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Performance assessment and system optimization of a combined cycle power plant (CCPP) based on exergoeconomic and exergoenvironmental analyses

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Abstract−We propose a systematic approach for performance evaluation and improvement of a combined cycle power plant (CCPP). Exergoeconomic and exergoenvironmental analyses are used to assess CCPP performance and suggest improvement potentials in economic and environmental aspects, respectively. Economic and environmental impacts of individual system components are calculated by cost functions and life cycle assessments. Both analyses are based on a CCPP case study located in Turkey, which consists of two gas turbine cycles and a steam turbine cycle with two different pressure heat recovery units. The results of the exergoeconomic analysis indicate that the combustion chamber and condenser have a high performance improvement potential by increasing capital cost. Furthermore, the exergoenvironmental analysis shows that the exergy destruction of the steam turbine and combustion chamber and/or the capacity of heat recovery units must be reduced in order to improve environmental performance. This study demonstrates that combined exergoeconomic and exergoenvironmental analyses are useful for finding improvement potentials for system optimization by simultaneously evaluating economic and environmental impacts.

Keywords: Life Cycle Assessment (LCA), Combined Cycle Power Plant (CCPP), Exergoeconomic, Exergoenvironmental, Improvement Potential

INTRODUCTION

The efficient use of energy resources has become a prominent issue due to the continuously increasing world population and rapid industrialization rate [1,2]. Several different types of power plants have been developed, but most have a low thermodynamic efficiency as a result of substantial heat losses during power generation. For this reason, particular attention has been paid to combined cycle power plants (CCPP) due to their higher thermal efficiency compared to power plants with separate steam and gas turbine cycles [3].

CCPPs use two power generation cycles, where the heat loss of one is used as the heat source of the other, leading to increased thermodynamic efficiency over single power generation cycles [1]. Exergy analysis is a powerful and efficient tool for evaluating and optimizing CCPP performance that has been carried out by many researchers [4]. Ameri et al. [5] conducted exergy analysis of each component of a CCPP in the northern part of Iran, and presented the first law efficiency, exergy efficiency, and exergy losses. Their results indicated that the components with the highest irreversibility (in descending order) are the combustion chamber, heat recovery steam generator (HRSG), gas turbine, and duct burner. Boyaghchi and Molaie [6] implemented an advanced exergy analysis to improve the design and operation of a real CCPP. A parametric analysis was also conducted to determine the sensitivity of the exergy efficiency and exergy loss to the turbine inlet temperature and the compressor pressure ratio. Sharma and Singh [7] performed an exergy analysis of a dual-pressure HRSG in a CCPP at Auraiya, India, and calculated the exergy loss and exergy efficiency at various dead-state temperatures. Their results showed that the high-pressure evaporator has the greatest irreversibility at various steam generation pressures and at elevated dead-state temperatures.

Economic and environmental assessments have also received increasing attention. Lee et al. [8] conducted an economic analysis of a commercial-scale coal-fired power plant equipped with a post-combustion CO_2 capture system (CCS). Their results showed that the levelized cost of electricity of a commercial-scale USC power plant with CCS will increase from 47 to 68 USD/tCO_2, and that the CO_2 cost which can be saved is 33 USD/tCO_2. Using life cycle assessment (LCA), Rasid et al. [9] concluded that palm bio-oil can be used in place of fossil fuels in future power plants since the production of palm bio-oil carries no negative environmental impacts.

It is possible to combine economic and environmental assessments with thermodynamic principles. Exergoeconomic analysis considers thermodynamic and economic principles simultaneously to provide performance information on cost-effective energy conversion systems [10]. The cost of the entire process is obtained by assigning a cost to all of the exergy streams in the system [11]. Similarly, exergoenvironmental analysis combines the principles of thermodynamics and LCA in order to obtain environmental information on energy conversion systems. In this case, LCA is used to assign an environmental impact to all of the exergy streams in the

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system [12]. Bagherneiad and Yahoubi [13] performed an exergoeconomic analysis to optimize an integrated solar combined cycle system by considering the investment cost of components and the cost of exergy destruction, which resulted in a 7.1% and 1.17% reduction in the cost of electricity produced in steam turbine and gas turbine cycles, respectively. Ahmadi and Dincer [14] conducted a thermodynamic analysis and thermoeconomic optimization of a dual-pressure CCPP, using a genetic algorithm to minimize the total cost of the plant. Their results indicate that the greatest performance improvements could come from improving the efficiency of the turbine and increasing the cost of fuel. Kelly et al. [15] analyzed an industrial combined heat and power plant using life cycle assessment (LCA) and presented its energy demand and global warming potential over a 30-year lifetime. Boyano et al. [16] conducted an exergoenvironmental analysis of a hydrogen production process using a steam reforming reactor, and based on the results were able to suggest some improvements for its design. Ganjehkaviri et al. [17] modeled a CCPP using combined exergoeconomic and environmental analyses to calculate the costs of electricity and exergy destruction, sustainability, carbon dioxide emission, and fuel consumption, and improved exergy efficiency by 6% and reduced CO_2 emission by 5.63%. Oyedepo et al. [18] presented a thermoeconomic and thermoenvironmental analysis of a gas turbine power plant in Nigeria, finding that a decrease of exergy destruction in the combustion chamber and an increase of the gas turbine inlet temperature would reduce the cost of exergy destruction, CO_2 emission, and overall environmental impact. Recent research efforts have focused on either exergoeconomic or exergoenvironmental analyses of CCPPs, but few researchers have carried out both simultaneously.

Ersayin and Ozgener [1] suggested the improvement and modification method for ATAER energy power plant located in Turkey by applying the energy and exergy analyses. They concluded that the improvement of heat transfer rate between the turbine and outside environment can minimize the energy and exergy losses of the power production components. Also, they propounded the adjustment of air-fuel ratio of combustion, reduction of excess air to decrease the losses of energy and exergy in a combustion chamber and suggested a redesigning of heat insulation system [1]. However, these suggestions focus on the improvement of the operational performance of CCPP without considering the economic and environmental aspects. Note that additional amount of energy cost is required and also additional pollutants are emitted to improve the performance of CCPP, which was interested in only the performance improvement without the systematic approach and may result in unsatisfactory environmental effect. Therefore, the suggestion for performance improvement and practical modified designing in a CCPP needs to be developed considering the economic and environmental analyses, where exergoeconomic and exergoenvironmental analyses of a real CCPP can be used as energy and exergy analyses.

This study proposes a systematic approach for finding improvement potentials of a real CCPP by the simultaneous exergoeconomic and exergoenvironmental analyses of energy system components. The exergoeconomic analysis calculates the total cost of the CCPP with the economic impact of each component and also evaluates the potential of economic improvement of each energy system component. Similarly, the exergoenvironmental analysis provides total environmental impact with environmental impact of each component and also evaluates the potential of the environmental improvement of each energy system component.

It has been well known that parameters such as natural gas price, interest rate, and capacity and efficiency of each component of energy system have significant influences on the total cost and the environmental impact [15]. It is important to evaluate the influence of sensitive parameters on the exergoeconomic and exergoenvironmental analyses checking the improvement potentials of CCPP with the economic and environmental impact. Therefore, the second contribution of this study is to evaluate the effects of the key parameters on the exergoeconomic and exergoenvironmental analyses using a sensitivity analysis, where the most influential parameters on the economic and environmental aspect of CCPP are determined.

This study consists of three major parts. First, exergoeconomic and exergoenvironmental analyses are conducted to investigate the cost flow and environmental impacts of the each stream in CCPP. Second, guidelines to the improvement of CCPP performance are suggested based on the results of the exergoeconomic and exergoenvironmental analyses. Third, a sensitivity analysis on the exergoeconomic and exergoenvironmental parameters is carried out and the effects of key parameters are evaluated.

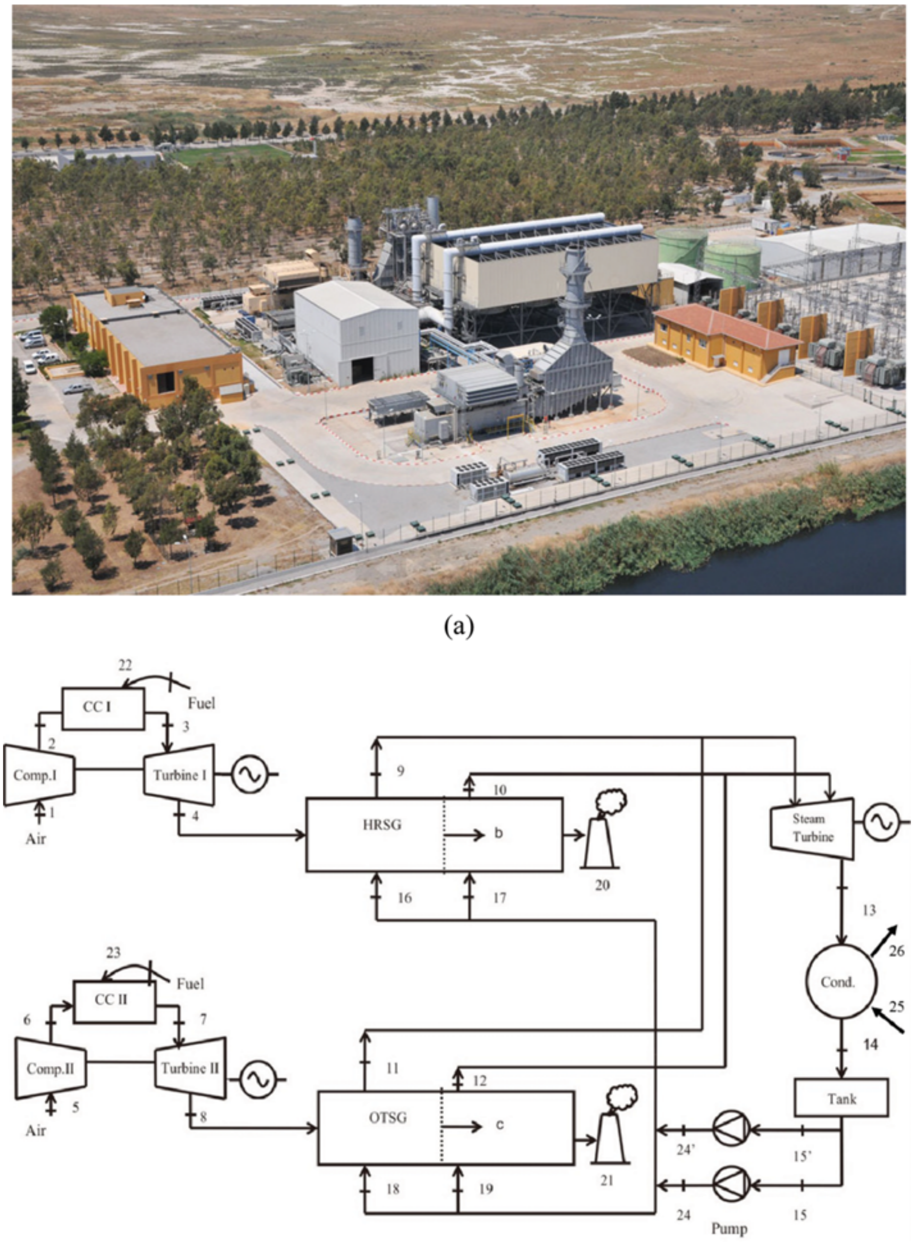
MATERIALS AND METHODS

1. Description of a CCPP

Fig. 1(a) shows a panorama and Fig. 1(b) shows an overall block diagram of the ATAER Energy Power Plant located in the Izmir Atatürk Industrial Zone in Turkey. The ATAER Energy Power Plant consists of three major parts. The first part contains two gas turbines where ambient air is compressed by a compressor. The compressed air is then sent to the combustion chamber where natural gas is injected. After the combustion reaction, high-temperature combustion gas passes through the gas turbine and generates 50 MW of nominal power while the expanded gas temperature decreases to 460 °C. The second major part contains heat recovery systems which are used to increase the efficiency of the power plant. Two types of heat recovery systems are used, including the heat recovery steam generator (HRSG) and the once-through steam generator (OTSG). The difference between these two is that the HRSG has a drum which saves the produced steam while the OTSG does not. In this part, the exhaust gas of gas turbines is used as a heat source to produce 114 t/h of steam at high pressure (5 MPa) and low pressure (0.5 MPa). The third part is the steam turbine which is operated by steam generated by the heat recovery systems. The steam turbine generates 24 MW of power using both high-pressure and low-pressure-generated steam. The thermodynamic properties of the ATAER power plant and the energy and exergy simulation results used in this study are presented in Tables 1 and 2 [1].

2. Exergoeconomic Analysis of a CCPP

The cost exergy unit of the product streams was investigated using cost formation equations [19]. To calculate the cost per



(a) (b)

Fig. 1. (a) Panorama of the ATAER power plant, (b) schematic diagram of the ATAER power plant [1].

exergy rate (or cost flow rate) of each stream, a cost balance equation with terms describing the cost flow rate of input and output streams, the required heat, the output work of the shaft, and the cost flow rate associated with capital investment, operation, and maintenance, was used. Eqs. (1) to (6) present the exergoeconomic formulation. The cost balance of component k is given by Eq. (1) [20]:

$$\sum \dot{C}_{out,\,k} + \dot{C}_{w,\,k} = \sum \dot{C}_{in,\,k} + \dot{C}_{q,\,k} + \dot{Z}_k \tag{1}$$

where k is a component index, $\dot{C}_{in}$ and $\dot{C}_{out}$ are the cost rates of input and output streams, respectively, $\dot{C}_w$ is the cost flow rate of work produced by the component, $\dot{C}_q$ is the cost flow rate of required heat, and $\dot{Z}$ is the sum of capital investment, operation, and maintenance costs. Each of the cost flow rates presented in Eq. (1) are calculated using Eq. (2):

$$\dot{C}_i = c_i \cdot \dot{m}_i \cdot e_i \tag{2}$$

where c_i is the cost per exergy of each of the streams.

$\dot{Z}$ in Eq. (1) is obtained from Eq. (3) as follows [20]:

$$\dot{Z}_k = \dot{Z}_k^{CI} + \dot{Z}_k^{OM} \tag{3}$$

where $\dot{Z}_k^{CI}$ is the capital investment of the k^{th} component and $\dot{Z}_k^{OM}$ is the operation and maintenance cost of the k^{th} component. The capital investment is calculated using Eq. (4)

$$\dot{Z}_k^{CI} = \left(\frac{CRF}{\tau}\right) \cdot Z_k \tag{4}$$

Table 1. Thermodynamic properties and energy and exergy data for the ATAER power plant [1]

Point	Type of stream	Temperature (°C)	Pressure (bar)	Mass flow rate (kg/s)	Enthalpy (kJ/kg)	Entropy (kJ/kg K)	Specific exergy (kJ/kg)	Exergy rate (kW)
0	Dead state	25	1.013	-	-	-	-	-
1	Air	12.2	1.01325	151.4	285.3	5.65	0.2148	57.03
2	Air	506.6	30.7	151.4	799.8	5.71	505.2	72263.42
3	Combustion gas	862	30.7	153.3	1333.5	8.41	708.1	126207.3
4	Combustion gas	463	1.01325	153.3	787.2	7.69	168.8	31322.3
5	Air	12.2	1.01325	151.4	285.3	5.65	0.2148	57.03
6	Air	506.6	30.7	151.4	799.8	5.71	505.2	72263.42
7	Combustion gas	862	30.7	153.3	1333.5	8.41	708.1	126207.3
8	Combustion gas	463	1.01325	153.3	787.2	7.69	168.8	31322.3
9	Steam	426	49.2	11.9	3260	6.747	1319	14920.81
10	Steam	226	5.3	3.8	2909	7.143	853.5	2981.1
11	Steam	430	50.07	11.7	3268	6.751	1326	15514.2
12	Steam	225	5.44	3.72	2906	7.126	855.8	3183.57
13	Water	41.3	0.1	31.12	2310.2	0.5896	4.72	3760
14	Water	39.2	0.1	31.12	164.2	0.5616	4.01	124.79
15	Water	39.2	0.1	15.42	164.2	0.5616	1.28	19.73
16	Water	135	49.2	11.9	168.6	0.5597	73.82	878.45
17	Water	39.2	5.3	3.8	164.6	0.5614	4.54	17.25
18	Water	133	50.07	11.7	168.6	0.5597	71.54	837.01
19	Water	39.2	5.44	3.72	164.6	0.5614	4.54	16.88
20	Flue gas	129	1.01325	153.3	403.86	7.22	15.64	4979.4
21	Flue gas	129	1.01325	153.3	403.86	7.22	15.64	4979.4
22	Natural gas	12.2	43	2.13	44000	-	46640	109596.7
23	Natural gas	12.2	43	2.13	44000	-	46640	109596.7
24	Water	41.3	5.3	15.42	173.4	0.5621	2.228	34.35

Table 2. Exergy destruction rate of ATAER power plant components [1]

Equipment	Exergy destruction rate (kW)
Compressor	3,925.61
Combustion chamber	65,962
Gas turbine	11,100
Heat recovery unit	7,971.75
Steam turbine	6,004
Condenser	22.1

where τ is the annual plant operation time, CRF is the capital recovery factor, and Z_k is the capital investment cost for each component. The CRF is calculated using Eq. (5):

$$\mathrm{CRF} = \frac{i_r(1+i_r)^n}{(1+i_r)^n - 1} \tag{5}$$

where i_r is the interest rate and n is the number of operation years.

The operation and maintenance costs are calculated using Eq. (6):

$$\dot{Z}_k^{OM} = \frac{\gamma_k \cdot Z_k}{\tau} \tag{6}$$

where γ_k is maintenance factor [21] and Z_k is the capital cost of the k^{th} component, which is calculated from the cost function given in Table 3 [22,23].

In the cost balance equation, Eq. (1), there is usually more than one inlet-outlet stream, so auxiliary thermodynamic equations are formulated by applying F and P principles based on a specific exergy cost method (SPECO) [24]. According to the F principle, exergy streams associated with the reduction of exergy through the component are defined as fuel streams. Similarly, the P principle defines the product as the sum of all exergy values at the outlet plus all of the increases in exergy between the inlet and outlet. Thus all streams in a CCPP are divided into fuel and product streams. The resulting cost balances and required auxiliary equations for each component are given in Table 4.

The cost balances in Table 4 are solved by the Engineer Equation Solver (EES) program, (version 8.4) to obtain the unit exergy cost of all exergy streams in the system. The natural gas cost (c_{22}, c_{23}) is considered as 4.37 $/GJ [25]. Exergoeconomic variables are used to evaluate the exergoeconomic performance and improvement potentials [19]. Exergoeconomic variables including the average unit cost of fuel, the average unit cost of product, the cost rate of exergy destruction, the cost rate of exergy loss, the relative cost difference, and exergoeconomic factor are given by Eqs. (7) to (12) as follows:

$$c_{F,k} = \frac{\dot{C}_{F,k}}{\dot{E}_{F,k}} \tag{7}$$

Table 3. Capital investment function for CCPP components [22,23]

No.	Component of system	Capital investment cost function	Remark	Reference
1	Air compressor (AC)	$Z_{AC}=44.71\cdot\dot{m}_{air}\cdot\frac{1}{0.95-\eta_C}\cdot r_p\cdot\ln(r_p)$	Z_{AC}: Capital investment of air compressor $\dot{m}_{air}$: Air flow rate η_C: Air compressor efficiency r_p: Pressure ratio in air compressor	[22]
2	Combustion chamber (CC)	$Z_{CC}=28.98\cdot\dot{m}_{air}\cdot(1+e^{0.015\cdot(T_{out}-1540K)})$	Z_{CC}: Capital investment of combustion chamber T_{out}: Temperature of outlet gas	[22]
3	Gas turbine (GT)	$Z_{GT}=301.45\cdot\dot{m}_{gas}\cdot\frac{1}{0.94\ -\ \eta_{GT}}\cdot$ $\ln\left(\frac{P_{in}}{P_{out}}\right)\cdot(1+e^{0.025\cdot(T_{in}-1570K)})$	Z_{GT}: Capital investment of gas turbine $\dot{m}_{gas}$: Combustion gas flow rate η_{GT}: Gas turbine efficiency P_{in} and T_{in}: Pressure and temperature of inlet flow P_{out}: Pressure of outlet flow	[22]
4	Pump	$Z_{pump}=308.9\cdot\dot{W}_{pump}^{C_{pump}}$	Z_{pump}: Capital investment of pump $\dot{W}_{pump}$: Power consumption of pump C_{pump}: 0.45 (If $0.3\le\dot{W}_{pump}\le20$)	[23]
5	Steam turbine (ST)	$Z_{ST}=3880.5\cdot P_{ST}^{0.7}\left(1+\left(\frac{0.05}{1-\eta_{ST}}\right)^3\right)\cdot$ $\left(1+5\cdot\exp\left(\frac{T_{in}-866K}{10.42K}\right)\right)$	Z_{ST}: Capital investment of steam turbine P_{ST}: Power generation of steam turbine η_{ST}: Steam turbine efficiency	[22]
6	Condenser (Cond)	$Z_{Cond}=Z_{R.Cond}\cdot\left(\frac{A_k}{A_R}\right)^{0.6}$ $A_k=\frac{Q_k}{U_k\cdot LMTD_k}$, $LMTD_k=\frac{(T_{h,i}-T_{c,i})-(T_{h,e}-T_{c,e})}{\ln\frac{T_{h,i}-T_{c,i}}{T_{h,e}-T_{c,e}}}$	Z_{Cond}: Capital investment of condenser $Z_{R.Cond}$: Reference cost of condenser in reference year A_k: The heat transfer area of component k A_R: Reference heat transfer area Q_k: Heat transfer flow through the component U_k: Heat transfer coefficient (=1 kW/m^{2}K) $LMTD_k$: Logarithmic mean temperature difference h and c: hot and cold streams i and e: inlet and outlet streams	[23]
7	Heat recovery steam generator	$Z_{HRSG}=4131.8\cdot\sum_i\left(f_{p,i}\cdot f_{T,steam,i}\cdot f_{T,gas,i}\cdot\left(\frac{\dot{Q}_i}{\Delta T_{ln,i}}\right)^{0.8}\right)$ $+13380\cdot\sum_j f_{p,j}\cdot\dot{m}_{stream,j}+1489.7\cdot\dot{m}_{gas}^{1.2}$ $f_{p,j}=0.0971\cdot\frac{p_j}{30\ bar}+0.9029$ $f_{T,stream,i}=1+\exp\left(\frac{T_{out,stream,i}-830K}{500K}\right)$ $f_{T'''gas,i}=1+\exp\left(\frac{T_{out,gas,i}-990K}{500K}\right)$	Z_{HRSG}: Capital investment of HRSG $\dot{Q}_i$: Heat transfer rate of HRSG $\Delta T_{ln,i}$: Logarithmic mean temperature difference $f_{p,i}$: Conversion factor of gas pressure $f_{T,stream,i}$: Conversion factor of out stream temperature $f_{T,gas,i}$: Conversion factor of out gas temperature	[22]

$$c_{p,k}=\frac{\dot{C}_{p,k}}{\dot{E}_{p,k}} \tag{8}$$

$$\dot{C}_{D,k}=c_{F,k}\cdot\dot{E}_{D,k} \tag{9}$$

$$\dot{C}_{L,k}=c_{F,k}\cdot\dot{E}_{L,k} \tag{10}$$

$$r_k=\frac{c_{p,k}-c_{F,k}}{c_{F,k}}=\frac{\dot{C}_{D,k}+\dot{Z}_k}{c_{F,k}\cdot\dot{E}_{p,k}}=\frac{1-\varepsilon_k}{\varepsilon_k}+\frac{\dot{Z}_k}{c_{F,k}\cdot\dot{E}_{p,k}} \tag{11}$$

$$f_k=\frac{\dot{Z}_k}{\dot{Z}_k+(\dot{C}_{D,k}+\dot{C}_{L,k})} \tag{12}$$

where k, F, P and D represent the component index, fuel stream, product stream, and exergy destruction, respectively.

3. Exergoenvironmental Analysis of a CCPP

Exergoenvironmental analysis is used to determine the extent to which each component of a system is responsible for the overall environmental impact and identify the greatest sources of the impact. Exergoenvironmental analysis consists of three steps: exergy analysis, LCA, and the assignment of environmental impacts to exergy streams in the system [12].

Step 1 - Exergy analysis

The results of exergy analysis driven by Ersayin and Ozgener [1] presented in Table 1 were used as the first step of exergoenvironmental analysis.

Table 4. Cost balance and auxiliary equations of CCPP components

Components	Cost balance and auxiliary equation	Components	Cost balance and auxiliary equation
Air	$c_1=c_5=c_{25}=0$	Heat recovery steam generator	$\dot{C}_4+\dot{C}_{16+17}+\dot{Z}_{HRSG}=\dot{C}_{20}+\dot{C}_{9+10}$ $c_{20}=c_4$, $c_9=c_{10}=c_{9+10}$ $c_{18}=c_{19}=c_{18+19}$
Compressor I	$\dot{C}_1+\dot{Z}_{comp}+\dot{C}_{w,\,comp}=\dot{C}_2$	Once through steam generator	$\dot{C}_8+\dot{C}_{18+19}+\dot{Z}_{OTSG}=\dot{C}_{21}+\dot{C}_{11+12}$ $c_{21}=c_8$, $c_{16}=c_{17}=c_{16+17}$ $c_{11}=c_{12}=c_{11+12}$
Combustion chamber I	$\dot{C}_2+\dot{C}_{22}+\dot{Z}_{cc}=\dot{C}_3$		
Gas turbine I	$\dot{C}_3+\dot{Z}_{GT}=\dot{C}_4+\dot{C}_{w,\,comp}+\dot{C}_{w,\,GT_{net}}$ $c_3=c_4$, $c_{comp.I}=c_{GT.I}$	Steam turbine	$\dot{C}_{9+10}+\dot{C}_{11+12}+\dot{Z}_{ST}=\dot{C}_{13}+\dot{C}_{w,\,ST}+\dot{C}_{w,\,pump}$ $c_{9+10}=c_{13}$
Compressor II	$\dot{C}_5+\dot{Z}_{comp}+\dot{C}_{w,\,comp}=\dot{C}_6$	Condenser	$\dot{C}_{13}+\dot{C}_{25}+\dot{Z}_{cond}=\dot{C}_{14}+\dot{C}_{26}$ $c_{13}=c_{14}$
Combustion chamber II	$\dot{C}_6+\dot{C}_{23}+\dot{Z}_{cc}=\dot{C}_7$	Tank	$c_{14}=c_{15}$
Gas turbine II	$\dot{C}_7+\dot{Z}_{GT}=\dot{C}_8+\dot{C}_{w,\,comp}+\dot{C}_{w,\,GT_{net}}$ $c_7=c_8$, $c_{comp.II}=c_{GT.II}$	Pump	$\dot{C}_{15}+\dot{Z}_{Pump}+\dot{C}_{w,\,pump}=\dot{C}_{24}$ $c_{24}=c_{16+17}$

Remark

i: The stream number in Fig. 1(b)
c_i: The cost per exergy of the i^{th} stream
$\dot{C}_i$: The cost flow rate of the i^{th} stream
$\dot{Z}_k$: The combination of capital investment, operation cost, and maintenance cost for the k^{th} component
$\dot{C}_{w,\,comp}+\dot{C}_{w,\,GT_{net}}$: The cost flow rate of work produced by gas turbine
$\dot{C}_{w,\,comp}$: The cost flow rate of work required for compressor
$\dot{C}_{w,\,ST}+\dot{C}_{w,\,pump}$: The cost flow rate of work produced by steam turbine
$\dot{C}_{w,\,pump}$: The cost flow rate of work required for pump

Step 2 - Life cycle assessment (LCA)

LCA is a method to evaluate the environmental impacts associated with a product over its entire life cycle. According to the International Standardization Organization (ISO), LCA consists of goal and scope definition, inventory analysis, impact assessment, and interpretation. Energy and mass obtained by physical laws for streams and materials referred in the literature for each CCPP component are considered in the inventory analysis [15]. The CML2002 method proposed by Centre of Environmental Science - Leiden University (CML), Leiden in Netherlands was used to assess quantitative impact using normalization and weighting. Abiotic depletion, acidification, eutrophication, fresh-water aquatic eco-toxicity, global warming, human toxicity, marine aquatic eco-toxicity, ozone depletion, photochemical ozone creation, and terrestrial ecotoxicity potential [26] are impact categories which have been included in the CML method. Results for each of the ten categories are obtained by classification, characterization, normalization, and weighting.

Step 3 - Assignment of environmental impact to exergy streams

Assignment of LCA results to exergy streams is carried out in analogy to the assignment of costs to exergy streams in exergoeconomics [22,27]. The environmental impact rate of stream j, $\dot{B}_j$, is calculated using Eq. (13):

$$\dot{B}_j=\dot{E}_j b_j \tag{13}$$

where $\dot{B}_j$ is the environmental impact expressed in a weighted value of LCA per time unit (mPt/s), b_j is the specific environmental impact which is the environmental impact per unit of exergy for the j^{th} stream (mPt/GJ), and $\dot{E}_j$ is exergy rate of the product (GJ exergy/s).

The environmental impact $\dot{Y}_k$ associated with the life cycle of the k^{th} component including construction ($\dot{Y}_k^{CO}$), operation and maintenance ($\dot{Y}_k^{OM}$), and disposal ($\dot{Y}_k^{DI}$), is given by Eq. (14) [12]:

$$\dot{Y}_k=\dot{Y}_k^{CO}+\dot{Y}_k^{OM}+\dot{Y}_k^{DI} \tag{14}$$

The environmental impact balance for the k^{th} component with n inlet streams and m outlet streams is given by Eqs. (15) and (16):

$$\sum_{j=1}^{m}\dot{B}_{j,\,k,\,out}=\sum_{j=1}^{n}\dot{B}_{j,\,k,\,in}+\dot{Y}_k \tag{15}$$

$$\sum_{j=1}^{m}(b_j\cdot\dot{E})_{j,\,k,\,out}=\sum_{j=1}^{n}(b_j\cdot\dot{E})_{j,\,k,\,in}+\dot{Y}_k \tag{16}$$

The reason for calculating the environmental impact balance is to obtain the environmental impact rate $\dot{B}_j$ and the specific environmental impact b_j. In general, the number of required auxiliary equations is equal to the number of streams minus the number of environmental impact balance equations. Auxiliary equations are formulated according to the F and P principles presented in section 2 - materials and methods [22]. The environmental impact balance and auxiliary equations used in this study are shown in Table 5. To obtain the value of $\dot{Y}_k$, the life cycle inventory data for the k^{th} component presented by Kelly et al. [15] is used. To get the values of $\dot{B}_j$, the environmental impact balance is also solved by the Engineer Equation Solver (EES) program. Based on Eq. (13), the specific environmental impact b_j is calculated using the obtained value of $\dot{B}_j$ and the exergy rate $\dot{E}_j$ listed in Table 1 [1].

Exergoenvironmental variables including the specific environmental impact of fuel and product, environmental impact of exergy destruction, total environmental impact associated with a component, relative difference of specific environmental impacts, and exergoenvironmental factors are used to evaluate the environmental performance of the system components as follows.

- *Specific environmental impact of fuel and product*

The average specific environmental impacts of product and fuel for the k^{th} component are calculated using Eqs. (17) and (18), respec-

Table 5. Environmental impact balance and auxiliary equations of CCPP components

Components	Cost balance and auxiliary equation	Components	Cost balance and auxiliary equation
Air	$b_1=b_5=b_{25}=0$	Heat recovery steam generator	$\dot{B}_4+\dot{B}_{16+17}+\dot{Y}_{HRSG}=\dot{B}_{20}+\dot{B}_{9+10}$ $b_{20}=b_4$, $b_9=b_{10}=b_{9+10}$ $b_{18}=b_{19}=b_{18+19}$
Compressor I	$\dot{B}_1+\dot{Y}_{comp}+\dot{B}_{w,\,comp}=\dot{B}_2$	Once through steam generator	$\dot{B}_8+\dot{B}_{18+19}+\dot{Y}_{OTSG}=\dot{B}_{21}+\dot{B}_{11+12}$ $b_{21}=b_8$, $b_{16}=b_{17}=b_{16+17}$ $b_{11}=b_{12}=b_{11+12}$
Combustion chamber I	$\dot{B}_2+\dot{B}_{22}+\dot{Y}_{cc}=\dot{B}_3$		
Gas turbine I	$\dot{B}_3+\dot{Y}_{GT}=\dot{B}_4+\dot{B}_{w,\,comp}+\dot{B}_{w,\,GT_{net}}$ $b_3=b_4$, $b_{comp.I}=b_{GT.I}$	Steam turbine	$\dot{B}_{9+10}+\dot{B}_{11+12}+\dot{Y}_{ST}=\dot{B}_{13}+\dot{B}_{w,\,ST}+\dot{B}_{w,\,pump}$ $b_{9+10}=b_{13}$
Compressor II	$\dot{B}_5+\dot{Y}_{comp}+\dot{B}_{w,\,comp}=\dot{B}_6$	Condenser	$\dot{B}_{13}+\dot{B}_{25}+\dot{Y}_{cond}=\dot{B}_{14}+\dot{B}_{26}$ $b_{13}=b_{14}$
Combustion chamber II	$\dot{B}_6+\dot{B}_{23}+\dot{Y}_{cc}=\dot{B}_7$	Tank	$b_{14}=b_{15}$
Gas turbine II	$\dot{B}_7+\dot{Y}_{GT}=\dot{B}_8+\dot{B}_{w,\,comp}+\dot{B}_{w,\,GT_{net}}$ $b_7=b_8$, $b_{comp.II}=b_{GT.II}$	Pump	$\dot{B}_{15}+\dot{Y}_{Pump}+\dot{B}_{w,\,pump}=\dot{B}_{24}$ $b_{24}=b_{16+17}$

Remark

j: The stream number in Fig. 1(b)
b_j: The specific environmental impact of the j^{th} stream
$\dot{B}_j$: The environmental impact of the j^{th} stream
$\dot{Y}_k$: The environmental impact associated with the life cycle of k^{th} component
$\dot{B}_{w,\,comp}+\dot{B}_{w,\,GT_{net}}$: The environmental impact of work produced by gas turbine
$\dot{B}_{w,\,comp}$: The environmental impact of work required for compressor
$\dot{B}_{w,\,ST}+\dot{B}_{w,\,pump}$: The environmental impact of work produced by steam turbine
$\dot{B}_{w,\,pump}$: The environmental impact of work required for pump

tively:

$$b_{P,\,k}=\frac{\dot{B}_{P,\,k}}{\dot{E}_{P,\,k}} \tag{17}$$

$$b_{F,\,k}=\frac{\dot{B}_{F,\,k}}{\dot{E}_{F,\,k}} \tag{18}$$

where P stands for product and F stands for fuel. These values are lower for components closer to the fuel stream of the overall system and higher for components closer to the product stream of the overall system [12].

- Environmental impact of exergy destruction

The environmental impact associated with exergy destruction within the k^{th} component $\dot{B}_{D,\,k}$ is obtained from Eq. (19):

$$\dot{B}_{D,\,k}=b_{F,\,k}\dot{E}_{D,\,k} \tag{19}$$

where the subscript D indicates exergy destruction.

- Total environmental impact associated with a component

The total environmental impact $\dot{B}_{TOT,\,k}$ is calculated by adding the component-related environmental impact $\dot{Y}_k$ and the environmental impact of exergy destruction $\dot{B}_{D,\,k}$:

$$\dot{B}_{TOT,\,k}=\dot{Y}_k+\dot{B}_{D,\,k} \tag{20}$$

- Relative difference of specific environmental impacts

The relative difference between the average specific environmental impacts of the product and fuel is found by the formula:

$$r_{b,\,k}=\frac{b_{P,\,k}-b_{F,\,k}}{b_{F,\,k}} \tag{21}$$

where $r_{b,k}$ represents the potential for reducing the environmental impact associated with the k^{th} component.

- Exergoenvironmental factor

The exergoenvironmental factor $f_{b,k}$ expresses the relative contribution of a component-related environmental impact $\dot{Y}_k$ to the total environmental impact $\dot{B}_{TOT,\,k}$.

$$f_{b,\,k}=\frac{\dot{Y}_k}{\dot{Y}_k+\dot{B}_{D,\,k}}=\frac{\dot{Y}_k}{\dot{B}_{TOT,\,k}} \tag{22}$$

When the exergoenvironmental factor is higher than approximately 0.7, the component-related environmental impact is dominant. On the other hand, when the exergoenvironmental factor is

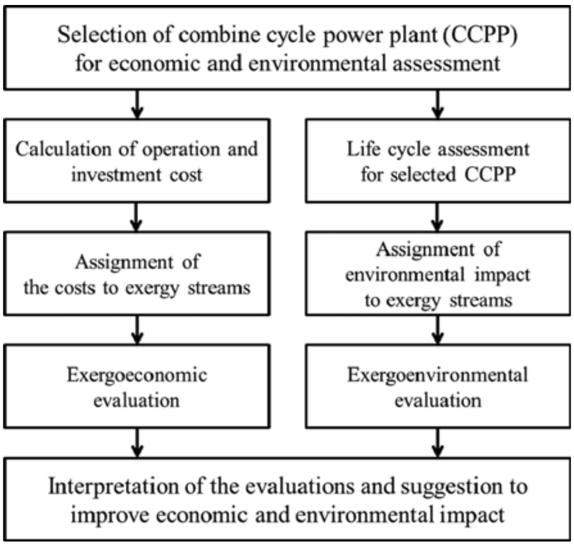


Fig. 2. The proposed framework for evaluating the economic and environmental impacts of a selected CCPP.

lower than approximately 0.3, exergy destruction dominates the environmental impact [12].

4. An Integrated Framework for the Exergoeconomic and Exergoenvironmental Analyses of a CCPP

Fig. 2 shows a proposed framework for evaluating the economic and environmental impacts of a CCPP. First, data was collected for a CCPP case study [1]. To assess two impacts, exergoeconomic and exergoenvironmental analyses were conducted. For exergoeconomic analysis, operation and investment costs were calculated and assigned to exergy streams. Based on exergoeconomic streams, exergoeconomic evaluation was carried out. For exergoenvironmental analysis, an LCA was conducted to obtain the environmental impacts of components of the CCPP. Next, the environmental impacts obtained from LCA were assigned to exergy streams and exergoenvironmental evaluation was carried out. With the aid of system evaluation, the performance of the CCPP was interpreted to find the components with the greatest economic and environmental impacts. Furthermore, the sensitivity analysis on the exergoeconomic and exergoenvironmental parameters was conducted to find the key parameters and evaluate the effects of key parameters on the exergoeconomic and exergoenvironmental analyses. Note that when one parameter is changed in the sensitivity analysis, the others are fixed. For the exergoeconomic aspect, the sensitive parameter affects the results of exergoeconomic analysis, such as total cost, exergoeconomic factor (f) and relative cost difference (r). To find the most sensitive parameter in exergoeconomic analysis, interest rate, annual plant operation time and natural gas price were selected as the parameters for sensitivity analysis. For the exergoenvironmental aspect, the sensitive parameters which affect total environmental impact $\dot{B}_{TOT}$ were found with sensitivity analysis at operation and construction phase, respectively. $\dot{B}_{TOT}$ was calculated by summing total environmental impact associated with a component $\dot{B}_{TOT,k}$ for all components of an energy system. The sensitive parameters at operation phase were the natural gas usage, the compressor, the electricity usage and the efficiencies of components. For the construction phase, the volume ratio of HRSG, steam turbine, compressor, combustion chamber, gas turbine and condenser were selected as the influential parameters.

RESULTS AND DISCUSSION

1. Exergoeconomic Analysis of a CCPP

Exergoeconomic analysis was conducted using the exergoeconomic formulation presented in section 2 - materials and methods. The unit cost per exergy for each stream was calculated with equations presented in Table 4 and analyzed by exergoeconomic

Table 6. Exergoeconomic variables of CCPP system components

Variable	Compressor	Combustion chamber	Gas turbine	Heat recovery unit	Steam turbine	Condenser
c_f ($/MJ)	0.0233	0.0044	0.0193	0.0193	0.0298	0.0298
c_p ($/MJ)	0.0271	0.0193	0.0233	0.0298	0.0382	0.1568
C_D ($/s)	0.1327	0.2432	0.2150	0.1803	0.1647	0.1084
C_L ($/s)	0	0	0.0000	0.0961	0	0.0208
Z_k ($/s)	0.1405	0.0003	0.1215	0.0243	0.0874	0.0007
$C_D+C_L+Z_k$ ($/s)	0.2732	0.2435	0.3365	0.3007	0.2522	0.1299
f (%)	51.42	0.1319	36.10	8.080	34.67	0.5416
r (%)	16.13	341.8	20.81	54.53	28.10	425.8

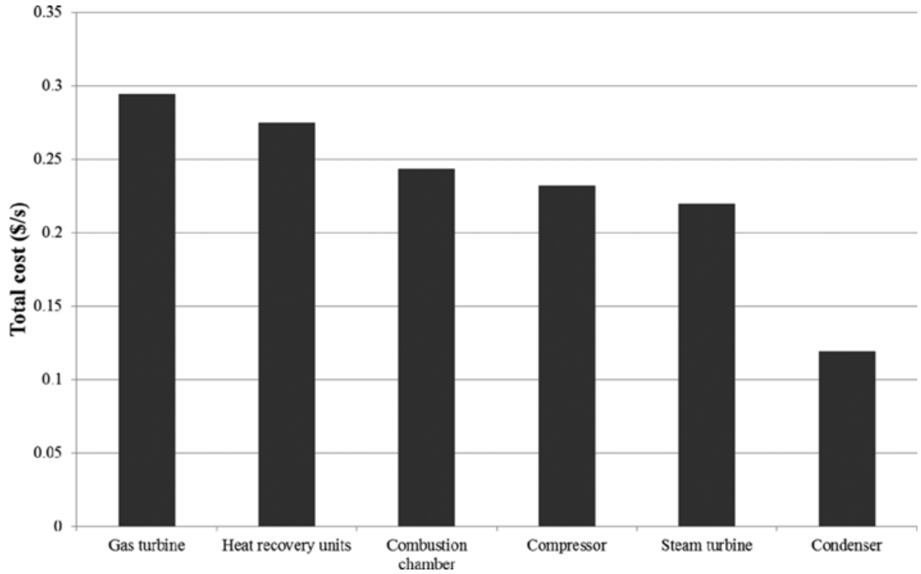


Fig. 3. Total cost of CCPP system components.

variables presented in Table 6.

In order to exergoeconomically analyze the system, the total cost as a summation of C_D, C_L, and Z_k must be calculated [27]. Fig. 3 represents the total cost of each component of the system. Of all the components in the system, the gas turbine had the maximum cost, and the pump had the minimum cost. The heat recovery units HRSG and OTSG had the second-highest total cost, and the combustion chamber, compressor, steam turbine, and condenser had the next-highest costs.

To analyze the improvement potential of each component, the exergoeconomic factor and relative cost difference were compared. The exergoeconomic factor is determined by the fraction of capital investment and total cost, and the relative cost difference is defined by the difference between the fuel cost and product cost. Components with small f and high r have a high potential to improve overall performance by increasing the capital investment or by decreasing exergy destruction and loss.

Figs. 4(a) and 4(b) show the exergoeconomic factors and relative cost differences of CCPP components. The combustion chamber and condenser have small f and high r indicating a high potential to improve performance, and therefore increasing the capital investment, perhaps by redesigning the combustion chamber and condenser, should be considered a priority. Changing the air-fuel ratio in the combustion chamber is another way to improve system performance. The heat recovery units also have small f and high r, but both values are relatively low. In this case, alternative ways (i.e., installation of a pre-heater for the heat recovery units) might be better than increasing capital investment to achieve overall system improvement. The gas turbine, compressor, and steam turbine have high f and small r, also at relatively low levels, which means that these components have a low potential to improve performance by increasing capital investment and have a low exergy destruction rate in the system. This agrees with the results of a previous study (Table 2); however, this analysis shows that the same conclusion can be reached by comparing exergoeconomic factors and relative cost differences.

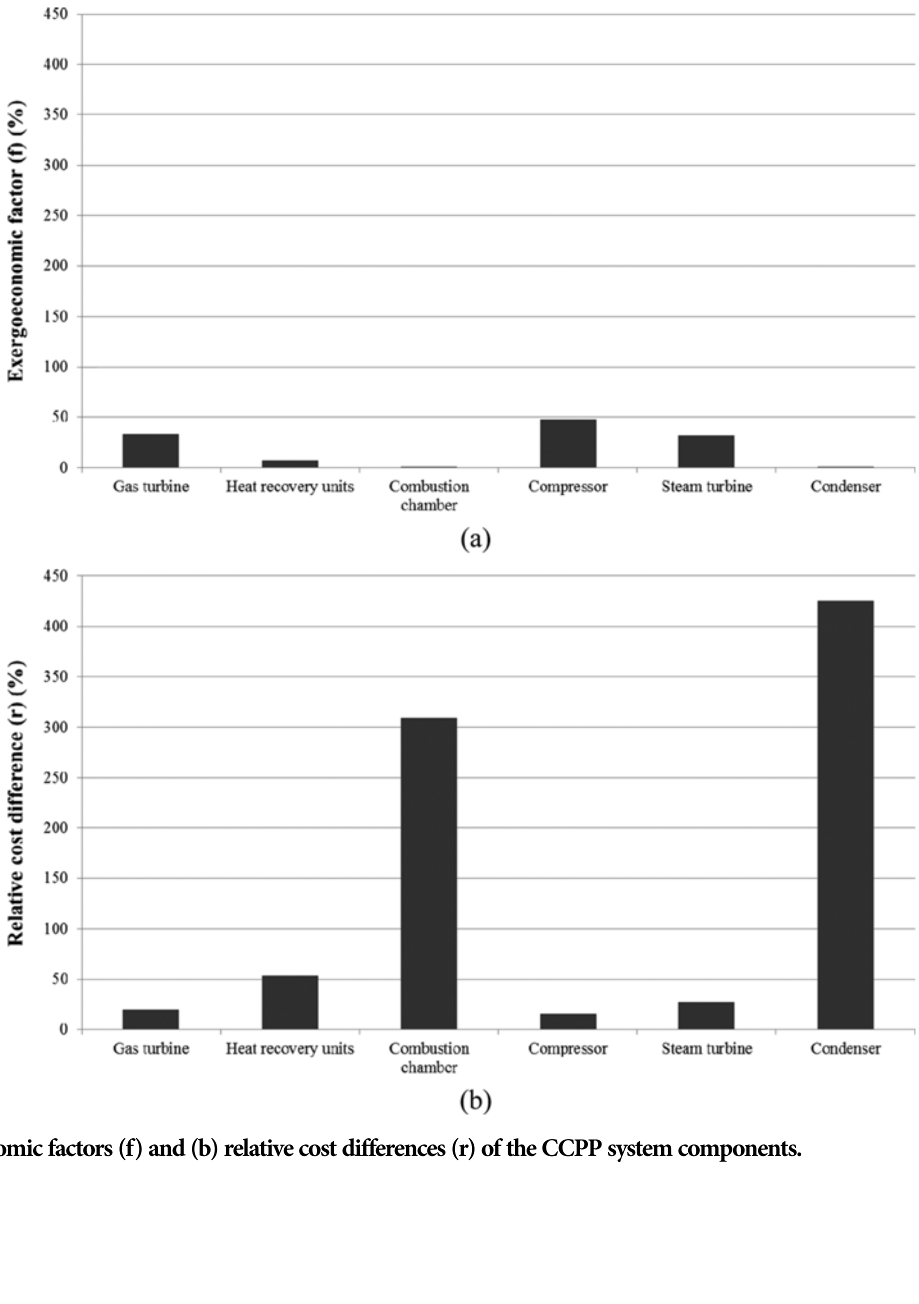


Fig. 4. (a) Exergoeconomic factors (f) and (b) relative cost differences (r) of the CCPP system components.

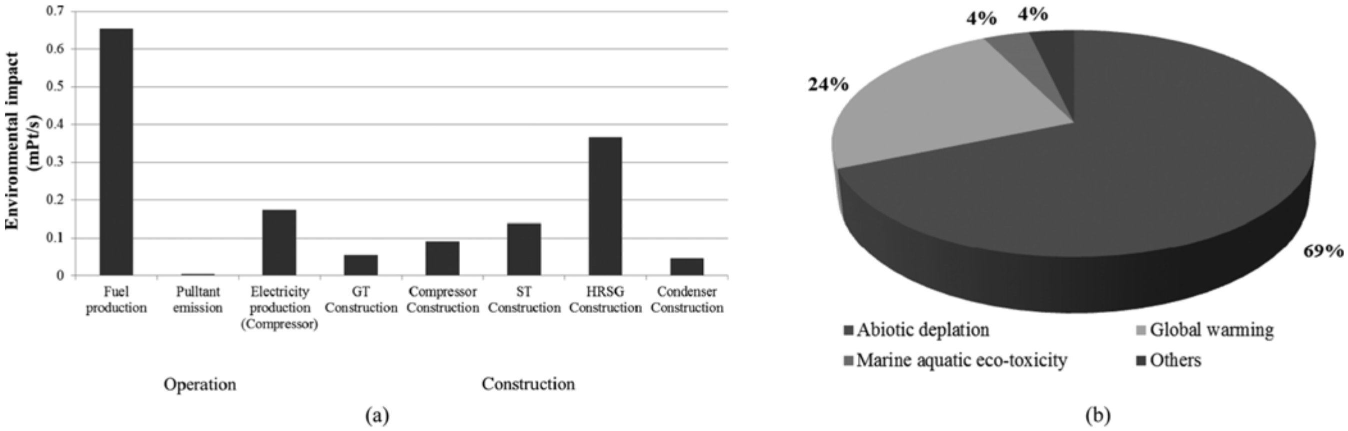


Fig. 5. (a) Total environmental impact of operation and construction stages using TOTAL, (b) relative contributions of individual impact categories to the total environmental impact.

2. Exergoenvironmental Analysis of a CCPP

The LCA of the system was modeled in TOTAL software. As a functional unit for the LCA, a net electricity generation of 1 kWh was selected. Fig. 5(a) presents the LCA results of each component giving the environmental impact of components during operation and construction. As shown in Fig. 5(a), in the operation stage, fuel production for combustion to increase the temperature and pressure of the compressed air has the highest environmental impact [28]. On the other hand, in the construction stage, construction of the heat recovery unit has the highest impact, because the required amount of reinforced steel is greatest for this component [15]. Furthermore, it can be seen in Fig. 5(b) that in the life cycle of the CCPP system, the contributions to the total environmental impact in order from highest to lowest are abiotic depletion, global warming, marine aquatic eco-toxicity and others, since abiotic depletion is most related to the production of steel (used to build components such as the turbine, heat recovery unit, compressor, etc.). Clearly, the construction stage has a large contribution to the overall environmental impact of a CCPP.

Fig. 6(a) shows the environmental impacts associated with exergy

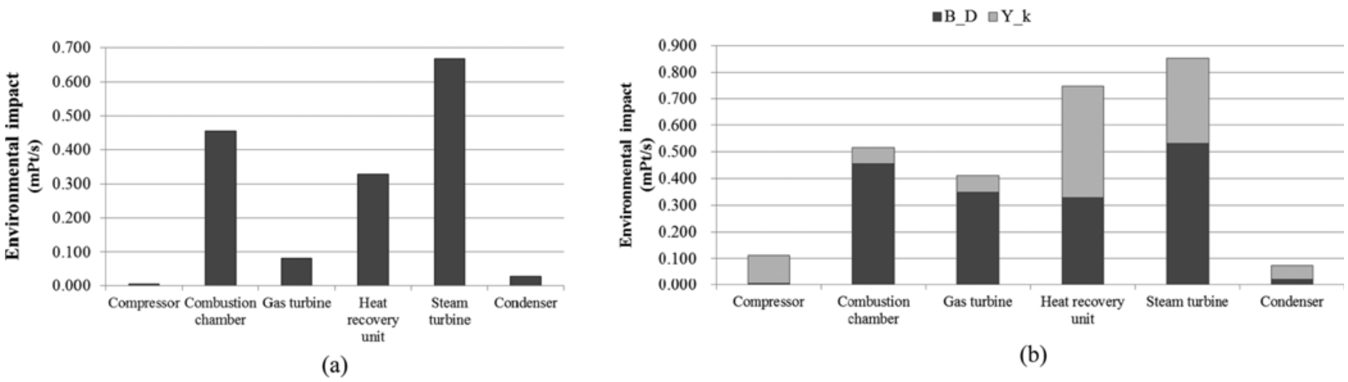


Fig. 6. (a) Environmental impact associated with exergy destruction $\dot{B}_{D,k}$ for different components, (b) sum of environmental impacts $\dot{B}_{TOT,k}$ for system components.

Table 7. Exergoenvironmental variables of CCPP system components

Variable	Compressor	Combustion chamber	Gas turbine	Heat recovery unit	Steam turbine	Condenser
$\dot{Y}_k$ (mPt/s)	0.105	0.061	0.061	0.422	0.160	0.053
$b_{F,k}$ (mPt/GJ)	1.420	6.898	7.313	41.065	110.999	1230.060
$b_{P,k}$ (mPt/GJ)	2.852	10.856	8.422	73.352	131.677	3984.790
$\dot{B}_{F,k}$ (mPt/s)	0.105	0.756	4.616	1.045	3.276	4.314
$\dot{B}_{P,k}$ (mPt/s)	0.211	0.817	4.678	1.466	3.436	4.366
$\dot{B}_{D,k}$ (mPt/s)	0.006	0.455	0.081	0.327	0.666	0.027
$\dot{B}_{TOT,k}$ (mPt/s)	0.111	0.516	0.143	0.749	0.827	0.080
$f_{b,k}$ (%)	94.977	11.906	43.104	56.294	19.367	65.974
$r_{b,k}$ (%)	100.825	57.386	15.170	78.624	18.629	223.951

destruction through the steam turbine, combustion chamber, heat recovery unit, compressor, gas turbine, and condenser. Note that the environmental impact of the pump was not included since it is negligible. It is seen in Fig. 6(a) that the combustion chamber represents extremely high exergy destruction (Table 2), while the specific environmental impact of the fuel stream to the steam turbine is relatively high (Table 7). The total environmental impact associated with a component $\dot{B}_{TOT,k}$ was used to identify the components with the greatest effect on the environmental impact as shown in Fig. 6(b). Similar to the environmental impacts associated with exergy destruction, the steam turbine, combustion chamber, and heat recovery unit are clearly the components which contribute most significantly to the overall environmental impact. In particular, the heat recovery unit contributed to the component-related environmental impact due to the construction process.

The relative difference of specific environmental impacts was used to investigate the improvement potentials of process components on their environmental performance. The condenser and compressor have a relatively high improvement potential, as indicated by their values of $r_{b,k}$ (Table 7). Therefore, the environmental impact of the condenser and compressor can be reduced with a smaller effort than other components.

Fig. 7 shows the exergoenvironmental factor that identifies the causes of the environmental impact associated with the k^{th} component. For the combustion chamber and steam turbine, exergy destruction is the main source of environmental impact. In the compressor, which has a $f_{b,k}$ value above 0.7, the environmental impact is dominated by the component-related environmental impact $\dot{Y}_k$.

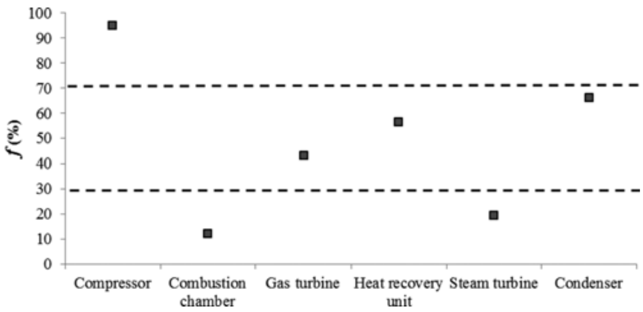


Fig. 7. Exergoenvironmental factor of system components in a CCPP.

Finally, the steam turbine and combustion chamber appear to have high improvement potentials with respect to reducing the exergy destruction within each component. The component-related environmental impact of the heat recovery units should also be reduced in order to improve the environmental performance of the CCPP.

3. Sensitivity Analysis

In the sensitivity analysis, the influences on the parameters of exergoeconomic and exergoenvironmental analyses of each energy system components in a CCPP are investigated.

For the exergoeconomic aspect, the natural gas price is the most

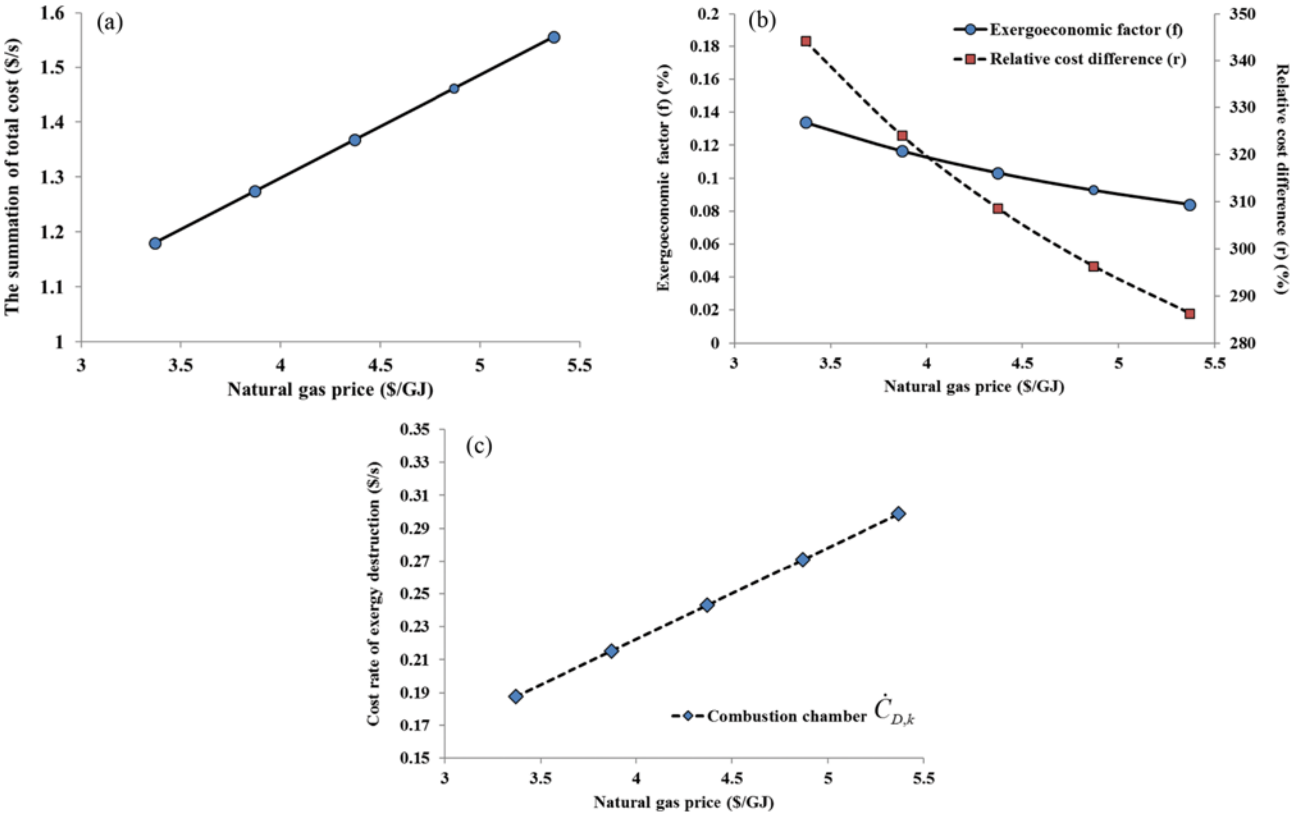


Fig. 8. The variation of (a) summation of total cost of CCPP components, (b) exergoeconomic factor and relative cost difference of combustion chamber, and (c) cost rate of exergy destruction of combustion chamber with respect to the natural gas price.

sensitive parameter on the total cost of CCPP, compared to the interest rate and annual plant operation time. It comes from that the value of exergy rate of the natural gas is larger than other streams (shown in Table 1) and the total cost is calculated by multiplying the price and the exergy rate of natural gas. Fig. 8 shows the sensitivity analysis result of the natural gas cost. As shown in Fig. 8(a), the increase of natural gas price leads to the increase of total cost of CCPP because only natural gas price increases without changes of other variables in the cost balances (shown in Table 4). Fig. 8(b) represents the changes in exergoeconomic factor (f) and relative cost difference (r) of combustion chamber with the natural gas price variations. The combustion chamber is shown as a dominant component on the total cost of CCPP, since the natural gas price directly affects the total cost of combustion chamber fueled by the natural gas. The increase of natural gas price leads to the concurrent decreases of f and r, where r shows a significant decrease with the increase of natural gas price as compared to f due to the increasing cost rate of exergy destruction $\dot{C}_{D,k}$ (shown in Fig 8(c)). It means that the natural gas price increases to improve the performance of the combustion chamber but leads to a question about how to decrease the exergy destruction in a unit. Therefore, the natural gas price is the influential parameter of exergoeconomic analysis, which affects the cost rate of exergy loss.

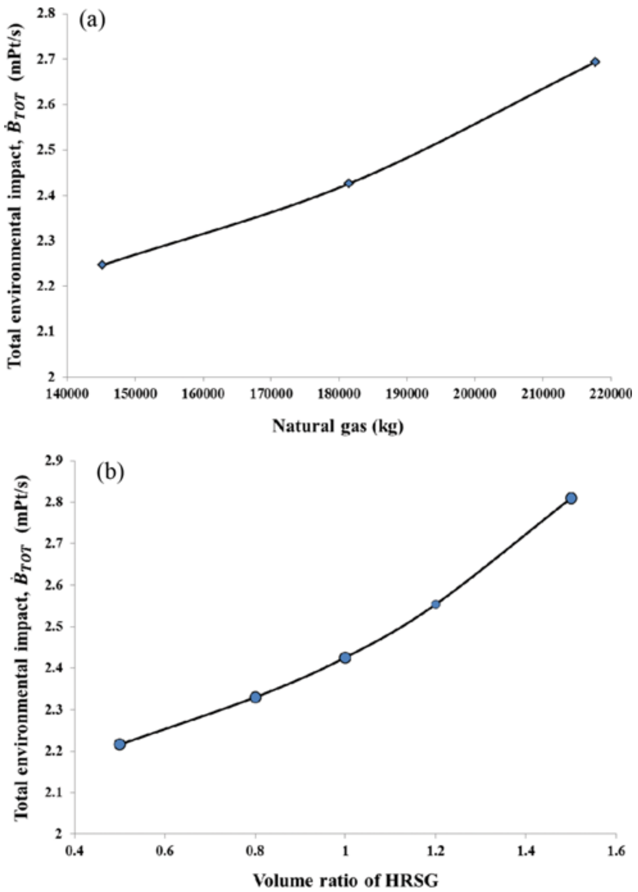


Fig. 9. The effect of (a) the amount of natural gas used in operation phase and (b) variation of volume fraction for HRSG and ST in construction phase.

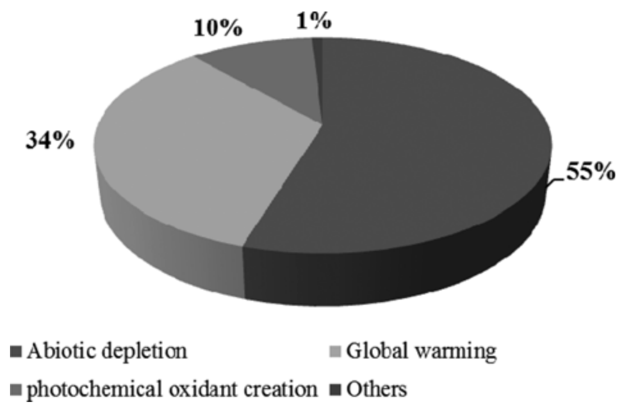


Fig. 10. Relative contributions of individual impact categories for the natural gas usage.

For the exergoenvironmental aspect, the most important parameter is the amount of fueled natural gas and the capacity of HRSG at the operation and construction phase of CCPP, respectively. Fig. 9(a) shows the variation of $\dot{B}_{TOT}$ in terms of natural gas usage at operation phase. The variation of natural gas usage has the largest effect on $\dot{B}_{TOT}$ compared with compressor electricity usage and efficiency of components. As the natural gas usage reaches a higher value, the total environmental impact of the CCPP significantly increases. The increased total environmental impact is strongly related to abiotic depletion, global warming and photochemical oxidant creation based on LCA results of the natural gas usage shown in Fig. 10. Note that the natural gas is burned to obtain high temperature and high pressure of flue gas in the combustion chamber producing CO_2 as a by-product of the combustion process. Therefore, the increase of natural gas usage leads more CO_2 emission from the CCPP at operational phase, which results in more impacts to the environment at operation phase. Fig. 9(b) shows the variation of $\dot{B}_{TOT}$ in terms of the ratio of the modified size to default size of the HRSG (i.e., volume ratio) at the construction phase. The variations of volume ratio of HRSG have larger effect on $\dot{B}_{TOT}$ than those of steam turbine, compressor, combustion chamber, gas turbine and condenser. The result of sensitivity analysis at the construction phase corresponds to the LCA result shown in Fig. 5(a), because the increase of HRSG capacity requires more amount of steel than other components at construction phase. Therefore, the volume of HRSG should be carefully designed considering the environmental aspect, although the larger capacity of the HRSG guarantees more production of electricity.

CONCLUSIONS

A combined exergoeconomic and exergoenvironmental approach is proposed to formulate guidelines for performance improvements in both the economic and environmental aspects of a CCPP. The ATAER Energy power plant located in Turkey, which consists of two gas turbine cycles and one steam turbine cycle with two heat generation units, was examined as a case study. Exergoeconomic and exergoenvironmental analyses were used to investigate the electricity cost rates and environmental impacts associated with individual CCPP components. The main conclusions are listed as follows:

1. Exergoeconomic analysis shows that the combustion chamber and condenser have a high performance improvement potential by increasing the capital investment of units. Heat recovery units also have a smaller performance improvement potential by the installation of an additional unit (i.e., pre-heater).

2. To improve the environmental performance of CCPP, exergy destruction in the steam turbine and combustion chamber should be reduced. In addition, the design of the heat recovery unit should be changed to lower its environmental impact during the construction stage.

3. Sensitivity analysis shows that the natural gas price is one of the influential parameters on the exergoeconomic analysis result. This parameter affects the potential of the exergy performance improvement of the CCPP components. In particular, the cost rate of exergy loss is greatly influenced by changing the natural gas price. Therefore, to suggest where and how to improve the performance of CCPP units in the economic aspect, variations of the cost rate of exergy loss with high natural gas price changes should be considered more detail. For the exergoenvironmental aspect, the natural gas usage and the capacity of heat recovery units are key parameters at the operation and construction phase, respectively. Because the total environmental impact is increased with increase in these two parameters, lower values of these parameters are favorable for a decision maker to evaluate the environmental aspect. This study showed that the exergoeconomic and exergoenvironmental analyses can improve the performance of CCPP by evaluating the potentials of the efficiency of energy system components of the CCPP. In addition, the guideline for improving performance of CCPP was suggested with respect of the economic and environmental viewpoint. Therefore, it is useful to provide a guideline about where and how to improve performance of CCPP when retrofitting and optimizing the power plant with respect to the economic and environmental impacts since it is able to provide the detailed information on energy system components of a power plant.

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NOMENCLATURE

A : heat transfer area [m^2]
$\dot{B}$: environmental impact rate expressed in a weighted value of LCA per time unit [mPt/s]
b : specific environmental impact which is the environmental impact per unit [mPt/GJ]
CRF : capital recovery factor
$\dot{C}$: cost flow rate of stream [$/s]
c : cost per exergy of stream [$/MJ]
$\dot{E}$: exergy rate [GJ exergy/s]
e : specific exergy [kJ/kg]
f : exergoeconomic factor
f_b : exergoenvironmental factor
i_r : interest rate
LMTD, ΔT_{ln} : logarithmic mean temperature difference [K]
$\dot{m}$: mass flow of stream [kg/s]
n : number of operation years [year]
P : power generation [kW]
p : pressure [bar]
Q : heat transfer flow [kW]
r : relative cost difference
r_b : relative difference of exergy related environmental impact
r_p : pressure ratio
T : temperature [K]
U : heat transfer coefficient [kW/m^{2}K]
W : work [kW]
$\dot{Y}$: component-related environmental impact rate associated with the life cycle [mPt/s]
$\dot{Z}$: sum of capital investment, operation and maintenance costs [$/s]

Greek Symbols

τ : annual plant operation time [hour]
η : efficiency
γ : maintenance factor

Subscripts

AC, comp : air compressor
CC : combustion chamber
Cond : condenser
c : cold
D : destruction
F : fuel
GT : gas turbine
h : hot
in : input
i, j : *i, j*th stream
k : *k*th component of the energy conversion system
L : exergy loss
out : output
P : product
q : required heat
R : reference
ST : steam turbine
TOT : total
w : work produced by the component

Superscripts

CI : capital investment
CO : construction
OM : disposal
DI : operation, maintenance

Abbreviations

CCPP : combined cycle power plant
HRSG : heat recovery steam generator
LCA : life cycle assessment
OTSG : once-through steam generator

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