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Assessment of a Real Combined Cycle Power Plant with Supplementary Firing Based on Advanced Exergy/Exergoeconomic Methods

T. Azizi[*]
M.Sc. Student

F. Ahmadi Boyaghchi [†]
Assistant Professor

This research performs the advanced exergy and exergoeconomic analyses of a combined cycle power plant (CCPP) located in Zavareh, Iran. The objective of this research is to evaluate the irreversibilities, their related cost rates of each part of the CCPP that can be avoided and the inefficiencies of each part that caused by other components. The advanced exergy and exergoeconomic analyses indicate that the most of the exergy destructions and their related cost rates within the combustion chambers and heat recovery steam generaters (HRSGs) are related to their performance. So, the focus should be on improving the performance of these components themselves, rather than the effects of the remaining components. Results indicate that system's improvement potential of the overall system and its related cost rate are 14% and 15%, respectively. Also, the improvement potential for the investment flow rate of the system is weak because 75% of them are unavoidable.

Keywords: CCPP, endogenous, exogenous, avoidable, unavoidable, investment cost rates

1 Introduction

Energy is one of the top 10 fundamental things in our regular life for almost everything. Power plants could play a crucial role in producing power. Between different kinds of power plants, CCPPs are attractive in electricity generation field due to their upper thermal efficiency than single steam or gas turbine power plants, and less environmental impact. Currently, a large amount of CCPPs have been installed and some of them have been working for many years [1-3]. All energy conversion systems must be studied in terms of energetic and economic view for an appropriate organization. In the practical literature, a large number of conventional exergy/exergoeconomic analyses of CCPPs may be found. There are many researchers who accomplished the conventional exergy and exergoeconomic methods analysis for the combined cycles [3-18].

But, conventional exergy/exergoeconomic analyses have some restrictions. Basically, the results of a conventional exergy/exergoeconomic analysis cannot be used to study the potential improvement of an energy conversion system or its components, and they don't offer any evidence about how one component influence one another performance or cost.

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[*] M.Sc. Student, Dep. of Mechanical Engineering, Alzahra University, Tehran.

[†] Corresponding Author, Assistant Professor, Dep. of Mechanical Engineering, Faculty of Engineering and Technology, Alzahra University, Tehran, fahmadi@alzahra.ac.ir, aboyaghchi@gmail.com

Advanced exergy/exergoeconomic analyses can explain this lack of information. The conventional exergy/exergoeconomic analyses could inform to misinterpretations resulting that caused indelicate improvement approaches. Furthermore, using only the conventional exergy/exergoeconomic analyses don't provide any data about the interconnections among the system components/related cost rates whereas these lack of information could be solved using an advanced exergy/exergoeconomic analyses. For increasing the system efficiency, industrial exertions can focus on the elements with the highest exergy destruction and cost rates. However, energy systems usually contain various components, such as turbines, condensers, compressors, etc. In order to consider the exergy destruction and the interactions between the components; an advanced exergy/exergoeconomic analysis is desired [19].

These analyses clearly detect the exergy destruction and separate them into two main groups: (a) endogenous-exogenous exergy destruction/cost rate and (b) avoidable-unavoidable exergy destruction/cost rate [20-24]. Tsatsaronis and Moung-Ho [25] were the first to discuss how to estimate the avoidable-unavoidable exergy destruction and investment costs. They evaluated parts of exergy destructions and investment costs of compressors, turbines, heat exchangers and combustion chambers, which were used to determine the improvement potentials of the performance and cost effectiveness of a thermal system. Tsatsaronis [22] introduced an advanced exergy/exergoeconomic analysis to use instead of conventional exergy/exergoeconomic analyses. He also identified exergoenvironmental analyses. He deliberated the faults of conventional exergy and exergoeconomic analyses in improving the performance/related cost of the energy conversion systems and concluded that the advanced exergy/exergoeconomic analyses can be a solution to these weaknesses. Morosuk et al. [26] discussed briefly the theory and applications of the conventional and advanced exergetic analyses. They concluded that the information resulted from the advanced exergy based method was very useful in developing approaches for improving the energy conversion systems. Here are a few studies on advanced exergy/exergoeconomic analyses of energy conversion systems. Until now, Various energy conversion systems have been investigated using exergy/exergoeconomic methods; such as a simple refrigeration cycle [27], a simple gas-turbine system with chemical reaction [23], a novel system for generating electricity [27], an oxy-fuel power plant with CO_2 capture [29], a supercritical coal-fired power plant [30], a system including LNG regasification and electricity generation [31], a geothermal district heating system (GDHS) [32-34], a trigeneration system [21], in order to identify different parts of exergy destructions. Also there are some publications on advanced exergy/exergoeconomic analyses of CCPPs that are mentioned here. Cziesla et al.[35] Calculated avoidable-unavoidable exergy destructions/related cost rates for each component of an externally fired combined cycle power plant. They discussed some features of the design and improvement of the cycle. Petrakopoulou et al. [36] analyzed a combined cycle power plant using both conventional and advanced exergetic analyses. They showed that most of the exergy destruction in the plant was unavoidable and component interactions do not contribute significantly to the irreversibilities. Petrakopoulou et al. [37] presented the application of an advanced exergy and exergoenvironmental analysis to a CCPP. They found that improvement of the plant could be achieved by increasing the performance of the combustion chamber, the expander, the compressor and the low-pressure steam turbine. Soltani et al. [38] reported an advanced exergy analysis for a recently developed configuration of an externally-fired combined-cycle power plant integrated with biomass gasification. They identified that little could be done to reduce the inefficiencies for components. Vuckovic et al. [39] analyzed a real industrial plant using both conventional and advanced exergy analyses, and exergoeconomic evaluation. Result showed that by improving the boiler operation, the greatest improvement in the efficiency of the overall system could be achieved. Açıkkalp et al. [40,41] analyzed an electricity generation facility in Turkey using advanced

exergy/exergoeconomic methods. They introduced the gas turbine and combustion chamber as the most important components. It was determined that interactions among the components were important.
In the present study, a computer program using EES software had been established for energy, exergy/exergoeconomic and advanced exergy/exergoeconomic of a dual pressure CCPP.

So, in summary, the followings are the detailed impact of this paper.
a) To develop a comprehensive model for a dual pressure CCPP.
b) To validate the developed model by comparing it with the information from real power plant.
c) To define exergy destruction rates/related cost rates, exergy efficiency and exergoeconomic factor for each component and the overall system using conventional exergy/exergoeconomic analyses.
d) To indicate the interconnections among system components and the possibilities for improving the system by advanced exergy/exergoeconomic analyses.

2 Combined cycle specification

The energy system reviewed in this research is a combined cycle power plant located in Zavareh, Iran consisting of an upper gas cycle and a lower steam cycle. The output power of this power plant is about 480 MW. The design diagram of the said power plant has been shown in Figure (1). This combined cycle system contains two air compressors (AC), two combustion chambers (CC), two gas turbines (GT), two dual pressure heat recovery steam generators (HRSG), two duct burners (DB), one steam turbine (ST), one air-cooled condenser (ACC), one boiler feed water pump (BFP) and one condensate extraction pump (CEP). Main fuel for the Zavareh combined cycle power plant is natural gas. Model of gas turbines of this combined cycle is Siemens V94.2.5. The pressure ratio of the compressor is 11.7. The gas leaving the combustion chambers enters the Gas turbine at 1060℃. The gases leaving the Gas turbine at 543.7℃ are heated up by using duct burner and transferred to the steam cycle by the heat recovery steam generator (HRSG).The dual pressure HRSG generates high pressure (HP) and low pressure (LP) steams respectively at 523℃ and 234℃. The rated steam turbine power output is 158.8MW (at base load).

The assumptions used in the mentioned analyses are as follows[42, 43]:

- All processes in this case were considered as steady-state and steady-flow.
- The air and the gases leaving combustion were assumed to be ideal gases.
- The injected fuel to the combustion chamber and duct burner assumed to be methane.
- The energy variation and the kinetic and potential exergies were supposed to be negligible.
- The turbine, compressor, pump, and the condenser have been assumed as adiabatic.
- The ambient conditions were supposed as equal to the conditions at the input to the compressor.
- The dead state for this case state was considered as P_o=1.01 bar and T_o=291.95 K.
- Pressure drop of 0.02 was assumed in combustion chamber.
- The mass flow rate of the duct burner is assumed to be constant.

3 Conventional exergy/exergoeconomic analyses

Conventional exergy/exergoeconomic analyses are performed following the approach defined in [39, 44].Under the assumption of steady-state operation, for each experimental component the following equations have to be defined:

– Mass balance equation, indicating the equivalence between mass flows sum of the inlet streams and the exit streams.

– Energy balance equation, according to the First Law of Thermodynamics, indicating balance between inlet streams enthalpies, exit streams enthalpies, energy transfer by heat with the surroundings, and energy transfer by work.

– Exergy balance equation, according to the Second Law of Thermodynamics, indicating balance between inlet streams exergies, exit streams exergies, exergy transfer by heat, exergy transfer by work, and exergy destruction and losses.

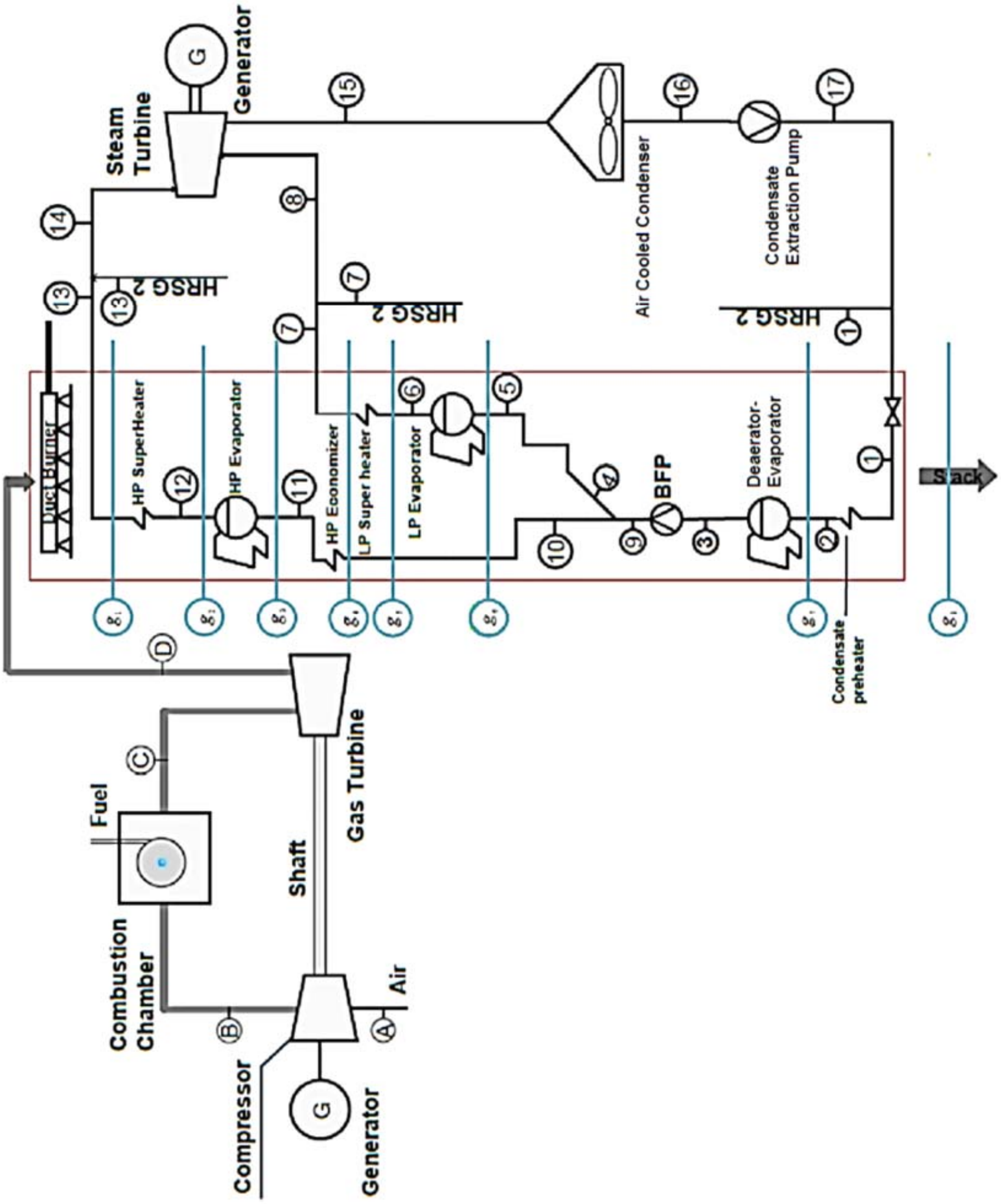

Figure 1 Schematic of the Zavareh dual pressure combined cycle

– Costs balance equation, indicating balance between costs associated with inlet and exit streams, transferred heat and work, as well as levelized investment and operation and maintenance costs.
– Other equations defining component specific mathematical relations.

3.1 Exergy analysis

Exergy equations are often represented in the form corresponding to the so-called ‘‘fuel-product’’ concept [39, 45], as shown in Eq. (3).

$$\dot{E}x_{F,k} = \dot{E}x_{P,k} + \dot{E}x_{L,k} + \dot{E}x_{D,k} \tag{1}$$

Where, $\dot{E}x_{L,k}$ is the rate of exergy loss of the system or control volume to the environment. Definition of fuel, product and rate of Exergy loss for components of the analyzed system is given in Table (1).The exergy destruction rate can be calculated as follows [9, 44]:

$$\dot{E}x_{F,k} = \dot{E}x_{P,k} + \dot{E}x_{D,k} \tag{2}$$

The exergetic efficiency of the kth components and the overall system are defined by the following equations [44]:

$$\eta_{ex,k} = \frac{\dot{E}x_{P,k}}{\dot{E}x_{F,k}} = 1 - \frac{\dot{E}x_{D,k}}{\dot{E}x_{F,k}} \tag{3}$$

$$\eta_{ex,tot} = \frac{\dot{E}x_{P,tot}}{\dot{E}x_{F,tot}} \tag{4}$$

Definition of exergy efficiency is showed in Table (1). The exergy destruction ratio is a scale of the effect of the rate of exergy destruction within each component to the decrease of the total exergetic efficiency that is expressed as follow [36, 44]:

$$y_{D,k} = \frac{\dot{E}x_{D,k}}{\dot{E}x_{F,tot}} \tag{5}$$

3.2 Exergoeconomic analysis

Exergoeconomic analysis means to reach a balance between high efficiency and suitable cost. The first study in this concern was planned in Ref. [44]. The approach used in this paper is the same as method of Lazzarett and Tsatsaronis in Ref [47]. The economic analysis of the cycle is accomplished considering the purchased equipment cost, operation and maintenance (O&M) cost and the cost of the energy input. The cost balance equation of each component with heat transfer and rated output work is written as follow:

$$\sum_{e} \dot{C}_{P,k} = \dot{C}_{F,k} + \dot{Z}_k^{CI} + \dot{Z}_k^{OM} \tag{6}$$

The cost rate of each stream j is calculated according to the value of exergy, i.e. $\dot{C}_j = c_j.\dot{E}_j$ [39].

Table 1 Definition of fuel, product and rate of exergy loss for system components

	Components	Exergy Efficiency	Rate of Exergy Loss	Exergy of Product	Exergy of Fuel
Gas Cycle					
	AC	$\frac{\dot{E}x_A-\dot{E}x_B}{\dot{W}_{AC}}$		$\dot{E}x_A-\dot{E}x_B$	$\dot{W}_{AC}$
	CC	$\frac{\dot{E}x_C}{\dot{E}x_B+\dot{E}x_{f,CC}}$		$\dot{E}x_C$	$\dot{E}x_B+\dot{E}x_{f,CC}$
	GT	$\frac{\dot{W}_{GT}}{\dot{E}x_C-\dot{E}x_D}$		$\dot{W}_{GT}$	$\dot{E}x_C-\dot{E}x_D$
	DB	$\frac{\dot{E}x_{g1}}{\dot{E}x_D+\dot{E}x_{ch,f,DB}}$		$\dot{E}x_{g1}$	$\dot{E}x_D+\dot{E}x_{ch,f,DB}$
HRSG					
	HP.SPH	$\frac{\dot{E}x_{13}-\dot{E}x_{112}}{\dot{E}x_{g1}-\dot{E}x_{g2}}$		$\dot{E}x_{13}-\dot{E}x_{12}$	$\dot{E}x_{g1}-\dot{E}x_{g2}$
	HP.EVA	$\frac{\dot{E}x_{12}-\dot{E}x_{11}}{\dot{E}x_{g2}-\dot{E}x_{g3}}$		$\dot{E}x_{12}-\dot{E}x_{11}$	$\dot{E}x_{g2}-\dot{E}x_{g3}$
	HP.ECO	$\frac{\dot{E}x_{11}-\dot{E}x_{10}}{\dot{E}x_{g3}-\dot{E}x_{g4}}$		$\dot{E}x_{11}-\dot{E}x_{10}$	$\dot{E}x_{g3}-\dot{E}x_{g4}$
	LP.SPH	$\frac{\dot{E}x_7-\dot{E}x_6}{\dot{E}x_{g4}-\dot{E}x_{g5}}$		$\dot{E}x_7-\dot{E}x_6$	$\dot{E}x_{g4}-\dot{E}x_{g5}$
	LP.EVA	$\frac{\dot{E}x_6-\dot{E}x_5}{\dot{E}x_{g5}-\dot{E}x_{g6}}$		$\dot{E}x_6-\dot{E}x_5$	$\dot{E}x_{g5}-\dot{E}x_{g6}$
	BFP	$\frac{\dot{E}x_{10}+\dot{E}x_4-\dot{E}x_3}{\dot{W}_{BFP}}$		$\dot{E}x_{10}+\dot{E}x_4-\dot{E}x_3$	$\dot{W}_{BFP}$
	DEA_EVA	$\frac{\dot{E}x_3-\dot{E}x_2}{\dot{E}x_{g6}-\dot{E}x_{g7}}$		$\dot{E}x_3-\dot{E}x_2$	$\dot{E}x_{g6}-\dot{E}x_{g7}$
	CPH	$\frac{\dot{E}x_2-\dot{E}x_1}{\dot{E}x_{g7}-\dot{E}x_{g8}}$		$\dot{E}x_2-\dot{E}x_1$	$\dot{E}x_{g7}-\dot{E}x_{g8}$
Steam Cycle					
	ST	$\frac{\dot{W}_{st}}{\dot{E}x_{14}+\dot{E}x_8-\dot{E}x_{15}}$		$\dot{W}_{st}$	$\dot{E}x_{14}+\dot{E}x_8-\dot{E}x_{15}$
	ACC	-	$\dot{E}x_{Air,out.ACC}-\dot{E}x_{Air,in.ACC}$		$\dot{E}x_{15}-\dot{E}x_{16}$
	CEP	$\frac{\dot{E}x_{17}-\dot{E}x_{16}}{\dot{W}_{CEP}}$		$\dot{E}x_{17}-\dot{E}x_{16}$	$\dot{W}_{CEP}$

An important variable of the exergoeconomic analysis is the relative cost difference. This variable expresses the relative increase in the unit costs of the exergy between fuel and product of the component that is defined as follow [44, 47]:

$$r_k = \frac{c_{P,k} - c_{F,k}}{c_{F,k}} = \frac{\dot{Z}_k}{c_{F,k}.\dot{E}x_{P,k}} + \frac{1-\eta_{ex,k}}{\eta_{ex,k}} \tag{7}$$

The contribution of the investment cost rate to the total sum of costs associated with capital and exergy destruction is expressed by the exergoeconomic factor that is determined for each component as follows [44, 47]:

$$f_k = \frac{\dot{Z}_k}{\dot{Z}_k + \dot{C}_{D,k}} \tag{8}$$

The objective is to reduce the cost related to the product of the whole plant [47].

4 Advanced exergy/exergoeconomic analyses

Advanced exergy/exergoeconomic analyses are used to determine which part of the irreversibilities and their related costs is affected by component interactions and which part can be avoided through technological/economical improvements of a plant. So, the interactions among different components of the system can be estimated and the quality of the conclusions obtained from an exergetic/exergoeconomic evaluation can be improved, when

- The exergy destruction in each (important) system component,
- The investment cost associated with such component, and
- The cost of exergy destruction within each (important) system component

are split into endogenous/exogenous and avoidable/unavoidable parts [24].

4.1 Advanced exergy analysis

Advanced exergy analysis allows realizing: a) the interconnections between the system components through splitting the exergy destruction into endogenous and exogenous parts, and b) the real improvement potentials of the system components and the overall system through splitting the exergy destruction into unavoidable and avoidable parts. Several approaches have been established for the exergy-destruction splitting through advanced exergy analysis [24].

4.1.1 Endogenous and Exogenous exergy destructions

Splitting the exergy destructions into endogenous ($\dot{E}x_{D,k}^{EN}$) and exogenous ($\dot{E}x_{D,k}^{EX}$) parts is more notable. Therefore, several thermodynamic methods have been considered to obtain their values [23, 27, 48]. In this paper the method of Ref. [23] is applied for splitting exergy destruction into exogenous and endogenous parts. Endogenous exergy destruction is the exergy destruction that happens in the component itself and is related only with the irreversibilities taking place in that component when the next conditions are at the same time satisfied:

-The component being considered operates with its real efficiency.

-All other components operate in an ideal condition (without irreversibilities) [20, 22].

In this way, the power output of the overall plant is kept constant in all estimations. The theoretical conditions for the most important components are displayed in Table (2). For the combustion chamber no theoretical conditions can be defined, due to the chemical reactions proceeding there. Different methods have been offered to overcome this problem [48]. One method, suggested in Ref. [36] is valid for more complex systems and has been applied here.

When theoretical operation is expected for a component or a group of components, the mass flow rates of the required air and fuel are calculated through the net power output of the plant ($\dot{W}_{net}$), and the excess air fraction (λ) for the combustion chamber, which have the same values as in the real case. For calculating the endogenous exergy destruction, the CC must operate with its real exergetic efficiency while in the theoretical case its exergy destruction must be set to zero.

$$\dot{E}x_{B}^{\mathrm{Real}} + \eta_{ex,CC} . \dot{E}x_{f,CC}^{\mathrm{Real}} = \dot{E}x_{C}^{\mathrm{Real}} \tag{9}$$

Theoretical conditions for CC are:

$$\eta_{ex,CC}^{Theory} = 1 \quad , \quad \dot{E}x_{D,CC}^{Theory} = 0$$

$$\dot{E}x_{B}^{Theory} + \dot{E}x_{f,CC}^{Theory} = \dot{E}x_{C}^{Theory} \tag{10}$$

Exogenous exergy destruction is the exergy destruction produced in the kth component by the operation of the remaining n-1components of the system. The exogenous part of the exergy destruction is the difference between the exergy destruction of a component (gained through conventional exergy analysis) and the endogenous exergy destruction value. After estimating the endogenous exergy destruction of the kth component, its exogenous exergy destruction is considered that Equation used for calculating exogenous part is as follow:

$$\dot{E}x_{D,k}^{EX} = \dot{E}x_{D,k}^{\mathrm{Real}} - \dot{E}x_{D,k}^{EN} \tag{11}$$

4.1.2 Unavoidable and Avoidable exergy destructions

Industrial and financial design restrictions define a minimum value of the exergy destruction. At any given state of industrial development, some exergy destruction within a system component will always be unavoidable due to thermodynamic and economic constraints. For calculating the unavoidable exergy destruction ($\dot{E}x_{D,k}^{UN}$), each component is considered in isolation and separated from the system, supposing the most satisfactory operating conditions. These conditions refer to minimum exergy destruction and are related to the operation with high efficiency and low losses. The assumptions for simulating unavoidable conditions depend on the decision maker and are uninformed moderately. In this study these assumptions have been selected by considering the maximum improvement potential that could be achieved for each plant component in the probable future and using Refs.[23, 36, 38, 40] that is given in Table (2). The value of $\dot{E}x_{D,k}^{UN}$ is calculated, using a method described in collected works [24, 25, 30, 35, 36, 38, 49, 50] , as follow:

$$\dot{E}x_{D,k}^{UN} = \dot{E}x_{P,k}^{\mathrm{Real}} . \left(\frac{\dot{E}x_{D,k}}{\dot{E}x_{P,k}} \right)^{UN} \tag{12}$$

Where, the value $\left(\dot{E}x_{D,k} / \dot{E}x_{P,k} \right)^{UN}$ is determined when all the component's exergy destructions are obtained on unavoidable conditions[35].

Table 2 Assumptions made for calculating theoretical operation conditions and unavoidable exergy destructions [23, 36, 38, 40]

Components	Unavoidable	Theoretical
AC	$\eta_{is} = 98\%$, $\eta_{mech} = 100\%$	$\eta_{is} = 100\%$, $\eta_{mech} = 100\%$
CC	$\dot{Q}_{loss} = 0$, $\Delta P = 0$, $\eta_{ex,comb} = 95\%$	$\dot{Q}_{loss} = 0$, $\Delta P = 0$, $\lambda_m = \lambda_{m,\mathrm{Real}}$, $\eta_{ex,comb} = 100\%$
GT	$\eta_{is} = 99\%$, $\eta_{mech} = 100\%$	$\eta_{is} = 100\%$, $\eta_{mech} = 100\%$
SPH	$\Delta T_{pp} = 0$	$\Delta T_{pp} = 0$
EVA	$\Delta T_{app} = 0$, $\Delta P = 0$	$\Delta T_{app} = 0$, $\Delta P = 0$
ECO	$\Delta T_{pp} = 1$, $\Delta P = 0$	$\Delta T_{pp} = 0$, $\Delta P = 0$
ST	$\eta_{is} = 97\%$, $\eta_{mech} = 100\%$	$\eta_{is} = 100\%$, $\eta_{mech} = 100\%$
PUMPs	$\eta_{is} = 95\%$, $\eta_{mech} = 100\%$	$\eta_{is} = 100\%$, $\eta_{mech} = 100\%$

The avoidable exergy destruction ($\dot{E}_{D,k}^{AV}$) points part of the exergy destruction that can be reduced and is the remaining part of the exergy destruction rate that denotes the improvement potential of the kth component. Equation used for calculating avoidable exergy destruction rates is as follow [23, 36, 40]:

$$\dot{E}x_{D,k}^{AV} = \dot{E}x_{D,k}^{\mathrm{Real}} - \dot{E}x_{D,k}^{UN} \tag{13}$$

The condenser is a dissipative component and cannot be analyzed with the equations presented here. Therefore, the estimation must be extended to contain dissipative components in the future. The operation of the deaerator basically depends on the operation of the nearby components. They also present very small values of exergy destruction. Thus, in this paper for the condenser and the deaerator, there is no difference between avoidable and unavoidable exergy destructions [29, 35, 36].

4.1.3 *Combination of the two splitting*

The Unavoidable endogenous exergy destruction ($\dot{E}x_{D,k}^{UN,EN}$), the Unavoidable exogenous ($\dot{E}x_{D,k}^{UN,EX}$), the avoidable exogenous ($\dot{E}x_{D,k}^{AV,EX}$) and the avoidable endogenous ($\dot{E}x_{D,k}^{AV,EN}$) parts of exergy respectively, are [22, 36, 40, 50].

Based on these separations and the meaning of each part, an advanced exergy analysis offers detailed information on the potential improvement to system efficiency by concentrating on the avoidable endogenous exergy destruction in a component. In Comparing with a conventional exergy analysis, this analysis based on the avoidable endogenous exergy destruction rather than the overall exergy destruction is more exact and detailed [19].

$$\dot{E}x_{D,k}^{UN,EN} = \dot{E}x_{P,k}^{EN} \cdot \left(\frac{\dot{E}x_{D,k}}{\dot{E}x_{P,k}} \right)^{UN} \tag{14}$$

$$\dot{E}x_{D,k}^{UN,EX} = \dot{E}x_{D,k}^{UN} - \dot{E}x_{D,k}^{UN,EN} \tag{15}$$

$$\dot{E}x_{D,k}^{AV,EX} = \dot{E}x_{D,k}^{EX} - \dot{E}x_{D,k}^{UN,EX} \tag{16}$$

$$\dot{E}x_{D,k}^{AV,EN} = \dot{E}x_{D,k}^{EN} - \dot{E}x_{D,k}^{UN,EN} \tag{17}$$

4.2 Advanced exergoeconomic analysis

Similarly to the exergy destruction rate, depending on if the cost of the exergy destruction rate and the investment cost can be avoided, they can be split into avoidable and unavoidable parts. The endogenous and exogenous parts of the costs are related to the internal operating conditions and the component interactions, respectively.

4.2.1 Avoidable and Unavoidable cost rates

The cost rates associated with the unavoidable and avoidable exergy destruction and investment are further defined as follows [20]:

$$\dot{C}_{D,k}^{UN} = c_{F,k}^{\mathrm{Re}al}.\dot{E}x_{D,k}^{UN} \tag{18}$$

$$\dot{C}_{D,k}^{AV} = \dot{C}_{D,k}^{\mathrm{Re}al} - \dot{C}_{D,k}^{UN} \tag{19}$$

Unavoidable investment cost rate ($\dot{Z}_k^{UN}$) for heat exchangers if gained using following equation[20]:

$$\dot{Z}_k^{UN} = \dot{Z}_k^{\mathrm{Re}al}.\left(\frac{PEC^{UN}}{PEC^{\mathrm{Re}al}}\right)_k \tag{20}$$

In the above equation PEC^{UN} is the purchased equipment cost of the kth component that is obtained through the unavoidable assumptions. For the other components $\dot{Z}_k^{UN}$ is a percentage of real investment cost rate ($\dot{Z}_k^{\mathrm{Re}al}$) that the assumptions are showed in Table (3). Most of the cost of the GT system, the steam turbines and the pumps was assumed to be unavoidable, due to very limited potentials of improvement in their design. On the other hand, most of the investment cost of the heat exchangers is found to be avoidable. The unavoidable cost of heat exchangers is estimated using unavoidable simulations that the assumption showed in Table (2) [20, 29]. Using the value of unavoidable investment cost rate, the avoidable investment cost rate ($\dot{Z}_k^{AV}$) is defined as follow:

$$\dot{Z}_k^{AV} = \dot{Z}_k^{\mathrm{Re}al} - \dot{Z}_k^{UN} \tag{21}$$

4.2.2 Endogenous and Exogenous cost rates

The costs associated with the endogenous and exogenous parts of the exergy destruction are defined as follows [20]:

$$\dot{C}_{D,k}^{EN} = c_{F,k}^{\mathrm{Re}al}.\dot{E}_{D,k}^{EN} \tag{22}$$

$$\dot{C}_{D,k}^{EX} = \dot{C}_{D,k}^{\mathrm{Re}al} - \dot{C}_{D,k}^{EN} \tag{23}$$

The investment cost rate parts of the kth component can therefore be defined as [20, 48]:

Table 3 Assumption for calculating unavoidable Investment cost rates for specified components [29, 41]

Components	$\dot{Z}_k^{UN}$ (% of $\dot{Z}_k^{Real}$)
GT	80
AC	90
CC	80
DB	80
ST	90
PUMPs	60

$$\dot{Z}_k^{EN} = \dot{E}_{P,k}^{EN} \cdot \left(\frac{\dot{Z}_k}{\dot{E}_P} \right)_k^{\mathrm{Re}al} \tag{24}$$

$$\dot{Z}_k^{EX} = \dot{Z}_k^{\mathrm{Re}al} - \dot{Z}_k^{EN} \tag{25}$$

4.2.3 Combination of the two cost splitting

The Unavoidable and Avoidable exergy destruction cost rates are divided into endogenous and exogenous parts, which are defined here as follows [20, 21, 33, 48]:

$$\dot{C}_{D,k}^{UN,EN} = c_{F,k}^{\mathrm{Re}al} . \dot{E}_{D,k}^{UN,EN} \tag{26}$$

$$\dot{C}_{D,k}^{UN,EX} = \dot{C}_{D,k}^{UN} - \dot{C}_{D,k}^{UN,EX} \tag{27}$$

$$\dot{C}_{D,k}^{AV,EN} = c_{F,k}^{\mathrm{Re}al} . \dot{E}_{D,k}^{AV,EN} \tag{28}$$

$$\dot{C}_{D,k}^{AV,EX} = \dot{C}_{D,k}^{UN} - \dot{C}_{D,k}^{AV,EX} \tag{29}$$

The Unavoidable and Avoidable investment cost rates are divided into endogenous and exogenous parts, which are defined here as follows [20, 21, 33, 48]:

$$\dot{Z}_k^{UN,EN} = \dot{E}_{P,k}^{EN} \cdot \left(\frac{\dot{Z}}{\dot{E}_P} \right)_k^{UN} \tag{30}$$

$$\dot{Z}_k^{UN,EX} = \dot{Z}_k^{UN} - \dot{Z}_k^{UN,EN} \tag{31}$$

$$\dot{Z}_k^{AV,EN} = \dot{Z}_k^{EN} - \dot{Z}_k^{UN,EN} \tag{32}$$

$$\dot{Z}_k^{AV,EX} = \dot{Z}_k^{EX} - \dot{Z}_k^{UN,EX} \tag{33}$$

5 Results and discussions

Each part of the CCPP shown in Figure (1) was individually studied and for each component mass, energy, exergy analysis and cost balances were determined. Some input data for the calculation, like points' pressures and temperatures are gotten from the mentioned real power plant. The certified information is used for lower heating values of the fuel, besides for the prices of energy supplies. The value of chemical exergy related to the fuel is significant. Engineering Equation Solver (EES) is used for solving the mathematical equations.

In the manner of conventional exergy analysis, exergy of fuel and product, exergy destruction, exergy efficiency and exergy destruction ratio for particular components are existed (Table (4)). In addition, the amounts of the exergy destruction rates, the exergy efficiency, and the exergy destruction ratio of the system component are shown in Figures (2–4), respectively. Exergy destruction rate is measure for the irreversibilities of an energy conversion system. Results of conventional exergy analysis showed that, the most significant components due to have the highest exergy destruction rates were the CCs (2×211.77=423.54 MW) followed by the HRSGs (209.42 MW) and the DBs (2×41.18=82.36 MW). High irreversibilities in the CCs and the DBs happened because of chemical reactions. Therefore, most focuses should be on the improvement of these components. Considering the components of the cycle one by one, again the CCs has the highest exergy destruction rate followed by the DBs and the LP.EVA (2×39.72=79.44 MW).

The minimum exergy destruction rate was due to the CEP (0.15 MW). The maximum exergy efficiency is owing to the GT (95.64%), while the minimum exergy efficiency is related to the ST (8.85%). The exergy efficiency of the overall cycle is 37%.

Another parameter to evaluate the system performance is the exergy destruction ratio ($y_{D,k}$). Values for the exergy destruction ratio indicate that the CCs ($2\times 16.41=32.82\%$) and the HRSGs (16.24 %) have the highest effect on reducing exergy efficiency of the overall system. Exergy destructions of the other components decrease the exergy efficiency of the overall system by 13.88%.

Table 4 Summary results of conventional exergy analysis

Components		$\dot{E}_{f,k}$, MW	$\dot{E}_{p,k}$, MW	$\dot{E}_{D,k}$, MW	ε_K, %	y_K , %
Gas cycle	**AC**	210.46	198.28	12.18	94.21	0.94
	CC	1218	1006	211.77	82.62	16.41
	GT	386.22	369.36	16.86	95.64	1.30
	DB	651	609.82	41.18	93.68	3.19
Steam Cycle	**ST**	184	163.48	20.51	8.85	1.59
	ACC	17.44	0	12.19	0	0.94
	CEP	0.53	0.41	0.15	78.13	0
HRSG	**CPH**	29.1	7.93	21.17	27.25	1.64
	DEA	1.61	0.58	1.03	35.84	0.08
	BFP	2.94	1.6	1.35	54.1	0.10
	LP.EVA	9.00	2.94	6.05	32.65	0.46
	LP.SPH	0.62	0.13	0.49	21.45	0.03
	HP.EVA	84	44.24	39.72	52.69	3.07
	HP.ECO	31	14.62	16.36	47.2	1.26
	HP.SPH	44.32	26	18.34	58.62	1.42
Overall HRSG		405.18	195.76	209.42	48.39	16.24
Overall system		1289.85	478	811.85	37	62.94

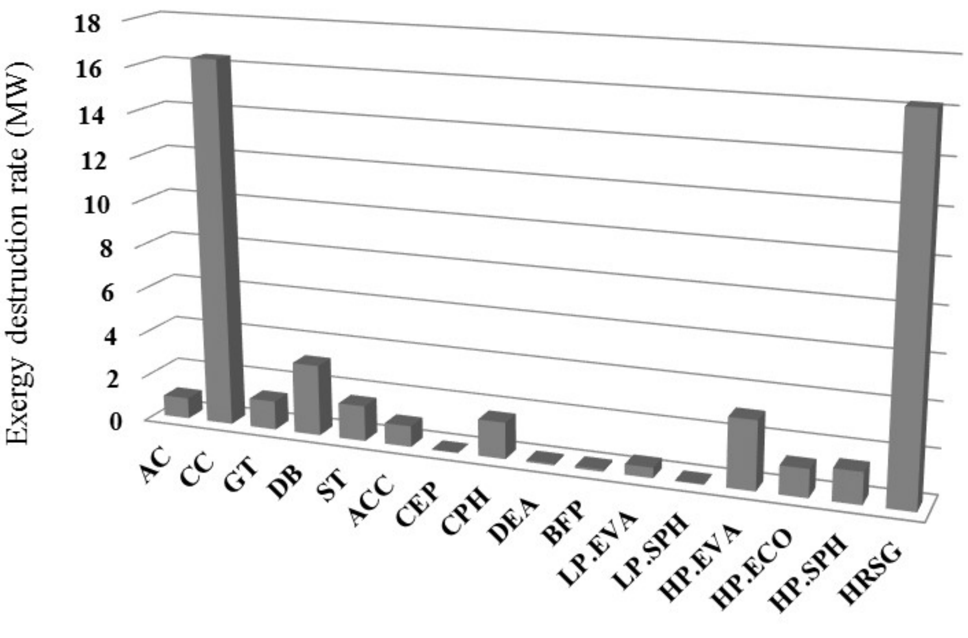

Figure 2 Exergy destruction rates of system components

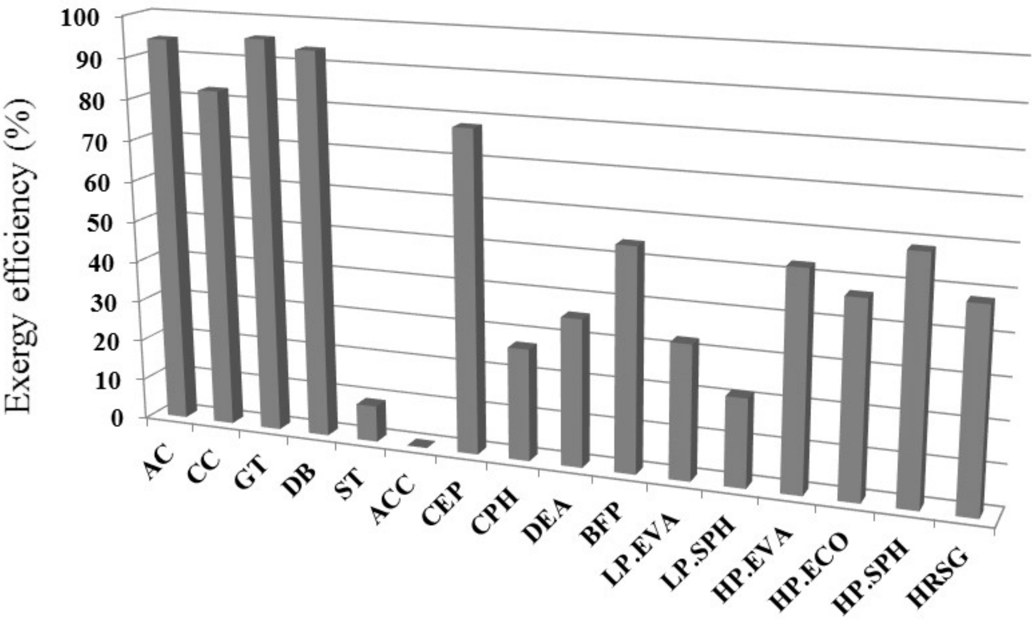

Figure 3 Exergy Efficiency of system components

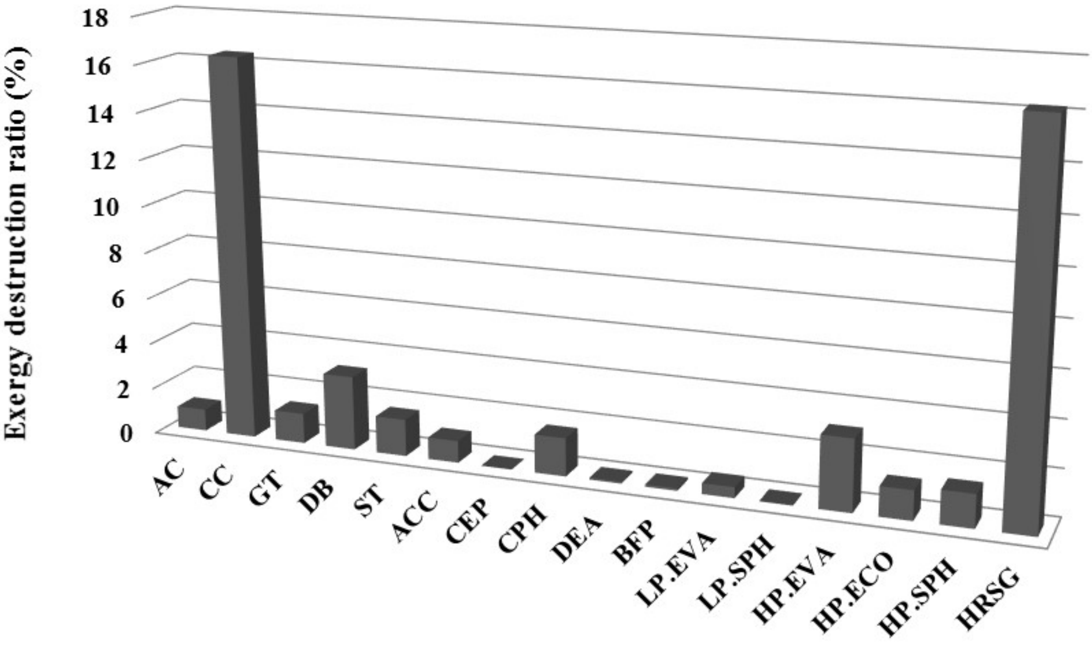

Figure 4 Exergy destruction ratio of system components

The results of the conventional exergoeconomic analysis for real operating conditions of the system components are shown in Table (5). In addition, the amounts of the relative cost difference, sum of the exergy destruction and investment cost rates and the exergoeconomic factor are shown in Figures (5–7), respectively. For analyzing components and the overall system through conventional exergoeconomic-base method, the prices of the provided air were assumed to be zero. The operation and maintenance cost rates were considered using the annual operating and maintenance costs as a percentage of components PECs, assuming 7000 operating hours per year. Results of the conventional exergoeconomic analysis, confirm the conclusions of the conventional exergy analysis. Components with the highest exergy destruction rates have also the highest exergy destruction cost rates ($\dot{C}_{D,k}$). So that, as the highest value of the exergy destruction cost rates is gotten for the HRSGs (8928.36 \$/h), followed by the CCs ($2\times3071.88=6143.76$ \$/h) that have the highest value of exergy destruction rates too. Values of exergoeconomic and non-exergoeconomic (investment) costs for each component and the whole cycle are presented in Table (5). The exergoeconomic factor shows information about the connection between the investment cost rates and the energy efficiencies of the system or the equipment. In the other hand, the exergoeconomic factor can be used to define the costs of the system causing from either the energy costs or the capital investments. A large exergoeconomic factor indicates that the components cost rates should be reduced to decrease the system cost rates, while a small exergoeconomic factor indicates that energy-efficient components should be utilized to reduce the cycle cost rates. The system consideration indicates that the GT has the maximum exergoeconomic factor (93%), while the HP.EVA has the minimum exergoeconomic factor (7%). Assuming HRSG as integrated equipment, CC has the minimum amount of exergoeconomic factor (14%).

Table 5 Summary results of conventional exergoeconomic analysis

Components		$\dot{C}_{D,k}$, **($/h)**	$\dot{Z}_{D,k}$, **($/h)**	$\dot{Z}_{D,k}+\dot{C}_{D,k}$, **($/h)**	f_K	r_K
Gas cycle	AC	370.08	1172.16	1542.24	0.76	0.26
	CC	3071.88	490.68	3562.56	0.14	0.24
	GT	304.16	4251.60	4555.76	0.93	0.68
	DB	740.50	146.66	887.16	0.16	1.42
Steam Cycle	ST	341.67	1901.88	2243.55	0.84	0.25
	ACC	5.20	25.31	30.51	0.82	4.77
	CEP	3.49	20.21	23.70	0.85	1.89
HRSG	CPH	911.88	135.08	1046.96	0.12	3.04
	DEA	44.60	19.90	64.50	0.25	2.40
	BFP	40.90	48.25	89.15	0.62	2.25
	LP.EVA	259.20	1159.20	1418.40	0.81	15.65
	LP.SPH	20.88	136.80	157.68	0.86	27.63
	HP.EVA	1692	140.40	1832.40	0.07	0.97
	HP.ECO	704.88	288.00	992.88	0.29	1.58
	HP.SPH	789.84	90.00	879.84	0.1	0.46
Overall HRSG		8928.36	4035.26	12963.62	0.31	
Overall Cycle		18251.96	18104.86	36356.82	0.5	

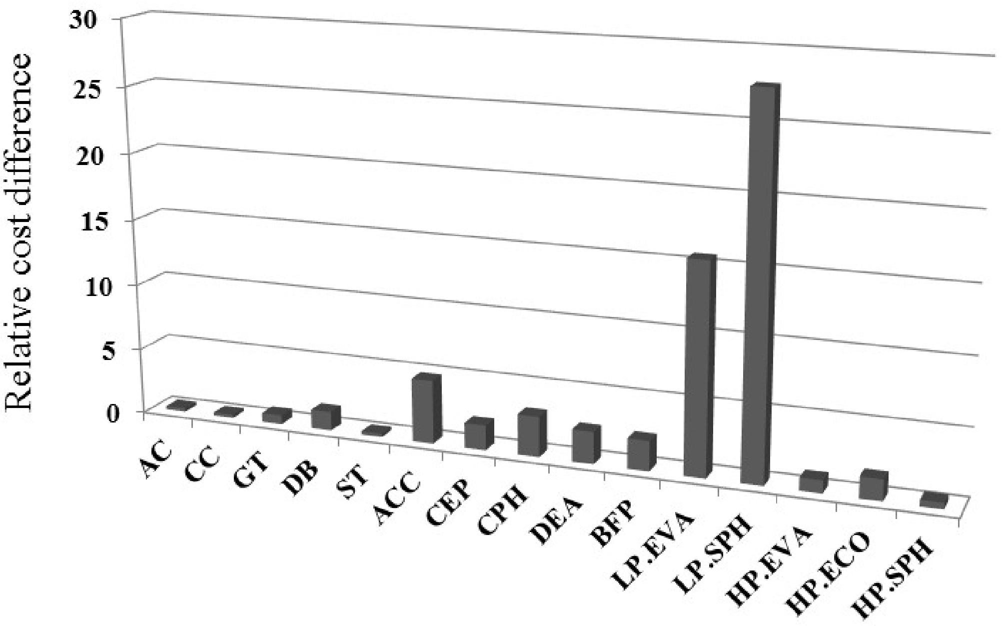

Figure 5 Relative cost difference of system components

The relative cost difference (r_k) specifies the relative dispute in the unit cost of exergy related to the product according to the unit cost of exergy related to the fuel for a component, and this variance has an important role to optimize and estimate the system components.

In the exergoeconomic analysis, primarily the components with high amount of relative cost difference are identified because a high value of relative cost difference shows that increasing of the exergy cost is great in these components.

The second stage is to considering the total cost rates ($\dot{Z}_k + \dot{C}_{D,k}$) of these components in the downward order and study them separately to see if increasing the investment cost to make the component more effective would bring down the $\dot{Z}_k + \dot{C}_{D,k}$ or not. In this paper, components within the HRSG consider separately, so the relative cost difference for the whole HRSG isn't calculated. Table (5) and Figure (5) show the components with highest relative cost difference are LP.EVA (27.63), LP.SPH (15.65), ACC (4.77) and CPH (3.04). Then, considering them separately in the downward order of the $\dot{Z}_k + \dot{C}_{D,k}$ (Table (5) and Figure (6)) show that, the sum of exergy destruction and investment cost rate is the highest for the two LP.EVAs ($2 \times 1418.40 = 2836.8$ $/h) followed by the two CPHs ($2 \times 1046.96 = 2093.92$ $/h), the two LP.SPHs ($2 \times 157.68 = 345.36$ $/h) and the ACC (30.51 $/h).Total required investment cost rates for the overall cycle is about 18,104.86 ($/h).

By means of exergoeconomic factor expresses the ratio of the non exergoeconomic cost rate to the total cost rate, comparatively high value of this factor for LP.EVA (81%) specifies that the impact of exergy destruction cost to the total cost is low (Table (5) and Figure (7)). It also advises that cost reserves in the overall system could be reached by improving the component efficiency or reducing the exergy destruction of a component, even if the investment cost of this component rises. Thus, the performance improvement of this component can be increase to some extent by investment cost into more efficient design.

The amount of exergoeconomic factor for the LP.EVA is to some extent high (81%). Therefore, no such recommendation can be made for this component. The value of exergoeconomic factor for the CPH is very low (12%). Therefore, the performance of this component can be exceptionally improved by capital investment into more efficient design. For the LP.SPH, the value of exergoeconomic factor is higher than the mentioned components (86%). Therefore, nothing special can be made for this component too. For the ACC the same result is indicated.

Unavoidable/Avoidable and Endogenous/Exogenous exergy destruction rates are considered using the advanced exergy analysis method. The results for the advanced exergy analysis are stated in Table (6).The details of the advanced exergy analysis of the system studied are presented as follows:

The endogenous exergy destruction rates were larger than the resultant exogenous exergy destruction rates for the CC, GT, DB, HP.EVA, ST and BFP that meant the exergy destruction in each of these components was due to the component itself. The highest endogenous exergy destruction was associated with the two CCs ($2 \times 172.89 = 345.78$ MW) due to the high irreversibility that were caused by the combustion chemical reaction, followed by the HRSG (148.67).

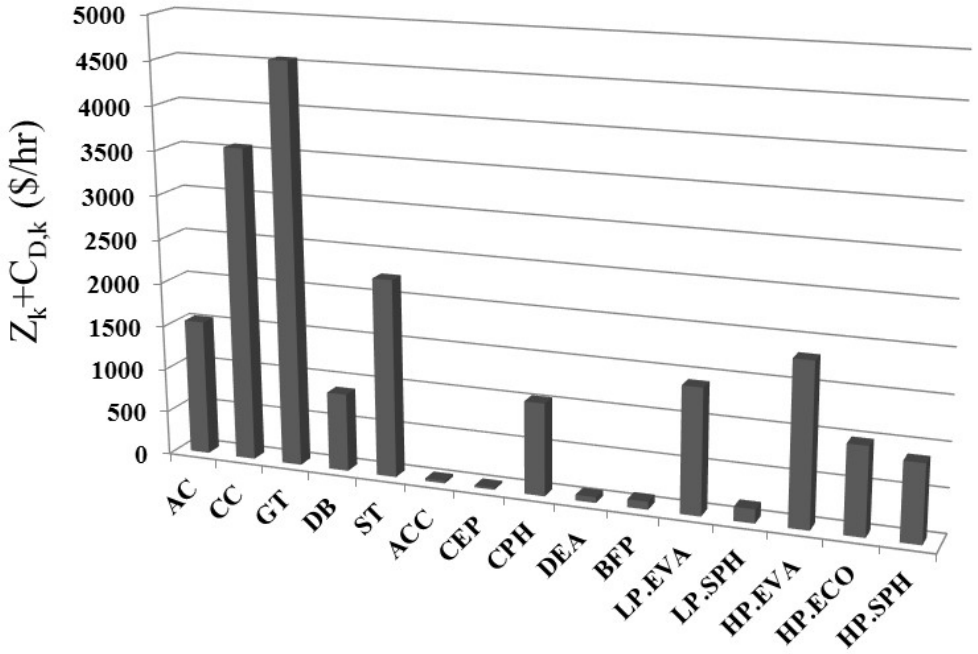

Figure 6 Sum of exergy destruction and investment cost rates of system components

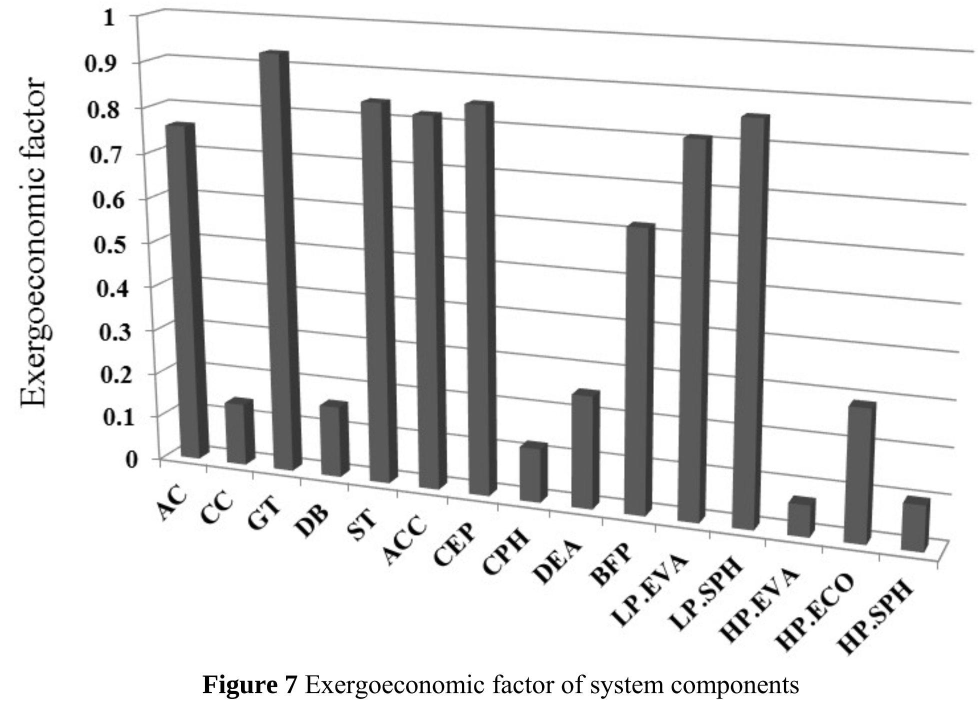

Figure 7 Exergoeconomic factor of system components

The exogenous exergy destruction rates were established to be bigger than endogenous exergy destruction rates for the HP.SPH, HP.ECO, CPH, LP.EVA, LP.SPH and CEP that meant these components were influenced by other components, and the exergy destruction within each of these components could be reduced by increasing the exergy destruction within the other components. The negative values of the exogenous exergy destructions ($\dot{E}_{D,k}^{EX}$) for GT (-44.05 MW), DB (-13.15 MW), BFP (-7.47 MW) and HP.EVA (-1.53 MW) showed that the exergy destruction within each of these components could be decreased by the increase in the exergy destruction within the other components.

Table 6 Summary results of advanced exergy analysis

Components		$\dot{E}_{D,k}$ **Splitting**				$\dot{E}^{UN}_{D,k}$		$\dot{E}^{AV}_{D,k}$	
		$\dot{Ex}^{EN}_{D,k}$ **MW**	$\dot{Ex}^{EX}_{D,k}$ **MW**	$\dot{Ex}^{UN}_{D,k}$ **MW**	$\dot{Ex}^{AV}_{D,k}$ **MW**	$\dot{Ex}^{UN,EN}_{D,k}$ **MW**	$\dot{Ex}^{UN,EX}_{D,k}$ **MW**	$\dot{Ex}^{AV,EN}_{D,k}$ **MW**	$\dot{Ex}^{AV,EX}_{D,k}$ **MW**
Gas Cycle	AC	7.17	5.00	3.9	8.3	3.82	0.074	3.35	4.93
	CC	172.89	38.88	210.4	1.40	249.9	-38.12	-77	78.4
	GT	60.91	-44.05	8.45	8.40	9.31	-0.86	2.87	5.53
	DB	54.33	-13.15	21.68	19.49	24.56	-2.88	29.76	-10.27
Steam Cycle	ST	13.23	7.28	8.22	12.29	3.78	4.43	9.45	2.84
	CEP	0.00	0.15	0.02	0.09	0.02	0.001	-0.02	0.11
HRSG	CPH	9.45	11.71	28.28	-7.11	22.42	5.85	-12.97	5.86
	BFP	8.82	-7.47	2.34	-0.99	22.68	-20.34	-13.85	12.87
	LP.EVA	0	6.00	0.67	5.38	0	0.67	0	5.38
	LP.SPH	0.08	0.40	0.17	0.31	0.15	0.02	-0.07	0.38
	HP.EVA	41.25	-1.53	35.06	4.65	46	-10.95	-4.76	9.41
	HP.ECO	4.23	12.13	11.04	5.32	4.59	6.44	-0.37	5.69
	HP.SPH	10.50	14.9	23.85	1.55	37.4	-13.55	-26.91	28.46
Overall HRSG		148.67	72.28	202.82	36.44	266.48	-83.16	-117.86	136.10
Sum of each part		148.67	56.82	699.92	113.65				
(Percentage of each part)		(93%)	(7%)	(86%)	(14%)				
Overall system		811.85		811.85					

When estimating energy conversion systems, one principally should attention to their avoidable exergy destruction rates; because it denotes the potential for improvement while unavoidable exergy destruction specified the limitations. The unavoidable exergy destruction was higher than the avoidable exergy destruction of most of the system components so that, as the overall system, apart from the ST (12.29 MW), AC (8.30 MW), LP.EVA (5.38 MW), LP.SPH (0.31 MW) and CEP (0.09 MW). This statement showed that the overall system had a low potential for improvement. The heat exchangers (LP.EVA, LP.SPH), whose design only allows the use of physical exergy, have great potential to perform useful work based on chemical exergy. But, these components don't take advantage of that potential. From another point of view, to produce steam with high temperature, a special quantity of fuel is consumed in the HRSG.

If the HRSG is assumed to be integrated equipment, within the whole cycle the CEP (0.09MW) followed by the CCs ($2\times1.4=2.8$ MW), had the smallest avoidable exergy destruction rate that indicated low possibility for improving these components among the system components. The high improvement potentials within the system components were in the two DBs ($2\times19.49=38.94$ MW), HRSG (36.44 MW) and ST (12.29 MW), which could be achieved by increasing the supplementary firing unit, the HRSG and the ST efficiency, respectively.

The largest portion of the avoidable exergy destruction rate within the DB was endogenous (29.76 MW) and the remaining portion (-10.27 MW) was exogenous. Within the ST, also the endogenous part of avoidable exergy destruction rate (9.45 MW) was greater than the other part (2.84 MW). But in the HRSG the avoidable exogenous exergy destruction (13.610 MW) is the higher part.

Using only the conventional exergy analysis, HRSG was concluded to have highest exergy destruction rate. Nevertheless, when evaluating this component using advanced exergy analysis, 67% of this component exergy destruction rate was specifies to be related to HRSG itself, because it has high endogenous exergy destruction rates. Endogenous exergy destruction rate for HRSG is (148.67 MW). Using advanced exergy analysis for HRSG determined that the focus should be on improving the performance of the HRSG itself, rather than the effects of the remaining components.

The negative amount for the avoidable exergy destruction rate ($\dot{E}x_{D,k}^{AV}$) signifies that the unavoidable conditions raise the exergy destruction rate of CPH and BFP in comparison with their real conditions. Furthermore, the negative value of avoidable endogenous exergy destruction rate in CC, HRSG and CEP means that under unavoidable conditions, the effect of avoidable exergy destruction of remaining components. Due to their inefficiencies on the kth component, is upper than the avoidable exergy destruction of the kth component.

The negative amounts of exogenous exergy destruction rates ($\dot{E}x_{D,k}^{EX}, \dot{E}x_{D,k}^{AV,EX}, \dot{E}x_{D,k}^{UN,EX}$) indicate that the exergy destruction rate in the GT, D, BFP, HP.EVA, CC and HP.SPH could be reduced by the increase in the exergy destruction rate in the other components [36,40]. The negative values calculated for the exogenous exergy destruction in some components are the result of mass flow rate and temperature differences between the endogenous and the real operating conditions. In the same way, the negative amounts of other kind of exergy destruction rates which is seen in Table (6) can be justified similarly.

The negative values of unavoidable exogenous exergy destructions ($\dot{E}x_{D,k}^{UN,EX}$) for CC, DB, BFP, HP.SPH, HP.EVA and GT, show which part of exergy destruction within these components that cannot be avoided by changing in other components exergy destruction rates, Whereas, the negative avoidable exogenous exergy destruction value ($\dot{E}x_{D,k}^{AV,EX}$) for DB, indicates portion of exergy destruction in this component that can be improved by increasing the other components exergy destructions. Totally, results for the analyzed power plant are shown for two statement: in Table (4), for real operating conditions (before the improvements) and in Table (6), for unavoidable operating conditions (after the improvements). It can be realized that exergy destruction rate of the whole cycle is reduced after improvement for 113.65 MW or 14%.

Results of advanced exergoeconomic analysis for the mentioned cycle are showed in Table (7) and Table (8) and are explained as follows:

Investigating Table (7), the following results can be obtained. To determine the potentials for improving the exergy destruction cost rates, the avoidable exergy destruction cost rates should be studied. Unavoidable exergy destruction cost rates define the limitations of the improvements represented. The CC (3052 \$/h), HP.EVA (1492 \$/h), CPH (1216.8 \$/h), HP.SPH (739.05 \$/h), HP.ECO (475.02 \$/h), DB (388.80 \$/h), GT (152.52 \$/h) and BFP (70.21 \$/h) have greater unavoidable exergy destruction cost rates than the avoidable ones, which clarifies low potentials for improving these components. In addition, the AC (252 \$/h), LP.EVA (231.73 \$/h), ST (204.73 \$/h), LP.SPH (13.35 \$/h) and CEP (2.73 \$/h) have greater avoidable exergy destruction cost rates, therefor; the focus of improvement should be on these components. The maximum improvement potential is in the DBs ($2\times350.92=701.84$ \$/h) which is relatively high according to its unavoidable exergy destruction cost ($2\times388.80=777.6$ \$/h) and can be achieved by enhancing the DBs efficiency. If the HRSG is assumed such as integrated equipment, instead of DBs it will have the maximum amount of avoidable exergy destruction cost rate (798.54 \$/h) in the cycle that shows the improvement potentials for this equipment.

Table 7 Summary results for advanced exergoeconomic analysis (exergy destruction cost rate)

Components		**Splitting $\dot{C}_{D,k}$**							
		$\dot{C}^{EN}_{D,k}$ **$/h**	$\dot{C}^{EX}_{D,k}$ **$/h**	$\dot{C}^{UN}_{D,k}$ **$/h**	$\dot{C}^{AV}_{D,k}$ **$/h**	$\dot{C}^{UN,EN}_{D,k}$ **$/h**	$\dot{C}^{UN,EX}_{D,k}$ **$/h**	$\dot{C}^{AV,EN}_{D,k}$ **$/h**	$\dot{C}^{AV,EX}_{D,k}$ **$/h**
Gas Cycle	AC	218.06	151.92	118.08	252	116.04	2.05	101.77	150.04
	CC	2507.76	563.76	3052	19.88	3607.2	-550.44	-1116.72	1136.76
	GT	1098.08	-794.22	152.52	151.64	167.97	-15.52	51.80	99.97
	DB	978.12	-234	388.80	350.92	442.08	-51.84	535.68	-183.60
Steam Cycle	ST	219.39	123	136.80	204.73	62.96	73.8	164.2	41.30
	CEP	0	3.56	0.57	2.73	0.54	0.03	-0.58	3.31
HRSG	CPH	407.16	504.36	1216.80	-306.25	965.88	251.64	-558.05	252.20
	BFP	267.98	-226.94	70.21	-26.07	689.04	-618.12	-396	370
	LP.EVA	0	258.44	28.80	231.73	0	28.81	0	230.95
	LP.SPH	3.42	16.92	7.20	13.35	6.12	0.83	-3.01	16.20
	HP.EVA	1757.6	-57.49	1492	200.30	1959.48	-466.56	-205.02	45.36
	HP.ECO	182.19	522.36	475.20	229.14	197.71	277.2	-15.93	244.80
	HP.SPH	325.51	461.88	739.05	49.15	1159.56	-371.36	-834.12	882.36
Overall HRSG		6017.32	2915.86	8131.50	798.54	9990.20	-1959.02	-3404.56	4203.10
Sum of each part (Percentage of each part)		15711.15 (86%)	2540.77 (14%)	15618.69 (85%)	2737.79 (15%)				
Overall system		18251.96		18251.96					

The exogenous exergy destruction cost rates in the most components of the cycle were lower than the endogenous exergy destructions cost rates, except for the HP.SPH (14.9 $/h), HP.ECO (12.13 $/h), CPH (11.71 $/h), LP.EVA (6 $/h) and the LP.SPH (0.4 $/h). This result specified that the components with higher exogenous exergy destruction cost rates than the endogenous ones were affected at upper levels by the other components, and the exergy destruction cost rates of these components could be reduced by increasing the exergy destruction of the other components. The latter conclusion was also confirmed by the negative amounts of the exogenous exergy destruction cost rates ($\dot{C}^{EX}_{D,k}, \dot{C}^{AV,EX}_{D,k}, \dot{C}^{UN,EX}_{D,k}$). So that, as the negative exogenous exergy destruction cost rates ($\dot{C}^{EX}_{D,k}$) within the GT (-794.22 $/h), DB (-234 $/h), BFP (-226.94$/h) and the HP.EVA (-57.49 $/h) indicated that the exergy destruction cost rates within these components can be decreased by increasing the exergy destruction cost rates within other components. Nevertheless, in the components with higher endogenous exergy destruction cost rates than the exogenous ones, most of the irreversibilities were caused by the component itself. As an example, considering the components one by one, the maximum endogenous exergy destruction cost rate was in the two CCs ($2\times 2507.76 = 5015.52$ $/h) because of the high irreversibilities in the combustion process. Assuming HRSG as integrated equipment, it will be the equipment has the highest endogenous exergy destruction cost rate (6017.32 $/h). Observing the avoidable exergy destruction cost rates of the system components, the exogenous parts of the avoidable exergy destruction cost rate were established to be higher than the endogenous avoidable exergy destruction parts, except for the DB(99.97 $/h) and ST (41.30 $/h) that means the improvement potential of a component is related usually to the other components.

The CPH and BFP have negative $\dot{C}_{D,k}^{AV}$ and $\dot{C}_{D,k}^{AV,EN}$ values for (-306.25, -558.05 \$/h) and (-26.07, -296 \$/h) respectively. Negative $\dot{C}_{D,k}^{AV}$ indicates that these components have a greater exergy destruction cost rate even under improved conditions, due to incensement of their exergetic efficiency under unavoidable conditions. Negative $\dot{C}_{D,k}^{AV,EN}$ indicates that the exergy destruction cost rates within the CPH and ST can be reduced by decreasing the steam mass flow rate or inlet specific exergy cost. Using these approaches, the endogenous exergy destruction cost rate of the CPH and the ST can be decreased; therefore, the available endogenous exergy destruction cost rates can be also decreased. In view of the conventional exergoeconomic analysis, it could be determined that the HRSG as integrated equipment and the two CCs had large exergy destruction cost rates. When analyzing these components using the advanced exergoeconomic method, it can be indicated that only 20-45% of the exergy destruction cost rates of these components are related to the other components because they had high endogenous exergy destruction cost rates. The results of the advanced exergoeconomic analysis of the HRSG and the CCs indicated that the analysis must be focused on the components themselves instead of other components. Investigating Table (8), the following results can be gotten. The exogenous investment cost rates of the studied CCPP's components were higher than its endogenous investment cost rates, not including the BFP (-309.53 \$/h), CPH (-24.60 \$/h), HP.EVA (9.62 \$/h) and LP.SPH (54.76 \$/h). These results specified that the system components interactions had significant effects to the investment cost rates. The negative value of exogenous investment cost rate within CPH (-24.60 \$/h) and BFP (-309.53 \$/h) exposed that mass flow rates required in the endogenous case increase that result in a higher rate of product exergy, when compared to the real condition. These results mean that the investment cost rate of a component with negative $\dot{Z}_{k}^{EX}$ increases when other components operate under theoretical conditions (without exergy destruction).

So, when the exogenous investment cost rate of a component is negative, the irreversibilities within the remaining components must be increased, with the purpose of decrease the cost rate of the considered component.

The improvement potential of the system was establish to be low, because the unavoidable parts of the investment cost rate of the components are bigger than the avoidable ones, except for the LP.EVA and the LP.SPH. Therefore, these components could improve the investment cost rates that these potentials of improvement were mainly related to the remaining components because of the higher avoidable exogenous investment cost rates. For a CCPP, the investment cost rates of the components are related to the remaining ones that mean interconnections between components within the system is strong for the investment cost rates and the higher exogenous avoidable investment costs are the most important evidence for it.

In addition, the difference between the absolute amounts of the endogenous and exogenous investment cost rates within some components was significant. For example, the exogenous investment cost rates were estimated to be 26-27 times higher than the endogenous cost rates in the AC and this ratio for the GT is 5 times.

In the manner of advanced exergoeconomic analysis, results for the analyzed power plant are shown for two statements: in Table (5), for real operating conditions (before the improvements) and in Table (7) and Table (8), for unavoidable operating conditions (after the improvements) associated with the exergy destruction and investment cost rates respectively. Cost rates of exergy destruction of the whole cycle were reduced for 15%, after improvements has value of 15618.69 (\$/h) and investment cost rates of the whole cycle are decreased for 25%, after improvements has value of 13341.8 (\$/h).

Table 8 Summary results for advanced exergoeconomic analysis (investment cost rates)

Components		Splitting $\dot{Z}_k$							
						$\dot{Z}^{UN}{}_k$		$\dot{Z}^{AV}{}_k$	
		$\dot{Z}^{EN}{}_k$ $/h	$\dot{Z}^{EX}{}_k$ $/h	$\dot{Z}^{UN}{}_k$ $/h	$\dot{Z}^{AV}{}_k$ $/h	$\dot{Z}^{UN,EN}{}_{D,k}$ $/h	$\dot{Z}^{UN,EX}{}_{D,k}$ $/h	$\dot{Z}^{AV,EN}{}_{D,k}$ $/h	$\dot{Z}^{AV,EX}{}_{D,k}$ $/h
Gas Cycle	AC	42.37	1129.68	1054.8	117.36	38.16	1016.64	-4.23	113.13
	CC	84.31	406.44	388.8	102.16	66.78	321.91	17.55	84.62
	GT	701.28	3551.4	3402.36	849.24	560.88	2841.48	140.25	660.91
	DB	13.06	133.59	117.32	29.33	10.45	106.86	2.60	26.72
Steam Cycle	ST	153.9	1748.16	1711.8	190.08	138.52	1573.27	15.39	3.69
	CEP	0	20.21	12.12	8.08	0	12.12	0	8.08
HRSG	CPH	131.44	-24.60	113.78	0	140.26	-26.03	0	0
	BFP	378	-309.53	41.18	7.06	226.75	-185.65	151.23	-144.2
	LP.EVA	0	1159.2	201.78	957.24	0	201.6	0	957.24
	LP.SPH	82.58	54.76	101.84	35.49	61.24	40.60	21.34	14.15
	HP.EVA	132.73	9.62	105.52	36.79	98.42	7.13	34.30	2.49
	HP.ECO	83.30	204.69	213.58	74.45	61.77	151.81	21.53	52.92
	HP.SPH	37.08	54.68	68.05	23.70	27.49	40.53	9.58	14.12
Overall HRSG		1690.26	2345	1691.46	2345.8	1231.86	459.6	476	1869.8
Sum of each part (Percentage of each part)		3526.2 (20%)	14578.6 (80%)	13341.8 (75%)	4663.8 (25%)	2722.92 (20%)	10618.17 (80%)	803.73 (17%)	3860.07 (83%)
Overall system		18104.86		18104.86		13341.80		4663.8	
						18104.86			

Figures (8–13) show the advanced exergetic parameters for the overall system. According to Figure (8), the endogenous exergy destruction cost rate has the maximum amount (86%), which verifies that the interconnections among the system components with the exergy destruction cost rates are very weak. A similar result is shown in Figure (9). The avoidable exergy destruction cost rate that is associated with improvement potentials of the overall system is only 15%. Considering the investment cost rates in Figures (10) and (11), the exogenous amount of the investment cost rates is especially great (80%), which indicates that the component interactions are strong for the investment cost rates in the system and improvement potentials of the investment cost rates is significantly low (25%). According to Figure (12), the endogenous unavoidable parts reach 74% for the overall system. The avoidable exogenous investment cost rate percentage is 84% according to Figure (13) that indicates high potential improvement associated with the components interconnections.

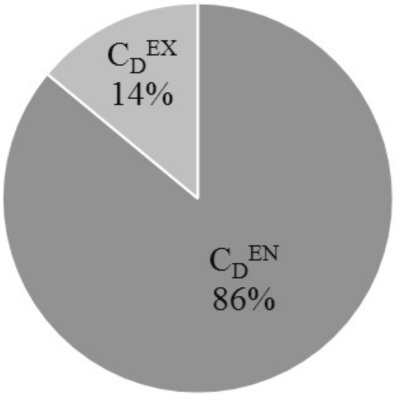

Figure 8 Endogenous and exeogenous exergy destruction cost rates of the CCPP

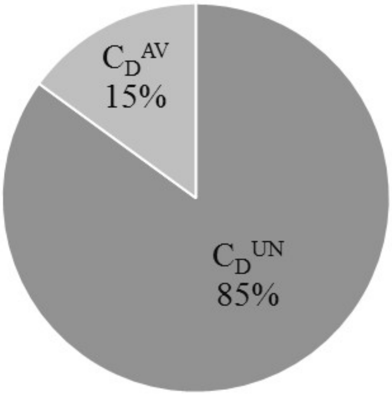

Figure 9 Unavoidable and Avoidable exergy destruction cost rates of the CCPP

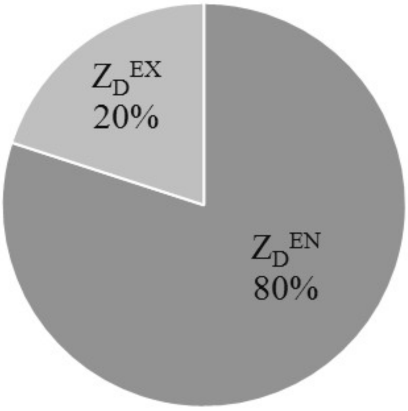

Figure 10 Endogenous and exogenous investment cost rates of the CCPP

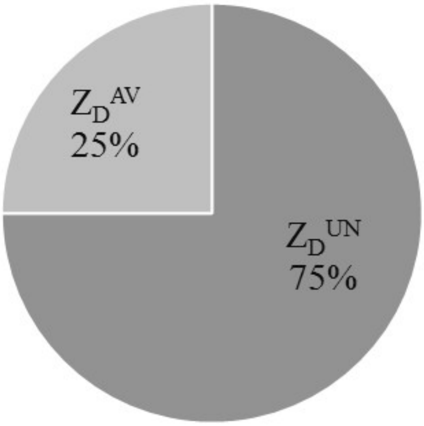

Figure 11 Unavoidable and Avoidable investment cost rates of the CCPP

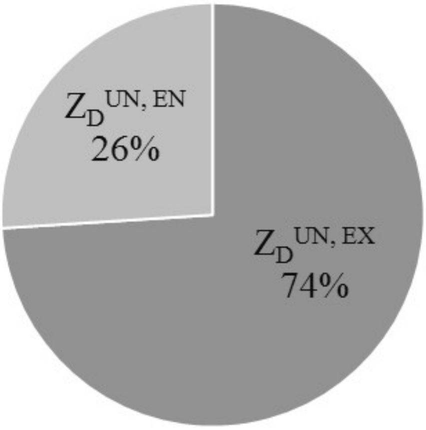

Figure 12 Unavoidable Endogenous and Unavoidable Exogenous investment cost rates of the CCPP

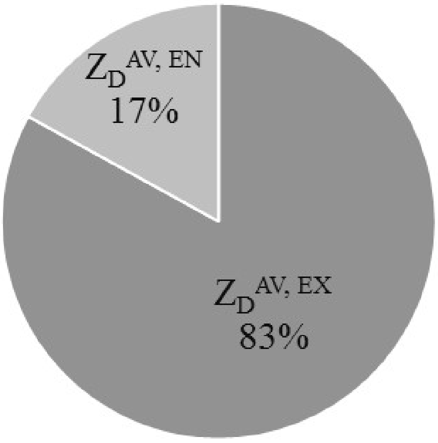

Figure 13 Avoidable Endogenous and Avoidable Exogenous investment cost rates of the CCPP

6 Conclusions

In this paper, we have evaluated the performance of a combined cycle power plant through advanced exergy/exergoeconomic analyses based on the real operating information. We have itemized some ultimate explanations as follows:

(a) The relations between the components are significantly week because the exogenous exergy destruction rate and its related cost rate of the whole cycle are only 7% and 14% of the total exergy destruction rate and the total exergy destruction cost rate, respectively.

(b) Avoidable exergy destruction of the overall system and its related cost rate is 14% and 15% respectively, that means system's improvement potential and its related cost rate is very low.

(c) The improvement potential for the investment flow rate of the system is weak because 75% of them are unavoidable.

(d) Advanced exergy/exergoeconomic analyses of the system determined that one should focus on the DB and ST for potentials of improving the system and related exergy destruction cost rates, which are the most important components of the system.

(e) The improvement potential for the investment flow rate of the LP.EVA and the GT is high because 41% and 36% of the total avoidable investment cost rate of the system are associated with them, respectively.

(f) This paper also obviously specifies that conventional exergy/exergoeconomic analyses are not sufficient to estimate an energy conversion system and it is suggested to perform advanced based exergoenvironmental analyses.

References

[1] Carapellucci, R., and Milazzo, A., "Repowering Combined Cycle Power Plants by a Modified STIG Configuration", Energy Conversion and Management, Vol. 48, pp. 1590-1600, (2007).

[2] Marrero, I.O., Lefsaker, A.M., Razani, A., and Kim, K.J., "Second Law Analysis and Optimization of a Combined Triple Power Cycle", Energy Conversion and Management, Vol. 43, pp. 557-573, (2002).

[3] Kaviri, A.G., Jaafar, M.N.M., and Lazim, T.M., "Modeling and Multi-objective Exergy Based Optimization of a Combined Cycle Power Plant using a Genetic Algorithm", Energy Conversion and Management, Vol. 58, pp. 94-103, (2012).

[4] Franco, A., and Russo, A., "Combined Cycle Plant Efficiency Increase Based on the Optimization of the Heat Recovery Steam Generator Operating Parameters", International Journal of Thermal Sciences, Vol. 41, pp. 843-859, (2002).

[5] Cihan, A., and Hacıhafızogˇlu, O., "Energy–exergy Analysis and Modernization Suggestions for a Combined-cycle Power Plant", International Journal of Energy Research, Vol. 30, pp. 115-126, (2006).

[6] Bassily, A.M., "Modeling, Numerical Optimization, and Irreversibility Reduction of a Triple-pressure Reheat Combined Cycle", Energy, Vol. 32, pp. 778-794, (2007).

[7] Sanjay, Y., Singh, O., and Prasad, B.N., "Energy and Exergy Analysis of Steam Cooled Reheat Gas–steam Combined Cycle", Applied Thermal Engineering, Vol. 27, pp. 2779-2790, (2007).

[8] Ameri, M., Ahmadi, P., and Khanmohammadi, S., "Exergy Analysis of a 420 MW Combined Cycle Power Plant", International Journal of Energy Research, Vol. 32, pp. 175-183, (2008).

[9] Ahmadi, P., and Dincer, I., "Thermodynamic Analysis and Thermoeconomic Optimization of a Dual Pressure Combined Cycle Power Plant with a Supplementary Firing Unit", Energy Conversion and Management, Vol. 52, pp. 2296-2308, (2011).

[10] Hajabdollahi, H., Ahmadi, P., and Dincer, I., "An Exergy-based Multi-objective Optimization of a Heat Recovery Steam Generator (HRSG) in a Combined Cycle Power Plant (CCPP) using Evolutionary Algorithm", International Journal of Green Energy, Vol. 8, pp. 44-64, (2011).

[11] Sanjay, Y., "Investigation of Effect of Variation of Cycle Parameters on Thermodynamic Performance of Gas-steam Combined Cycle", Energy, Vol. 36, pp. 157-167, (2011).

[12] Ibrahim, T.K., and Rahman, M.M., "Effect of Compression Ratio on Performance of Combined Cycle Gas Turbine", International Journal of Energy Engineering, Vol. 2, pp. 9-14, (2012).

[13] Tajik Mansouri, M., Ahmadi, P., and Kaviri, A.G., "Exergetic and Economic Evaluation of the Effect of HRSG Configurations on the Performance of Combined Cycle Power Plants", Energy Conversion and Management, Vol. 58, pp. 47-58, (2012).

[14] Ibrahim, T.K., and Rahman, M.M., "Study on Effective Parameter of the Triple-pressure Reheat Combined Cycle Performance", Thermal Science, Vol. 17, pp. 497-508, (2013).

[15] Kaviri, A.G., Jaafar, M.N.M., Lazim, T.M., and Barzegaravval, H., "Exergo Environmental Optimization of Heat Recovery Steam Generators in Combined Cycle Power Plant Through Energy and Exergy Analysis", Energy Conversion and Management, Vol. 67, pp. 27-33, (2013).

[16] Taghavi, M., Abdollahi, M., and Salehi, G., "Thermodynamic and Thermo Economic Optimization of Combined Cycle Power Plant", International Journal of Materials, Mechanics and Manufacturing, Vol. 1, pp. 186-190, (2013).

[17] Ghazi, M., Ahmadi, P., and Salehi, G.,"Modeling and Thermo-economic Optimization of Heat Recovery Heat Exchangers using a Multimodal Genetic Algorithm", Energy Conversion and Management, Vol. 58, pp. 149-156, (2012).

[18] Kotas, T.J., "The Exergy Method of Thermal Plant Analysis", Chemie Ingenieur Technik, Vol. 59, pp. 365-365, (1987).

[19] Yang, H., "Advanced Exergy Analysis for a Solar Double Stage Absorption Chiller", Dissertations, Doctoral Thesis, Dep. of Architecture, Carnegie Mellon University, Pennsylvania, United State, (2012).

[20] Petrakopoulou, F., "Comparative Evaluation of Power Plants with CO2 Capture: Thermodynamic, Economic and Environmental Performance", Berlin Technical University, Institut für Energietechnik, Doctoral Thesis, (2010).

[21] Açıkkalp, E., Aras, H., and Salehi, G., "Advanced Exergoeconomic Analysis of a Trigeneration System using a Diesel-gas Engine", Applied Thermal Engineering, Vol. 67, pp. 388-395, (2014).

[22] Tsatsaronis, G., "Recent Developments in Exergy Analysis and Exergoeconomics", International Journal of Exergy, Vol. 5, pp. 489-499, (2008).

[23] Morosuk, T., and Tsatsaronis, G., "Advanced Exergy Analysis for Chemically Reacting Systems–Application to a Simple Open Gas-turbine System", Institute of Marine Propulsion Plants Operation, Maritime Academy of Szczecin, Poland Institute for Energy Engineering, Technische Universität Berlin, Germany Int. J. of Thermodynamics, Vol. 12, pp. 105-111, (2009).

[24] Tsatsaronis, G., and Morosuk, T., "Understanding and Improving Energy Conversion Systems with the Aid of Exergy–based Methods", International Journal of Exergy, Vol. 11, pp. 518-542, (2012).

[25] Tsatsaronis, G., and Park, M. H., "On Avoidable and Unavoidable Exergy Destructions and Investment Costs in Thermal Systems", Energy Conversion and Management, Vol. 43, pp. 1259-1270, (2002).

[26] Morosuk, T., Tsatsaronis, G., and Schult, M., "Conventional and Advanced Exergetic Analyses: Theory and Application", Arabian Journal for Science and Engineering, Vol. 38, pp. 395-404, (2013).

[27] Kelly, S., Tsatsaronis, G., and Morosuk, T., "Advanced Exergetic Analysis: Approaches for Splitting the Exergy Destruction into Endogenous and Exogenous Parts", Energy, Vol. 34, pp. 384-391, (2009).

[28] Tsatsaronis, G., and Morosuk, T., "Advanced Exergetic Analysis of a Novel System for Generating Electricity and Vaporizing Liquefied Natural Gas", Energy, Vol. 35, pp. 820-829, (2010).

[29] Petrakopoulou, F., Tsatsaronis, G., and Morosuk, T., "Cost Reduction Strategies for an Oxy-fuel Power Plant with CO2 Capture: Application of an Advanced Exergoeconomic Analysis to an Advanced Zero Emission Plant", IMECE2011, Vol. 4, Energy Systems Analysis, Thermodynamics and Sustainability; Combustion Science and Engineering; Nanoengineering for Energy, Parts A and B Denver, Colorado, USA, November 11–17, (2011).

[30] Wang, L., Yang, Y., Morosuk, T., and Tsatsaronis G., "Advanced Thermodynamic Analysis and Evaluation of a Supercritical Power Plant", Energies, Vol. 5, pp. 1850-1863, (2012).

[31] Morosuk, T., Tsatsaronis, G., Boyano, A., and Gantiva, C., "Advanced Exergy-based Analyses Applied to a System Including LNG Regasification and Electricity

Generation", International Journal of Energy and Environmental Engineering, Vol. 3, pp. 1-9, (2012).

[32] Hepbasli, A., and Keçebaş, A., "A Comparative Study on Conventional and Advanced Exergetic Analyses of Geothermal District Heating Systems Based on Actual Operational Data", Energy and Buildings, Vol. 61, pp. 193-201, (2013).

[33] Keçebaş, A., and Hepbasli, A., "Conventional and Advanced Exergoeconomic Analyses of Geothermal District Heating Systems", Energy and Buildings, Vol. 69, pp. 434-441, (2014).

[34] Tan, M., and Keçebaş, A., "Thermodynamic and Economic Evaluations of a Geothermal District Heating System using Advanced Exergy-based Methods", Energy Conversion and Management, Vol. 77, pp. 504-513, (2014).

[35] Cziesla, F., Tsatsaronis, G., and Gao, Z., "Avoidable Thermodynamic Inefficiencies and Costs in an Externally Fired Combined Cycle Power Plant", Energy, Vol. 31, pp. 1472-1489, (2006).

[36] Petrakopoulou, F., Tsatsaronis, G., Morosuk, T., and Carassai, A., "Conventional and Advanced Exergetic Analyses Applied to a Combined Cycle Power Plant", Energy, Vol. 41, pp. 146-152, (2012).

[37] Petrakopoulou, F., Tsatsaronis, G., and Morosu, T., "Environmental Evaluation of a Power Plant using Conventional and Advanced Exergy-based Methods", Energy, Vol. 45, pp. 23-30, (2012).

[38] Soltani, S., Yari, M., Mahmoudi, S.M.S., and Morosuk, T., "Advanced Exergy Analysis Applied to an Externally-fired Combined-cycle Power Plant Integrated with a Biomass Gasification Unit", Energy, Vol. 59, pp. 775-780, (2013).

[39] Vučković, G.D., Stojiljković, M.M., and Vukić, M.V., "Advanced Exergy Analysis and Exergoeconomic Performance Evaluation of Thermal Processes in an Existing Industrial Plant", Energy Conversion and Management", Vol. 85, pp. 655-662, (2014).

[40] Açıkkalp, E., Aras, H., and Hepbasli, A., "Advanced Exergy Analysis of an Electricity-Generating Facility using Natural Gas", Energy Conversion and Management, Vol. 82, pp. 146-153, (2014).

[41] Açıkkalp, E., Aras, H., and Hepbasli, A., "Advanced Exergoeconomic Analysis of an Electricity-generating Facility that Operates with Natural Gas", Energy Conversion and Management, Vol. 78, pp. 452-460, (2014).

[42] Dincer, I., and Rosen, M., "*Exergy Energy, Environment, and Sustainable Development*", Elsevier, Amsterdam, London, (2007).

[43] Rosen, M.A., and Dincer, I., "Thermoeconomic Analysis of Power Plants: An Application to a Coal Fired Electrical Generating Station", Energy Conversion and Management, Vol. 44, pp. 2743-2761, (2003).

[44] Bejan, A., and Tsatsaronis, G., "*Thermal Design and Optimization*", John Wily & Sons, New York, (1996).

[45] Tsatsaronis, G., and Winhold, M., "Exergoeconomic Analysis and Evaluation of Energy-conversion Plants-I. A New General Methodology", Energy, Vol. 10, pp. 69-80, (1985).

[46] Lazzaretto, A., and Tsatsaronis, G., "SPECO: A Systematic and General Methodology for Calculating Efficiencies and Costs in Thermal Systems", Energy, Vol. 31, pp. 1257-1289, (2006).

[47] Petrakopoulou, F., Boyano, A., and Cabrera, M., "Exergoeconomic and Exergo-environmental Analyses of a Combined Cycle Power Plant with Chemical Looping Technology", International Journal of Greenhouse Gas Control, Vol. 5, pp. 475-482, (2011).

[48] Phil, M., and Kelly, S., "Energy Systems Improvement Based on Endogenous and Exogenous Exergy Destruction",Technische Universität Berlin, Doctoral Thesis, (2008).

[49] Morosuk, T., and Tsatsaronis, G., "A New Approach to the Exergy Analysis of Absorption Refrigeration Machines", Energy, Vol. 33, pp. 890-907, (2008).

[50] Morosuk, T., and Tsatsaronis, G., "Advanced Exergetic Evaluation of Refrigeration Machines using Different Working Fluids", Energy, Vol. 34, pp. 2248-2258, (2009).

Nomenclature

$\dot{E}$	Exergy rate (kW)
c	Unit exergy cost ($/MWh)
$\dot{C}$	Exergy cost rate ($/h)
f	Exergoeconomic factor
$\dot{m}$	Mass flow rate (kg/s)
y	Exergy destruction ratio
P	Pressure (kPa)
r	Relative cost difference
T	Temperature (K)
$\dot{Z}$	Capital investment cost flow rate ($/h)

Abbreviations

AC	air compressor
ACC	air-cooled condenser
BFP	boiler feed water pump
CC	combustion chamber
CCPP	combined cycle power plant
CEP	condensate extraction pump
CPH	condensate preheater
DB	duct burner
DEA	deaerator
ECO	economizer

EVA	evaporator
GT	Gas turbine
HP	high pressure
LHV	low heating value
LP	Low pressure
SPH	super heater

Superscripts

AV	avoidable
EN	endogenous
EX	exogenous
Real	real condition
Theory	theoretical condition
UN	unavoidable

Subscripts

app	approach point
ch	chemical
D	destruction
e	outlet
ex	exergy
F	fuel
i	inlet
is	isentropic
k	kth component
L	loss
mech	mechanical
n	nominal
P	product
ph	physical
pp	pinch point
th	thermal
tot	total
0	ambient conditions

Greek letters

η	Efficiency (%)

چکیده

در این پژوهش یک سیکل ترکیبی واقع در زواره، ایران با استفاده از تحلیل پیشرفته اگزرژی و اگزرژواکونومیک مورد ارزیابی قرار گرفته است.

هدف از این پژوهش ارزیابی برگشت ناپذیریها، نرخ هزینه های قابل اجتناب مربوط به آنها در هر قسمت از سیکل و برگشت ناپذیریهای ناشی از تعاملات سایر المانها با المان مربوطه می باشد. تحلیل اگزرژی و اگزرژواکونومیک نشان می دهد که بیشترین تخریب اگزرژی و نرخهای هزینه مربوط به آنها در محفظه های احتراق و مولدهای بخار بازیاب حرارتی اتفاق می افتد.

بنابراین لازم است توجه ویژه ای جهت بهبود عملکرد این دو المان نسبت به اثر سایر المانها صورت گیرد. نتایج نشان می دهد که پتانسیل بهبود کل سیستم و نرخ هزینه مربوط به آن پایین و به ترتیب حدود ۱۴٪ و ۱۵٪ است. همچنین پتانسیل بهبود نرخ جریان هزینه سرمایه گذاری سیستم بعلت سهم بالای بخش غیر قابل اجتناب که حدود ۷۵٪ می باشد، بسیار پایین است.