APPLICATION OF EXERGOECONOMIC ANALYSIS FOR POWER PLANTS

by

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Currently, energy resources are rapidly consumed. Therefore, scientists and engineers study the effective use of energy. In the present study, a thermodynamic and exergoeconomic analysis was performed in a thermal power plant in Turkey. The study involved determining the thermodynamic properties of 27 node points in a thermal power plant unit, and this was followed by calculating energy and exergy values of every node. Mean exergy costs were calculated by establishing energy and exergy balances of the equipment with respect to the calculated results. Subsequently, lost and damaged energies and exergies were calculated, and exergoeconomic factors were determined. The equipments were compared with each other on a graph based on the obtained results. The maximum rate of exergy loss and cost of exergy destruction corresponded to 79.5% and 886,66 \$/h, respectively. The maximum exergy losses in a thermal power plant occurred in the boiler, turbine groups, condenser, heating group, pumps, and auxiliary groups. The highest and second highest law efficiencies of the studied thermal power plant corresponded to 32.3% and 28.5%, respectively. The study also involved presenting suggestions for improvement. Additionally, exergoeconomic analyses were conducted while considering the power plants' investment and equipment maintenance costs. It is expected that the calculation method and the obtained results can be applied to other thermal power plants.

Key words: *exergoeconomic analysis, thermal power plant, exergy analysis, thermodynamic analysis*

Introduction

Efficient use of energy is a necessity as a result of rapid increases in world population and technological developments. Techniques that combine scientific disciplines (mainly thermodynamics) with economic disciplines (mainly cost accounting) are used in the analysis and design of energy systems to achieve optimum designs [1]. Unit price is crucial in energy use. The factors that determine price correspond to production facility and fuel used. High efficiency of a production facility ensures the production of energy that exceeds the amount of fuel used and decreases unit cost of energy. Exergy analysis determines areas of irreversibility in a system. Efficiency of a system can be increased by eliminating or decreasing this irreversibility. However, cost of modified components increases the cost of unit energy. It is important to adopt additional measures such that unit product cost does not increase. It is not possible to provide maximum exergy efficiency in this manner. However, the highest possible value of efficiency

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and the lowest possible value of cost are determined. This analysis method is termed as exergoeconomic analysis [2].

Extant studies examined performance analyses of power plants. [3-15]. Erdem *et al.*, [3] designed point performance analyses based on energetic and exergetic criteria, such as thermal efficiency, exergetic efficiency, exergy loss, and exergetic performance coefficient for all considered plants to obtain comprehensive evaluations. Bilgen [4] presented exergetic and engineering analyses as well as simulation of gas turbine-based cogeneration plants consisting of a gas turbine, heat recovery steam generator, and steam turbine. In the study, an algorithm was developed to simulate the systems. Two cogeneration cycles, namely a cycle consisting of a gas turbine and another cycle consisting of a gas turbine and steam turbine, which were employed to produce electricity and process heat, were analysed. Suresh *et al.* [5] conducted a 4-E (namely energy, exergy, environment, and economic) analysis of solar thermal aided coal fired power plants to establish their techno-economic viability. Zhang *et al.* [6] applied a cost analysis method based on structural theory of thermoeconomics to a 300 MW pulverized coal fired power plant located in Yiyang, Hunan Province, China. The results of the study indicated that unit exergy cost of product was insufficient to reflect and quantify real causes of the variation in the production/thermodynamic performance of a component. Oktay [7] investigated Turkish coal fired power plants, examined an example plant, and focused on rehabilitation of current plants. The studied plant corresponded to the first and only circulating fluidized bed power plant in the country. Exergy efficiencies, irreversibilities, and improvement factors for the turbine, steam generator, and pumps were calculated for the selected plant (Can Power Plant). Aljundi [8] analysed the Al-Hussein Power Plant in Jordan from an energy and exergy perspective. This involved determining the energy loss, exergy destruction, and investigated the effect of variations in the reference environment state (dead state) with respect to the exergy analysis. Shokati *et al.* [9] performed a comparative analysis of Rankine and absorption power cycles based on an exergo-economic analysis that was performed using the specific exergy costing method. Ganjehkaviri *et al.* [10] investigated modelling and optimization of combined cycle power plants based on exergoeconomic and environmental analyses. Regulagadda *et al.* [11] conducted a detailed exergy analysis of a thermal power plant to assess the distribution of irreversibilities and losses that contribute to the loss of efficiency in system performance. Rosen and Dincer [12] investigated the application of energy and exergy analysis to a power plant that was operated with coal by changing dead state conditions. Specifically, energy and exergy analyses were applied to the entire system and every component of the system separately, and the results were then analysed. Arslan [13] performed energy and exergy analyses with respect to the Seyitomer thermal power plant. The study involved separately establishing energy and exergy balances on every equipment, determining mean energy and exergy losses, and offering solutions by establishing a connection between the results of the analysis and determining the equipment to be corrected. In a study, Kaya [14] examined a simple Rankine steam cycle and applied exergy analysis to the cycle. Thus, parameters affecting net power output were determined by comparing thermal efficiency of the system in addition to exergy efficiency of the system that was considered as a closed and adiabatic system. In a study, Coskun *et al.* [15] performed energy and exergy analyses with respect to the Cayırhan thermal power plant. They determined that the thermal and Second law efficiencies of the thermal power plant corresponded to 38% and 53%, respectively, by means of the obtained thermodynamic properties.

In the present study, thermodynamic properties of input and output of a thermal power plant unit were used to perform energy and exergy analyses on the thermal power plant based on the First and Second laws of thermodynamics. The obtained results were used to evaluate and suggest improvements in the equipment. Furthermore, exergoeconomic analysis was applied based on exergy losses in the power plant. The initial investment cost, cost of exergy losses, and the cost of exergoeconomic factors in each unit were calculated in the economic analysis. The energy and exergy analyses of thermal power plants are generally available in extant studies. A few previous studies focus on exergoeconomic analysis. In this study, initial investment and operating costs were used in the economic analysis by considering interest and inflation rates. In this context, the cost of exergy losses and exergoeconomic factors in each unit as obtained in the present study differ from those derived by extant studies.

Power plants description

The Tuncbilek area is located at a distance of 62 km from Kutahya between the towns of the provinces of Kutahya Tavsanli and Domanic. The geographic co-ordinates latitude, corresponds to 39º35', 39º46' North, the longitude, corresponds to 29º15', 29º30', and the altitude, corresponds to 930 m, fig. 1.


Figure 1. View of the thermal power plant site

The Tuncbilek thermal power plant was established to evaluate low-quality lignite reserves. The second unit of the thermal power plant is composed of a turbine group of 150 MW, a steam boiler, a condenser, heating groups, and a gland condenser and an ejector termed as an auxiliary group. The turbine group is composed of low pressure, medium pressure, and high pressure turbines. Additionally, the heating groups are composed of four low pressure and two high pressure feeding water heaters and degasser (DEG) components. The flow diagram of the plant is depicted in fig. 2.

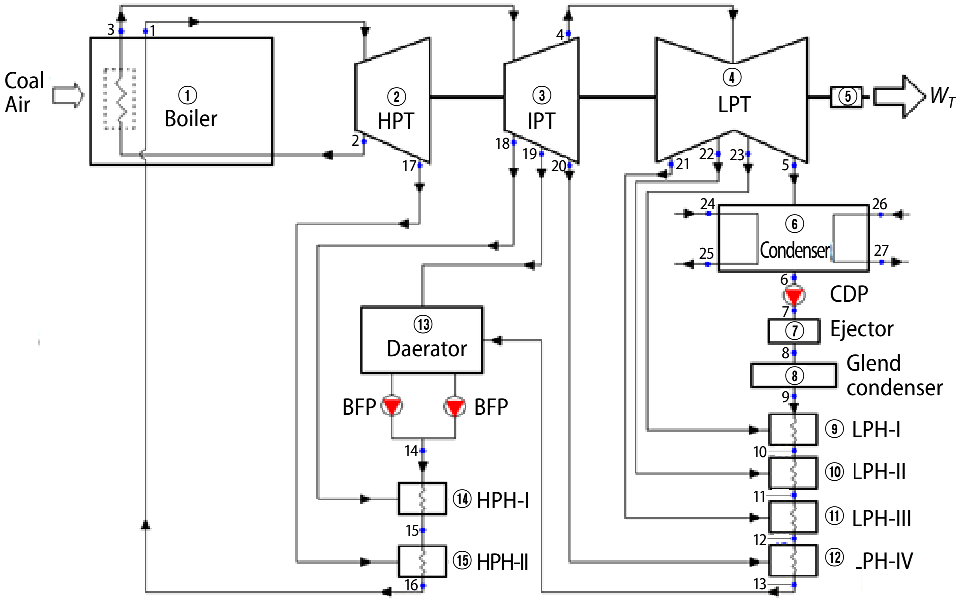

Figure 2. Thermal power plant flow diagram

In the Tuncbilek thermal power plant, 27 node points were determined. Temperature, pressure, and flow values at these points were measured continuously. The values measured using the sensors placed at the node points in the plant (Oem pressure transmitter, PT-100 thermocouple, GT-TD turbine type flow meter) were summed up in minutes by means of a 16-channel Kehao DT200-B type data-logger. Furthermore, the units of the Tuncbilek thermal power plant were kept under control and recorded by using SCADA. The data collected by the datalogger and SCADA control program were combined, and the average of the values of the node points was obtained. The undefined flow values at the determined node points were found by substituting the enthalpy values obtained by the temperature and pressure value of that point into the power formula for the equipment, eq. (4). The determined values were compared with the values obtained by the SCADA program. Calculations and evaluations were performed with the help of the specified data. Table 1 lists the results of the uncertainty analysis of thermal power plant measuring devices used in a unit of the power plant. Tables of uncertainty derived from property values correspond to ±0.20.

The measured values of the nodal points shown in fig. 2 for the thermal power plant, and the enthalpy and entropy values of the nodal points are listed in tab. 2.

Table 1. Measurement accuracy

Measured physical parameters				
Order No	Quantity	Instrument	Unit	Total uncertainty
1	Pressure	Transmitter	[bar]	±0.03
2	Temperature	Thermocouple	[°C]	±0.20
3	Flow rate	Flow meter	[kgs^{-1}]	±0.15
Derived physical parameters				
Order No	Quantity		Unit	Total uncertainty
1	Specific exergy		[kJkg^{-1}]	±0.33
2	Energy flow		[kW]	±0.05
3	Exergy flow		[kW]	±0.06
4	Exergy efficiency		η_{II}	±1.25

Energy and exergy analysis

The principle of conservation of energy is applied for continuous flow open systems [16]:

$$\dot{Q} - \dot{W} = \sum \dot{m}_{\mathrm{o}} \theta_{\mathrm{o}} - \sum \dot{m}_i \theta_i \tag{1}$$

Specifically, θ denotes the total energy of a unit mass of the fluid including flow:

$$\theta = h + \mathrm{ke} + \mathrm{pe} \tag{2}$$

$$\dot{Q} - \dot{W} = \sum \dot{m}_{\mathrm{o}} \left(h_{\mathrm{o}} + \frac{1}{2} V_{\mathrm{o}}^2 + \mathrm{g} z_{\mathrm{o}} \right) - \sum \dot{m}_i \left(h_i + \frac{1}{2} V_i^2 + \mathrm{g} z_i \right) \tag{3}$$

Input and output states are indicated with index 1 and index 2, respectively. It is considered that mass-flow is not subject to change and thus $(\dot{m} = \dot{m}_1 = \dot{m}_2)$ and that potential and kinetic energies are not subject to change. Thus, the equality of energy status for a transient and an output and continuous output open system is expressed:

$$\dot{Q} - \dot{W} = \dot{m} \left[h_2 - h_1 \right] \, [\mathrm{kW}] \tag{4}$$

Table 2. Thermodynamic properties of 27 node points in the thermal power plant

Node number	Phase state	Temperature	Pressure	Flow	Enthalpy	Entropy
		T [°C]	P [bar]	$\dot{m}$ [kgs^{-1}]	h [kJkg^{-1}]	s [kJkg^{-1}K^{-1}]
1	Steam	535	132	116.6	3427.2	6.4984
2	Steam	375	33	106.5	3173.1	6.7823
3	Steam	530	30	106.5	3524.2	7.3162
4	Steam	275	3.7	89.9	3017.1	7.5316
5	Steam	52	0.1	77.2	2596.4	8.1858
6	Liquid	46	0.1	77.2	192.6	0.6517
7	Liquid	46	14.25	77.2	192.6	0.6517
8	Liquid	44	13.5	77.2	184.3	0.6253
9	Liquid	44	13.5	77.2	184.3	0.6253
10	Liquid	57	12.3	79.9	238.6	0.7932
11	Liquid	75	12	83	313.9	1.0155
12	Liquid	118	12	89.9	490.1	1.5059
13	Liquid	147	11.8	95.2	619.3	1.8114
14	Liquid	175	138	100.4	741.2	2.0909
15	Liquid	201	138	106.5	856.9	2.3403
16	Liquid	241	138	116.6	1042.1	2.7106
17	Steam	360	33	10.1	3131.9	6.6944
18	Steam	300	16	6.1	3034.8	6.8844
19	Steam	300	6	5.2	3061.6	7.3724
20	Steam	232	3	5.3	2994.1	7.5648
21	Steam	155	0.5	6.9	2789.9	7.9619
22	Steam	77	0.4	3.1	2660.2	7.8168
23	Steam	66	0.2	2.7	2631.6	8.1032
24	Liquid	25	1.6	3150	104.9	0.3674
25	Liquid	31	1.2	3150	130	0.4506
26	Liquid	25	1.6	3150	104.9	0.3674
27	Liquid	31	1.2	3150	130	0.4506
W_T	109.2 MW					

The exergy of fuel is calculated by using the equation:

$$\dot{E}x = \dot{E}x_{\mathrm{PH}} + \dot{E}x_{\mathrm{CH}} \tag{5}$$

The physical and chemical exergies of the fuel are calculated based on eqs. (6) and (7), respectively. The specific physical exergy of fuel is calculated according to eq. (6):

$$Ex_{\mathrm{PH}} = (h - h_0) - T_0(s - s_0) \tag{6}$$

The physical exergy of the fuel also corresponds to zero. The specific chemical exergy of the fuel is calculated by using eq. [7]:

$$\left[1.0401 + 0.1728\frac{\mathrm{h}}{\mathrm{c}} + 0.0432\frac{\mathrm{o}}{\mathrm{c}} + 0.2169\frac{\mathrm{s}}{\mathrm{c}}\left(1 - 2.0628\frac{\mathrm{h}}{\mathrm{c}}\right)\right]\mathrm{LHV} \tag{7}$$

where h, c, o, and s denote mass fractions of hydrogen, carbon, oxygen, and sulphur, respectively. The reaction equation of lignite coal of the fuel of the thermal power plant is expressed:

$$\left(0.04283\mathbf{C}+0.03900\mathbf{H}+0.00136\mathbf{N}+0.00072\mathbf{S}+0.00756\mathbf{O}\right)+$$
$$+1.5\times 0.03674\left(\mathbf{O}_2+3.76\mathbf{N}_2\right)\rightarrow 0.04283\mathbf{CO}_2+0.20787\mathbf{N}_2+0.03067\mathbf{H}_2\mathbf{O}+0.00072\mathbf{SO}_2 \tag{8}$$

Exergy amount lost per unit time for any element of the system is expressed by using eqs. (9) and (10):

$$\dot{E}x_{\mathrm{L}}=\dot{E}_{\mathrm{Q}}-\dot{E}_{\mathrm{W,E}}+\Sigma\,\dot{E}_{\mathrm{mass},i}-\Sigma\,\dot{E}_{\mathrm{mass},e} \tag{9}$$

$$\dot{E}x_{L}=\Sigma\left(1-\frac{T_0}{T}\right)\dot{Q}-\dot{W}+\Sigma\,\dot{m}_i e_i-\Sigma\,\dot{m}_e e_e \tag{10}$$

The $\dot{E}x_{\mathrm{L}}$ denotes exergy flow lost and in these types of equations, it indicates the total of exergy flow transferred from any element (in which lost exergy flow is examined with respect to another element) and exergy flow that is consumed (due to irreversibility and cannot be used in any other place). This is expressed:

$$\sum_{x=1}^{n}\dot{E}x_{L_x}=\dot{E}x_{L_1}+\dot{E}x_{L_2}+\cdots+\dot{E}x_{L_n} \tag{11}$$

The exergetic efficiency is calculated by using eq. (12):

$$\eta_{\mathrm{II}}=\frac{W}{\dot{E}x_{\mathrm{fuel}}} \tag{12}$$

On the other hand, lost energy within the entire system corresponds to the total of exergy lost on each element. The exergy loss rate corresponds to the ratio of lost exergy in any unit or element to the exergy rate lost within the entire system:

$$y_{\mathrm{L}}=\frac{\dot{E}x_{\mathrm{L}}}{\Sigma\,\dot{E}x_{\mathrm{L}}} \tag{13}$$

Energy balances are formed with the help of fig. 2 and eq. (4), and exergy balances are formed with the help of fig. 2 and eq. (10). The energy and exergy balances determined for the system units are given in tab. 3.

Exergoeconomic analysis

In a system working in a continuous flow, mass and energy input and output occur within the system. Mass and energy transfer in the system corresponds to exergy transfer that occurs simultaneously. Although a part of the transferred exergy is removed from the system, a part of the exergy disappears within the system due to irreversibility. If c denotes price of unit exergy, then total exergy price is expressed with eq. (14) for component k. In the equation, $\dot{E}x$, denotes exergy flow while $\dot{C}$ denotes the price of exergy flow. This leads to the following expression:

$$\dot{C}_k=c_k\dot{E}x_k=c_k(m_k Ex_k) \tag{14}$$

$$\dot{C}_{\mathrm{w}}=c_{\mathrm{w}}\dot{W} \tag{15}$$

$$\dot{C}_{\mathrm{q}}=c_{\mathrm{q}}Ex_{\mathrm{q}} \tag{16}$$

Table 3. Energy and exergy balance in the Tuncbilek thermal power plant [17]

Unit	Energy balance	Exergy balance
Boiler	$\dot{Q}_\mathrm{B} = \dot{E}_1 + \dot{E}_3 + \dot{E}_\mathrm{FG} - \dot{E}_{16} - \dot{E}_2 - \dot{E}_\mathrm{air} - \dot{E}_\mathrm{fuel}$	$\dot{E}x_{16} + \dot{E}x_2 + \dot{E}x_\mathrm{air} + \dot{E}x_\mathrm{fuel} =$ $= \dot{E}x_1 + \dot{E}x_3 + \dot{E}x_\mathrm{FG} + \dot{E}x_\mathrm{L,boiler}$
Turbine group	$\dot{Q}_\mathrm{T} = \dot{E}_2 + \dot{E}_{17} + \ldots + \dot{E}_{23} + \dot{E}_5 -$ $-\dot{E}_1 - \dot{E}_3 - \dot{E}_4 + \dot{W}_\mathrm{T}$	$\dot{E}_1 + \dot{E}_3 + \dot{E}_4 = \dot{E}_2 + \dot{E}_{17} + \ldots +$ $+\dot{E}_{23} + \dot{E}_5 + \dot{E}x_\mathrm{w,T} + \dot{E}x_\mathrm{L,T}$
Condenser	$\dot{Q}_\mathrm{C} = \dot{E}_6 + \dot{E}_{25} + \dot{E}_{27} - \dot{E}_5 - \dot{E}_{24} - \dot{E}_{26}$	$\dot{E}x_5 + \dot{E}x_{24} + \dot{E}x_{26} = \dot{E}x_6 + \dot{E}x_{25} +$ $+\dot{E}x_{27} + \dot{E}x_\mathrm{L,C}$
Ejector	$\dot{Q}_\mathrm{E} = \dot{E}_8 - \dot{E}_7$	$\dot{E}x_7 = \dot{E}x_8 + \dot{E}x_\mathrm{L,E}$
Glend condenser	$\dot{Q}_\mathrm{GC} = \dot{E}_9 - \dot{E}_8$	$\dot{E}x_8 = \dot{E}x_9 + \dot{E}x_\mathrm{L,GC}$
LPH-I	$\dot{Q}_\mathrm{ABSI-I} = \dot{E}_{10} - \dot{E}_9 - \dot{E}_{23}$	$\dot{E}x_9 + \dot{E}x_{23} = \dot{E}x_{10} + \dot{E}x_\mathrm{L,LPH-I}$
LPH-II	$\dot{Q}_\mathrm{ABSI-II} = \dot{E}_{11} - \dot{E}_{10} - \dot{E}_{22}$	$\dot{E}x_{10} + \dot{E}x_{22} = \dot{E}x_{11} + \dot{E}x_\mathrm{L,LPH-II}$
LPH-III	$\dot{Q}_\mathrm{ABSI-III} = \dot{E}_{12} - \dot{E}_{11} - \dot{E}_{21}$	$\dot{E}x_{11} + \dot{E}x_{21} = \dot{E}x_{12} + \dot{E}x_\mathrm{L,LPH-III}$
LPH-IV	$\dot{Q}_\mathrm{ABSI-IV} = \dot{E}_{13} - \dot{E}_{12} - \dot{E}_{20}$	$\dot{E}x_{12} + \dot{E}x_{20} = \dot{E}x_{13} + \dot{E}x_\mathrm{L,LPH-IV}$
Daerator	$\dot{Q}_\mathrm{D} = \dot{E}_{14} - \dot{E}_{13} - \dot{E}_{19}$	$\dot{E}x_{13} + \dot{E}x_{19} = \dot{E}x_{14} + \dot{E}x_\mathrm{L,D}$
HPH-I	$\dot{Q}_\mathrm{HPH-I} = \dot{E}_{15} - \dot{E}_{14} - \dot{E}_{18}$	$\dot{E}x_{14} + \dot{E}x_{18} = \dot{E}x_{15} + \dot{E}x_\mathrm{L,HPH-I}$
HPH-II	$\dot{Q}_\mathrm{HPH-II} = \dot{E}_{16} - \dot{E}_{15} - \dot{E}_{17}$	$\dot{E}x_{15} + \dot{E}x_{17} = \dot{E}x_{16} + \dot{E}x_\mathrm{L,HPH-II}$
BFP	$\dot{Q}_\mathrm{BFP} = \dot{E}_{14} - \dot{E}_{14}$	$\dot{E}x_{14} = \dot{E}x_{14} + \dot{E}x_\mathrm{L,BFP}$
CDP	$\dot{Q}_\mathrm{CDP} = \dot{E}_7 - \dot{E}_6$	$\dot{E}x_6 = \dot{E}x_7 + \dot{E}x_\mathrm{L,CDP}$

Components available within a system are studied separately while calculating exergy cost. With respect to component k of the system, the cost balance equation is expressed:

$$\sum C_{\mathrm{e},k} + C_{\mathrm{w},k} = C_{\mathrm{q},k} + \sum C_{i,k} + Z_k \tag{17}$$

In the equation, Z_k denotes levelled monetary value such that it includes the investment, operation, and maintenance costs of component k within the system. The value, Z, is a function of parameters such as annual operational period, system life, interest, and escalation. While calculating the Z value, the total of initial investment corresponding to unit time and operational costs are multiplied by a *factor levelled to a specific value (A)*. The factor for levelling to a specific value is expressed in eq. (18):

$$A = \frac{\mathrm{CELF}}{1 + r_i} \tag{18}$$

In the equation, CELF value denotes fixed escalation correction factor while r_i denotes interest rate. Fixed escalation correction factor is expressed by the equation:

$$\mathrm{CELF} = \frac{k\left(1 - k^n\right)}{1 - k}\mathrm{CRF} \tag{19}$$

In the equation, capital regain factor (CRF) value includes capital regain factor, and the k value includes price correction factor levelled to a specific value. The n value is expressed as the expected life for a system or component. The CRF is expressed:

$$\mathrm{CRF} = \frac{i_{\mathrm{eff}}(1+i_{\mathrm{eff}})^n}{(1+i_{\mathrm{eff}})^n - 1} \tag{20}$$

In the previous equation, i_{eff}, value denotes the repayment rate. The price correction factor is expressed by the equation:

$$k = \frac{1+r_n}{1+i_{\mathrm{eff}}} \tag{21}$$

The assessment of the performance of a component requires an understanding of the relative importance of each category. This is achieved through a thermoeconomic (exergoeconomic) factor that is defined for each component. The following expression is stated for component *k* of an exergoeconomic factor system.

$$f = \frac{\dot{Z}}{\dot{Z} + c_p \dot{E}x_k} \tag{22}$$

On the other hand, the cost valued with the help of the previous expressions can be stated:

$$Z = A\left[\frac{\text{investment cost}}{\text{system life x annual working time}} + \frac{\text{electric} + \text{maintenance cost}}{\text{annual working time}}\right] \tag{23}$$

The following assumptions are employed in the previous calculation:

– It is assumed that the power plant operates for 7745 h annually.
– It is assumed that 125 tonne of Tuncbilek brown coal with low calories are used per hour on average within the power plant.
– It is assumed that the interest rate corresponds to 3% ($r_i = 0.03$), the annual regular increase rate corresponds to 4% ($r_n = 0.04$), and the repayment rate corresponds to 6% ($i_{eff} = 0.06$).
– It is assumed that the operational life of the power plant corresponds to $n = 20$.

Table 4 lists the initial investment cost and operating costs of system units required for exergoeconomic analysis of the thermal power station based on acceptances.

Table 4. Equipment costs of the power plant

Unit	COSTS			
	Initial investment [\$]	Annual taxes, insurance and staff [\$]	Spare parts [\$]	Outlined initial investment operation and maintenance, Z [$\$\mathrm{h}^{-1}$]
Boiler	19.933.000	498.325	996.650	448.45
Turbine group	13.909.000	347.725	695.450	312.92
Condenser	873.900	21.848	43.695	11.79
CDP	114.550	2.864	5.728	2.57
DEG	198.500	4.963	9.925	4.46
BFP	251.650	6.292	12.583	5.66
Ejector	32.700	818	1.635	0.74
LPH-I	133.050	3.326	6.653	2.3
LPH-II	138.100	3.453	6.905	3.12
LPH-III	152.600	3.815	7.630	3.44
LPH-IV	165.800	4.145	8.290	3.74
HPH-I	181.350	4.534	9.068	4.1
HPH-II	182.550	4.564	9.128	4.11

Table 5 lists the system units identified in fig. 2 and exergoeconomic equations and auxiliary equations determined for the system units by using eq. (17).

Table 5. Exergoeconomic balance of Tuncbilek thermal power plant

Unit	Exergoeconomic equations	Helper equations
Boiler	$c_{\text{fuel}}\dot{E}x_{\text{fuel}} + c_a\dot{E}x_a + c_2\dot{E}x_2 + c_{16}\dot{E}x_{16} + Z_{\text{boiler}} = = c_{\text{FG}}\dot{E}x_{\text{FG}} + c_1\dot{E}x_1 + c_3\dot{E}x_3$	$c_1 = c_2 = c_3 = c_{16}$, $c_f = c_{\text{FG}}$, $c_a = 0$ \$/kj
Turbine group	$c_1\dot{E}x_1 + c_3\dot{E}x_3 + c_4\dot{E}x_4 + Z_{\text{TG}} = c_2\dot{E}x_2 + c_4\dot{E}x_4 + +c_5\dot{E}x_5 + c_{17}\dot{E}x_{17} + \ldots + c_{23}\dot{E}x_{23} + c_{\text{wT}}\dot{E}x_{\text{wT}}$	$c_1 = \ldots = c_5 = c_{17} = \ldots = c_{23}$
Condenser	$c_5\dot{E}x_5 + c_{24}\dot{E}x_{24} + c_{26}\dot{E}x_{26} + Z_C = c_4\dot{E}x_4 + +c_{25}\dot{E}x_{25} + c_{27}\dot{E}x_{27}$	$c_5 = c_6$, $c_{24} = \ldots = c_{27}$
CDP	$c_6\dot{E}x_6 + c_{\text{w,CDP}}\dot{E}x_{\text{w,CDP}} + Z_{\text{CDP}} = c_7\dot{E}x_7$	$c_6 = c_7$
Ejector	$c_7\dot{E}x_7 + Z_{\text{eje}} = +c_8\dot{E}x_8$	$c_7 = c_8$
Glend condenser	$c_8\dot{E}x_8 + Z_{\text{GC}} = c_9\dot{E}x_9$	$c_8 = c_9$
LPH-I	$c_9\dot{E}x_9 + c_{23}\dot{E}x_{23} + Z_{\text{LPH-I}} = c_{10}\dot{E}x_{10}$	$c_9 = c_{10} = c_{23}$
LPH-II	$c_{10}\dot{E}x_{10} + c_{22}\dot{E}x_{22} + Z_{\text{LPH-II}} = c_{11}\dot{E}x_{11}$	$c_{10} = c_{11} = c_{22}$
LPH-III	$c_{11}\dot{E}x_{11} + c_{21}\dot{E}x_{21} + Z_{\text{LPH-III}} = c_{12}\dot{E}x_{12}$	$c_{11} = c_{12} = c_{21}$
LPH-IV	$c_{12}\dot{E}x_{12} + c_{20}\dot{E}x_{20} + Z_{\text{LPH-IV}} = c_{13}\dot{E}x_{13}$	$c_{12} = c_{13} = c_{20}$
DEG	$c_{13}\dot{E}x_{13} + c_{19}\dot{E}x_{19} + Z_{\text{DEG}} = c_{14}\dot{E}x_{14}$	$c_{13} = c_{14} = c_{19}$
HPH-I	$c_{14}\dot{E}x_{14} + c_{18}\dot{E}x_{18} + Z_{\text{HPH-I}} = c_{15}\dot{E}x_{15}$	$c_{14} = c_{15} = c_{18}$
HPH-II	$c_{15}\dot{E}x_{15} + c_{17}\dot{E}x_{17} + Z_{\text{HPH-II}} = c_{16}\dot{E}x_{16}$	$c_{15} = c_{16} = c_{17}$
BFP	$c_{14}\dot{E}x_{14} + c_{\text{w,BFP}}\dot{E}x_{\text{w,BFP}} + Z_{\text{BFP}} = c_{14}\dot{E}x_{14}$	$c_{14} = c_{14}$

The energy rate, physical exergy, chemical exergy, and exergy rate values of the nodal points shown in fig. 2 of the thermal power plant are given in tab. 6.

In the thermodynamic analysis of the thermal power plant, the turbines were analysed as a single turbine group; the ejector, glend condenser, and DEG were analysed as an auxiliary group, LPH-I, LPH-II, LPH-III, LPH-IV, HPH-I, and HPH-II heaters were analysed as a heater group, and the pumps were analysed as a pump group.

Based on results of the analyses, input, output, and lost energy ratios, and input, output and lost exergy ratios, and Second law efficiency values of the thermal power station units are given in tab. 7.

An examination of tab. 7 and fig. 3 in conjunction with each other indicated that the units with the lowest exergy efficiency corresponded to the condenser with 63.78% exergy efficiency and boiler with 63.84% exergy efficiency. The reason for the lower efficiency of the second law is that the pump operated in a single phase.

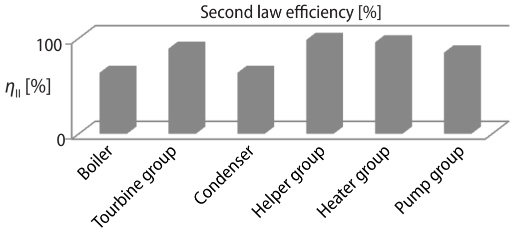

Figure 3. The Second law efficiency of the units of the power plant

As a result of these energy and exergy analyses, the input exergy, output exergy, and

Table 6. Energy and exergy balance of thermal power plants

Node	$\dot{E}$ [kW]	$\dot{E}x_{\mathrm{PH}}$ [kW]	$\dot{E}x_{\mathrm{CH}}$ [kW]	$\dot{E}x$ [kW]
1	399611.52	174349.7	291.5	174641.2
2	337935.15	123177.9	266.25	123444.2
3	375327.3	143622.7	266.25	143889
4	271237.29	69877.5	224.75	70102.25
5	200442.08	12477.9	193	12670.9
6	14868.72	230.8	193	423.8
7	14868.72	232.37	193	425.37
8	14227.96	197.63	193	390.63
9	14227.96	197.63	193	390.63
10	19061.74	542.52	199.75	742.27
11	26056.19	1320.53	207.5	1528.03
12	44061.78	4131.8	224.75	4356.55
13	58952.6	8001.56	238	8239.56
14	74413.47	12316.06	251	12567.06
15	91267.3	17483.04	266.25	17749.29
16	121508.86	27860.4	291.5	28151.9
17	31632.19	11529.75	25.25	11555
18	18512.28	6025.82	15.25	6041.07
19	15920.31	4519.94	13	4532.94
20	15868.73	3945.26	13.25	3958.51
21	19250.31	2911.39	17.25	2928.64
22	8246.62	1039.71	7.75	1047.46
23	7105.32	597.88	6.75	604.63
24	330435	31.5	7875	7906.5
25	409500	996.66	7875	88766
26	330435	31.5	7875	7906.5
27	409500	996.66	7875	8871.66

exergy losses within the units available in the power plant are shown in fig. 4. As deduced from the figure, the maximum exergy loss is observed in the boiler, and this is followed by the turbine group and condenser. Furthermore, losses in the heating group, pumping group, and auxiliary groups are relatively low.

Exergy losses and exergoeconomic factors should be jointly assessed to identify equipment that requires improvements in the power plant. The cost of exergy destruction of

Table 7. Energy and exergy balance of thermal power plant units

UNİT	$\dot{E}_{\mathrm{in}}$ [kW]	$\dot{E}_{\mathrm{out}}$ [kW]	$\dot{E}_{\mathrm{L}}$ [kW]	$\dot{E}x_{\mathrm{in}}$ [kW]	$\dot{E}x_{\mathrm{out}}$ [kW]	$\dot{E}x_{\mathrm{L}}$ [kW]	η_{II} [%]
Boiler	979834.65	858128.99	121705.66	608455.15	388498.17	219956.98	63.84
Turbine group	1046176.10	1035330.28	10845.82	388632.45	346085.60	42546.85	89.05
Condenser	861312.08	833868.72	27443.36	28483.90	18167.12	10316.78	63.78
Helper group	103969.60	102869.39	1100.21	13620.10	13381.49	238.61	98.24
Heater group	369703.46	360908.47	8794.99	63468.95	60767.60	2701.35	95.74
Pump group	8000.00	6120.00	1880.00	7000.00	5950.00	1050.00	85.00

components C [$\$\text{h}^{-1}$] and exergoeconomic factors, f, are calculated to perform thermo-economic analyses of units available within the power plant. Figure 5 shows the cost of exergy destruction of components C [$\$\text{h}^{-1}$].

A closer examination of the cost of exergy destruction of components as shown in fig. 5 indicates that the highest loss exergy cost occurs in the boiler, turbine group, and condenser, respectively. Exergoeconomic factor, f [%], values of components are provided in fig. 6.

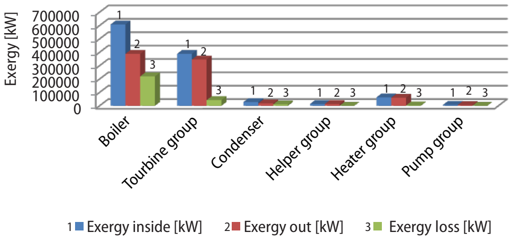

Figure 4. Exergy values of the components

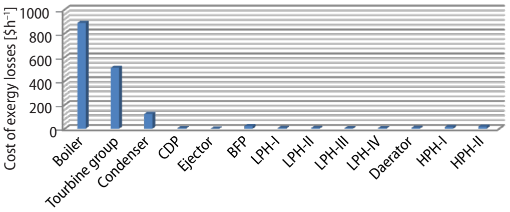

Figure 5. Cost of exergy destruction of components

An examination of fig. 6 reveals that the lowest exergoeconomic factor value corresponds to the condenser. The exergoeconomic value of the boiler is at a level such that it is possible to apply the improvements.

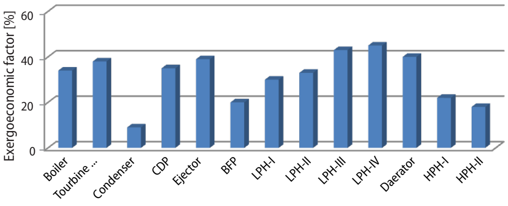

Figure 6. Exergoeconomic factor values of components

Results and conclusions

The study involved conducting exergoeconomic analysis by performing energy, exergy, and thermoeconomic analyses on the second unit of Tuncbilek thermal power plant that is still active in Turkey with respect to the laws of thermodynamics. The results obtained from the analyses are discussed below.

With respect to the energy analysis performed for the thermal power plant, the results indicate that the maximum energy loss among the units in the system occurs in the boiler. The units with the highest values of energy loss in descending order are as follows: 121705.66 kW in the boiler, 42546.85 kW in the turbine group, 10316.78 kW in the condenser, 8794.99 kW in the heater group, 1880.00 kW in the pump group, and 1100.21 kW in the auxiliary group. The ratio of the energy loss of the boiler (that is, ratio of the most energy lost in a component to the total energy loss of the system) corresponds to 70.85%.

The results of exergy analysis related to the system units indicate that the values of loss of exergy in descending order are: 219956.98 kW in the boiler, 42546.85 kW in the turbine group, 10316.78 kW in the condenser, 2701.35 kW in the heater group, 1050.00 kW in the pump group, and 238.61 kW in the helper group.

With respect to the exergoeconomic analysis, the total cost for the units with the highest loss of exergy in descending order are as follows: 448.45\$/h in the boiler, 312.92 \$/h in the turbine group, and 11.79 \$/h in the condenser. Similarly, the exergy cost distribution in descending order is: 886.86 \$/h in the boiler, 510.35 \$/h in the turbine group, and 123.67 \$/h in the condenser. The calculated exergoeconomic factor values corresponded to 33.58% in the boiler, 38.02% in the turbine group, and 8.70% in the condenser.

The results indicate that the exergoeconomic factor calculated for any system component corresponds to a low value, and this indicates that savings are achieved by reducing exergy loss. In contrast, a high exergoeconomic factor indicates that the initial investment cost of the element exceeds exergy efficiency. In this case, it is necessary to conduct studies aimed at reducing the initial investment cost of the relevant member [21]. In this context, elements in the system with maximum exergy losses correspond to the boiler, turbine group, and condenser. From the initial investment cost viewpoint, the initial investment cost of the boiler significantly exceeds that of the other units. Additionally, the exergoeconomic factor value is relatively low when compared to other units. Thus, it is necessary to first consider the boiler in the planned improvements. It is also necessary to thoroughly analyse factors that cause exergy losses in the boilers. The reason for the exergy loss in the boilers corresponds to the energy types with an irregular combustion phenomenon such as chemical energy, heat energy, and internal energy. These energy sources lose excessive amounts of energy during conversion. The high efficiency of the boiler is a significant factor that influences the performance of the system. In order to reduce energy losses in the boiler, it is necessary to prevent the formation of layers on the inner and outer surfaces of the pipes that obstruct heat transfer to prevent the discharge of the obtained heat through the flue gas. A factor that directly affects the efficiency of the boiler corresponds to the amount of air necessary for combustion. It is important to determine the optimal value of the air excess co-efficient during ignition. Therefore, it is essential to revise fresh air fans and to consider an automatic control technique. The loss of exergy in the turbine group is very low when compared to that of the boiler. Improvements to the turbine group will increase turbine efficiency, increase the availability of intermediate steam from the turbine stages, and increase the efficiency of the front heaters. However, it should be noted that the exergoeconomic factor of the turbine group is significantly high when compared with that of other equipment. Improvements in the turbine group will improve the performance of the equipment and will increase the cost of the system. Therefore, it is possible to optimize the intermediate steam obtained from the best improvement turbine without increasing the turbine cost and to thereby increase system efficiency. The situation is different for condensers that play a substantial role in conversion. They are characterized by irreversibility and high energy losses. Additionally, the exergoeconomic factor can reach a minimum of 9%, and this indicates that improvements that are considered for the condenser may not significantly increase investment costs of the system. The energy and exergy loss-related shares of other equipment within the system are low, and thus improvements applied to these types of equipment will not significantly contribute to system performance and could lead to an increase in the costs.

In the study, the results of energy and exergy analyses indicate that improvements with respect to a power plant increase performance and decrease the amount of fuel required. This eliminates the degree of environmental pollution caused by hazardous gases released due to burning. Analyses also underline that if in thermal power plants costs are examined in improvements will be beneficial in increasing the efficiency in plants. Hence, it is necessary to perform exergy analyses in planned power plants and to increase the performance of the power plant to optimal values in order to decrease operational costs of thermal power plants and eliminate environmentally hazardous gas emissions.

Nomenclature

$\dot{C}$ – exergy cost [$\$\text{h}^{-1}$]
c – unit exergy cost, [$\$\text{kJ}^{-1}$]
E – energy, [kJ]
$\dot{E}$ – flow of energy, [kW]
$\dot{E}_\text{L}$ – exergy loss, [kW]
$\dot{E}x$ – exergy rate, [kW]
$\dot{E}x_\text{L}$ – exergy loss, [kW]
Ex_CH – chemical exergy, [kJ]

Ex_{PH} – physical exergy, [kJ]
f – exergoeconomic factor
h – entalpy, [kJkg^{-1}]
ke – kinetic energy
$\dot{m}$ – mass-flow, [kgs^{-1}]
pe – potential energy
Q – heat energy, [kJ]
$\dot{Q}$ – heat flux, [kW]
s – entropy for unit mass, [kJkg^{-1}K^{-1}]
W – work, [kJ]
$\dot{W}$ – power, [kW]
$\dot{W}_{\mathrm{T}}$ – total power from turbine group, [kW]
y_{L} – energy loss rate
$\dot{Z}$ – cost rate associated with capital investment, [\$h^{-1}]

Greek symbol

η – efficiency, [%]

Acronyms

BFP – boiler feed pump
CDP – condenser discharge pump
DEG – daerator, degasser
HPH – high pressure feed water heater
HPT – high pressure turbine
IPT – intermediate pressure turbine
LHV – lower heat value of fuel
LPH – low pressure feed water heater
LPT – low pressure turbine

Subscripts and superscripts

B – boiler
C – condenser
CH – chemical
D – daerator, degasser
E – ejector
e – exit
F – fuel
FG – flue gas
GC – glend condenser
i – input
k – levelised price correction factor, component
L – loss
o – output, reference environment
PH – physical
q – heat
w – work
T – turbine group, total

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