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Exergy and Energy Analysis of Gas Turbine Generator X Combined Cycle Power Plant Using Cycle-Tempo Software

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ABSTRACT

Increasing electricity production must continue to be pursued to meet the increasing electricity needs of the community. One of the efforts that engineers can make is to improve the performance of the main suppliers of electricity needs. It is impossible to separate the role of the system's components from the performance of the gas turbine generator. This journal discusses exergy and energy analysis in the gas turbine generator of X combined cycle power plant through simulation with Cycle-Tempo software. The simulation results show that the highest system energy efficiency is owned by the gas turbine generator unit 2.3 of 35.541%, with a system exergy efficiency of 34.069%. The lowest system energy efficiency is owned by the gas turbine generator unit 2.1 of 31.669%, with a system exergy efficiency of 30.355%. The gas turbine generator component with the lowest exergy efficiency occurs in the combustion chamber of the gas turbine generator unit 2.2 of 76.81%, with exergy destruction of 92.581 MW. Meanwhile, the gas turbine generator component with the highest exergy efficiency occurred in the turbine of the gas turbine generator unit 2.3 of 96.81%, with exergy destruction of 9.762 MW. The simulation results that have been carried out show that the performance of the components in the gas turbine generator is still in good performance, with the lowest exergy efficiency above 75%.

1. Introduction

The consumption of world electricity needs has increased significantly due to an increase in the world's population and technological developments. The highest per capita electricity consumption in the GCC (Gulf Cooperation Council) countries from 1975 to 2018 was 21 MWh/capita [1]. The increase in electricity consumption by 793% from 1990 to 2018 made Indonesia a consumptive country in the use of electrical energy [2]. Increasing electricity production must continue to be pursued to meet the community's increasing electricity needs. One of the efforts that can be made is to optimize the performance of power plants as the main supplier of human electricity needs. Gas turbine generator

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(GTG) is a component commonly used in power plants with fuel sources in the form of coal, natural gas, and distillate oil [3-6]. The compressor, combustion chambers, and turbines are the main components that make up a gas power plant or gas turbine generator system [5–11]. Several authors have widely used the gas turbine generator system and its components in research, especially the review of its performance. Exergy and energy analysis is the right way to analyze the power generation system's actual performance so that the losses in the system can be known accurately [12]. Ogunedo and Okoro [8] reported the exergy efficiency of the Afam IV gas turbine components, namely the compressor at 99%, the combustion chamber at 76%, and the turbine at 96%. Based on this research, the system loses energy of 2.23 kJ for every 1 MW of power output in the combustion chamber. Ivan *et al.,* [13] investigate the energy efficiency and exergy efficiency of a closed-cycle CO_2 gas turbine. The energy efficiency of the closed cycle CO_2 gas turbine with a regenerator is 36.6%, while the energy efficiency of this cycle without a regenerator is 16.91%. The turbine component in the closed cycle CO2 gas turbine has the highest exergy efficiency among other components, which is 95.39%. Abuelnuor *et al.,* [14] carried out a destructive exergy evaluation at Garri "2" power plant in Sudan. The exergy destruction from the combustion chamber is 63%, and the exergy destruction from the gas turbine is 13.6%. Tiwari *et al.,* [15] present an exergy analysis of a power plant in India. Tiwari *et al.,* reported that the exergy destruction of the combustion chamber is 35% of the total exergy destruction of gas turbine generators.

This journal simulates a 93 MW load on the gas turbine generator X combined cycle power plant, a power plant located in X, Indonesia. This gas turbine generator consists of 6 units divided into two generating blocks. The choice of this discussion is because there are no authors who have evaluated the thermodynamic performance, especially energy efficiency, exergy efficiency, and exergy destruction on the gas turbine generator of X combined cycle power plant. The use of cycle tempo in calculating exergy and energy has been carried out by several researchers, as stated in this section. The research was conducted in situ at a state-owned company, so the results of this study cannot be compared with other power plants due to differences in the configuration and model of the power plant. There is a lot of exergy destruction in the gas turbine generator components of X combined cycle power plant because the plant has been operating since 1999 [16]. The software used in conducting the simulation is Cycle-Tempo software. Cycle-Tempo is a flow-sheet program on a computer used in thermodynamic optimization and modeling of energy systems [17,18]. This software is used in various thermodynamic cycle studies. The Cycle-Tempo program was used by Jamel *et al.,* [17] to simulate an Iraqi power plant. From simulations with a capacity of 200 MW, they present a profile of exergy losses and temperatures in the generator components. Mahendra *et al.,* [18] simulated the effect of a feedwater heater on the operation of a steam power plant using Cycle-Tempo 5.0. The results indicate that feedwater heaters cause an increase in net plant heat rate. Pinto *et al.,* [19] performed Cycle-Tempo simulations with ten different configurations of gas microturbine. The simulation results show the isentropic power and efficiency of each different configuration. Raghulnath *et al.,* [20] and Muslim *et al.,* [21] developed a variation of the Cycle-Tempo model of the Organic Rankine Cycle. Research conducted by Rajeev *et al.,* [22], namely energy and exergy analysis at a 3x500MW power plant using Cycle-Tempo software, got the largest validation error in his research at 9.07%. Simulation with Cycle-Tempo software requires validation to determine the accuracy of the simulation results. The purpose of this study is to carry out an energy and exergy analysis to evaluate the efficiency of the gas turbine generator used in the X combined cycle power plant. The validation process is carried out by comparing the output power of the simulation process with the output power data owned by the company.

2. Methodology

2.1 Research Method

The research began by conducting literature studies in international journals, conference journals, and other scientific literature sourced from Science Direct, Research Gate, Springer Link, Scopus, ProQuest, Google Scholar, and several official websites. Literature studies were also carried out through the library at X combined cycle power plant to find some data about the gas turbine generator used at the plant. The problem that arises in studying the literature is that there is no exergy evaluation at X combined cycle power plant, especially for each component of the gas turbine generator. Based on field observations, the performance review of the gas turbine generator is carried out by evaluating energy. The required parameters are reviewed from the governing equation used in modeling the gas turbine generator to perform the Cycle-Tempo simulation. The determination of the parameters entered is useful so that data errors do not occur in the Cycle-Tempo software when the simulation starts. From these predetermined data parameters, data collection can be done by observing daily operating data in the control building of X combined cycle power plant, such as temperature data, pressure data, fuel data, and output power data. Input data for Cycle-Tempo software's modeling of the gas turbine generator comes from operational data. The simulation results are validated by comparing the output power error value with the company data output power. The error value is still accepted if the error value obtained is not more than 9.07% [22]. The analysis is continued when the validation has been met. Analysis of energy efficiency, exergy efficiency, and exergy destruction was done using Cycle-Tempo software simulation results. The performance of the gas turbine generator is determined by the factors that have been analyzed. The conclusions of this journal include gas turbine generators with the best and lowest performance and components of gas turbine generators with the highest and lowest exergy efficiency and the exergy destruction that occurs.

2.2 Governing Equation

The Brayton cycle governs how the gas turbine generator operates, as depicted in Figure 1. This cycle consists of 2 adiabatic or isentropic processes and two constant pressure or isobaric processes [11]. Energy analysis is used to see the energy balance of a system, where the energy in is equal to the energy out. Energy is the ability to do work. In this cycle, the equation used in calculating the energy efficiency system of a gas turbine generator can be written as follows:

$$\eta = \frac{\dot{W}_T - \dot{W}_C}{\dot{Q}_{CC}} \tag{1}$$

Exergy analysis uses the calculation of the entropy generation of components to determine the thermodynamic performance of energy systems accurately. In contrast to energy, exergy can be conceptualized as the maximum work that can be done or the energy available to a system under certain conditions [8]. The ratio of actual work to net exergy value entering the system determines the exergy efficiency of the system [11]. Energy efficiency in the system is significantly influenced by the amount of exergy destruction. The following equation can be used to express the gas turbine generator system's energy efficiency:

$$\eta_e = \frac{\dot{W}_T - \dot{W}_C}{\dot{Ex}_{Net}} \tag{2}$$

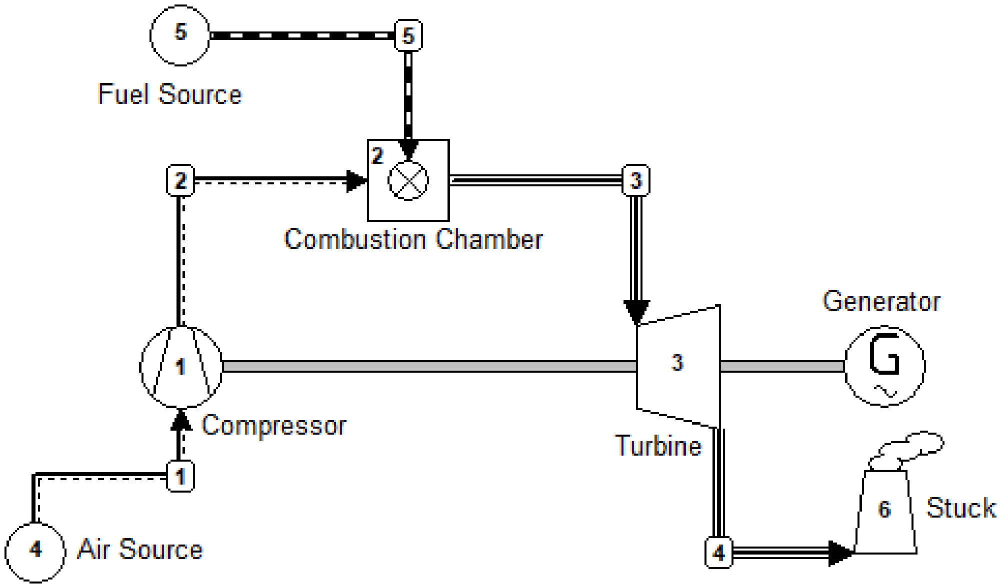
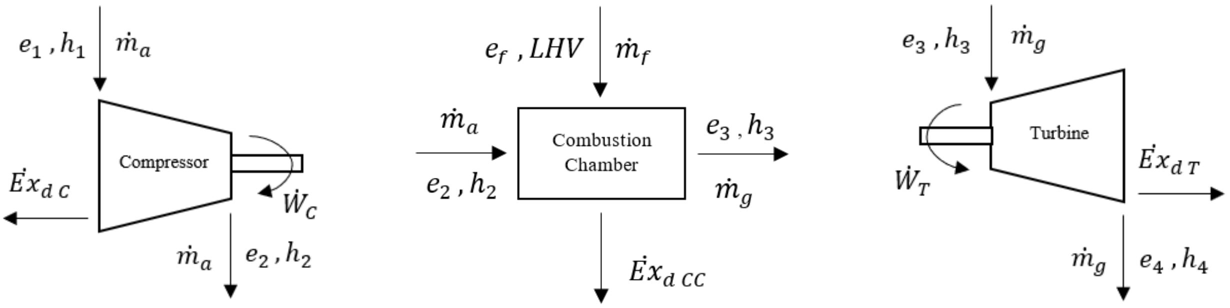


Fig. 1. Gas turbine generator

The schematic diagram of the compressor, combustion chamber, and turbine is shown in Figure 2. This diagram is used for thermodynamic analysis of the compressor, combustion chamber, and turbine. Table 1, Table 2, and Table 3 present the equations of power, heat transfer rate, exergy destruction, and exergy efficiency of gas turbine generator components.



(a) (b) (c)

Fig. 2. Schematic diagram (a) Compressor (b) Combustion Chamber (c) Turbine

Table 1
Power or heat transfer rate equation each component

Component	Power or Heat Transfer Rate	Eq.
Compressor	$\dot{W}_C = \dot{m}_a(h_2 - h_1)$	Eq. (3)
Combustion Chamber	$\dot{Q}_{CC} = \dot{m}_f \times LHV$	Eq. (4)
Turbine	$\dot{W}_T = \dot{m}_g(h_3 - h_4)$	Eq. (5)

Table 2
Exergy destruction equation each component

Component	Exergy Destruction	Eq.
Compressor	$\dot{Ex}_{d\,C} = \dot{W}_C - \dot{m}_a[(h_2 - h_1) - T_0(s°_2 - s°_1 - R\ln\frac{p_2}{p_1})]$	Eq. (6)
Combustion Chamber	$\dot{Ex}_{d\,CC} = \dot{m}_a\left[(h_2 - h_0) - T_0\left(s°_2 - s°_0 - R\ln\frac{p_2}{p_0}\right)\right] + \dot{m}_f\left[\gamma_f . \frac{\dot{Q}_{CC}}{f}\right]$ $-\dot{m}_g[(h_3 - h_0) - T_0(s°_3 - s°_0 - R\ln\frac{p_3}{p_0})]$	Eq. (7)
Turbine	$\dot{Ex}_{d\,T} = \dot{m}_g[(h_3 - h_4) - T_0(s°_3 - s°_4 - R\ln\frac{p_3}{p_4})] - \dot{W}_T$	Eq. (8)

Table 3
Exergy efficiency equation each component

Component	Exergy Efficiency	Eq.
Compressor	$\eta_{e\,C} = \frac{\dot{W}_C - \dot{Ex}_{d\,C}}{\dot{W}_C}$	(9)
Combustion Chamber	$\eta_{e\,CC} = \frac{\dot{m}_g e_3}{\dot{m}_a e_2 + \dot{m}_f e_f}$	(10)
Turbine	$\eta_{e\,T} = \frac{\dot{W}_T}{\dot{W}_T + \dot{Ex}_{d\,T}}$	(11)

2.3 Parameter and Data

The parameters and data used in the simulation are presented in this section. Based on the builder equation described in the previous section, the input data parameters required in this simulation are determined. The operational data of the gas turbine generator is obtained by observing daily operating data in the control building of X combined cycle power plant PT X. Operational data was taken on November 11, 2021, for gas turbine generator block 1 and September 13, 2021, on gas turbine generator block 2. This data is then averaged for each unit and used in Cycle-Tempo simulation input. Table 4 is the operational data input for gas turbine generator block 1 and block 2 X combined cycle power plant.

Table 4
Operational data input gas turbine generator

Parameter	Symbol	Unit	Gas Turbine Generator Unit					
			1.1	1.2	1.3	2.1	2.2	2.3
Inlet Air Temperature	T_1	°C	30.361	30.034	30.250	29.470	29.660	29.450
Inlet Air Pressure	p_1	Bar	1.013	1.013	1.013	1.013	1.013	1.013
Compressor Exit Temperature	T_2	°C	346.65	342.26	352.13	345.46	357.36	347.25
Compressor Exit Pressure	p_2	Bar	9.351	9.575	9.801	9.710	9.970	9.460
Ambient Temperature	T_0	°C	30.361	30.034	30.238	29.470	29.660	29.450
CH_4 Percentage	-	%	90.34	90.34	90.34	90.34	90.34	90.34
Natural Gas Mass Flow Rate	$\dot{m}_f$	kg/s	6.164	6.155	6.280	6.120	6.120	6.140
Natural Gas Inlet Temperature	T_f	°C	31.140	31.140	31.140	31.140	31.140	31.140
Dilute Coefficient	-	-	3.4	3.4	3.4	3.4	3.4	3.4
Turbine Inlet Temperature	T_3	°C	1068	1068	1068	1068	1068	1068
Combustion Chamber Pressure Drop	Δp	bar	0.072	0.072	0.072	0.072	0.072	0.072
Turbine Exit Temperature	T_4	°C	557.70	556.62	555.23	570.35	550.66	540.09

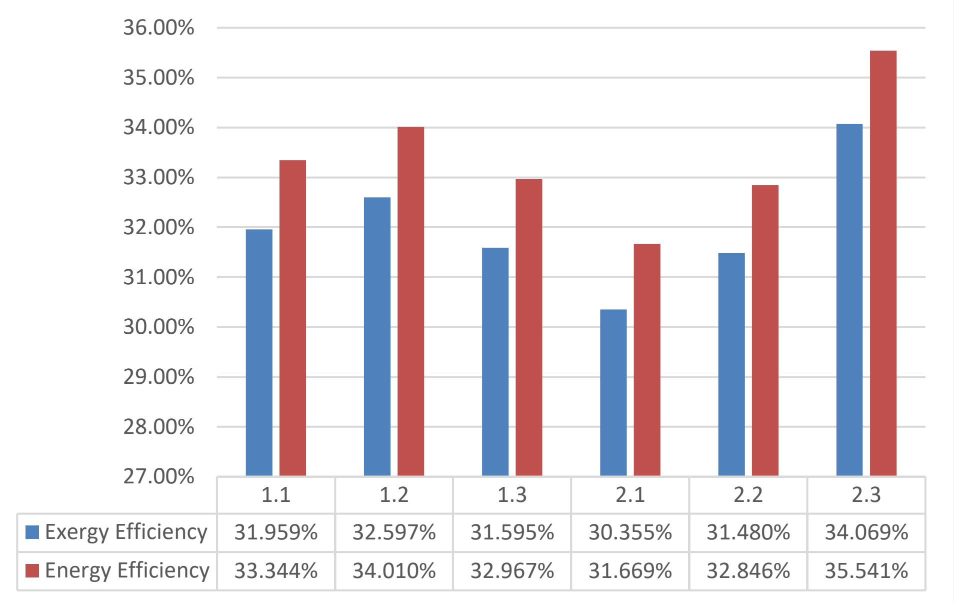
3. Results and Discussion

The simulation process ends with the validation process. It is necessary to calculate the error. This calculation compares the simulation results with the company's existing data conditions. Based on the outcomes of the Cycle-Tempo simulation with the company's power data, this value displays the power deviation produced by the gas turbine generator. Table 5 shows the error comparison of the simulation power parameters with existing conditions. Based on Table 5, the error value in the most extensive simulation is 6.36%. Based on these results, the simulation has a relatively small error.

Table 5
Simulation error

Test Time	Gas Turbine Generator Unit	Power Simulation Results (MW)	Power Existing (MW)	Error
November	1.1	95.24	94.08	1.23%
	1.2	97.00	93	4.30%
	1.3	95.93	92.95	3.21%
September	2.1	89.81	94.92	5.38%
	2.2	93.15	94.89	1.83%
	2.3	101.12	95.07	6.36%

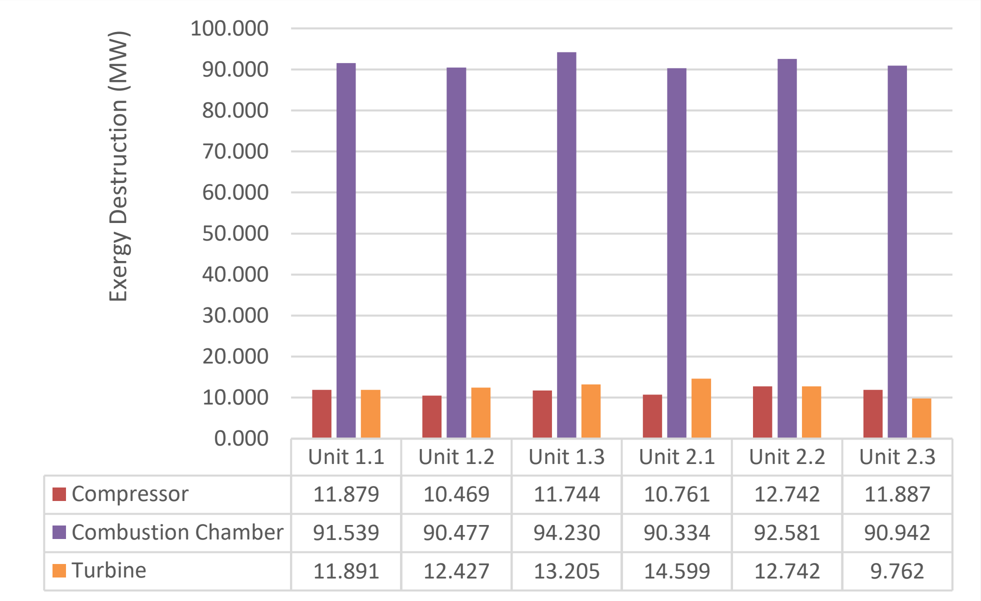
Figure 3 displays the system energy efficiency and system exergy efficiency of each gas turbine generator based on Cycle-Tempo simulation. Based on the simulation results with operational data on 11 November 2021 for gas turbine generator block 1 and 13 September 2021 in gas turbine generator block 2, the highest values of energy efficiency and exergy efficiency of gas turbine generators are 28.149% and 34.069%, respectively, while the lowest values are 25.082% and 30.355%, respectively. The highest value of energy efficiency and exergy efficiency is owned by gas turbine generator unit 2.3, while the lowest value is owned by gas turbine generator unit 2.1. The impact of the environment on the gas turbine generator system accounts for the distinction between energy efficiency and exergy efficiency. This value is also influenced by fuel composition, generator loading, and mass flow rate in a system.



	1.1	1.2	1.3	2.1	2.2	2.3
🟦 Exergy Efficiency	31.959%	32.597%	31.595%	30.355%	31.480%	34.069%
🟥 Energy Efficiency	33.344%	34.010%	32.967%	31.669%	32.846%	35.541%

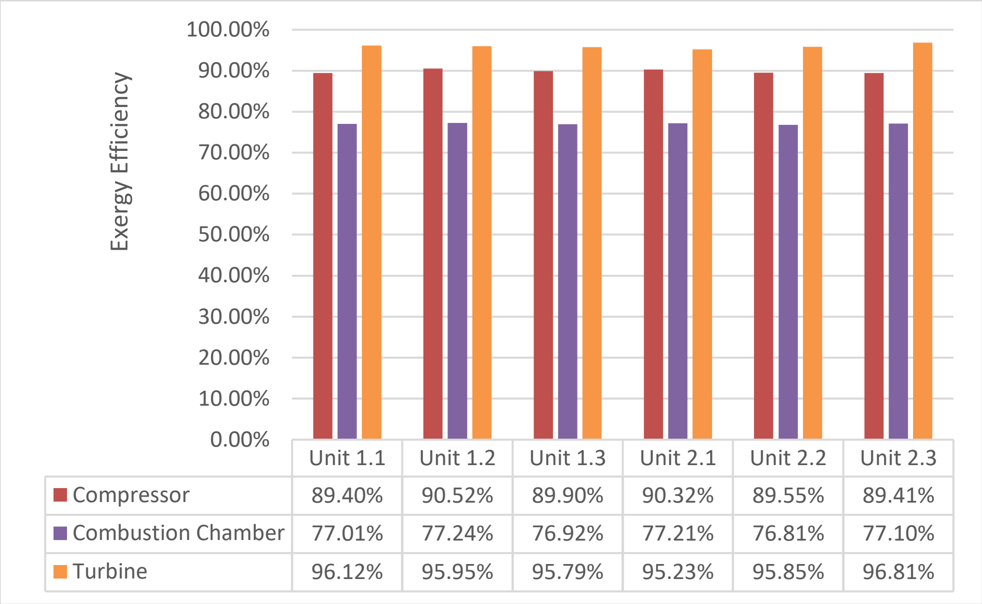
Fig. 3. Energy efficiency and exergy efficiency of each gas turbine generator unit

From the simulations, performance evaluations for each component were also obtained. Figure 4 and Figure 5 show the exergy destruction and exergy efficiency of the gas turbine generator component in each unit, respectively. The most immense compressor exergy efficiency value is owned by the gas turbine generator unit 1.2 of 90.52%, with the exergy destruction of 10.469 MW. The lowest compressor exergy efficiency value is owned by gas turbine generator unit 1.1 of 89.40% with exergy destruction of 11.879 MW. The immense exergy efficiency value in the combustion chamber component is owned by gas turbine generator unit 1.2 of 77.24%, with exergy destruction of 90.477 MW. The lowest exergy efficiency value of the combustion chamber is owned by the gas turbine generator unit 1.1 of 77.24%, with the exergy destruction of 91.539 MW. In the turbine component, the most immense turbine exergy efficiency value is owned by the gas turbine generator unit 2.3 of 96.81%, with the exergy destruction of 9.762 MW. The lowest turbine exergy efficiency value is owned by gas turbine generator unit 2.1 of 95.23% with exergy destruction of 14.599 MW.



	Unit 1.1	Unit 1.2	Unit 1.3	Unit 2.1	Unit 2.2	Unit 2.3
🟥 Compressor	11.879	10.469	11.744	10.761	12.742	11.887
🟪 Combustion Chamber	91.539	90.477	94.230	90.334	92.581	90.942
🟧 Turbine	11.891	12.427	13.205	14.599	12.742	9.762

Fig. 4. Exergy destruction of each component gas turbine generator



	Unit 1.1	Unit 1.2	Unit 1.3	Unit 2.1	Unit 2.2	Unit 2.3
🟥 Compressor	89.40%	90.52%	89.90%	90.32%	89.55%	89.41%
🟪 Combustion Chamber	77.01%	77.24%	76.92%	77.21%	76.81%	77.10%
🟧 Turbine	96.12%	95.95%	95.79%	95.23%	95.85%	96.81%

Fig. 5. The exergy efficiency of each component gas turbine generator

The amount of exergy losses strongly influences the exergy efficiency of gas turbine generator components. This destructive exergy can be in the form of vibration, friction, or expansion of each component. Additionally, the rate of heat transfer from the component to the environment, as well as the mass flow of air and fuel, all have an impact on the component's ability to exergy destruction. The ambient temperature variation impacts the exergy destruction because the temperature has an impact on the working fluid's entropy. The simulation results that have been carried out show that the performance of the components in the gas turbine generator is still in good performance, with the lowest exergy efficiency above 75%. However, it is necessary to carry out preventive maintenance to maintain good performance on the components of the gas turbine generator [23]. It is possible to keep efficiency close to maximum efficiency by performing routine maintenance on the mechanical systems of the components. By minimizing wasted energy, expenses for fuel or oil needs can be reduced, so the economic costs incurred can be reduced too [24-27]. Imagine that the gas turbine generator's efficiency is significantly reduced. It is necessary to immediately check and repair it, even if it is necessary to carry out a maintenance outage or overhaul. Maintenance outage or overhaul aims to maintain the pressure and temperature of the working fluid produced by each component so that the fuel used can be suppressed.

4. Conclusion

The simulation results were carried out to become a review of the gas turbine generator performance. According to the results of the Cycle-Tempo simulation, the highest system energy efficiency value is owned by gas turbine generator unit 2.3 of 28.149% with a system exergy efficiency value of 34.069%. Meanwhile, the lowest system energy efficiency value is owned by gas turbine generator unit 2.1 of 25.082% with an efficiency value system exergy of 30.355%. The efficiency value from the simulation results shows that the gas turbine generator system still has good performance. The simulation results that have been carried out show that the performance of the components in the gas turbine generator is still in good performance with the lowest exergy efficiency above 75%, even though the exergy destruction that occurs is quite extensive. The gas turbine generator component with the lowest exergy efficiency occurs in the combustion chamber of the gas turbine generator unit 2.2 of 76.81%, with exergy destruction of 92.581 MW. Meanwhile, the gas turbine generator component with the biggest exergy efficiency happened in the turbine of the gas turbine generator unit 2.3 component of 96.81% with exergy destruction of 9.762 MW.

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