Technical and Environmental Assessment of a Combined Heat and Power Rankine Cycle System Based on Natural Gas Boiler

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In this paper, a Rankin cycle-based heat and power generation system is simulated. The input energy of the system is supplied by the combustion of natural gas in the boiler. Condenser heat recovery is used to supply thermal energy and on the other hand, the power generated by the turbine is used to supply electricity demand. The first and second laws of thermodynamics and the law of conservation of mass are used to analyze the energy and exergy performance of the system. Finally, the effect of changing each of the performance parameters on the energy and CO2 emission of the system is investigated. According to the results, the turbine output power, net power production, electrical efficiency, energy efficiency, exergy efficiency, and CO2 production is obtained as 354.63 kW, 353.53 kW, 24.23%, 94.92%, 74.38%, and 81.1 g/s, respectively. Furthermore, the simulation results show that increasing the turbine inlet temperature increases electrical efficiency and exergy. Increasing the condenser outlet temperature also reduces electrical and exergy efficiency. On the other hand, increasing natural gas consumption only increases CO2 production and does not affect electrical, energy, and exergy efficiencies. © 2022 Journal of Energy Management and Technology

keywords: *Cogeneration system, Rankine cycle, energy and exergy analysis, environment*

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1. INTRODUCTION

Global warming and declining fossil fuels are the two main concerns of energy producers. Carbon dioxide emissions are constantly increasing, although some policies have been implemented to limit their emissions. For example, from 1990 to 2007, carbon dioxide emissions in the United States increased by 17 percent [1]. Besides, global energy consumption is expected to increase by about 40% between 2006 and 2030 [12]. Therefore, finding energy-efficient systems is now much more important than ever. Potentially efficient technology is the cogeneration system. Many researchers have focused on the simulation and optimization of cogeneration systems. Some of these research papers are described below.

Al-Sulaiman et al. [3] developed a CCHP system from the point of view of exergy in three modes: only power generation, power and heat generation, and power and heat and cooling generation. The results showed that solar collectors and evaporators are the main cause of exergy destruction in the system. Besides, it was revealed that the exergy efficiency is much higher in the third model. Al-Sulaiman et al. [4] proposed a CCHP system that consisted of an absorption refrigeration subsystem, an organic Rankin turbine, a heat exchanger for heating, and a biomass burner. The system uses octane and sawdust as fuel. The effect of three parameters including evaporator pinch temperature, pump inlet temperature, and turbine inlet pressure on energy efficiency, exergy efficiency, net power, the power to cooling ratio, and power to heating ratio was investigated. The results showed that the efficiency of the trigeneration system is much higher than the case where only power or power and heating are produced. This efficiency in some cases reached up to 88%. Ebrahimi et al. [5] proposed a CCHP system for a residential building and analyzed its heating and cooling performance. The proposed system included ejector refrigeration, steam turbine, and steam generator, and its working fluid was water. The results of their study showed that cogeneration is always superior in terms of energy saving compared to the case where there is a separate production of power, heat, and cold. The exergy destruction of each element was calculated and it was observed that the steam generator has the highest rate of exergy destruction in both winter and summer. Besides, the results of the system optimization using the GA algorithm showed that the highest efficiency in summer reaches 22.82%, and in winter reaches 62.15%. Al-Sulaiman et al. [6] analyzed three biomass, fuel cell, and solar cogeneration systems, all based on the organic Rankin cycle. They first modeled the exergy of all three systems, then used thermoeconomic analysis of the systems using the Specific Exergy Costing (SPECO) method and fuel-product laws. This study deals with the application of thermoeconomic analysis methods to the optimization of cogeneration systems. Liu et al. [7] introduced a CCHP system as an example of a distributed energy production system to study the types of these systems. In the first part of the research, they explained how these systems work what are the advantages of the components required in these systems. In the second part, different structures, design methods, management, control, and optimization of these systems are discussed. In the last section, the development history of these systems in the United States, Britain, and China are analyzed and the use of renewable energy, including wind and solar energy, is predicted in the near future. Pirkandi et al. [8] simulated and optimized a combined heat and power (CHP) system integrated with a micro-gas turbine. They used MATLAB code to simulate and optimize the integrated system. They also carried out a sensitivity analysis to have a good insight into their study. Finally, they optimized the system performance based on the exergy analysis and utilization of economic and environmental functions. Khoshbazan et al. [9] studied a small power and heat generation system equipped with a solar sterling motor to supply electricity and heat required for a building in three different cities of Iran according to climatic conditions. Their study showed that the highest efficiency of solar Stirling engine was obtained in Mashhad with approximately 44%. Besides, the maximum carbon dioxide reduction by utilizing this system is obtained in Tehran. Kazagic et al. [10] optimized a modular district heating solution based on CHP and Renewable Energy Source (RES) systems. In the results of this analysis, suitable indicators for economic and environmental sustainability have been identified. Olympios et al. [11] designed and implemented a fact-based multi-objective function, taking into account the risk-return transactions due to the uncertainty of the exported electricity price, to control a combined heat and power system. In this study, a lot of effort has been made to understand the real challenges and assess the impact of uncertainty in the use of advanced algorithms in the real world. The model presented in this study applies a two-stage control structure including an optimization framework for the real-time CHP heat and power system operating program including intelligent communication between two controllers for continuous motor monitoring and control. Electricity price uncertainty is reduced at intervals by the use of production forecast balances. The use of this model in a study sample for 40 days of experience confirms that the predicted electricity price is almost realized, saving 23% in this period and saving up to 35% in the energy costs of the complex in the one-day modeling period. B. Azizimehr et al. [12] analysis and optimization of a solar micro combined cooling, heating, and power system by using the Teaching–Learning-Based Optimization (TLBO) algorithm for domestic application. They added a storage tank to the system for stability. For single-objective and multi-objective optimization, they used the TLBO algorithm, which increased thermal efficiency by 27.85% and exergy efficiency by 27.66%, respectively. In other research, they used the PSO algorithm for the same system which improved 27.65% thermal efficiency, 27.46% exergy efficiency, and reduced 11.98% of the system cost rate [13]. V.V.Klimenko et al. [14] evaluated the combined heat and power system performance under the warming climate. The most striking result was that the CHP efficiency drop may be leveled by an adjustment of the extreme cold temperature values according to the observed climate dynamics when designing the CHP plants. R. Asadi et al. [15] reviewed optimization algorithms for combined cooling, heating, and power (CCHP) systems incorporating solar and geothermal energy. Their results showed that the utilization of CCHP systems is more efficient than simple single objective production systems. Furthermore, the use of Nano-fluids in solar collectors instead of water increases the heat transfer efficiency, and specifically those of SiO2, CuO, AL2O3, and TiO2 lead to high performance.

In the present study, the results of a simulation of a Rankine cycle heat and power generation system are presented. Three parameters of energy efficiency, exergy efficiency, electrical efficiency, and CO2 emission are used to evaluate the performance of the system. First, the studied system is investigated thermodynamically, and finally, the effect of changing functional parameters on thermodynamic and environmental performance is investigated.

2. METHODOLOGY

The heat generated from the combustion of natural gas in the boiler is transferred to the working fluid of the cycle (water) and converts its state to saturated steam. Saturated steam enters the turbine at a lower temperature as its pressure decreases. In the condenser, the fluid state reaches the saturated liquid and then enters the pump to increase the pressure. By continuing this cycle, the required electrical power and heat are produced. The mechanical power generated by the steam turbine is converted into electrical power using the electric generator. Condenser heat recovery also provides the required thermal energy (Figure 1). The input data for the system simulation is shown in Table 1.

A. Energy analysis

In the energy analysis of the system, the law of conservation of mass and energy has been used. Each component in the system is considered a control volume. For a control volume with input i and output o, mass and energy conservation can be written as follows [12, 13]:

$$\sum \dot{m}_i = \sum \dot{m}_o \tag{1}$$

$$\sum \dot{Q} - \sum Q\dot{W} = \sum \dot{m}_o h_o \tag{2}$$

The following assumptions are considered in energy analysis:

- ✓ The system is in stable condition and pressure drop in pipes, boilers, and heat exchangers is ignored.

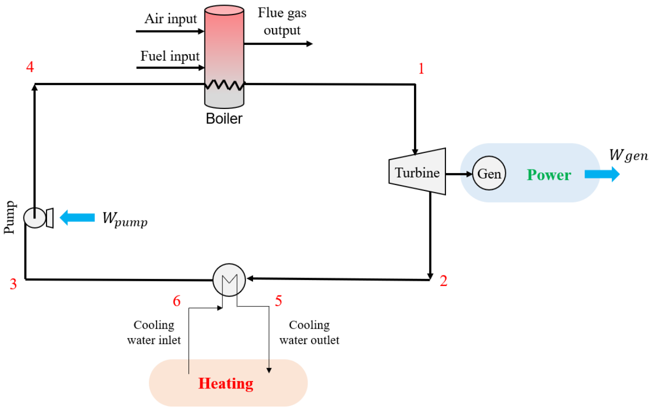

Fig. 1. Scheme of the cogeneration system.

Table 1. Input data

Parameter	**Unit**	**Value**
Inlet natural gas	Mol	2
Boiler efficiency (η_b)	%	80
Generator efficiency (η_{gen})	%	95
Heat exchanger efficiency (η_{HE})	%	95
Turbine isentropic efficiency ($\eta_{Turbine,ise}$)	%	85
Pump isentropic efficiency ($\eta_{Pump,ise}$)	%	75
Turbine inlet temperature (T_1)	$^{\circ}C$	200
Condenser outlet temperature (T_3)	$^{\circ}C$	40
The cooling water inlet temperature (T_6)	$^{\circ}C$	25
Cooling water pressure (P_5, P_6)	kPa	100
Dead state temperature (T_0)	$^{\circ}C$	25
Dead state pressure (P_0)	kPa	100

- ✓ Isentropic efficiencies are considered for the turbine and pump.
- ✓ The condenser output and turbine inlet states are considered saturated liquid and saturated vapor, respectively.
- ✓ Potential and kinetic energies are ignored.

Energy and mass balance equations for different components of the cogeneration system are written as follows:

Boiler:

$$\begin{gathered} m_1\left(h_1-h_4\right)=Q_b \eta_b \\ m_1=m_4 \end{gathered} \tag{3}$$

Turbine:

$$\begin{gathered} W_T=m_1\left(h_1-h_2\right) \\ m_1=m_2 \\ \eta_{\text{Turbine , ise}}=\frac{h_2-h_1}{h_{2,s}-h_1} \end{gathered} \tag{4}$$

Condenser:

$$\begin{gathered} m_2\left(h_2-h_3\right)=\frac{m_5\left(h_5-h_6\right)}{\eta_{\text{condenser}}} \\ m_5=m_6 \end{gathered} \tag{5}$$

Pump:

$$\begin{gathered} W_p=m_3\left(h_4-h_3\right) \\ m_3=m_4 \\ \eta_{\text{Pump},ise}=\frac{h_3-h_{4,s}}{h_3-h_4} \end{gathered} \tag{6}$$

B. Exergy analysis

Exergy means the maximum amount of work that can be obtained from a given amount of energy. In other words, this is one of the characteristics of the system and the environment [19]:

$$\begin{aligned} & \Psi=\left(h_{\text{tot}}-T_0 s\right)-\left(h_{\text{tot},0}-T_0 s_0\right)= \\ & \left(h-T_0 s+\frac{1}{2} V^2+g Z\right) \\ & -\left(h_0-T_0 s_0+g Z_0\right) \end{aligned} \tag{7}$$

This equation is written in the absence of the effects of nuclear, magnetic, electrical, and surface tension energies. The total enthalpy represents the terms of potential and kinetic energy. The flow in the environment has zero exergy. On the other hand, the amount of exergy can be defined as the difference between work and heat in terms of irreversibility, or change in energy quality. In the exergy analysis of the present study, the following assumptions are taken into account:

- ✓ Only physical exergies are considered for the flows.
- ✓ Potential and kinetic exergies are ignored because velocity changes are negligible.
- ✓ The chemical exergy of the material is ignored.

By applying the first and second laws of thermodynamics, exergy equations are obtained as follows [17]:

$$\dot{E}_Q+\sum_i \dot{m}_i e_i=\sum_e \dot{m}_e e_e+\dot{E}_W+\dot{E}_D \tag{8}$$

$$\dot{E}_Q=\left(1-\frac{T_0}{T}\right) \dot{Q} \tag{9}$$

$$\dot{E}_W=\dot{W} \tag{10}$$

where $\dot{E}_Q$ and $\dot{E}_W$ are the heat transfer exergies and work that cross the boundaries of the control volume, respectively.

C. Boiler system analysis

A boiler in the studied system is a control volume in which water enters with ambient temperature and pressure and exits with high temperature as a saturated vapor. The most common boilers that use natural gas for combustion are water tube boilers. In this type of boiler, water flows inside the pipes and direct fire hits the pipes. These boilers can be made up to pressures above 100 bar. The schematic of the combustion chamber and the heat transfer of the boiler is shown in Figure 2. According to this schematic, the hot flame from the combustion of fuel and air in the combustion chamber directly hits the pipes containing water, and the water inside the pipes is heated and reaches the state of saturated vapor. Table 2 shows the molar percentage of components of the natural gas in the boiler. Table 3 also shows the molar percentage of air components at 1 atmospheric pressure and 60% relative humidity. The balanced equation of

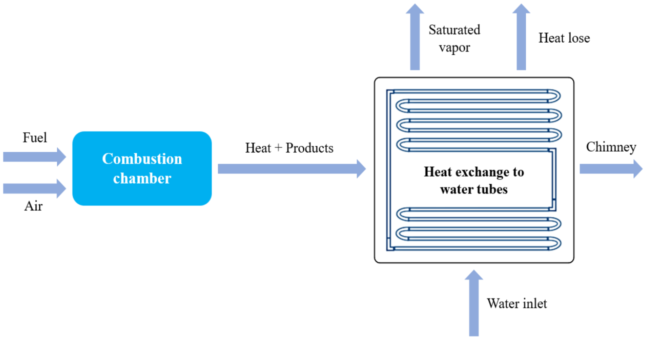

Fig. 2. Scheme of the combustion chamber and heat transfer of the boiler.

Table 2. The molar percentage of natural gas components in the boiler

Compound	Formula	Molar fraction (%)
Methane	CH_4	47.5
Ethane	C_2H_6	8.2
Propane	C_3H_8	8.6
Butane	C_4H_{10}	3.7
Pentane	C_5H_{12}	0.8
Hydrogen	H_2	28
Nitrogen	N_2	3.2
Total	-	100

the combustion in the mentioned conditions (pressure = 1atm, relative humidity = 60%) is written as follows [18]:

$$\begin{aligned}&\left(\begin{aligned}&47.5\%CH_4 + 8.2\%C_2H_6\\&+8.6\%C_3H_8 + 3.7\%C_4H_{10}\\&+0.8\%C_5H_{12} + 28\%H_2 + 3.2\%N_2\end{aligned}\right)\\&+2.933\left(O_2 + 3.7N_2 + 0.09026H_2O\right) \rightarrow\\&1.085CO_2 + 2.323H_2O+\\&11.27N_2 + 0.8784O_2\end{aligned} \tag{11}$$

Table 3. The molar percentage of air components (pressure=1atm, relative humidity=60%)

Compound	Formula	Molar fraction (%)
Oxygen	O_2	20.55
Nitrogen	N_2	76.62
Water	H_2O	1.88
Carbon dioxide	CO_2	0.3
Other	-	0.92
Total	-	100

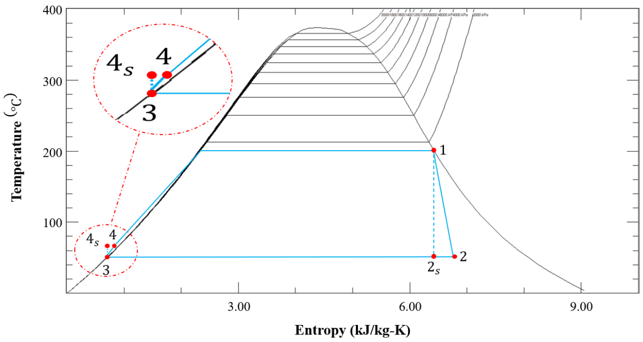

Fig. 3. Temperature-enthalpy diagram of the cycle.

To calculate the amount of heat transferred to water in the cycle, we need to calculate the low heating value (LHV) of the fuel. To calculate the LHV of natural gas, which consists of several different gases, according to the values in Table 2 and the heating value of each gas, the LHV of the fuel is determined by the following equation [19]:

$$\begin{aligned}&LHV_{naturalgas} =\\&\left[\begin{aligned}&(802.3\times 475) + (1427.8\times 8.2)\\&+(1926.4\times 8.6) + (2657\times 3.7)\\&+(3272.1\times 0.8) + (241.8\times 28)\end{aligned}\right]\\&\times {}^{1000}/_{100} = 866146\text{kJ/kmol}\end{aligned} \tag{12}$$

According to this equation, for burning one kilomole of natural gas, 866146 kilojoules of thermal energy will be released. Some of this heat in the boiler is lost in the form of losses or comes out from the chimney. We determine the amount of effective heat transferred to the water cycle with a boiler efficiency (in this article equal to 80%).

$$\dot{Q}_b = J_b \times \dot{Q}_{combustion} \tag{13}$$

3. RESULTS

A. System performance

The system is simulated in basic operating conditions (according to the data in Table 1) and the results for the thermodynamic characteristics of the fluid at different points of the cycle are shown in Table 4. The thermodynamic properties of the fluid are obtained in the temperature-entropy diagram according to Figure 3. Table 5 also shows the operating parameters of the system including turbine output power, pump power consumption, total output power, energy or thermal efficiency, exergy efficiency, and CO2 emissions for the base state. In this table, the energy efficiency include both electrical and non-electrical energy. Also, If we reduce the pump power consumption from the turbine power generation, the net power is obtained. To analyze the performance of the system in different operating conditions, the effect of changing the effective parameters such as turbine inlet temperature, condenser outlet temperature, and natural gas molar rate on the system performance was studied. The impact of these changes is discussed below.

B. Parametric analysis

Effect of the turbine inlet temperature: In this section, the effect of turbine inlet temperature on energy efficiency, exergy efficiency, electrical efficiency, and CO2 emission is investigated. As shown in Figure 4, increasing the turbine inlet temperature

Table 4. Thermodynamic properties of the fluid at different points of the cycle

Point	Temperature (K)	Pressure (kPa)	Enthalpy (kJ/kg)	Entropy (kJ/kg.K)	Exergy (kJ)	Mass flow rate (kg/s)
1	473.16	1555.3	2792.0	6.430	464.36	0.528
2	313.16	7.3	2120.4	6.808	50.15	0.528
3	313.16	7.3	1675.7	0.572	0.75	0.528
4	313.32	1555.3	1696.5	0.574	1.59	0.528
5	303.32	100	1265.7	0.439	8.39	45.330
6	298.16	100	1046.9	0.367	0	45.330

Table 5. Values of system performance parameters

Parameter	Unit	Value
Turbine power production	(kW)	354.63
Pump power consumption	(kW)	1.09
Net power	(kW)	353.53
Electrical efficiency	(%)	24.23
Energy efficiency	(%)	94.92
Exergy efficiency	(%)	74.38
CO2 emission	(g/s)	81.10

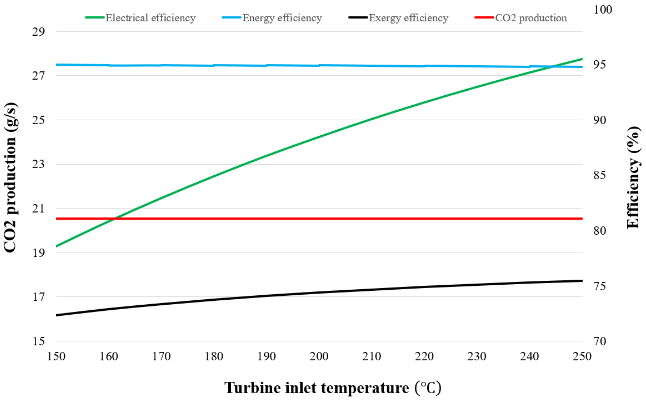

Fig. 4. The effect of turbine inlet temperature on system performance.

from 150 to 250 $^{\circ}C$ has little effect on total energy efficiency and CO2 emission. Instead, increasing this temperature dramatically increases electrical efficiency and exergy efficiency. As increasing the turbine inlet temperature increases the enthalpy of fluid at the turbine inlet, it increases the turbine output capacity and increases the electrical efficiency of the system. As the production capacity of the cycle increases, the heat energy recovered from the system decreases, and overall energy efficiency remains unaffected by these changes. Increasing the share of electrical energy in the total energy produced by the system also naturally increases the exergy efficiency of the system because the exergy of electricity is much greater than the exergy of heat. Finally, because the increase in temperature within the cycle does not change the amount of natural gas consumed, the CO2 emission is not affected by these changes.

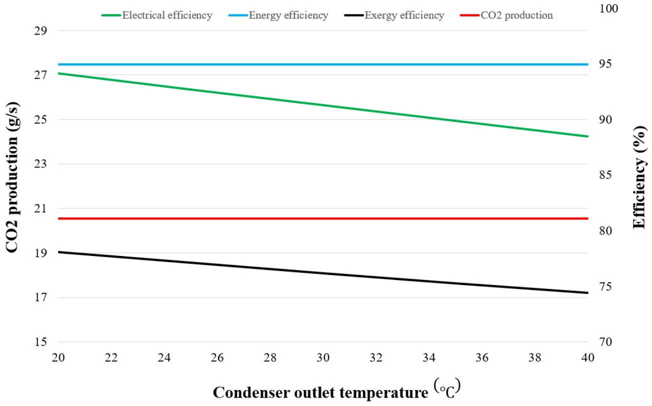

Fig. 5. The effect of condenser outlet temperature on system performance.

Effect of the condenser outlet temperature: In this section, the effect of condenser outlet temperature on energy efficiency, exergy efficiency, electrical efficiency, and CO2 emission is investigated. As shown in Figure 5, increasing the condenser outlet temperature from 20 to 40 $^{\circ}C$, as described before, has little effect on the total energy efficiency and CO2 emission. However, increasing this temperature reduces the electrical efficiency and exergy efficiency. As increasing the condenser outlet temperature reduces the system's output power, the system's electrical efficiency decreases. By reducing the production capacity of the cycle, the heat energy recovered from the system increases and overall energy efficiency remains unaffected by these changes. Reducing the share of electrical energy in the total energy produced by the system also naturally reduces the system's exergy efficiency. According to the previous argument, because the increase in temperature within the cycle does not change the amount of natural gas consumed, the CO2 emission is not affected by these changes.

Effect of natural gas consumption: In this section, the effect of natural gas consumption on energy efficiency, exergy efficiency, electrical efficiency, and CO2 emission is investigated. As shown in Figure 6, an increase in natural gas consumption does not affect electrical, energy, or exergy efficiencies other than an increase in CO2 emission. Electrical, energy, and exergy efficiencies are a function of the thermodynamic conditions of the cycle and are not dependent on the amount of natural gas consumed. Changes in natural gas consumption (despite the constant conditions of the boiler in terms of temperature and pressure) only change the amount of heat transferred to the cycle and the cycle flow changes in proportion to its input.

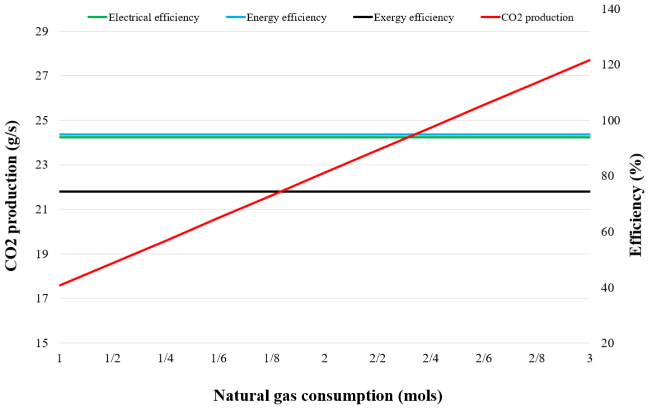

Fig. 6. The effect of natural gas consumption on system performance.

4. CONCLUSION

In this paper, a cogeneration system was investigated in terms of thermodynamics and the environment. The system consisted of a Rankin cycle that uses thermal energy from the combustion of natural gas in the boiler as its input energy. The first law and the second law of thermodynamics with mass conservation were used to simulate the system. To analyze the system performance, the effect of changing important parameters such as turbine inlet temperature, condenser outlet temperature, and natural gas consumption on system performance including electrical efficiency, energy efficiency, exergy efficiency, and CO2 emission was investigated. The main result was that increasing the turbine inlet temperature increases electrical efficiency and exergy. Increasing the condenser outlet temperature also reduces electrical and exergy efficiency. On the other hand, increasing natural gas consumption only increases CO2 emission and does not affect electrical, energy, and exergy efficiencies. Exercoeconomic analysis of the system and multi-objective optimization of system performance can be considered a continuation of this work.

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