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Energy, Exergy, Exergoeconomic, and Environmental (4E) Analysis of the Existing Gas Turbine Power Plants in BOB - PT. Bumi Siak Pusako - Pertamina

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ABSTRACT

The power plants in Indonesia are mostly used to supply energy for the industrial sector, including the upstream oil and gas as well as mining companies. Several companies operating in Riau contribute to the status of the region as the largest oil producer in Indonesia. These companies rely on self-generated electricity for their operations with subsequent impact on the environment. Therefore, this research was conducted to analyze the flow of energy, exergy, exergoeconomic, and environment at the 6 MW power plant operated by BOB - PT Bumi Siak Pusako - Pertamina Hulu. The second law of thermodynamics was used to evaluate energy efficiency as the maximum achievable effort. This was further integrated with economic principles to appraise the useful and wasted costs associated with thermodynamic systems through the concept of exergoeconomics. The results showed that the thermal efficiency of the gas turbine power plant was 42.85% and the exergy efficiency was 33.22% with the largest loss recorded in the combustion chamber to be 3.091 MW in the form of vibration, friction, or expansion of the components. It was also discovered that the exergy efficiency of each component was above 75%, thereby indicating the components of the gas turbine power plant components were in good condition. Moreover, the largest exergy destruction cost was 2349.16 USD/h and the exergy cost was 3,778.05 USD/kWh. The exhaust emission generated by the gas turbine power plant was 0.21 kg/s or equivalent to 0.1425 kg/kWh requiring a forest area of 11.63 ha. The results showed that the analytical method used could be comprehensively developed and applied to other power plants in Indonesia. It could also be used to understand system performance, identify energy losses, optimize energy efficiency, and link economic aspects with energy use.

1. Introduction

The management of the Coastal Plan Pekanbaru (CPP) block was entrusted to BOB – PT Bumi Siak Pusako – Pertamina Hulu for a contract period of 20 years from August 8, 2002 to August 8, 2022 by the Indonesian government through a cost-recovered cooperation system [1]. The block required a

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large amount of electrical energy from its 4x6 MW gas power plant operating for 10 years to conduct production processes. The energy produced cannot be created nor destroyed and this means there is a need for quantitative analysis of its utilization. The second law of thermodynamics has never been applied in qualitative analysis to evaluate energy as the maximum useful effort known as exergy and its loss due to irreversible work processes. Moreover, this principle can also be combined with the laws of economics to assess the useful and lost costs of a thermodynamic unit through the concept of exergy-economics. The process is to determine the points of loss on each equipment and assess the associated cost [2, 3]. There is also the need to analyze the energy lost in the form of exhaust gases to determine the potential sources and effects on the environment (environment). This is in line with the Kyoto Protocol where the United Nations (UN) countries under the auspices of the United Nations Framework Convention on Climate Change (UNFCC) signed an agreement to regulate the level of greenhouse gas emissions to address the problem of global warming and climate change [4, 5].

Several studies were observed to have been conducted on energy, exergy, exergoeconomics, and environment analysis. For example, Martin *et al.,* [6] focused on the exergy analysis of the 20 MW Gas Turbine Power Plant in Pekanbaru Riau and reported the largest exergy destruction of 71.03% in the combustion chamber followed by 16.65% in the gas turbine and the smallest 12.33% in the compressor, The thermal efficiency was found to be 33.77% and the exergy or second law of thermodynamics efficiency was 32.25% [6]. Zueco *et al.,* [7] also analyzed the exergy of steam turbine power plants and estimated the energy efficiency to be 32% while the exergy efficiency was 31%. The maximum source of exergy destruction was found in the steam boiler with 79.0% followed by the stack losses (10.7%), condenser (5.6%), and the turbine (4.7%) [7].

Martin *et al.,* [8] conducted an exergoeconomic analysis on the 21.6 MW gas turbine power plant in Riau, Indonesia and showed that the largest damage was in the combustion chamber with a magnitude of 21,851.18 kW followed by the compressor and gas turbine with 8,495.48 kW and 3,094.34 kW respectively. The economic analysis produced a total exergy damage cost of 2,793.14 USD/hour comprising of 1,066.43 USD/hour for the compressor, 1,561.46 USD/hour for the combustion chamber, and 165.25 USD/hour for the gas turbine. The thermal and exergy efficiencies were also recorded to be 24.51% and 22.73%, respectively [8].

Yohana *et al.,* also simulated the energy and exergy of a gas turbine generator x combined cycle power plant using cycle-tempo software. The results showed that the highest system energy efficiency was in the gas turbine generator unit 2.3 with 35.541% and exergy efficiency was 34.069%. The gas turbine generator component with the lowest exergy efficiency was the combustion chamber unit 2.2 with 76.81% and an exergy destruction of 92.581 MW [9].

Shamet *et al.,* [10] determined the heat loss and exergy destruction for each equipment in a steam power plant in Sudan. The results showed that the condenser was the main source of energy loss at approximately 67% while the boiler was found to have contributed the largest percentage to the exergy destruction at approximately 84.36%. The destruction could be reduced by preheating the inlet water to a sufficient temperature and controlling air to fuel ratio [10]. Ahmadi *et al.,* [11] also studied the steam power plant in Iran and showed that 69.8% of the total energy lost in the cycle was in the condenser while the boiler was discovered to be the main equipment wasting exergy with 85.66% [11].

Several studies were observed to have also focused on economic analysis. For example, Martin *et al.,* [12] conducted energy and thermo-economic analysis on crude oil gathering station and hydrocarbon transport, and the results showed that the highest energy flow was in the wash tank amounting to 183,546 kW followed by the shipping pump with 240,346.34 kW and the heater with 398.4 kW. Moreover, the largest exergy destruction was recorded in the wash tank, totaling 73,418 kW, followed by the shipping pump with 0.319 kW and the heater with 0.363 kW. The total cost of exergy destruction for all the equipment was calculated to be 64,243.29 USD per year [12]. Mohammadi *et al.,* [13] also analyzed the thermo-economic properties of a combined gas turbine, steam, and organic Rankine cycle. The result showed that the combustion chamber was the largest source of crushing exergy and the exergoeconomic analysis showed an efficiency of 40.75% and an average production cost of 439 million USD/year [13].

Research was also observed to have been conducted on the environment such as Javadi *et al.,* [14] that analyzed 4E at a power plant in Iran and found the energy efficiency to be 8.12% while the exergy destroyed was 7233 kJ/kWh and the temperature of the flue gases affecting the environment was 2.53% [14]. Moreover, Shamoushaki *et al.,* [15] focused on the Aliabad Katoul gas turbine power plant in northern Iran and reported 45.1% exergy efficiency for 1.91-2.21 USD/s with a CO_2 emission level of 0.89 kg/MWh. The pressure ratio in the compressor was found to be 12-16 bar and the CO_2 emission was 0.71 kg/MWh with an exhaust gas temperature of 900 K-1400 K [15].

Sohbari *et al.,* [16] also conducted a 4E analysis to determine the ability of a thermoelectric generator to boost the power capacity of the Kalina cycle by 0.29 to 0.82 kW. The energy and energy efficiencies of the cycle were found to be 32% and 63.23%, respectively while the application of the waste heat recovery cycle was able to reduce fuel consumption by 15.60 liters per hour on average [16]. Furthermore, Wang *et al.,* [17] studied a new cogeneration system known as SOFC-ICE-SCO2-HRSG hybrid and the results showed that the net output power was 288.94 kW while the total output power was 345.58 kW. The overall energy and energy efficiencies were recorded to be 65.82% and 42.28% respectively, and the system produced 0.4712 kg/kWh of CO_2 emissions at a social cost estimated to be 3.34 USD/GJ [17]. Exergy was considered the best method to evaluate the overall and component efficiency as well as to identify and assess thermodynamic losses of cogeneration plants with back pressure condensing and extraction steam turbines compared to the conventional energy analysis.

Thermodynamic systems that transform economic parameters into operational expenses can be referred to as "work-economics." The advancement of thermoeconomic theory allows the usage of these systems to calculate the operational costs associated with the decrease in useful energy due to the irreversibility of the conversion process [18, 19]. Moreover, the exergy-economic method is required to optimize costs by assessing the energy losses and inefficiencies within a system and determining its effectiveness. This method involves investigating and evaluating the areas where the most exergy destruction occurs and quantifying the associated costs.

Exergy analysis and exergy economics provide a comprehensive understanding of energy losses in gas turbine power plants across different equipment and operational stages. This means companies can enhance their profitability by leveraging the insights from this research to mitigate exergy losses and minimize associated expenses.

Several studies were discovered to have been conducted on energy, exergy, exergoeconomic, and environmental analyses but none combined all these variables. Some focused on energy and exergy while others preferred exergy and exergoeconomic or the combination of exergy and environment. Therefore, this study was used to implement the 4E analysis specifically on a 6 MW gas turbine power plant. The process was based on field observations applied to retrieve primary and secondary data. The primary data were in the form of the log sheet containing input and output parameters associated with the operations of the gas turbine power plant while the secondary ones were working drawings and specifications of the equipment. The data collection process was followed by the calculation of the work and heat energies, the efficiency of the components, the largest exergy loss, exergy destruction costs, and the CO_2 emissions released to the environment.

The aim of this study was to investigate the performance of a gas turbine power plant, identify the location of the largest exergy loss, determine the total cost loss due to exergy destruction, as well as evaluate the total CO_2 emissions and the environmental costs.

2. Methodology

This research was conducted using a descriptive quantitative approach by describing the object or subject according to actual conditions using mathematical variables. The wastes from each sub-process of the study object were also identified. This conformed with energy and energy analyses applied to determine the equipment efficiency and energy waste in each sub-process. The primary data collected were related to the operation of the equipment such as the input and output parameters, energy flow, types of energy transferred such as heat, work, and mass, the economics, and the environment. The secondary data generated were official data documented by the company such as working drawings, population data, equipment technical specifications, and literature reviews.

2.1 Energy

Energy analysis was conducted using the Brayton cycle principle which focused on determining the input and output energy in the system. The equation is presented as follows [3]:

$$E_{in} - E_{out} = \Delta E_{system} \tag{1}$$

Where, E_{in} is the energy entering, E_{out} is the energy leaving, and ΔE_{system} is the change in the energy of the system. Moreover, the total rate of mass entering and leaving the control volume is the same as presented in the following Eq. (2) [3]:

$$\sum \dot{m}_{in} = \sum \dot{m}_{out} \tag{2}$$

Where, $\sum \dot{m}_{in}$ is the total rate of mass entering and $\sum \dot{m}_{out}$ is the total rate of mass leaving the system.

The amount of energy transmitted is equal to the difference between the amount of incoming and exiting energy. This is known as the energy balance and occurs in the form of heat, work, and mass as follows [3]:

$$\dot{Q} + \sum \dot{m}_{in}\, h_{in} = W + \sum \dot{m}_{out}\, h_{out} \tag{3}$$

Where, $\dot{Q}$ is the net heat input, W is the net work output, and $\sum \dot{m}_{in}\, h_{in}$ and $\sum \dot{m}_{out}\, h_{out}$ are the energy of the fluid stream at any inlet or exit per unit mass respectively.

Therefore, the energy efficiency of each cycle can be determined using the following equation [3]:

$$\eta = \frac{\dot{W}_{net}}{\dot{Q}_{in}} \tag{4}$$

2.2 Exergy

Exergy is classified into chemical and thermomechanical categories. The thermomechanical aspect is defined as the absence of magnetic, electrical, nuclear, and surface tension effects. It is also known as the maximum amount of work a system is capable of performing as it transits from a specific beginning to a finite dead or environmental state through a reversible process. The thermomechanical exergy can be expressed as follows [20]:

$$\dot{E}^{th} = \dot{E}^{PH} + \dot{E}^{KN} + \dot{E}^{PT} \quad (5)$$

This shows the possibility of breaking the thermomechanical exergy E^{th} into three parts including the physical E^{PH}, kinetic E^{KN}, and potential exergies E^{PT}. This research was conducted with disregard for the kinetic and potential components, thereby indicating the inclusion of only the physical component. The source of the specific physical exergy is presented in the following Eq. (6) [20]:

$$\dot{e}^{PH} = (h - h_0) - T_0(s - S_0) \quad (6)$$

Where, h, s, and T represent temperature, entropy, and enthalpy respectively. The subscript 0 indicates the environmental conditions.

The chemical exergy is defined as the amount of work that can be done before a system reaches its true dead state. It can be represented using the following equation [20]:

$$\bar{e}^{CH} = \sum x_k \bar{e}_k^{CH} + \bar{R}T_0 \sum x_k \ln x_k \quad (7)$$

Where, R is the universal gas constant, x_k is the mole fraction of gas k in the ambient gas phase, and e^{CH} is the chemical exergy per mole of gas k.

The assumptions are as follows:

i. All processes of the cycle are in a steady state [20].
ii. Air compressor and gas turbine are assumed to be adiabatic [20].
iii. The lower heating value of the fuel (methane) is 50,017.48 kJ/kg.
iv. The principles of ideal gas mixtures are used for air and combustion products [20].
v. The pressure drop factor in the combustion chamber is 3% [21].

2.3 Exergoeconomic

The Specific Exergy Cost Method (SPECO) was adopted for this research. The process required first determining all the energetic and exergetic flows in the boundaries of the desired portions. The second stage was to design the product and fuel for each component based on the criterion that every exergy addition to a component counted as fuel and every exergy removal counted as a product. Finally, the cost balance and auxiliary equations for each part were written based on the following relationship [20] :

$$\sum_e \dot{C}_{e,k} + \dot{C}_{e,k} = \dot{C}_{q,k} + \sum_i \dot{C}_{i,k} + \dot{Z}_k \quad (8)$$

$$\dot{C}_j = c_j \dot{E}_j \quad (9)$$

Where, $\dot{C}$ is the cost rate (USD/h), e and i are entering and exiting flow rates, and $\dot{Z}_k$ is the entire cost rate related to capital investment, operation, and maintenance for component *k*.

The Purchase Equipment Cost (PEC) for the components of the gas turbine cycle is stated as follows:

The PEC for the Air Compressor is presented in the following Eq. (10) [20]:

$$PEC_{AC} = \left(\frac{71.10\dot{m}_a}{0.9-\eta_{sc}}\right)\left(\frac{P_2}{P_1}\right)\ln\left(\frac{P_2}{P_1}\right) \tag{10}$$

PEC for the Combustion Chamber

$$PEC_{CC} = \left(\frac{46.08\dot{m}_a}{0.995-\frac{P_4}{P_3}}\right)[1+\exp(0.018T_4-26.4)] \tag{11}$$

PEC for the Gas Turbine,

$$PEC_{GT} = \frac{479.34\,\dot{m}_g}{0.92-\eta_{sc}}\ln\left(\frac{P_4}{P_5}\right)[1+\exp(0.036\,T_4-54.4)] \tag{12}$$

The capital investment as well as the operation and maintenance costs rate are written as [20]:

$$\dot{Z}_k = PEC_k \cdot CRF \cdot \frac{\varphi}{N} \tag{13}$$

Where, PEC_k is the purchase cost of the equipment K in US dollars, φ is the maintenance factor considered as 1.06, and N is the annual operating hours of the system.

The Capital Recovery Factor (CRF) depends on the interest rate as well as the estimated equipment lifetime and can be determined using the following relation [20] :

$$CRF = \frac{i(1+i)^{BL}}{(1+i)^{BL}-1} \tag{14}$$

Where, i is the interest rate and BL is the lifetime of the system considered 12% and 20 years, respectively [20].

2.4 Environment

The greenhouse effect is usually produced due to the accumulation of exhaust gases trapping heat in the atmosphere. It is influenced by several factors such as carbon dioxide, clouds, humidity, dust, and ozone. The power plant emissions affecting geothermal energy can be calculated as follows [22]:

$$CO_2 = \dot{m} \times mass\ fraction\ CO_2 \tag{15}$$

Where, CO_2 is the amount of CO_2 emission and $\dot{m}$ is the mass flow rate. Meanwhile, the CO_2 emissions can be reduced and oil saved using the following equations [22]:

$$CO_2\ Emission\ Reduction\left(\frac{kg}{year}\right) = sm_{CO_2} \times 8760 \times \left(\frac{\dot{W}_{net}}{10^3}\right) \tag{16}$$

$$Annually\ Saved\ Petroleum\ \left(\frac{Lit}{year}\right) = 0.266\left(\frac{Lit}{kWh}\right) \times 8760 \times \left(\frac{\dot{W}_{net}}{10^3}\right) \tag{17}$$

The environmental cost rates of the emission can be determined in USD/s using the following equation [20].

$$\dot{C}_{CO2} = C_{CO2} \times \dot{m}_{CO2} \tag{18}$$

Where, C_{CO2} is the cost units of the environmental effects of CO_2 emissions considered as 0.2086 USD/kg. Moreover, the cost rates of the environmental damages were directly summed with other costs linked to the system in this research [20].

The sequestration of carbon dioxide (CO_2) was observed to vary across different types of land use. The CO_2 absorption rate for fields was 657.00 tons per hectare per year, multitype agroforestry ranged from 3679.20 to 7358.40 while forests and plantations had approximately 569.40 tons of CO_2 per hectare each year [23].

2.5 Data

The parameters and data used in the simulation are presented in this section. Moreover, the builder equation described in the previous section was used to determine the input data parameters required for simulation. The operational data of the gas turbine power plant studied were also obtained through the daily observation of the control building in August, September, and October 2021 as presented in the following Table 1.

Table 1
Average data measured and observed at the gas turbine power plant

Parameters	Unit	August 2021
LHV Fuel	kJ/Kg	50,017.48
Compressor intake air temperature (T_1)	K	301.4
Compressor outlet air temperature (T_2)	K	683.7
Turbine outlet air temperature (T_4)	K	738.5
The temperature of the fuel entering the combustion chamber (T_5)	K	584.6
Compressor intake air pressure (P_1)	Kpa	101.325
Compressor outlet pressure (P_2)	Kpa	1247
The pressure of the fuel entering the combustion chamber (P_5)	Kpa	2030
Ambient air temperature (T_0)	K	301.4
Environmental air pressure (P_0)	Kpa	101.325

Natural gas was observed to be the main fuel utilized in the gas turbine power plant. It consists of a mixture of hydrocarbons primarily methane (CH_4) and some others such as ethane (C_2H_6), propane (C_3H_8), and butane (C_4H_{10}) as indicated in the following Table 2.

Table 2
Gas analysis at BOB - PT Bumi Siak Pusako – Pertamina Hulu, Riau, Indonesia

Gas Composition	Unit	Result
Methane (CH_4)	% mol	89.5136
Ethane (C_2H_6)	% mol	3.7489
Propane (C_3H_8)	% mol	1.7866
i-Butane (C_4H_{10})	% mol	0.3361
n-Butane (C_4H_{10})	% mol	0.3721
i-Pentane (C_5H_{12})	% mol	0.1131
n-Pentane (C_5H_{12})	% mol	0.0698
Hexane (C_6H_{14})	% mol	0.0970
Water (H_2O)	% mol	0.0887
Nitrogen (N_2)	% mol	0.4154
Carbon Dioxide (CO_2)	% mol	3.4585

3. Results and Discussion

Observational data were obtained from the record of the company in the form of a log sheet and based on the measurements conducted in the field. Moreover, the components analyzed include compressor, combustion chamber, and gas turbine as presented in Figure 1.

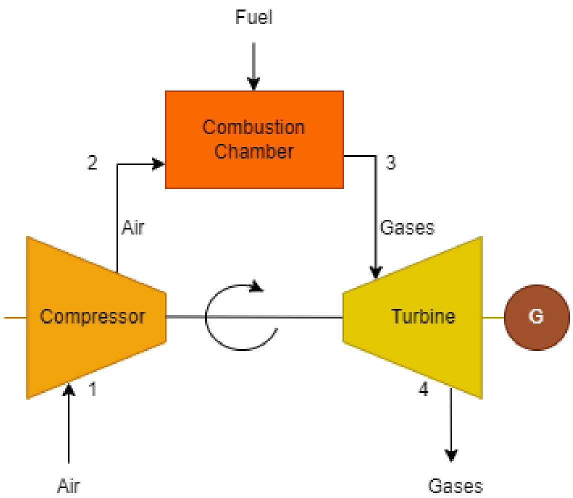

Fig. 1. Power generator cycle

The relationships described in the previous section for each component were used to determine the work and hear as presented in the following Table 3. The results showed that the work output of the gas turbine was 7.436 MW and the efficiency of the system was 42.906%.

Table 3
Value of W and Q of each component

Parameter	Unit	Value
$W_{compressor}$	MW	9.895
$W_{turbine}$	MW	16.626
$W_{nett\ gas}$	MW	7.436
Q_{in}	MW	17.331
System efficiency	%	42.906

The fuel, product, destruction, and efficiency associated with exergy in each component are listed in Table 4 and it was discovered that the largest exergy loss was in the combustion chamber with 3.091 MW while the efficiency was 87.773%. This was followed by the compressor with 2.039 MW and 77.811% and then the gas turbine at 1.091 MW and 95.080%. Moreover, the total exergy destruction was recorded to be 6.221 MW.

Table 4
Exergy value for each component

Component	Exergy fuel (MW)	Exergy product (MW)	Exergy destruction (MW)	Efficiency exergy (%)
Compressor	9.895	7.856	2.039	77.811
Combustion chamber	25.187	22.160	3.091	87.773
Gas turbine	22.160	21.101	1.091	95.080

The percentage of energy input and loss in each component of the plant as well as the output are presented in the Grassmann diagram in Figure 2.

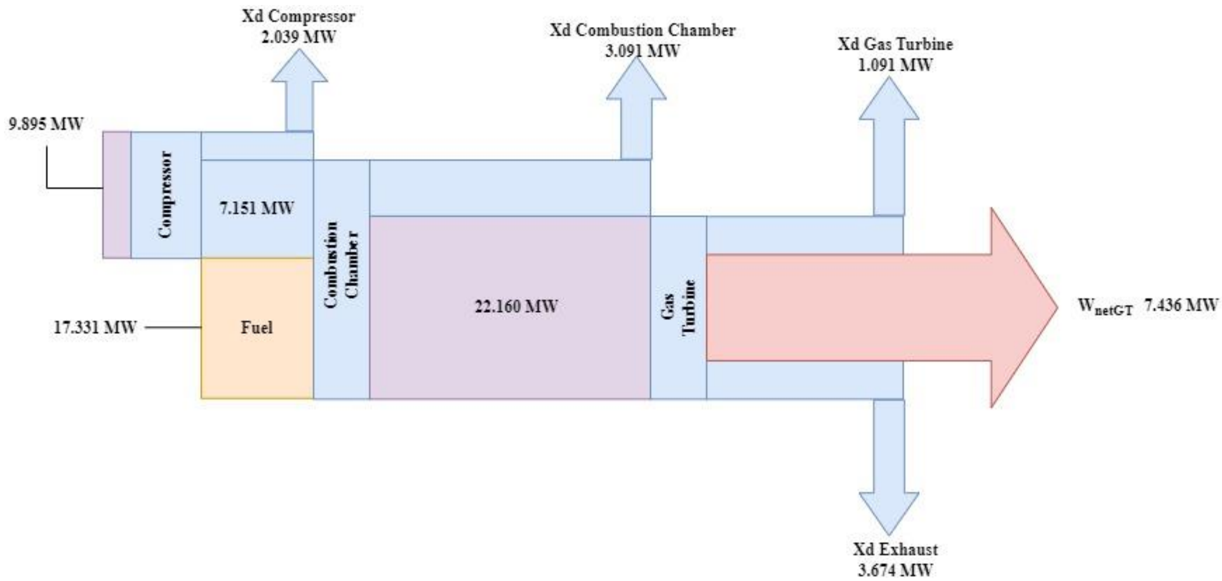

Fig. 2. Grassman diagram of the gas turbine power plant

The energy and exergy analyses results were observed to have led to several suggestions to optimize the plant through a regular maintenance process. It was discovered that the largest energy destruction was in the combustion chamber at 3,091 MW and this was associated with the presence of unburned fuel, incomplete combustion, and heat loss to the environment. The exergy losses found in other components such as compressors and gas turbines were in the form of vibration, friction, and expansion. The results further showed that the components of the plant were in good condition as indicated by the exergy efficiencies recorded to be above 75% for each. However, it was suggested that preventive maintenance needed to be conducted to keep the components in good condition [24].

The exergy and its destruction cost presented in Table 5 showed that the specific exergy price was for electricity ($c_{electricity}$) at 0.15 USD/kWh and fuel (c_{fuel}) at 0.76 USD/kWh.

Table 5
Calculation of cost associated with exergy destruction

Component	Exergy cost (USD/kWh)	Exergy destruction cost (USD/h)
Compressor	1,484.25	1,549.64
Combustion chamber	3,778.05	2,349.16
Gas turbine	3,324	829.16

Table 5 shows that the largest cost was recorded in the combustion chamber because it had the highest exergy destruction followed by the compressor and gas turbine. This was indicated by the exergy cost of 3,778.05 USD/kWh and exergy destruction cost of 2,349.16 USD/h in the combustion chamber followed by the compressors at 1,484.25 USD/kWh and 1,549.64 USD/h and the smallest values were in gas turbine with 3,324 USD/kWh and 829.16 USD/h respectively.

The PEC, annual levelized, and component rate of the plant are also presented in the following Table 6.

Table 6
Calculation of PEC, annual levelized cost, and component rate

Component	PEC (USD)	Annual levelized cost (USD/year)	Component cost rate (USD/hour)
Compressor	3,939,341.12	526,992.55	63.77
Combustion chamber	146,612.07	19,628.24	2.38
Gas turbine	2,480,627.23	332,103.35	40.19

The results showed that the highest PEC value was in the compressor at 3,939,341.12 USD with an annual levelized cost of 526,992.55 USD/year and a component cost rate of 63.77 USD/hour. Moreover, the total PEC, annual levelized, and component cost rates were recorded to be 6,563,580.43 USD, 878,724.14 USD/year, and 106.33 USD/hour respectively.

Several studies were observed to have been conducted on exergy analysis of gas turbine power plants and the results are presented in the following Table 7 for comparison.

The highest exergy destruction value was recorded in the combustion chamber and this was associated with the very high temperature in the component leading to a significant temperature difference between the system and its surroundings. Meanwhile, a higher temperature difference usually leads to a greater potential for exergy loss. The next exergy destruction was found in the air compressor followed by the gas turbine and this was found to be similar to the findings of previous studies [8, 25].

The highest cost loss value was recorded in the combustion chamber followed by the gas turbine and the compressor. This was associated with the carbon dioxide emissions and exhaust heat produced in the combustion chamber due to the reaction between fuel and the measured exhaust gas temperature. Moreover, a higher load was expected to cause a higher gas flow rate and this led to the production of a greater amount of carbon dioxide. This was further proportional to an increase in the heat generated by the exhaust.

Trees and forests were found to be important in reducing the carbon dioxide emissions in the air. It was reported that each generator produced 0.21 kg/s of CO_2 and the system achieved an emission rate of 0.1425 kg/kWh. This showed that a forest area of 11.63 ha was required to absorb the emission from the plant. The conversion of this value to liters per year led to the saving of 14,721 liters of petroleum in a year. It was also noted that the exhaust heat released to the environment at an average temperature of 738.54 K was 7654.04 KW.

Table 7
Exergy destruction rate and exergetic efficiency comparison with other studies

Authors	Exergy destruction (kW)			Cost of exergy destruction (USD/h)			Environment	
	Air compressor	Combustion chamber	Gas turbine	Compressor	Combustion chamber	Gas Turbine	Total CO_2 (Kg/kWh)	Forest area needed (ha)
Egware *et al.,* 2014 [25]	3,688	94,764	3,070	-	-	-	-	-
Martin *et al.,* 2016 [6]	3,810	21,980	5,150	-	-	-	-	-
Ibrahim *et al.,* 2017 [26]	8,495	334,271	51,622	-	-	-	-	-
Martin *et al.,* 2021 [8]	8,490	21,850	3,090	1,066.43	1,561.46	165.25	-	-
Ding *et al.,* 2021 [27]	702	3,237	2,715	1,145	21.77	78.34	-	-
Kareem *et al.,* 2023 [28]	21,170	176,100	23,730	120	735.8	124.2	0.489	-
This paper	2,039	3,091	1,091	1,362.48	1,962.28	212,79	0.1425	11.63

4. Conclusion

In conclusion, this research was conducted to determine the performance of a gas turbine power plant and the results showed that the energy and exergy efficiencies were 42.902% and 33.505%. Moreover, the largest exergy destruction of 3.091 MW was found in the combustion chamber at an exergy cost of 3,778.05 USD /kWh and a destruction cost of 2,349.16 USD/h, and this was associated with the very high temperature in the component. The highest PEC value was recorded in the compressor at 3,939,341.12 USD with an annual levelized cost of 526,992.55 USD /year and a component cost rate of 63.77 USD/hour. Furthermore, the gas turbine power plant generated 0.200582 kg/s of CO_2 and maintained an emission rate of 0.1425 kg/kWh, and this showed that a forest area of 11.63 hectares was required to absorb the gas emitted. The conversion of this value to liters per year led to the saving of 14,721 liters of petroleum in a year.

These results can serve as valuable references for comprehending, optimizing, economically assessing, and conserving energy in gas turbine power plant systems in order to make informed decision-making regarding the environmental consequences. Meanwhile, it was observed that the calculation processes were a little bit complex and required precise data to yield accurate results. It was discovered that energy, exergy, exergetics, and exergoeconomics analyses are essential tools for managing energy and environmental systems but they need to be applied appropriately within the relevant context to explore the benefits.

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