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Comparative energetic and exergetic performance analyses for coal-fired thermal power plants in Turkey

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A R T I C L E I N F O

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The purpose of this study is to analyze comparatively the performance of nine thermal power plants under control governmental bodies in Turkey, from energetic and exergetic viewpoint. The considered power plants are mostly conventional reheat steam power plant fed by low quality coal. Firstly, thermodynamic models of the plants are developed based on first and second law of thermodynamics. Secondly, some energetic simulation results of the developed models are compared with the design values of the power plants in order to demonstrate the reliability. Thirdly, design point performance analyses based on energetic and exergetic performance criteria such as thermal efficiency, exergy efficiency, exergy loss, exergetic performance coefficient are performed for all considered plants in order to make comprehensive evaluations. Finally, by means of these analyses, the main sources of thermodynamic inefficiencies as well as reasonable comparison of each plant to others are identified and discussed. As a result, the outcomes of this study can provide a basis used for plant performance improvement for the considered coal-fired thermal power plants.

1. Introduction

The amount of energy consumption is one of the most important indicator showing the development stages of countries and living standards of communities. Population increment, urbanization, industrializing, and technologic development result directly in increasing energy consumption. As a parallel, this rapid growing trend brings about the crucial environmental problems such as contamination and greenhouse effect. Currently, 80% of electricity in the world is approximately produced from fossil fuels (coal, petroleum, fuel-oil, natural gas) fired thermal power plants (TPPs), whereas 20% of the electricity is compensated from different sources such as hydraulic, nuclear, wind, solar, geothermal and biogas [1].

In Turkey, although the share of TPPs generating electricity is approximately 61% within the total installed power, its ratio at the compensation of electricity demand is about 80% (39.5% natural gas, 32.6% coal and 7.9% fuel-oil) [2]. Nowadays, 50% of the amount of electricity generated from TPPs is depended on imported fuel sources, especially natural gas. If the importing increment continuous as the rate of the last decade, it is expected that the imported fuel share will be 76% at 2020 [3]. It is obvious that the main solution of this problem is efficiently utilization of the domestic fuel sources. For Turkey, coal is an essential domestic source that the predicted reserve is 8 billion metric tons, ranking Turkey seventh largest in the world [4]. Accordingly, enhancing the performances of coal-fired TPPs is a crucial objective in terms of economic, energy policy, national security, fuel reserve, and environmental concerns. In relation to this issue, a study revealing the performance conditions of existing coal-fired TPPS will be the first step for determining efficient ways of better performance.

Generally, performances of thermal power plants are evaluated through energetic performance criteria based on First Law of Thermodynamics, which are electrical power and thermal efficiency. In recent decades, exergetic performance analysis based on Second Law of Thermodynamics has found as useful method in the design, evaluation, optimization and improvement of thermal power plants [5–8]. Exergetic performance analyses can not only determine magnitudes, location and causes of irreversibilities in the plants, but also provide more meaningful assessment of plant individual components' efficiency [9,10]. These points of exergetic performance analyses are the basic differences from energetic

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Nomenclature

$\dot{E}x$	exergy transfer rate (kW)
$\dot{e}x$	specific exergy (kJ kg^{-1})
$\dot{E}x_D$	exergy destruction rate (kW)
h	enthalpy (kJ kg^{-1})
LHV	lower heat value (kJ kg^{-1})
$\dot{m}$	mass flow rate (kg s^{-1})
s	entropy (kJ kg^{-1} K^{-1})
T	temperature (K or °C)
$\dot{W}$	electrical power output (kW)
$\dot{Q}$	heat transfer rate (kW)

Greek letters

η	efficiency
ζ	exergetic performance coefficient

Subscripts

B	boiler
C	condenser
fw	feed water
in	inlet
out	outlet
P	pump
rh	reheat
s	steam
sh	superheat
T	turbine
th	thermal

performance analyses. Therefore, it can be said that performing exergetic and energetic analyses together can give a complete depiction of system characteristics. Such a comprehensive analysis will be a more convenient approach for performance evaluation and determination of the steps towards to improvement direction.

In the literature, there exist a number of papers concerning energetic and exergetic performances of coal-fired thermal power plants [11–20]. For instance, Bhatt and Rajkumar [11] presented different ways of enhancing the performance of the coal-fired thermal power plants. Aljundi [12] determined the location of the most energy and exergy losses for Al-Hussein thermal power plant in Jordan through the energy and exergy analyses and, investigated the effects of variation of the reference ambient conditions on exergetic performance. Oktay [13] analyzed the irreversibilities, exergy efficiency and improvement factors of plant components (boiler, steam turbines, pumps, etc.) for a fluidized bed 2 × 160 MW thermal power plant in Turkey. Srinivas [14] attempted an analysis for a Rankine cycle based thermal power plant with feed water heaters from both first law and second law point. He investigated the effect of number of feed water heaters and other operating parameters on the performance by generalizing the procedure. Kopac and Hilalci [15] calculated heat losses from energy analysis and analyzed exergy losses of the plant at different ambient temperatures from exergy analysis. Rosen [16] made a thermodynamic comparison of coal-fired and nuclear electrical generating stations using energy and exergy analyses. Rosen and Raymond [17] carried out energy and exergy analyses for a coal-fired steam power plant and evaluated possible modifications to improve the efficiency of the plant. Dincer and Al-Muslim [18] conducted a thermodynamic analysis for a Rankine cycle reheat steam power plant. In these studies, the analyses were carried out for a single power plant. Moreover, it is seen from these studies contents that different definitions for a specific performance criterion are used. For example, lower heating values of fuels are used in the definition of thermal efficiency while some of them use the higher heating values. In addition, it is observed that the definition of exergy efficiency for components is different. Furthermore, since companies designing power plant use generally gross electricity power instead of net electricity power in the thermal efficiency calculation, it is possible that there are important difference between the analysis results in the literature and information of the companies. In fact, there is confusion on this subject and the difficulties related to definitions of performance criteria were emphasized by some researchers [21–23]. They examined and discussed the views regarding efficiency, loss and exergy based performance measures.

Keeping in view the facts stated above, it can be expected that performing an analysis based on the same definition of performance criteria will be meaningful for performance comparisons, assessments and improvement for thermal power plants. Additionally, considering both of energetic and exergetic performance criteria together can guide the ways of efficient and effective usage of coal resources because of taking into account the quality and quantity of the energy used to generate electricity power in TPPs. For these reasons, the purpose of this study presented here is to carry out energetic and exergetic performance analyses, at the design conditions, for the existing nine coal-fired thermal power plants under control governmental bodies in Turkey in order to identify the needed improvement. For performing this aim, thermodynamic models for the considered power plants are developed on the basis of mass, energy and exergy balance equations. The thermodynamic models are simulated and the simulation results are compared with values at design conditions of the TPPs for model validation. Then, the defined energetic and exergetic performances are determined for the all plants. In the direction of the comprehensive analysis results, the requirements for performance improvement are evaluated.

2. Characteristics of the considered coal-fired thermal power plants

The coal-fired thermal power plants under control governmental bodies in Turkey have been considered in this study. For these coal-fired TPPs, the technical data are summarized in Table 1. The installed capacity of the considered coal-fired thermal power plant is about 6426 MW. The average age of these power plants is above 15 years. All of these plants were established as sub-critical steam conditions. The power plants use generally low quality coal (lignite). The main steam pressure and temperature conditions for these power plants are the range of 127.5–172 bar and 530–545 °C, respectively. The feed water to boiler is heated up to 215–257 °C in a 5–8 stage feed-water preheating systems.

3. Analysis methodology

3.1. Modeling approach

In order to analyze the energetic and exergetic performances, thermodynamic models are developed using zero-dimensional approach for each investigated coal-fired thermal power plant in the scope of this study. One unit of each power plant is considered in the modeling process. In the model development, the continuous

Table 1
Technical data of the coal-fired power plants for design conditions in Turkey.

Technical data	Coal-fired power plants[a]										
	Ya-PP	Ke-PP	Ye-PP	Se-PP	Can-PP	Ca-PP	Ka-PP	AE-PP	Or-PP	So-PP	Tu-PP
Total Power (MW)	630	630	420	600	320	300	457	1440	210	990	429
Unit number	3	3	2	4	2	2	3	4	1	6	5
Unit Power (MW)	210	210	210	150	160	150	157	360	210	165	160.9
Main steam pressure (bar)	127.5	127.5	127.5	134.9	172	136.3	133.4	167.7	127.5	139.26	133.4
Main steam temperature (°C)	535	535	535	540	540	538	535	538	540	540	535
Main steam flowrate (t/h)	636	636	636	535	456.2	480	480	1037	632	525	500
Reheat pressure (bar)	22.36	22.36	22.36	37.28	39.7	39.33	36.35	37.27	25.5	31.38	36.29
Reheat temperature (°C)	535	535	535	535	540	538	535	538	540	540	535
Reheat flowrate (t/h)	532.7	532	532.7	390	405.6	415	410.5	920.9	567.97	448	38.5
Low/high pressure pre-heater number	5/3	5/3	5/3	4/2	4/2	3/2	3/2	5/2	5/3	4/2	5/2
Condenser temperature (°C)	39.4	39.4	39.4	37.6	42.7	38.7	35.75	38.7	45	38	38.6
Condenser cold water temperature (°C)	27	20	27	27	30.7	22	24	22	24	27	27
Condenser cold water flowrate (t/h)	33,000	32,000	32,000	23,000	15,800	20,000	18,500	26,410	27,500	22,600	22,000
Flue gas temperature (°C)	160	160	160	150	138	157	159	155	160	157	160
Coal type	Lignite	Lignite	Lignite	Lignite	Lignite	Hard coal	Lignite	Lignite	Lignite	Lignite	Lignite
LHV (kJ/kg)	7326	7326	7326	7326	10,884	12,979	5442	4814	9628	6280	9210

[a] Ya-Yatagan; Ke-Kemerkoy, Ye-Yenikoy; Se-Seyitomer; Can-Can; Ca-Catalagzi; Ka-Kangal; AE-Afsin Elbistan; Or-Orhaneli; So-Soma; Tu-Tuncbilek.

mass flow diagrams of the mentioned power plants are formed by using the information obtained from both plants' managers and on-site investigations. In these diagrams, the mass flow lines in the continual working condition of the plants are drawn. As shown in Fig. 1, a continuous mass flow diagram for one unit of any power plant modeled in this study includes the main components such as high, intermediate and low pressure turbine groups (HPT, IPT and LPT, respectively), a boiler (B), several pumps (P), a dearetor (D), a generator (G), a condenser (C), low and high pressure feed water heater groups (LPH and HPH, respectively). The thermodynamic models are based on fundamental mass, energy and exergy balance principles. By using the balance equations for each component in the power plant model, it is possible to compute energy and exergy terms such as turbine work outputs, pump power consumptions, boiler heat requirements, energy and exergy flows at each node of the plants, component exergy efficiencies, irreversibilities in the plants, and so on. The background information of energetic and exergetic analysis is presented in the following subsections. The whole power plant models are developed on the basis of the following assumptions. i) Plant performances at design conditions are evaluated, ii) Each component in the power plant model is considered as a single control volume, iii) Each component works under steady-state conditions, iv) Ideal gas principles are considered for all gas components, v) Kinetic and potential energy terms

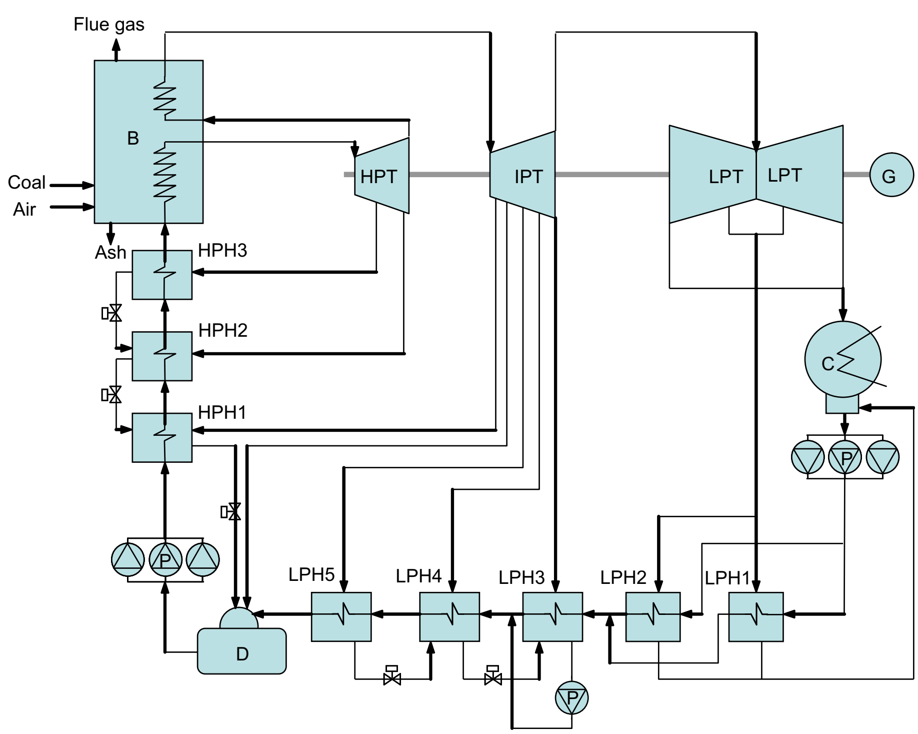


Fig. 1. Simplified mass flow diagram for one of the investigated coal-fired thermal power plants.

and their exergy effects are neglected, vi) Environment temperature and pressure are 25 °C and 1.013 bar, vii) Temperature difference between the component control volumes and immediate surroundings is neglected.

3.2. Energetic performance analysis

Energetic performance analysis is based on first law of thermodynamics. According to first law of thermodynamics, the main performance criteria are commonly power output and thermal efficiency. These parameters are also decisive performance criteria in the economic analysis of power plants. In this analysis, the input and output values of the plant components can be determined using the measured/calculated thermodynamic variables such as enthalpy, pressure, temperature, entropy, mass flow rate and quality. Accordingly, the power output of a steam turbine is calculated as follows:

$$\dot{W}_T = \dot{m}_{in}(h_{in} - h_1) + (\dot{m}_{in} - m_1)(h_1 - h_2) + (\dot{m}_{in} - \dot{m}_1 - \cdots - \dot{m}_n)(h_n - h_{out}) \tag{1}$$

where, the subscripts of 1,2,...n represent the number of steam extraction in the steam turbine. As internal power consumption in the plants, only the power consumed by pumps is considered in the model. The calculation of pump power can be simply given as following:

$$\dot{W}_P = \dot{m}(h_{out} - h_{in})/\eta_P \tag{2}$$

where, η_P is pump efficiency. Net electrical power output is given by:

$$\dot{W}_{Net} = \sum \dot{W}_T - \sum \dot{W}_P \tag{3}$$

The total required heat energy in the boiler can be determined from:

$$\dot{Q}_B = [\dot{m}_{sh}(h_{sh,out} - h_{sh,in}) + \dot{m}_{rh}(h_{rh,out} - h_{rh,in})]/\eta_B \tag{4}$$

where, the subscripts of sh and rh indicate superheat and reheat conditions, respectively. Also, η_B denotes the boiler efficiency. The boiler inlet enthalpy ($h_{sh,in}$) in Eq. (4) is calculated from energy balance equation for feed water heater:

$$(\dot{m}_s h_s)_{in} + (\dot{m}_{fw} h_{fw})_{in} = (\dot{m}_s h_s)_{out} + (\dot{m}_{fw} h_{fw})_{out} \tag{5}$$

where, s and fw are subscripts representing steam and feed water, respectively. Also, it can be noted that the outlet temperatures of other feed water heaters are determined as the approach in Eq. (5). The thermal efficiency of the power plants can be calculated as follows:

$$\eta_{th} = \frac{\dot{W}_{Net}}{\dot{m}_{coal} \text{LHV}} \tag{6}$$

where, LHV is lower heating value of coal. $\dot{m}_{coal}$ is coal flow rate and it is found as below:

$$\dot{m}_{coal} = \frac{\dot{Q}_B}{\text{LHV}} \tag{7}$$

3.3. Exergetic performance analysis

Exergetic performance analysis is based on second law of thermodynamics. The results obtained from such an analysis can be used as a guide for diminishing the irreversibilities in the power plants and thereby enhancing their performances. In fact, exergy is a thermodynamic indicator that shows the transformation potential and convertible limit of an energy carrier to maximum theoretical work under the conditions imposed by an environment at given pressure and temperature [9,10]. In the scope of this exergetic performance analysis study, exergy efficiency and exergy destruction rate of both plant and plant component are determined. In addition, exergy losses per unit power output in the plants are defined and used as a new exergetic performance criterion.

For control volume of any plant component at steady-state conditions, a general equation of exergy destruction rate derived from the exergy balance can be given as [9,10]:

$$\dot{E}x_D = \sum (\dot{E}x)_{in} - \sum (\dot{E}x)_{out} + \left[\sum \left(\dot{Q}(1 - \frac{T_o}{T}) \right)_{in} - \sum \left(\dot{Q}(1 - \frac{T_o}{T}) \right)_{out} \right] \pm \dot{W} \tag{8}$$

where the first two terms of right hand side represent exergy of streams entering and leaving the control volume. The third and fourth terms are the exergy related to heat transfer by heat. T_o is the environment temperature of the system's surroundings and $\dot{Q}$ represents heat transfer rate across the boundary of the system at a constant temperature of T. The last term is work transfer rate to or from the control volume.

In this study, only physical exergy by mass flows crossing the control volume is considered and given as [9,10]:

$$\dot{E}x = \dot{m}[(h - h_o) - T_o(s - s_o)] \tag{9}$$

where, h and s represent specific enthalpy and entropy, respectively.

In the exergetic performance analysis, exergy efficiency gives a measure of the performance of a system or a component. Exergy efficiency of the components in the investigated power plants is defined based on *product* and *fuel* approach given in the literature. The *fuel* represents the net exergy resources spent in this component for generating the product while the *product* indicates the desired purpose of including the component into the power plant [9]. Accordingly, exergy destruction and exergy efficiency of the main component in a coal-fired power plant are given in Table 2.

Total exergy destruction rate in the plant can be determined as sum of exergy destruction rates of components:

$$\dot{E}x_{D,total} = \sum \dot{E}x_{D,i} = \dot{E}x_{D,B} + \dot{E}x_{D,T} + \dot{E}x_{D,C} + \dot{E}x_{D,P} + \dot{E}x_{D,H} \tag{10}$$

For the whole thermal power plant, the exergy efficiency can be given as:

$$\eta_{Ex} = \frac{\dot{W}_{Net}}{\dot{m}_{coal} \cdot ex_{coal}} \tag{11}$$

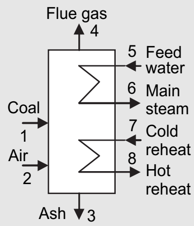
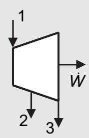
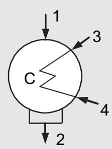
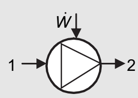
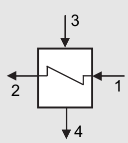
where, ex_{coal} is specific exergy of coal used in the plant. Its value is very changeable depending on coal chemical compounds. The coal specific exergy is determined based on the studies [24].

The other important exergetic performance criterion defined in this study is the amount of exergy loss rate per unit power output and it can be written as following equation:

$$\zeta = \frac{\dot{E}x_{D,total}}{\dot{W}_{Net}} \tag{12}$$

By considering energetic and exergetic performance criteria in the analysis, enhanced plant assessment can be carried out and thus comprehensive information required for performance improvement will be obtained.

Table 2
Exergetic performance equations for main components of a thermal power plant.

Component name	Component figure	Exergy destruction rate	Exergy efficiency
Boiler		$\dot{E}x_{D,B} = \dot{E}x_1 + \dot{E}x_2 + \dot{E}x_5 + \dot{E}x_7 - \dot{E}x_3 - \dot{E}x_4 - \dot{E}x_6 - \dot{E}x_8$	$\eta_{Ex,B} = (\dot{E}x_6 - \dot{E}x_5) + (\dot{E}x_8 - \dot{E}x_7)/(\dot{E}x_1 + \dot{E}x_2) - (\dot{E}x_3 + \dot{E}x_4)$
Turbine		$\dot{E}x_{D,T} = \dot{E}x_1 - \dot{E}x_2 - \dot{E}x_3 - \dot{W}$	$\eta_{Ex,T} = \dot{W}/\dot{E}x_1 - \dot{E}x_2 - \dot{E}x_3$
Condenser		$\dot{E}x_{D,C} = \dot{E}x_1 + \dot{E}x_3 - \dot{E}x_2 - \dot{E}x_4$	$\eta_{Ex,C} = \dot{E}x_4 - \dot{E}x_3/\dot{E}x_1 - \dot{E}x_2$
Pump		$\dot{E}x_{D,P} = \dot{E}x_1 + \dot{W} - \dot{E}x_2$	$\eta_{Ex,P} = \dot{E}x_2 - \dot{E}x_1/\dot{W}$
Feed water heater		$\dot{E}x_{D,H} = \dot{E}x_1 + \dot{E}x_3 - \dot{E}x_2 - \dot{E}x_4$	$\eta_{Ex,H} = \dot{E}x_2 - \dot{E}x_1/\dot{E}x_3 - \dot{E}x_4$

4. Results and discussion

For nine power plants mentioned in Table 1, the computational models based on their thermodynamic models are developed using Engineering Equation Solver software [25]. Yenikoy power plant (Ye-PP) and Kemerkoy power plant (Ke-PP) are not included to the analysis in that the technical characteristics of these plants are similar to that of Yatagan power plant (Ya-PP). The developed plant models are simulated for carrying out the energetic and exergetic performance analyses.

Initially, some energetic simulation results based on the developed models are compared with the design values of the power plants in order to show the models' accuracy. As given in Table 3, the simulation results of the developed models are demonstrated to supply very accurate and reliable results. Comparisons between the actual design and simulated results show that the differences are very small for all the plants. For instance, the error percentages for power outputs of the plants are within the range of 0.11–5.06%. Thus we can state the models are useful tool to analyze the performances of thermal power plants.

Table 3
Comparison of some design data with simulation results for the thermal power plants.

Parameters		Power plants[a]								
		Ya-PP	Se-PP	Can-PP	Ca-PP	Ka-PP	AE-PP	Or-PP	So-PP	Tu-PP
FW Temp at boiler inlet (°C)	Design	243	248	247	240	248	252.2	243	234	245
	Simulation	229.7	246.7	248.6	227.7	249.6	255.4	234.7	238.8	250.3
	Error (%)	5.4	0.52	0.6	5.12	0.64	1.26	3.41	2.01	2.16
FW Temp at deaerator inlet (°C)	Design	144	133	151.3	133.5	133.4	129.9	144	122.5	148.9
	Simulation	139.1	132	147.4	130.9	134.5	136.8	142.4	127.5	149.5
	Error (%)	3.4	0.75	2.58	1.94	0.83	5.31	1.11	3.92	0.4
Net power output (MW)	Design	210	150	160	150	157	360	210	165	160.9
	Simulation	216.94	153.6	159.83	157.59	158.75	370.70	216.20	166.84	157.82
	Error (%)	3.33	2.37	0.11	5.06	1.12	2.97	2.95	1.12	1.91

[a] Ya-Yatagan; Ke-Kemerkoy, Ye-Yenikoy; Se-Seyitomer; Can-Can; Ca-Catalagzi; Ka-Kangal; AE-Afsin Elbistan; Or-Orhaneli; So-Soma; Tu-Tuncbilek.

Table 4
Energetic performance results of the thermal power plants.

		Power plants[a]								
		Ya-PP	Se-PP	Can-PP	Ca-PP	Ka-PP	AE-PP	Or-PP	So-PP	Tu-PP
Heat supplied to boiler (kW)		586,142	403,819	379,443	416,020	426,887	869,336	574,519	462,415	410,539
Turbines power output (kW)	HPT	69,406	43,553	45,412	39,002	52,815	103,054	63,986	47,090	39,552
	IPT	107,742	68,225	60,896	52,054	70,277	163,107	109,558	73,659	62,762
	LPT	44,824	45,000	58,778	70,207	39,909	98,506	47,263	50,169	59,660
	Total	221,972	156,778	165,085	161,263	163,000	371,276	220,807	170,917	161,974
Power consumption of pumps (kW)	CPs	365.7	226	400	163	273.5	374.9	228.6	279.7	461
	2.CPs	63.1	36.6	43.9	27	31.54	200.8	24.02	17.1	–
	FWPs	4606	2955	4817	3479	3942	8746[b]	4354	3781	3692
	Total	5034.8	3217.6	5260	3670	4247	575.7	4606.8	4078	4153
Heat transfer rate at low pressure heaters (kW)	1	8679	10,106	4013	12,501	13,953	29,864	11,044	9959	4737
	2	20,043	13,178	4815	15,182	15,722	22,764	19,174	9169	13,865
	3	12,801	13,446	15,807	13,762	12,845	20,305	13,732	10,366	13,266
	4	10,285	–	13,265	–	–	18,923	16,890	11,018	19,937
	5	–	–	–	–	–	40,282	7956	–	–
	Total	51,808	36,725	37,900	41,445	42,520	132,139	68,795	40,512	51,805
Heat transfer rate at high pressure heaters (kW)	1	17,591	21,758	15,872	8937	19,598	44,786	14,286	14,044	17,920
	2	36,800	5153	20,068	35,090	27,608	51,271	29,624	39,234	28,803
	3	24,184	–	–	–	–	–	15,655	–	–
	Total	78,575	26,911	35,940	44,027	47,206	96,057	59,565	53,278	48,723
Rejected heat rate from condenser (kW)		275,888	199,116	196,615	205,455	205,961	400,659	278,542	209,487	199,616
Thermal efficiency (%)		37.01	38.03	42.12	37.88	37.19	42.64	37.63	36.08	38.44

[a] Ya-Yatagan; Ke-Kemerkoy, Ye-Yenikoy; Se-Seyitomer; Can-Can; Ca-Catalagzi; Ka-Kangal; AE-Afsin Elbistan; Or-Orhaneli; So-Soma; Tu-Tuncbilek.
[b] This power consumption of the pumps is compensated from extra turbine.

With using the developed model, energetic performances such as thermal efficiency, net power output, power generation and consumption at related components are computed and the results are given in Table 4. When Tables 1 and 4 are examined together, it is seen that Can (Can PP) and Afsin Elbistan (AE-PP) are the highest thermal efficiency in the considered power plants because of their higher boiler outlet pressure (170–172 bar) than those of other plants. In addition, we can observe from these tables that the thermal efficiencies of the plants having lower boiler outlet pressure (130–136 bar) is within the range of 36–38%. It is certain that general plant performance is based on plant component performances. Therefore, in order to increase general plant performance, it is important to determine which components are primarily considered in the improvement order. However, for enhancing general plant performance, taking decisions depended on only energetic performance results cannot be healthy and reliable. For example, by considering the information in Table 4 with Table 6 together, it is clearly seen that although the waste heat in the condenser is considerably high, its exergetic value (in other words its quality) is significantly low. This fact confirms that only energetic analysis is not adequate to reveal explicit presentation of plant performance. Therefore, the results obtained from energetic performance analysis should be considered with those of exergetic performance analysis allowing an improved comprehension by quantifying the effect of irreversibility occurring in the plant along with its location.

Fuel exergy, plant exergy efficiency, total exergy loss rate, exergy loss rate per unit power output at design conditions are presented in Table 5 for investigating each plant. The most two important performance criteria in terms of exergetic analysis are exergy efficiency (η_{Ex}) and exergetic performance coefficient (ζ). Exergetic performance of the power plants increases with reduction of the exergetic performance coefficient and increment of exergy efficiency. As shown in Table 5, the best plant performance with regard to exergetic performance coefficient coincides with that of exergy efficiency. Hence, either exergetic performance coefficient or exergy efficiency can be used as exergetic performance criterion. On the other hand, the exergy efficiency gives about the necessary fuel exergy input in order to produce certain exergy output while exergetic performance coefficient gives information about the exergy losses. For that reason, taking into account these two criteria together in the analysis can provide the information concerning not only plant exergy output but also plant exergy losses. The values of exergetic performance coefficients vary between 1.5 and 3.04 for the studied power plants while their values of exergy efficiency change within the range of 28.55–37.88%. According to considered exergetic performance criteria (η_{Ex} and ζ), the plant having the highest exergetic performance is Can thermal power plant.

Component exergy efficiency, component exergy destruction rate and its ratio within total exergy destruction rate ($R_{Ex,D}$) of the investigated thermal power plants are given in Table 6. The results given in this table explain why Can power plant has the best performance; exergy efficiency of the boiler having circulating fluidized bed combustor technology is the highest value in all plant boilers. The most important reason is that the boiler of Can power plant has higher steam pressure than those of other plants. When

Table 5
Exergetic performance results of the thermal power plants.

Performance	Power plants[a]								
	Ya-PP	Se-PP	Can-PP	Ca-PP	Ka-PP	AE-PP	Or-PP	So-PP	Tu-PP
Fuel exergy (kW)	679,069	487,508	421,891	447,888	556,058	1,142,127	609,204	515,690	476,981
Total exergy loss (kW)	470,245	466,458	239,770	270,288	374,103	728,917	380,256	326,688	286,785
Exergy loss per unit power (–)	2.17	3.04	1.50	1.72	2.356	1.97	1.76	1.96	1.82
Exergy efficiency (%)	31.95	31.50	37.88	35.19	28.55	32.46	35.49	32.35	33.09

[a] Ya-Yatagan; Ke-Kemerkoy, Ye-Yenikoy; Se-Seyitomer; Can-Can; Ca-Catalagzi; Ka-Kangal; AE-Afsin Elbistan; Or-Orhaneli; So-Soma; Tu-Tuncbilek.

Table 6
Exergetic performance results for the main components of the thermal power plants.

Components		Power plants									
		Components title	Ya-PP	Se-PP	Can-PP	Ca-PP	Ka-PP	AE-PP	Or-PP	So-PP	Tu-PP
Boiler		η_{Ex} (%)	40.84	36.75	48.23	45.47	36.45	39.00	45.77	41.43	44.00
		$\dot{E}x_D$ (kW)	394,906	440,525	214,781	238,529	344,557	680,012	325,161	294,721	256,923
		$R_{Ex,D}$ (%)	83.98	94.44	89.57	88.25	92.10	93.29	85.51	90.21	89.57
Turbines	HPT	η_{Ex} (%)	68.13	96.75	84.85	90.32	90.86	94.22	90.51	85.12	88.32
		$\dot{E}x_D$ (kW)	32,464	1461	8108	4180	4016	6322	6711	8229	5232
		$R_{Ex,D}$ (%)	6.90	0.31	3.38	1.55	1.07	0.867	1.76	2.52	1.83
	IPT	η_{Ex} (%)	92.02	95.98	96.12	88.93	92.94	97.89	90.97	89.99	93.85
		$\dot{E}x_D$ (kW)	9347	2859	2459	6480	5337	3520	10876	8192	4109
		$R_{Ex,D}$ (%)	1.99	0.61	1.02	2.40	1.43	0.483	2.86	2.51	1.44
	LPT	η_{Ex} (%)	80.1	85.45	90.03	88.6	84.19	86.16	64.42	86	86.36
		$\dot{E}x_D$ (kW)	11,139	7662	6510	9030	9920	15,828	26,101	8166	9422
		$R_{Ex,D}$ (%)	2.37	1.64	2.71	3.34	2.65	2.37	6.86	2.5	3.29
Pumps	CP	η_{Ex} (%)	60.66	81.49	60.82	67.37	41.24	78.73	90.68	65.67	65.91
		$\dot{E}x_D$ (kW)	143.9	41	156.7	53.42	160.7	79.76	21.3	96.02	157
		$R_{Ex,D}$ (%)	0.03	0.01	0.06	0.02	0.04	0.011	0.005	0.03	0.05
	2.CP	η_{Ex} (%)	64	83.29	63.99	66.82	58.91	78.74	92.42	67.77	–
		$\dot{E}x_D$ (kW)	22.99	6.12	15.62	8.957	12.96	42.68	1.82	5.58	–
		$R_{Ex,D}$ (%)	0	0	0	0	0	0.006	0	0	–
	FWP	η_{Ex} (%)	60.85	86.53	58.83	69.78	60.5	78.51	75.03	70.36	52.35
		$\dot{E}x_D$ (kW)	1803	398	1983	1051	1557	1879	1087	1121	1759
		$R_{Ex,D}$ (%)	0.38	0.09	0.82	0.39	0.42	0.258	0.28	0.34	0.61
Low pressure heaters	1	η_{Ex} (%)	86.61	77.43	90.97	69.52	67.37	81.47	65.72	85.48	73.29
		$\dot{E}x_D$ (kW)	2143	405.2	56.29	760.4	795.1	942.7	565.3	200.7	233.5
		$R_{Ex,D}$ (%)	0.46	0.09	0.02	0.28	0.21	0.13	0.14	0.06	0.08
	2	η_{Ex} (%)	75.97	84.63	81.27	81.83	83.66	92.33	68.15	90.49	81.29
		$\dot{E}x_D$ (kW)	1200	504	171.3	670.4	627.1	371.8	1525	162.7	560.8
		$R_{Ex,D}$ (%)	0.26	0.11	0.07	0.25	0.16	0.05	0.4	0.05	0.2
	3	η_{Ex} (%)	87.78	73.95	79.43	86.02	88.83	94.38	79.57	91.21	87.89
		$\dot{E}x_D$ (kW)	452.2	1170	871.4	523	432.1	293.6	833.3	212.5	422.4
		$R_{Ex,D}$ (%)	0.1	0.25	0.36	0.19	0.11	0.04	0.21	0.07	0.15
	4	η_{Ex} (%)	97.3	–	97.49	–	–	94.6	80.71	92.19	87.27
		$\dot{E}x_D$ (kW)	115.6	–	112.4	–	–	302.7	1142	221.7	731.5
		$R_{Ex,D}$ (%)	0.02	–	0.04	–	–	0.04	0.3	0.07	0.26
	5	η_{Ex} (%)	–	–	–	–	–	85.53	85.31	–	–
		$\dot{E}x_D$ (kW)	–	–	–	–	–	3641	1021	–	–
		$R_{Ex,D}$ (%)	–	–	–	–	–	0.5	0.26	–	–
High pressure heaters	1	η_{Ex} (%)	93.32	90.74	89.54	87.47	90.93	91.84	86.33	92.4	93.95
		$\dot{E}x_D$ (kW)	395	775.1	720.2	506.2	734.3	1548	777.2	437.7	403.8
		$R_{Ex,D}$ (%)	0.08	0.17	0.3	0.19	0.2	0.212	0.2	0.13	0.14
	2	η_{Ex} (%)	99.88	93.92	95.35	87.46	93.24	95.75	88.81	93.6	93.71
		$\dot{E}x_D$ (kW)	14.27	655.8	421.7	1453	848.1	986.5	1434	822.1	598.5
		$R_{Ex,D}$ (%)	0	0.14	0.17	0.54	0.22	0.135	0.37	0.25	0.21
	3	η_{Ex} (%)	99.2	–	–	–	–	–	91.27	–	–
		$\dot{E}x_D$ (kW)	63.25	–	–	–	–	–	627.1	–	–
		$R_{Ex,D}$ (%)	0.01	–	–	–	–	–	0.16	–	–
Condenser		η_{Ex} (%)	62.72	47.33	80.22	54.72	62.65	59.74	68.98	74.01	58.45
		$\dot{E}x_D$ (kW)	16,036	9996	3403	7403	5106	13,147	2371	4100	6232
		$R_{Ex,D}$ (%)	3.41	2.14	1.42	2.61	1.36	1.80	0.62	1.26	2.18

Tables 5 and 6 are examined together, it is understood that the effect of boiler performance, indicating higher exergy losses than other components, on the overall plant exergy efficiency is significant. It can be concluded that the boilers are vital components needed to be investigated principally for enhancing plants' overall exergetic performance.

5. Conclusion

In this study, performance analyses and comparison of nine coal-fired power plants in Turkey have been performed at design conditions by means of energetic and exergetic methods. In the analyses, the developed model for each power plant using the mass, energy and exergy balance equations, and system and component performance criteria such as thermal efficiency, exergy efficiency, exergy destruction have been determined and compared with each other. Considering energetic and exergetic performance methods together can enable the designer to quickly locate and evaluate the inefficiencies in the process. Comprehensive discussions on the analysis results have been made. As a conclusion, energetic and exergetic analyses and their results obtained in this study scope are to constitute a comprehensive background (basis) to engineers and researchers in terms of the issues of methods and priorities for performance improvement of both plant components and overall plant.

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