



Exergy Analysis and Optimization of Combined Brayton and Rankine Cycles

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Abstract:

There are many energy sources on the World that can be classified as renewable and non-renewable energies. The non-renewable energies which are exhaustible and often harmful to the environment. The usage of all these renewable and non-renewable energies efficiently is very important in technology and industry. The concept of exergy and exergy analysis is very important methods to show the inefficiencies and the irreversibility's in a system and its devices. In this study, exergy analysis methods are applied to efficient combine cycle and cogeneration systems. The destruction of exergy has been examined for combined cycles and cogeneration system to find the optimum working conditions. It is found that as the pump pressure of the Rankine cycle increases from 400 kPa to 7600 kPa, the exergy efficiency increases from 76% to 85%, and as the compression pressure of the Brayton cycle increases from 400 kPa to 2200 kPa, the exergy efficiency increases from 72% to 79%. When these operating conditions, where the two cycles will operate at their optimum, are applied together, the exergy efficiency of the all cycle exceeds 86%. When the operating conditions, where the Brayton and Rankine cycles are at their maximum efficiency, are applied together, the optimum operating conditions of the system are obtained.

1. Introduction

Due to the exhaustibility and rapid structuring of energy in the world, and consequently the increasing amounts spent on energy, exergy analysis offers significant savings in determining energy losses in thermal systems. Exergy is the amount of useful energy that can be obtained from an energy source or the potential of that energy to do work. With the understanding of enriching exergy analysis, it has been used in many ways in recent years by applying it to various systems and solutions. Later, exergy-based analysis studies were carried out through economic analyses [1, 2]. Growth studies have been strengthened based on these analyses. In this way, systems have benefited both economically and in terms of efficiency. However, exergy analysis is still involved in these costs. Exergy losses show an inverse relationship with the destruction caused by the increase in exergy during this process, and with resource consumption. This natural exergy is

important in terms of energy production and consumption [3, 4].

The significance of this research is evident in the findings. Importance and justification of the Research Combined cycle power plants offer high power and efficiency, as well as flexible operation. They are suitable for various operating conditions, can be quickly commissioned, can easily adapt to variable load and full load conditions, and can operate with high efficiency in variable load conditions [5, 6].

In the design of existing power plants and new power plants to be built, attention should be paid not only to the conversion of energy but also to its usability. It has been seen that details of energy and exergy efficiency is a useful method for energy use analysis with various data [7, 8].

In the study conducted by Yılmaz (2012), the author identified the locations and areas of exergy loss in a 50 MW gas-fired combined cycle power plant. This was achieved by applying both conventional and

advanced exergy analysis techniques. The research also highlighted potential areas for improvement. As a result, it was concluded that 6,874 kW of exergy destruction in the boiler could be prevented, while 12,371 kW was unavoidable. The highest preventable exergy destruction was found at this location. The highest exergy destruction was observed in the condenser with 22,997 kW, and it was suggested that a significant portion of this, especially 20,193 kW, was unavoidable. It was possible that adjustments would result in an avoidable exergy value of 17,260 kW [9].

Karaali and Öztürk (2015; 2016), analysed to improve the efficiency of a cogeneration system and showed some important methods to obtain exergetic and exergoeconomic optimum working conditions [10, 11].

Karaali and Keven (2022), studied by using some criteria for the evaluation of four kind of cogeneration cycles and found that the criteria of exergetic efficiency is the best among others [12, 13].

The greatest advantage of combined cycle power plants is their high efficiency among fossil fuel power plants. Nowadays, net efficiencies of 55% are achieved in reheated and three-pressure stage combined cycles based on gas turbines with power outputs exceeding 200 MW. In addition to high efficiency, combined cycle power plants have many other advantages. Among these is the flexibility of combined cycles to serve in many different areas. Combined cycle power plants can only generate electricity. In addition, by using the intermediate steam taken from either the steam turbine or the boiler in the process or in district heating, they can also serve as a heat-power system with a thermal efficiency of approximately 85-90%. Combined cycles have a very wide range of fuel usage possibilities, including all liquid fuels from crude oil to fuel oil and diesel, all types of natural gas, and even coal through gasification [13, 14, 15]. In addition, gas turbine burners can be designed to burn two fuels if desired. For example, some combined cycle power plants use fuel oil as well as natural gas as needed. The need of the cooling water in combined cycle power plants is lower than in other conventional power plants. However, in combined cycles, steam turbines account for only 33% of the total electricity production [16, 17].

In conclusion, many problems related to cooling water are significantly reduced, resulting in lower system costs and reduced heat release to the environment. The Combined cycles power plants are preferred due to their cost-effectiveness. They are more economical than other options due to the low unit investment cost of the boiler/steam turbine. When viewed from an environmental perspective,

another important benefit of combined cycle power plants emerges[18]. Recently, there has been a significant increase in the importance given to the environment, resulting in a large reduction in hazardous substance emissions within permitted levels. Consequently, the need for combined cycle technologies is increasing. What is important here is that combined cycle power plants operating with high efficiency produce 40-45% less CO₂ per unit of electricity compared to other thermal power plants. However, especially in natural gas combined cycle power plants, no solid matter emissions are formed and NO_x emissions are well below acceptable threshold values [19, 20]. In addition to these, integrated power plants have other advantageous features that can be expressed as follows:

Combined cycles power plants are simpler to operate, as they have a more modular structure and a shorter construction process compared to conventional thermal power plants. Therefore, the personnel requirement for operation is lower. The area required for the entire power plant is less than that of conventional thermal power plants [20].

2. Material and Methods

The combined cycle consisting of Brayton and Rankine cycles, which is a district heating system examined in this thesis and analysed in terms of energy, exergy and performance, is given in Figure 1. As seen here, the system can be operated as a cogeneration system for district heating in winter, and since there is no need for heat energy in summer, it produces electrical energy as a combined cycle. Common reference environmental conditions are given below.

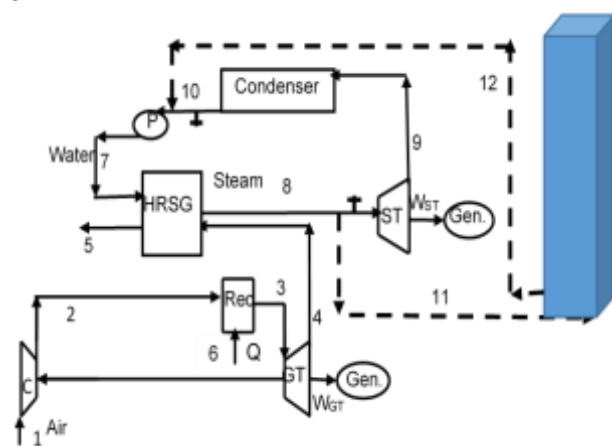


Figure 1. Combined cycle integrated district heating system

The common reference environmental conditions taken for the cycle are ambient temperature $T_0=20$ °C, ambient pressure $P_0=101.3$ kPa.

Table 1. Equations for mass, energy balance, and entropy generation [18, 19, 20].

DEVICE	Mass Eq.	Energy Eq.	Entropy Eq.
Compressor	$\dot{m}_1 = \dot{m}_2$	$\dot{m}_1 h_1 + \dot{W}_K = \dot{m}_2 h_2$	$\dot{m}_1 s_1 - \dot{m}_2 s_2 + S_{Gen,C} = 0$
Recuperator	$\dot{m}_2 = \dot{m}_3$	$\dot{m}_2 h_2 + \dot{Q}_R = \dot{m}_3 h_3$	$\dot{m}_2 s_2 - \dot{m}_3 s_3 + S_{Gen,R} = 0$
Gas Turbine	$\dot{m}_3 = \dot{m}_4$	$\dot{m}_3 h_3 = \dot{W}_{GT} + \dot{m}_4 h_4$	$\dot{m}_3 s_3 - \dot{m}_4 s_4 + S_{Gen,GT} = 0$
(HRSG)	$\dot{m}_4 = \dot{m}_5$ $\dot{m}_7 = \dot{m}_8$	$\dot{m}_4 h_4 - \dot{m}_5 h_5 = \dot{m}_8 h_8 - \dot{m}_7 h_7$	$\dot{m}_4 s_4 - \dot{m}_5 s_5 + \dot{m}_7 s_7 - \dot{m}_8 s_8 + S_{Gen,HRSG} = 0$
Steam Turbine	$\dot{m}_7 = \dot{m}_8$	$\dot{m}_7 h_7 = \dot{W}_{ST} + \dot{m}_8 h_8$	$\dot{m}_7 s_7 - \dot{m}_8 s_8 + S_{Gen,ST} = 0$
Condenser	$\dot{m}_9 = \dot{m}_{10}$	$\dot{m}_9 h_9 = \dot{Q}_{Co} + \dot{m}_{10} h_{10}$	$\dot{m}_9 s_9 - \dot{m}_{10} s_{10} + S_{Gen,Co} = 0$
Pump	$\dot{m}_{10} = \dot{m}_7$	$\dot{m}_{10} h_{10} + \dot{W}_P = \dot{m}_7 h_7$	$\dot{m}_{10} s_{10} - \dot{m}_7 s_7 + S_{Gen,P} = 0$

Table 2. Exergy, entropy and exergy efficiency equations [18, 19, 20].

DEVICE	Exergy Loss	Exergy Efficiency
Compressor	$\dot{E}x_1 + \dot{W}_C - \dot{E}x_2 = \dot{E}_{Loss,C}$	$\eta_{ex,C} = \frac{\dot{E}x_2}{\dot{E}x_1 + \dot{W}_C}$
Recuperator	$\dot{E}x_3 - \dot{E}x_2 = \dot{E}_{Loss,R}$	$\eta_{ex,R} = \frac{\dot{E}x_3 - \dot{E}x_2}{\dot{Q}_F}$
Gas Turbine	$\dot{E}x_3 - \dot{W}_{GT} - \dot{E}x_4 = \dot{E}_{Loss,GT}$	$\eta_{ex,GT} = \frac{\dot{W}_{GT} + \dot{E}x_4}{\dot{E}x_3}$
HRSG	$\dot{E}x_4 - \dot{E}x_5 - \dot{E}x_7 + \dot{E}x_8 = \dot{E}_{Loss,HRSG}$	$\eta_{ex,HRSG} = \frac{\dot{E}x_7 - \dot{E}x_8}{\dot{E}x_4 - \dot{E}x_5}$
Steam Turbine	$\dot{E}x_7 - \dot{E}x_8 - \dot{W}_{ST} = \dot{E}_{Loss,ST}$	$\eta_{ex,ST} = \frac{\dot{E}x_8 + \dot{W}_{ST}}{\dot{E}x_7}$
Condenser	$\dot{E}x_9 - \dot{Q}_{Co} - \dot{E}x_7 = \dot{E}_{Loss,Co}$	$\eta_{ex,Co} = \frac{\dot{Q}_{Co} + \dot{E}x_7}{\dot{E}x_9}$
Pump	$\dot{E}x_{10} + \dot{W}_P = \dot{E}x_7 + \dot{E}_{Loss,P}$	$\eta_{ex,P} = \frac{\dot{E}x_7}{\dot{E}x_{10} + \dot{W}_P}$

Table 1 and Table 2 give the formulas for mass balance, energy balance, entropy production, exergy balance and exergy efficiency of the system elements used in the Rankine and Brayton combined cycle.

3. Results and Discussions

The data obtained as a result of the calculations are given in this section in the form of tables and the drawn curves are presented below with their interpretations.

Table 3 shows the characteristics table for the summer months. Here, the system generates electricity in a Brayton and Rankine cycle combined cycle configuration.

Table 4 shows the characteristics table for the winter months. Here, the system generates electricity in the Brayton cycle and heat for heating that is called cogeneration cycle configuration.

Table 3. Winter time working conditions.

NO	Tem. (°C)	Pres. (kPa)	Mass Flow (kg/s)	Enthal. (kJ/kg)	Entropy (kJ/kgK)	Exergy (kW)
0	20	100	-	293,4	6,847	-
0w	20	100	-	83,93	0,2962	-
1	20	101,3	200	293,3	6,842	0
2	454	2200	200	743,3	6,892	87022
3	1200	2200	200	707,3	7,703	211937
4	501,9	120	200	1606	7,798	44244
5	40	110	200	313,5	6,884	1518
6	-	-	-	-	-	124915
7	35,4	7600	29,75	154,9	0,5073	271,2
8	494,9	7600	29,75	154,3	6,739	42225
9su*	-	-	-	-	-	-
10su*	-	-	-	-	-	-
11wi**	45,8	10	29,75	2235	7,054	42225
12wi**	35	10	29,75	2134	0,5051	43,44

su*: Summer, wi**: Winter

Table 4. Summer time working conditions

NO	Tem. (°C)	Pres. (kPa)	Mass Flow (kg/s)	Enthal. (kJ/kg)	Entropy (kJ/kgK)	Exergy (kW)
0	20	100	-	293,4	6,847	-
0w	20	100	-	83,93	0,2962	-
1	20	101,3	200	293,3	6,842	0
2	454	2200	200	743,3	6,892	87022
3	1200	2200	200	707,3	7,703	211937
4	501,9	120	200	1606	7,798	44244
5	40	110	200	313,5	6,884	1518
6	-	-	-	-	-	124915
7	35,4	7600	29,75	154,9	0,5073	271,2
8	494,9	7600	29,75	154,3	6,739	42225
9su*	45,8	10	29,75	2235	7,054	42225
10su*	35	10	29,75	2134	0,5051	43,44
11wi**	-	-	-	-	-	-
12wi**	-	-	-	-	-	-

su*: Summer, wi**: Winter

Figure 2 is showing the effect of the compressor outlet pressure on the exergy efficiency of the entire system in the form of curves. When the compressor outlet pressure is increased, the exergy efficiency of the entire system increases from 72% to 79%. That

is, the increasing in exergy efficiency is around 10%. Increasing the compressor outlet pressure also improves the efficiency of the Brayton cycle in the system.

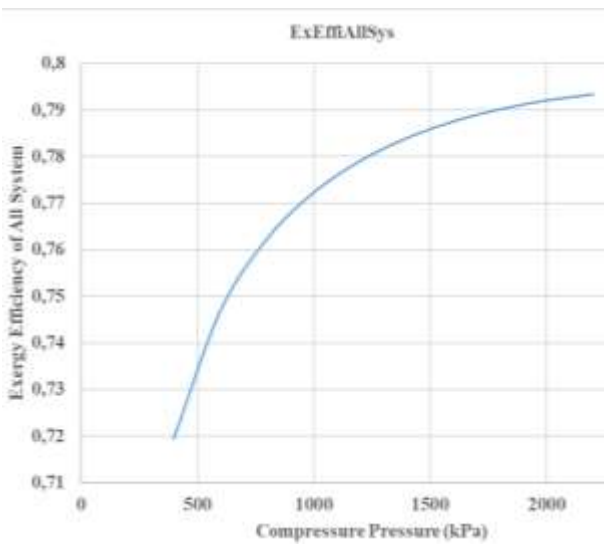


Figure 2. Effect of compressor outlet pressure on the exergy efficiency of the entire system.

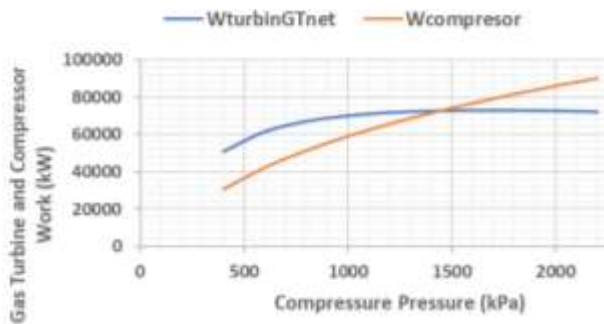


Figure 3. Effect of compressor outlet pressure on gas turbine and compressor power.

Figure 3, is showing the effect of the compressor outlet pressure of the system on the gas turbine and compressor power in the form of curves. When the compressor outlet pressure is increased, the net power obtained from the gas turbine increases up to 2200 kPa pressure, however, at higher pressures, the gas turbine power decreases and the power consumed by the compressor increases rapidly. We have an optimum point here about 1200 kPa pressure which is important.

Figure 4 shows the effect of the system's compressor outlet pressure on the gas turbine and compressor exergy loss in the form of curves. When the outlet pressure of the compressor is increased, the exergy loss of the compressor increases by a very small amount, which the exergy loss in the gas turbine increases from 32600 kW to 95600 kW. The exergy loss in the gas turbine is around 300%.

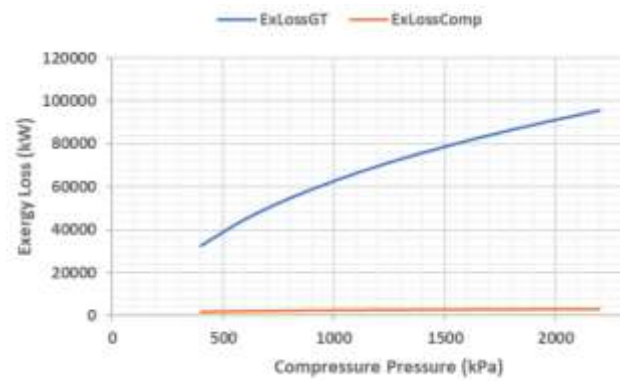


Figure 4. Effect of compressor outlet pressure on gas turbine and compressor exergy loss.

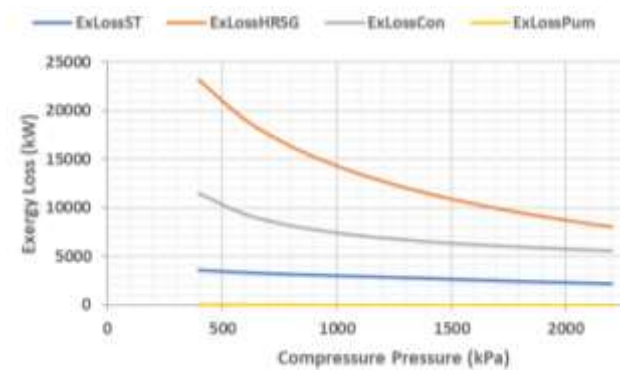


Figure 5. Effect of compressor outlet pressure on exergy loss of Rankine cycle devices.

Figure 5 is showing the effect of the system's compressor outlet pressure on the exergy loss of Rankine cycle devices in the form of curves. When the compressor outlet pressure is increased, the exergy loss in the steam turbine decreases by approximately 33%, the exergy loss in the condenser decreases by approximately 50%, and the exergy loss in the HRSG decreases by approximately 73%. Increasing the compressor outlet pressure reduces the exergy loss of Rankine cycle devices and improves the performance of the Rankine cycle.

Figure 6 is showing the effect of the pump outlet pressure of the system on the power of the entire system in the form of curves.

The relevant values are also given in Table 14. When the pump outlet pressure is increased, the power of the entire system increases from 95600 kW to 106300 kW, which is an increase of approximately 12%.

Figure 7 is showing the effect of the system's pump outlet pressure on the exergy efficiency of Rankine cycle devices in the form of curves. The relevant values are also given in Table 9. When the pump outlet pressure is increased, the exergy efficiency of the steam turbine decreases by 3%, and the exergy efficiency of the pump decreases by about 5%, but the exergy efficiency of the HRSG increases from 74% to 97%.

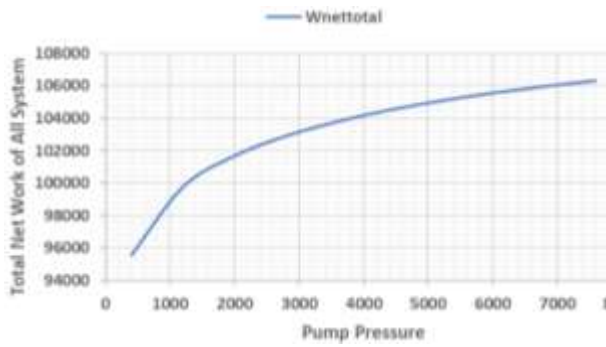


Figure 6. Effect of pump outlet pressure on the power of the entire system.

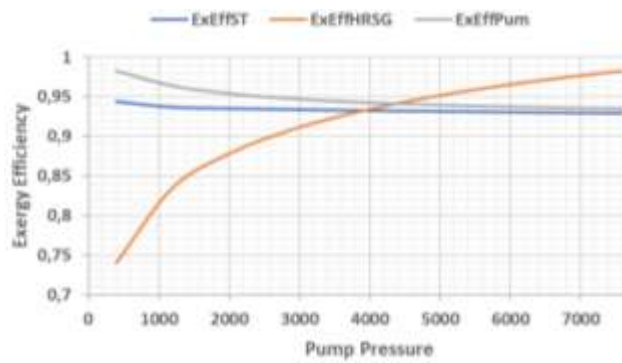


Figure 7. Effect of system pump outlet pressure on the exergy efficiency of Rankine cycle devices.

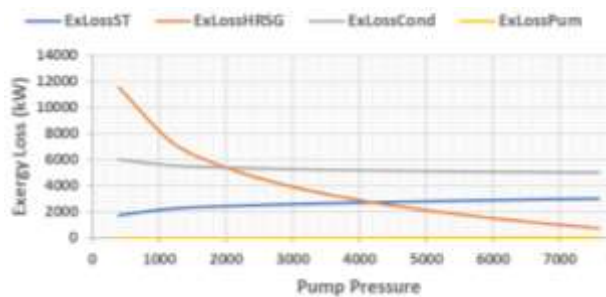


Figure 8. Effect of the pump of the system outlet pressure on exergy loss in devices.

Figure 8 shows the effect of the system's pump outlet pressure on exergy loss in the devices as curves. When the pump outlet pressure is increased, the exergy loss in the steam turbine increases by approximately 50%. While the exergy loss in the pump is very small and approximately constant, the exergy loss of the HRSG decreases significantly (approximately 90%). The exergy loss in the condenser decreases by approximately 15%. These devices are Rankine cycle devices and it is understood that they are significantly affected by the change in pump pressure.

4. Conclusions

With the depletion of energy resources, exergy analysis, also known as the 2. law of

thermodynamics, has been developed to better utilize existing energy resources. Exergy is defined

Table 5. The optimum working conditions and points obtained at $P_2=2200$ kPa ve $P_7=7600$ kPa pressures.

OPTIMUM WORKING CONDITIONS AND POINTS for $P_2=2200$ kPa ve $P_7=7600$ kPa		
$T_0=20$ °C	$m_{air}=200$ kg/s	effi=0,92
$T_{0K}=293,2$ K	$s_{10}=0,5051$ kJ/kgK	$m_{w^*}=29,75$ kg/s
$T_1=20$ °C	$h_0=293,3$ kJ/kg	$ST_{out}=98400$ kW
$T_2=454$ °C	$h_{0w}=84,01$ kJ/kg	$ST_{in}=98400$ kW
$T_3=1200$ °C	$h_1=293,3$ kJ/kg	$HRSG_{out}=102439$ kW
$T_4=501,9$ °C	$h_{10}=146,6$ kJ/kg	$HRSG_{in}=102439$ kW
$T_5=40$ °C	$h_2=743,3$ kJ/kg	$W_{nettot}=106311$ kW
$T_7=35,36$ °C	$h_{2s}=707,3$ kJ/kg	$W_{pump}=246,5$ kW
$T_8=494,9$ °C	$h_3=1606$ kJ/kg	$AllSys_{out}=172461$ kW
$T_9=45,81$ °C	$h_4=795$ kJ/kg	$AllSys_{in}=172461$ kW
$T_{10}=35$ °C	$h_{4s}=724,5$ kJ/kg	$Ex_1=0$ kW
$P_0=101,3$ kPa	$h_5=313,5$ kJ/kg	$Ex_2=87022$ kW
$P_1=101,3$ kPa	$h_7=154,9$ kJ/kg	$Ex_3=211937$ kW
$P_2=2200$ kPa	$h_{7s}=154,3$ kJ/kg	$Ex_4=44244$ kW
$P_3=2200$ kPa	$h_8=3392$ kJ/kg	$Ex_5=1518$ kW
$P_4=120$ kPa	$h_9=2235$ kJ/kg	$Ex_6=124915$ kW
$P_5=110$ kPa	$h_{9s}=2134$ kJ/kg	$Ex_7=271,2$ kW
$P_7=7600$ kPa	$En_1=0$ kW	$Ex_8=42225$ kW
$P_8=7600$ kPa	$En_{10}=1864$ kW	$Ex_9=5049$ kW
$P_9=10$ kPa	$En_2=89993$ kW	$Ex_{10}=43,44$ kW
$P_{10}=10$ kPa	$En_3=262453$ kW	$Ex_{11}=42225$ kW
$s_0=6,842$ kJ/kgK	$En_4=100329$ kW	$Ex_{12}=43,44$ kW
$s_{0w}=0,2965$ kJ/kgK	$En_5=4022$ kW	$ExEff_{GT}=0,5491$
$s_1=6,842$ kJ/kgK	$En_6=172461$ kW	$ExEff_{ST}=0,929$
$s_2=6,892$ kJ/kgK	$En_7=2110$ kW	$ExEff_{HRSG}=0,9827$
$s_{2s}=6,842$ kJ/kgK	$En_8=98417$ kW	$ExEff_{com}=0,967$
$s_3=7,703$ kJ/kgK	$En_9=63991$ kW	$ExEff_{pump}=0,9354$
$s_4=7,798$ kJ/kgK	$W_{Comp}=89993$ kW	$ExEff_{ALLSYS}=0,8511$
$s_{4s}=7,703$ kJ/kgK	$W_{Compis}=82793$ kW	$ExLoss_{Com}=2971$ kW
$s_5=6,884$ kJ/kgK	$Com_{out}=82793$ kW	$ExLoss_{con}=5005$ kW
$s_7=0,5073$ kJ/kgK	$Com_{in}=82793$ kW	$ExLoss_{pum}=18,8$ kW
$s_{7s}=0,5051$ kJ/kgK	$GT_{out}=262453$ kW	$ExLoss_{HRSG}=772$ kW
$s_8=6,739$ kJ/kgK	$GT_{in}=262453$ kW	$ExLoss_{GT}=95561$ kW
$s_9=7,054$ kJ/kgK	$Rec_{out}=262453$ kW	$ExLoss_{ST}=2998$ kW
$s_{9s}=6,739$ kJ/kgK	$Rec_{in}=262453$ kW	

w*: water

as the useful portion of the energy produced. The useful portion refers to the portion of energy that can be converted into another form of energy. Exergy analysis determines energy losses in thermal systems and measures are taken to reduce these losses. Increasing the pump pressure of the Rankine cycle from 400 kPa to 7600 kPa increases the exergy efficiency from 76% to 85%, and increasing the compression pressure of the Brayton cycle from 400 kPa to 2200 kPa increases the exergy efficiency from 72% to 79%. When these operating conditions, where the two cycles will operate optimally, are applied together, the exergy efficiency of the entire system exceeds 86%. The optimal operating conditions of the system are achieved when the Brayton and Rankine cycles are applied together, which is the maximum efficiency of the cycle.

Author Statements:

- **Ethical approval:** The conducted research is not related to either human or animal use.
- **Conflict of interest:** The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper
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- **Use of AI Tools:** The author(s) declare that no generative AI or AI-assisted technologies were used in the writing process of this manuscript.

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