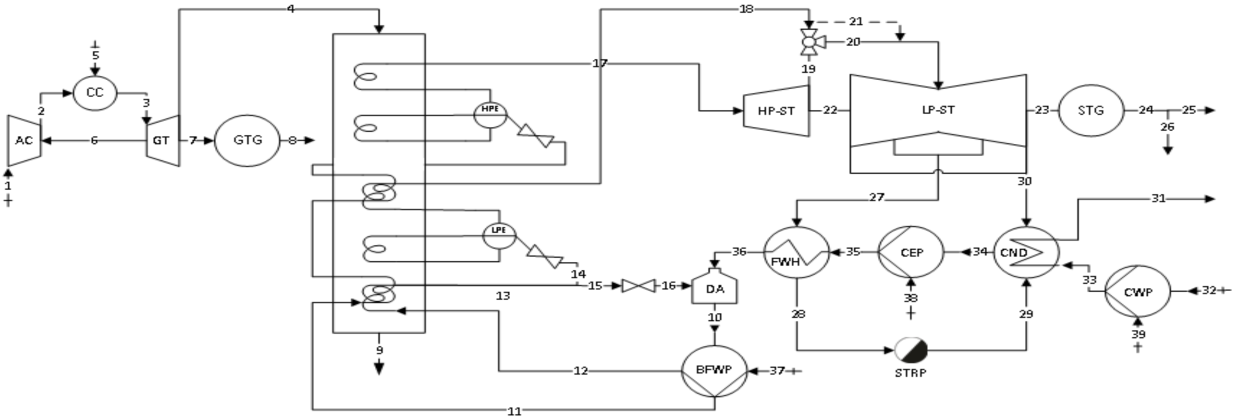

Fig.1: Schematic diagram of the selected combined cycle power plant.

Table 1: Design data and parameters of the plant [1].

Parameters	Values
Ambient condition	25 °C/1.013 bar
Compressor inlet temperature	25 °C
Compressor inlet pressure	1.013bar
Compressor pressure ratio	12.5 [-]
Compressor air mass flow rate	2x450 kg/s
Compressor efficiency	89.0 %
Air gas constant	0.288 kJ/kg.K
Air “kappa”	1.38
Specific heat capacity air	1.06 kJ/kg.K
Combustion efficiency	98%
Combustor pressure drop	0.5 bar
LHV (NG) of fuel	44.5 MJ/kg
Turbine inlet temperature	1142.0 °C
Turbine exit pressure	1.023 bar
Gas turbine efficiency	90.3%
Temperature of gases at HRSG outlet	125.8 °C
Exhaust gas constant	0.288 kJ/kg.K
Exhaust “kappa”	1.38
Continue Table 1;	
Specific heat capacity for gas	1.134 kJ/kg.K
HP steam turbine inlet temperature	515.0 °C
Steam turbine efficiency	82.3 %
Deaerator pressure	1.19 bar
Condenser pressure	0.063 bar
Cooling water inlet temperature	27 °C
Cooling water outlet temperature	34.3 °C
Generator efficiency	98. %

4. Thermodynamic Model and Analysis

The present study introduces a comparative energy and exergy analysis for Benghazi-North combined power plant based on the design condition with the following assumptions:

1. Full load, design operating condition of the power plant is considered.
2. Air and combustion products are treated as ideal gas.
3. The kinetic and potential energies of fluid streams are neglected.
4. Natural gas is supplied to the system as fuel.
5. Only the chemical exergy of the fuel is considered.
6. 2xHRSG and 2xGT are treated as one control volume each.

With regard of the Figure 1, each component in the power plant was considered as a control volume and analyzed separately. Three balance equations were written for each component including mass, energy and exergy. The basic balance equations are [10];

For mass balance: $\sum \dot{m}_{in} - \sum \dot{m}_{out} = 0.0$ (1)

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for energy balance:

$$\sum \dot{m}_{in} h_{in} - \sum \dot{m}_{out} h_{out} + \sum Q_{in} - \sum Q_{out} + \sum P_{in} - \sum P_{out} = 0.0 \quad (2)$$

and for exergy balance:

$$\sum EX_{in} - \sum EX_{out} + \sum P_{in} - \sum P_{out} - EXD = 0.0 \quad (3)$$

4.1. Energy Analysis

4.1.1. Air compressor (AC)

Knowing the air inlet pressure and temperature, outlet pressure and compressor efficiency, the final outlet temperature of the compressor is calculated as:

$$T_2 = T_1 \times \left(1 + \left(\frac{1}{\eta_C} \right) \times \left(r_C^{\frac{\gamma_C - 1}{\gamma_C}} - 1 \right) \right) \quad (4)$$

The required power for the compressor is equal to

$$P_6 = \dot{m} \times Cpa \times (T_2 - T_1) \quad (5)$$

4.1.2. Combustion Chamber (CC)

From the energy balance in the combustion chamber, the fuel mass flow rate (m_5) can be calculated from the equation

$$\dot{m}_5 = \frac{\dot{m}_2 \left(C_{pg} \times T_3 - C_{pa} \times T_2 \right)}{\eta_{cc} LHV - C_{pg} \times T_3} \quad (6)$$

Thus, the mass flow rate of the combustion products is given by

$$\dot{m}_3 = \dot{m}_2 + \dot{m}_5 \quad (7)$$

Where is fuel mass flow rate (kg/s), is air mass flow rate (kg/s), LHV is low heating value (kJ/kg), T_3 turbine inlet temperature, Cp_a and Cp_g are the specific heats of air and gas product respectively.

4.1.3. Gas Turbine (GT)

The exhaust gases temperature from the gas can be expressed as:

$$T_4 = T_3 \times \left[1 - \eta_T \times \left(1 - (r_T)^{\left(\frac{\gamma_T - 1}{\gamma_T} \right)} \right) \right] \quad (8)$$

The total output mechanical power of the gas turbine is expressed as:

$$P_T = \dot{m}_3 C_{pg} (T_3 - T_4) \quad (9)$$

Hence the net mechanical power (P_7) output from the gas turbine is

$$P_7 = P_T - P_6 \quad (10)$$

The gross electrical power (P_8) output from gas turbine is

$$P_8 = P_7 \times \eta_G \quad (11)$$

4.1.4. Heat Recovery Steam Generator (HRSG)

Gas side

$$\dot{m}_4 - \dot{m}_9 = 0.0 \quad (12)$$

Steam side

$$\dot{m}_{11} - \dot{m}_{17} = 0.0 \quad (13)$$

$$\dot{m}_{12} - \dot{m}_{13} = 0.0 \quad (14)$$

$$\dot{m}_{14} - \dot{m}_{18} = 0.0 \quad (15)$$

The overall energy balance equation of the steam and flue gases is:

$$\dot{m}_{11} h_{11} + \dot{m}_{12} h_{12} - \dot{m}_{13} h_{13} + \dot{m}_{14} h_{14} - \dot{m}_{17} h_{17} - \dot{m}_{18} h_{18} + \dot{m}_4 h_4 - \dot{m}_9 h_9 = 0.0 \quad (16)$$

Assuming that the HRSG is well insulated, one obtains the following relation from Eqs. (12, 13, 14 and 15, and rearranging, for the calculation of the mass flow rate of feed-water enters the HRSG:

$$\dot{m}_{11} = \dot{m}_4 \left(\frac{h_9 - h_4}{h_{11} - h_{17}} \right) + \beta \times (h_{12} - h_{13}) + \alpha - \left(\frac{h_{10} - h_{36}}{h_{16} - h_{36}} \right) + \beta \times \left(\alpha - \left(\frac{h_{10} - h_{36}}{h_{16} - h36} \right) \times (h_{14} - h_{18}) \right) \quad (17)$$

where:

$$\beta = \left(\frac{\alpha}{1. - \alpha} \right) \quad (18)$$

$$\alpha = \frac{\dot{m}_{12}}{\dot{m}_{10}} = 0.364 \quad (19)$$

and:

$$\dot{m}_{12} = \frac{\alpha \times \dot{m}_{11}}{1. - \alpha} \quad (20)$$

Thus, the mass flow rate of each state point in Figure 1 can be now calculated using the above mass balance equation as following.

4.1.5. Splitter

$$\dot{m}_{13} - \dot{m}_{14} - \dot{m}_{15} = 0.0 \quad (21)$$

$$h_{13} = h_{14} = h_{15} = 0.0 \quad (22)$$

4.1.6. Expansion valve

$$\dot{m}_{15} - \dot{m}_{16} = 0.0 \quad (23)$$

$$h_{15} = h_{16} \quad (24)$$

4.1.7. Deaerator (DA)

$$-\dot{m}_{10} + \dot{m}_{16} + \dot{m}_{36} = 0.0 \quad (25)$$

$$-\dot{m}_{10} h_{10} + \dot{m}_{16} h_{16} + \dot{m}_{36} h_{36} = 0.0 \quad (26)$$

4.1.8. High Pressure Steam Turbine (HPST)

$$\dot{m}_{17} - \dot{m}_{19} = 0.0 \quad (27)$$

$$P_{22} = \dot{m}_{17} h_{17} - \dot{m}_{19} h_{19} \quad (28)$$

ISSN 2522-6967

4.1.9. Mixer

$$\dot{m}_{18} + \dot{m}_{19} - \dot{m}_{20} = 0.0 \quad (29)$$

$$\dot{m}_{18} h_{18} + \dot{m}_{19} h_{19} - Q_{21} = 0.0 \quad (30)$$

Mixing points need mass flow data to calculate thermodynamic properties. Thus, the energy feed stream '21'was introduced and the enthalpy behind the mixing state point '20' is calculated from assumed feed stream as follows:

$$h_{20} = \frac{Q_{21}}{\dot{m}_{20}} \quad (31)$$

4.1.10. Low Pressure Steam Turbine (LPST)

$$\dot{m}_{20} - \dot{m}_{27} - \dot{m}_{30} = 0.0 \quad (32)$$

$$P_{23} = \dot{m}_{20} h_{20} + P_{22} - \dot{m}_{27} h_{27} - \dot{m}_{30} h_{30} \quad (33)$$

The net electrical power (P_{25}) output from steam turbines is

$$P_{25} = P_{24} - P_{26} \quad (34)$$

$$P_{24} = P_{23} \times \eta_G \quad (35)$$

$$P_{26} = P_{37} + P_{38} + P_{39} \quad (36)$$

4.1.11. Pumps

Cooling water pump (CWP)

$$\dot{m}_{32} - \dot{m}_{33} = 0.0 \quad (37)$$

$$P_{39} = \dot{m}_{33} h_{33} - \dot{m}_{32} h_{32} \quad (38)$$

$$h_{33} = \frac{(p_{33} - p_{32}) \times 100}{\rho_w \times \eta_p} + h_{32} \quad (39)$$

Condenser extraction pump (CEP)

$$\dot{m}_{35} - \dot{m}_{34} = 0.0 \quad (40)$$

$$P_{38} = \dot{m}_{35} h_{35} - \dot{m}_{34} h_{34} \quad (41)$$

$$h_{35} = \frac{(p_{35} - p_{34}) \times 100}{\rho_w \times \eta_p} + h_{34} \quad (42)$$

Boiler Feed-water pump (BFWP)

$$\dot{m}_{10} - \dot{m}_{11} - \dot{m}_{12} = 0.0 \quad (43)$$

$$h_{11} = \frac{(p_{11} - p_{10}) \times 100}{\rho_w \times \eta_p} + h_{10} \quad (44)$$

$$h_{12} = \frac{(p_{12} - p_{10}) \times 100}{\rho_w \times \eta_p} + h_{10} \quad (45)$$

$$P_{39} = \dot{m}_{11} h_{11} + \dot{m}_{12} h_{12} - \dot{m}_{10} h_{10} \quad (46)$$

4.1.12. Steam condenser (CND)

$$\dot{m}_{33} - \dot{m}_{31} = 0.0 \quad (47)$$

$$\dot{m}_{29} + \dot{m}_{30} - \dot{m}_{34} = 0.0 \quad (48)$$

$$\dot{m}_{29} h_{29} + \dot{m}_{30} h_{30} - \dot{m}_{34} h_{34} - \dot{m}_{31} h_{31} + \dot{m}_{33} h_{33} = 0.0 \quad (49)$$

4.1.13. Feed-water Heater (FWH)

$$\dot{m}_{35} - \dot{m}_{36} = 0.0 \quad (50)$$

$$\dot{m}_{27} - \dot{m}_{28} = 0.0 \quad (51)$$

$$\dot{m}_{27} h_{27} - \dot{m}_{28} h_{28} + \dot{m}_{35} h_{33} - \dot{m}_{36} h_{36} = 0.0 \quad (52)$$

4.1.14. Steam Trap (STRP)

$$\dot{m}_{28} - \dot{m}_{29} = 0.0 \quad (53)$$

$$h_{28} = h_{29} \quad (54)$$

4.2. Exergy Analysis

The value of physical exergy flow rate at various state points in the objective system can be calculated by the following equations [6]: For steam and water,

$$EX_i = \dot{m}_i \left((h_i - h_0) - T_0 (s_i - s_0) \right) \quad (55)$$

and for ideal gas,

$$EX_i = \dot{m}_i \left((h_i - h_0) - T_0 \left((s_i - s_0) - R \ln\left(\frac{p_i}{p_0} \right) \right) \right) \quad (56)$$

Where h_i, s_i and p_i are the enthalpy, entropy and pressure of the substance i respectively, and h_0, s_0, T_0 and p_0 are those at standard ambient conditions.

With using these equations (55 and 56) for determined all points, the values of exergy flow rates are calculated. Also, having of input and output exergy flow rate amount of each power plant components, the exergy destruction rate in each component is calculated with using relations shown in Table 2.

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Table 2: Exergy Destruction Rate Equations for Power Plant Components.

Component	Exergy Destruction (EXD)	Energy loss (ENL)
AC	$=EX_1+P_6-EX_2$	-
CC	$=EX_2-EX_3+EX_5$	-
GT	$=EX_3-EX_4-P_6-P_7$	-
GTG	$=EX_7-EX_8$	-
HRSG	$=EX_4-EX_9+EX_{11}+EX_{12}$ $-EX_{13}+EX_{14}-EX_{17}-EX_{18}$	$=ENL_9$
HP-ST	$=EX_{17}-EX_{19}-P_{22}$	-
LP-ST	$=EX_{20}+P_{22}-P_{23}-EX_{27}$ $-EX_{30}$	-
CND	$=EX_{29}+EX_{30}+EX_{33}$ $-EX_{31}-EX_{34}$	$=ENL_{31}$
FWH	$=EX_{27}-EX_{28}+EX_{35}-EX_{36}$	-
DA	$=-EX_{10}+EX_{16}+EX_{36}$	-
BFWP	$=EX_{10}-EX_{11}-EX_{12}+P_{37}$	-
CWP	$=EX_{32}-EX_{33}+P_{39}$	-
CEP	$=EX_{34}-EX_{35}+P_{38}$	-
Splitter	$=EX_{13}-EX_{14}-EX_{15}$	-
Valve	$=EX_{15}-EX_{16}$	-
Mixer	$=EX_{18}+EX_{19}-EX_{20}$	-
Steam Trap	$=EX_{28}-EX_{29}$	-
STG	$=P_{23}-P_{24}$	-

Total exergy destroyed in the power plant (EXD_{total}) is given as:

$$EXD_{total}=\sum EXD_i \tag{57}$$

Total exergy losses in the power plant (EXL_{total}) is given as

$$EXL_{total}=\sum EXL_i \tag{58}$$

The exergy destruction ratio (EXDR) and the exergy loss ratio (ENLR) can be compared to the rate of exergy flow of fuel in the plant and written as:

$$EXDR=\left(\frac{EXD_i}{EX_{fuel}}\right)*100\% \tag{59}$$

$$ENLR=\left(\frac{EXL_i}{EX_{fuel}}\right)*100\% \tag{60}$$

The overall exergy efficiency (η_{EX}) of the power plant is given as:

$$\eta_{EX}=\left(\frac{Exergy\ \ rate\ \ output}{Exergy\ \ rate\ \ input}=1-\frac{EXD_{total}+EXL_{total}}{EX_{fuel}}\right)*100\% \tag{61}$$

Where, EX_{fuel} is the exergy flow rate of the fuel and is given by [2,9]:

$$EX_{fuel}=1.064\times\dot{m}_f\times LHV_{fuel} \tag{62}$$

The overall energy efficiency (η_{EN}) of the power plant is given as:

$$\eta_{EN}=\left(\frac{Energy\ \ rate\ \ output}{Energy\ \ rate\ \ input}=\frac{P_8+P_{25}}{Q_{fuel}}\right)*100\% \tag{63}$$

Where:

$$Q_{fuel}=\dot{m}_f\times LHV_{fuel} \tag{64}$$

The heat rate (HR) is a measure used to determine how efficiently a generator uses heat energy. It can be expressed as:

$$HR=\frac{Heat\ \ Supplies}{Power\ \ Generated}=\frac{3600}{\eta_{EN,plant}} \tag{65}$$

The specific fuel consumption (SFC) is the ratio of fuel used by the power plant to a certain amount of power produced. It can be determined by the equation:

$$SFC=\frac{3600\times\dot{m}_5}{P_8+P_{25}} \tag{66}$$

5. Calculation Results and Discussions

A computer program was developed based on the thermodynamic models as discussed in previous sections. The computational procedure is outlined in the flow chart of the program shown in Figure 2.

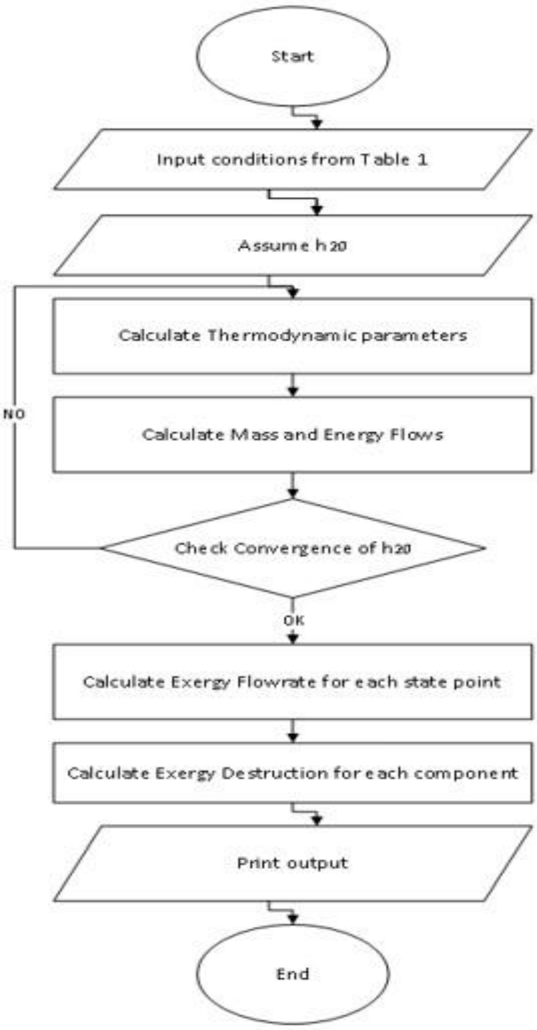

Fig. 2: Calculation Flow Chart.

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The energy and exergy analysis on the power plant are performed with assumptions made above and given parameters in Table 1. Firstly, different thermodynamic parameters at each state point (Fig. 1) in the power plant are calculated, secondly the results of mass, energy and exergy rates are obtained, and tabulated in Table 3.

Finally, the values in Table 3 are used to calculate the energy and exergy balance and exergy destruction and energy losses ratios for each component (Table 4). Moreover, energy and exergy efficiencies, heat rate and specific fuel consumptions of the power plant are calculated. The obtained results are tabulated in Table 5 and were validated with manufacture's published data for design operating condition. They showed high compatibility with the proposed model.

Table 3: Mass, energy and exergy rates and thermodynamic parameters at varies power plant state points in Fig. 1.

State	*Substance*	*p(bar)*	*T(°C)*	*h(kJ/kg)*	*s(kJ/kg.K)*	*ṁ(kg/s)*	*EN(MW)*	*EX(MW)*
1	Air	1.013	25.0	26.34	0.00	900.00	23.85	0.00
2	Air	12.50	359.2	380.9	0.073	900.00	342.81	299.3
3	Combustion gases	12.00	1141.9	1296.0	1.056	919.41	1191.56	877.83
4	Combustion gases	1.034	530.6	578.12	1.074	919.41	531.53	212.68
5	Natural gas	30.00	25.0	56.25	-1.762	19.41	863.94	919.23
6	Power to AC	-	-	-	-	-	318.96	318.96
7	Net power output GT	-	-	-	-	-	341.07	341.07
8	Electrical power GT	-	-	-	-	-	334.25	334.25
9	Combustion gases	1.012	125.8	131.0	0.304	919.41	120.44	12.87
10	Water	1.19	104.6	438.48	1.359	174.60	76.56	6.65
11	Water	115.0	106.5	454.81	1.37	111.05	50.51	5.66
12	Water	7.5	104.7	439.26	1.359	63.55	27.9	2.47
13	Water	5.90	158.4	682.72	1.926	63.55	43.40	7.18
14	Water	5.90	158.4	682.72	1.926	27.5	18.76	3.1
15	Water	5.90	158.4	682.72	1.926	36.10	24.63	4.08
16	Water	1.19	104.6	682.72	2.01	36.1	24.63	3.23
17	Superheat steam	80.60	515.0	3434.61	6.769	111.1	381.4	157.83
18	Superheat steam	5.50	287.6	3037.71	7.370	27.47	83.5	23.21
19	Superheat steam	4.930	164.1	2775.72	6.884	111.1	308.3	80.8
20	Superheat steam	4.910	187.2	2827.68	7.01	138.5	391.7	102.9
21	Energy flow	-	-	-	-	-	391.7	391.7
22	Power from HP-ST	-	-	-	-	-	73.2	73.2
23	Power from LP-ST	-	-	-	-	-	147.5	147.5
24	Gross elec. power ST	-	-	-	-	-	144.5	144.5
25	Net elec. power ST	-	-	-	-	-	142.0	142.0
26	Auxiliary Power	-	-	-	-	-	2.5	2.5
27	Steam	0.77	92.5	2547.2	7.13	14.1	35.8	6.00
28	Saturated water	0.77	92.5	387.5	1.221	14.1	5.5	0.40
29	Water	0.063	37.1	387.50	1.282	14.1	5.5	0.14
30	Wet steam	0.063	37.1	2262.50	7.33	124.5	281.6	10.33
31	Water	1.5	34.3	143.76	0.495	8713.0	1252.5	6.54
32	Water	1.013	27.0	113.2	0.395	8713.0	986.4	0.0
33	Water	1.57	27.01	113.3	0.396	8713.0	986.98	1.39
34	Saturated water	0.063	37.1	155.20	0.533	138.5	21.5	0.13
35	Water	5.00	37.1	155.80	0.533	138.5	21.6	0.21
36	Water	1.19	89.5	374.90	1.20	138.5	52.0	3.6
37	Power to BFWP	-	-	-	-	-	1.86	1.86
38	Power to CEP	-	-	-	-	-	0.08	0.08
39	Power to CWP	-	-	-	-	-	0.57	0.57

Table 4: Energy and Exergy balance of each component.

Component	EXD+EXL		ENL	
	MW	%	MW	%
2xAC	19.655	2.14	-	-
2xCC	340.70	37.06	-	-
2xGT	5.122	0.56	-	-
2xGTG	6.822	0.74	-	-
2xHRSG	35.688	3.88	120.4	14.0
HLP-ST	16.104	1.75	-	-
CND	11.735	1.28	266.2	31.0
FWH	2.245	0.25	-	-
DA	0.143	0.02	-	-
BFWP	0.389	0.04	-	-

Cont. Table 4

CWP	0.363	0.04	-	-
CEP	0.0064	0.001	-	-
Splitter	0.000	0.00	-	-
Valve	0.846	0.10	-	-
Mixer	1.146	0.13	-	-
Steam Trap	0.252	0.03	-	-
STG	2.949	0.32	-	-
Total	444.20	48.3	386.6	45.0

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Table 5: Performance of the power plant.

Overall Energy efficiency	55.0 %
Overall Exergy efficiency	52.0 %
Heat Rate	6530.53 kJ/kWh
Specific Fuel Consumption	0.147 kg_f/kWh

In Figure 3, the exergy destruction rates for all Benghazi north power plant components at the design operating condition are shown. The greatest exergy destruction rate is shown at the combustion chamber, due to large temperature differences, mixing and chemical reactions as confirmed by [2,6,8]. The HRSG represents the second major source of exergy destruction rate in the plant, which may attribute to the temperature differences among the gases and steam streams. The third source of exergy destruction occurs in air compressor, as a result of compression and friction. The steam turbine represents the forth source, as a result of expansion and friction. The fifth source of exergy destruction occurs in steam condenser, feed-water heater and deaerator due to heat transfer and mixing in the deaerator. Finally, the exergy destructed in the electrical generators, steam mixer and expansion valve and steam trap, which attributed to the electrical heat rejected, friction and throttling processes respectively.

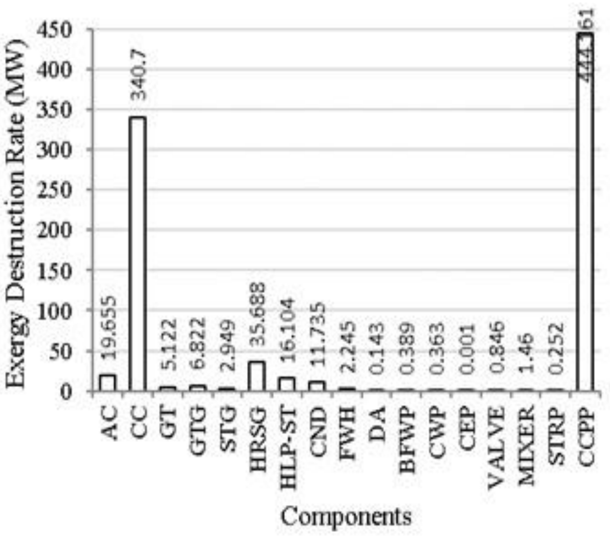

Fig. 3: Exergy destruction rate of the CCPP components.

Figure 4 and 5 shows the detailed energy and exergy balance of the power plant at the operating design condition. The only major components in the power plant are considered in this comparison. It shows that there are very significant differences between energy lost and exergy destruction for different process components. The energy balance showed that the primary source of energy loss is the condenser where 31% of the total loss occurs. In contrast, the exergy analysis showed that the loss from the condenser was only 1.28% of the total. According to the energy balance, the second largest source of energy loss is the HRSGs, which accounts for 14%. The exergy balance revealed that the loss of useful energy (exergy) is in the CCs, with losses of 37.06 %. It indicates that the waste heat in the condenser does not match potential to be utilized as a source of useful work and to improve the power plant efficiency. On other hand, farther investigation of exergy lost in the combustion chamber may show some opportunities for improvement. The results of exergy analysis are markedly different from the results of the energy balance, which shows most of the energy being lost in the condenser.

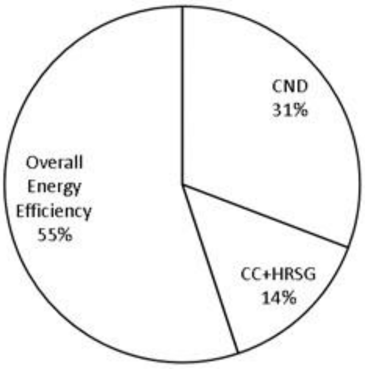

Fig. 4: Energy balance of the CCPP

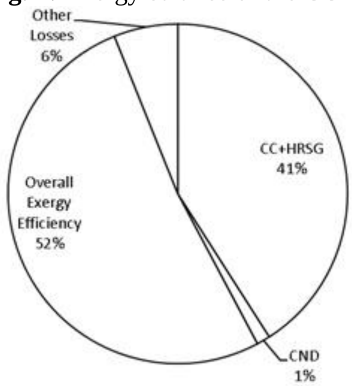

Fig. 5: Exergy balance of the CCPP.

6. Conclusions

This study reveals that, the exergy analysis approach provides a useful thermodynamic tool than energy analysis approach for the performance analysis of the power plant. The exergy analysis identifies areas where most of the useful energy is lost and discusses potential of the lost energy for improvement of the power plant efficiency, also enables all loss sources to be located and quantified. An energy and exergy balance of the complete plant was made. It has been observed that the energy losses are associated mainly with energy loss in condenser and stack whereas exergy losses are dominated by the losses in the combustion chamber and steam generator unit (HRSG). The results showed that maximum exergy destruction occurs in the CC (340.7 MW, 37.06% of fuel input exergy), followed by the HRSG (35.7 MW, 4. 0%), AC (19.7 MW, 2.14%) and turbines (16.1MW, 1.8%). The energy and exergy efficiencies of the power plant are calculated as 55. % and 52.%, respectively. Certain processes like throttling, heat transfers, expansion and friction involve no energy losses but they degrade the quality of energy and therefore involve exergy destruction. Exergy analysis is valuable not only for pinpointing useful energy (exergy) losses but also for direct application to the design of energy systems and for other engineering projects as maintenance and power plant modification to improve the thermodynamic performance.

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Nomenclature

C_p - specific heat at constant pressure (kJ/kg.K)
EX - exergy flow rate (kW)
EN - energy flow rate (kW)
ENL - energy loss (kW)
EXD - exergy destruction rate (kW)
EXDR - exergy destruction ratio (%)
EXL - exergy loss rate (kW)
EXLR - exergy loss ratio (%)
h - specific enthalpy (kJ/kg)
HR - heat rate (kJ/kWh)
$\dot{m}$ - mass flow rate (kg/s)
LHV - lower heating value (kJ/kg)
p - pressure (bar)
P - power (kW)
Q - heat transfer rate (kW)
SFC - specific fuel consumption (kg/kWh)
s - specific entropy (kJ/kg.K)
r_C - compression ratio (-)
r_T - expansion ratio (-)
R - universal gas constant (kJ/kg.K)
T - temperature (°C or K)

Abbreviations

AC - air compressor
BFWP - boiler feedwater pump
CC - combustion chamber
CCPP - combined cycle power plant
CEP - condenser extraction pump
CND - steam condenser
CWP - cooling water pump
DA - deaerator
GT - gas turbine
GTG - gas turbine generator
HRSG - heat recovery steam generator
HP-ST - low pressure steam turbine
HPE - high pressure evaporator
HLP-ST - high and low pressure steam turbines
LP-ST - low pressure steam turbine
LPE - low pressure evaporator
STRP - steam trap
STG - steam turbine generator

Greek Letters

α - mass ratio (-)
γ - specific heat capacity ratio (-)
ρ - density, kg/ m^3
η - efficiency (%)

Subscripts

a - air
C - compressor
CC - combustion chamber
EN - energy
EX - exergy
f - fuel
g - gas products
G - electrical generator
o - ambient condition
P - pump
T - turbine
w - water
1 to 39 - cycle state points in Fig.1