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ARTICLE

Exergy Analysis and Performance Improvement of the Wasit Thermal Power Plant Using Particle Swarm Optimization with Reduced Exergy Destruction

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ABSTRACT: Increasing electricity demand and the reduced efficiency of steam power plants operating below their design load highlight the need to improve the performance of existing generating units rather than relying solely on constructing new power plants. This study aims to enhance the exergy performance of the Wasit Thermal Power Plant by adjusting controllable operating variables without modifying the existing plant design or equipment. A component-level exergy analysis was first performed using actual steady-state operating data to identify the major sources of irreversibility. The boiler, turbine group, and condenser accounted for approximately 98% of the total exergy destruction. Based on the exergy diagnosis and sensitivity analysis, four controllable operating variables within safe operating ranges were selected because of their direct influence on the major sources of exergy destruction: main steam pressure (13.5–15.5 MPa), main steam temperature (525°C–540°C), reheat steam temperature (525°C–540°C), and condenser pressure (0.007–0.013 MPa). These variables were simultaneously optimized using Particle Swarm Optimization (PSO) to maximize the overall exergy efficiency while maintaining a constant fuel flow rate. Thermodynamic and operational constraints related to low-pressure turbine (LPT) outlet steam quality, heater terminal temperature difference (TTD), and drain cooler approach (DCA), condenser feasibility, and mass balance were imposed to ensure physically realistic and safe operating conditions. The optimal values of the main steam pressure, the main reheat steam temperatures, and the condenser pressure are 13.5 MPa, 540°C, 540°C, and 0.008219 MPa, which achieved the highest overall exergy efficiency and the lowest total exergy destruction. As a result, the overall exergy efficiency increased from 34.7% to 36.3%, total exergy destruction decreased by approximately 11.81 MW, and turbine shaft work increased from 249 to 261 MW. The results demonstrate that diagnosis-driven constrained optimization of controllable operating variables can effectively improve the exergy performance of existing steam power plants without design modifications.

KEYWORDS: Energy production; exergy analysis; exergy destruction; particle swarm optimization (PSO); thermal power plant; thermal operational optimization

1 Introduction

On a global scale, and with the ability to provide stable and continuous electrical power, steam power plants are considered one of the major sources of electricity generation [1,2]. In the Iraqi power sector, power plants remain the backbone of electricity generation, accounting for 96.6% of the country's total electricity production, while hydropower and solar energy contribute only about 3.39% and 0.059%, respectively [3]. According to the Iraqi Ministry of Electricity (2024), government-owned steam thermal power plants contribute approximately 19% of the total electricity generation, with a total design capacity of about 6500 MW. Among them, the Wasit Thermal Power Plant is the largest, with a design capacity

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of 2540 MW, representing 39% of the total design capacity of Iraq's government steam thermal power plants. However, the plant is currently operating at about 1453 MW, approximately 42.8% below its design capacity [4,5], highlighting the need to improve the performance of existing generating units through operational optimization rather than major design modification. Energy analysis is widely used to evaluate power plant performance and identify the major sources of energy losses [6]. Therefore, many researchers have employed both energy and exergy analyses to assess power plant performance under different operating conditions. In Jordan, Aljundi conducted a study of energy and exergy analysis in 2009 for the Al-Hussein Thermal Power Plant, the study investigated the main sources of performance losses. The results of the energy analysis were that the condenser is the main plant component that loses energy, with almost 134 MW rejected to the surrounding environment, and 13 MW was contributed by the boiler. Meanwhile, the exergy analysis tells a different story, which indicated that the dominant source of irreversibility was the boiler, which accounted for 77% of total exergy destruction, and in second place came the turbine with 13%, and then the condenser with 9%. In this study, it was concluded that the overall thermal and exergy efficiencies are approximately 26% and 25%, respectively [7]. Similar results have been reported by Ćehajić in 2023, who researched the Tuzla thermal power plant, which is located in Bosnia and Herzegovina. Ćehajić concluded that the main source of exergy destruction was the boiler, and turbine in second place and the condenser as the third source, with a limited contribution [8]. In 2025, using actual operating data and under different operating conditions, Kurkus-Gruszecka and his colleagues. They have evaluated the performance of a 500 MW steam power plant in Poland, and they concluded that the boiler remained the dominant source of exergy destruction, with combustion and heat transfer processes accounting for more than 60% of the total exergy losses [9]. In Iraq, different cases of power plants have been studied and analyzed in terms of energy and exergy efficiency. Al-Musayyib thermal power plant was studied by Majed and Farhan [10], and Shaheed et al. [11]; Al-Qayara gas power plant was studied by Talal and Akroot [12]; Kirkuk power plants were studied by Ahmed et al. [13]. Ahmed et al. [14]; and the Al-Taji power plant was studied by Kareem et al. [15]. All these Iraqi studies confirmed that energy and exergy analysis were important for identifying performance losses and improving Power plant operation under different conditions. In general, these studies explain the value of energy and exergy analyses in detecting the major thermodynamic losses in power plants. Yet, they mainly focused on performance diagnosis without covering the analysis to constrained optimization of controllable operating parameters. In India, Kumar et al. performed a parametric analysis of a Rankine cycle steam power plant in 2025, using boiler pressure and condenser pressure as the main operating variables. They concluded that using parametric analysis is effective in identifying which operating condition has the ability to improve plant performance [16]. For complex engineering systems such as power plants, identifying solutions so close to optimum in the optimization algorithms is an effective tool for that purpose and more efficient than parametric analysis [17]. In 2018, Elahifar et al. studied the optimization of the exergy efficiency of the Zarand steam power plant, reported that by using three methods—the Firefly Algorithm, Genetic Algorithm, and PSO the results of optimization were almost identical, with a difference of 0.04% [18]. Ni et al. applied Particle Swarm Optimization (PSO) to an optimally integrated energy system based on a solar-thermal-assisted advanced adiabatic compressed air energy storage (AA-CAES) system. conducted a study to demonstrate that PSO is a reliable and accurate optimization tool with fast convergence, making PSO a tool suitable for complex nonlinear energy systems [19]. It has been reported by Groniewsky applied (PSO) to the exergoeconomic optimization of a thermal power plant, and that using PSO has the ability to reach a near-stable solution after approximately 10 iterations, demonstrating its rapid convergence and stable optimization performance [20]. Valencia Ochoa et al. (2020) applied (PSO) to the energy and exergy optimization of an integrated S-CO_2 Brayton and Organic Rankine Cycle. PSO was compared with RPS and GA, and found that PSO achieved the lowest exergy destruction among the tested algorithms. It was shown that PSO achieved better performance for the investigated cases, with faster convergence and

stable behavior [21]. In General, previous exergy studies [7–9] successfully recognized the major sources of thermodynamic losses in power plants, with the boiler generally reported as the main source of exergy destruction. Previous Iraqi studies primarily focused on energy and exergy performance assessment [10,13], while other studies extended the analysis to investigate the effects of ambient temperature and operating parameters [11,14,15]. Performance improvement through waste heat recovery and solar integration was also investigated [12]. However, these studies did not address constrained operational optimization of controllable parameters using an optimization algorithm, and none examined the Wasit Thermal Power Plant. Kumar et al. [16], the analysis was advanced by examining the impacts of two operating parameters through parametric analysis, whereas optimization methods allow interacting variables to be optimized simultaneously to a defined objective [17]. Since the purpose of the present study is plant performance improvement rather than algorithm comparison, PSO was carefully chosen as the optimization tool. This choice is supported by Elahifar et al. [18], who reported only a 0.04% difference among solutions obtained using PSO, GA, and the Firefly Algorithm, and by Ni et al. [19], who explained the reliability, accuracy, and rapid convergence of PSO for complex nonlinear energy systems. Additional evidence was reported by Groniewsky [20], where PSO approached a stable solution after nearly 10 iterations, and by Valencia Ochoa et al. [21], where PSO accomplished lower exergy destruction than RPS and GA. These results support the suitability of PSO for the constrained multi-variable optimization considered in this study. Novelty and contribution of the present study: The present study develops a diagnosis-driven optimization approach for the Wasit Thermal Power Plant. First, component-level exergy analysis is used to identify and quantify the major sources of irreversibility. Based on this diagnosis, four controllable operating variables, namely main steam pressure, main steam temperature, reheat steam temperature, and condenser pressure, are selected because they directly affect the dominant sources of exergy destruction and can be adjusted during normal plant operation. Before simultaneous optimization, a parametric sensitivity analysis is performed by varying each selected variable individually within its practical operating range while maintaining the remaining operating parameters at their baseline values. This analysis evaluates the influence of each variable on the major sources of exergy destruction and provides further justification for its inclusion in the optimization process. The four variables are subsequently optimized simultaneously using PSO within practical operating ranges and subject to thermodynamic, physical, and operational constraints to ensure feasible operating conditions. The objective function is formulated to maximize the overall exergy efficiency while evaluating the corresponding reduction in total exergy destruction and improvement in plant performance. The main contribution of this study is the integration of plant-specific exergy diagnosis, parametric sensitivity analysis, and constrained optimization of practically adjustable operating variables. This integrated framework provides feasible performance improvements that can be implemented without equipment replacement or major modifications to the existing plant design.

2 Methodology

2.1 Power Plant Description

Unit 1 of the Wasit TPP was selected for the case study in this work. It is in Wasit Governorate in Iraq on the Tigris River. This plant contains six generating units, in two stages. Four units have a 330 MW electric production capacity, and the two remaining units have a capacity of 610 MW, making 2540 MW the designed total capacity [22]. The capacity of the first unit is 330 MW, and the energy source supplied to this unit is Iraqi crude oil. The modified Rankine cycle is the principle on which this unit operates, with reheating and regenerative feedwater heating. Steam is generated in a high-pressure single-drum natural circulation boiler. It expands through high-pressure (HPT), intermediate-pressure (IPT), and low-pressure (LPT) turbine stages, with reheating between the HPT and IPT stages. Then, the exhaust steam from the

LPT is condensed in the condenser and converted back into water before passing through four low-pressure feedwater heaters, a deaerator, and three high-pressure feedwater heaters before returning to the boiler, HPT, IPT, LPT, condenser, feedwater heaters, deaerator, and pumps, as shown in Fig. 1 [23,24]. Unit one in the Wasit TPP structure is shown in Fig. 1, while the components are described in Table 1.

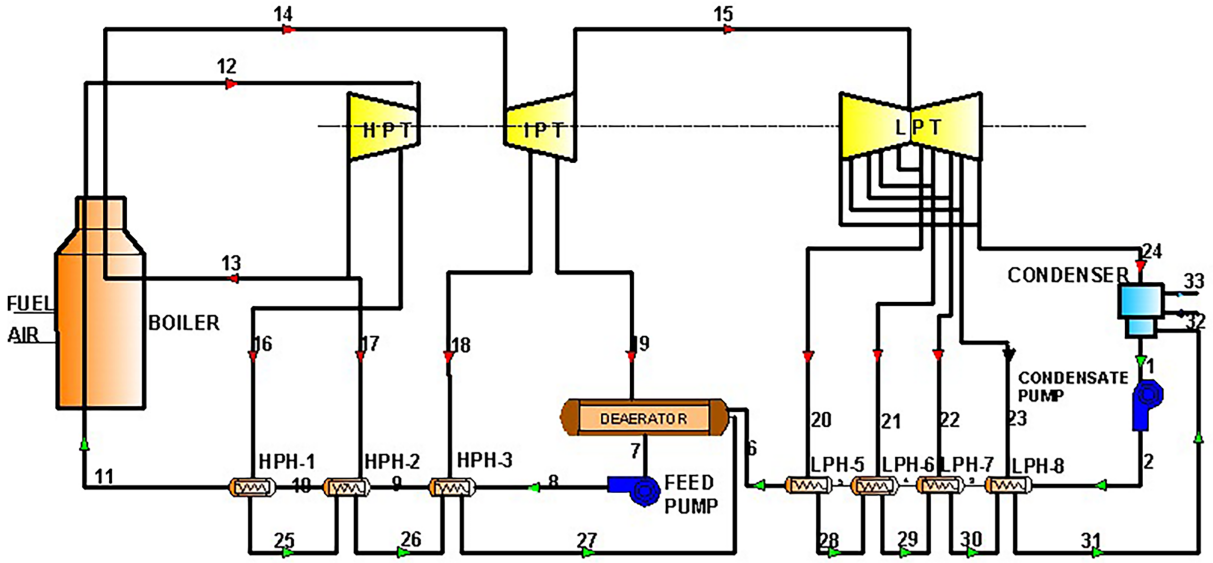


Figure 1: Schematic diagram of the steam power plant and definition of the main state points.

Table 1: Description of major components used in Fig. 1.

Component	Description	Component	Description
HPT	High Pressure Turbine	LPH-5	Low Pressure Heater No. 5
IPT	Intermediate Pressure Turbine	LPH-6	Low Pressure Heater No. 6
LPT	Low Pressure Turbine	LPH-7	Low Pressure Heater No. 7
HPH-1	High Pressure Heater No. 1	LPH-8	Low Pressure Heater No. 8
HPH-2	High Pressure Heater No. 2	HPH-3	High Pressure Heater No. 3

The hydrothermal properties of each measurement or control point in Fig. 1 are described in the description in Table 2.

Table 2: The hydrothermal properties of Unit-1 in Wasit TPP.

Point No.	Description	Point No.	Description	Point No.	Description
1	Condensate Water Pump Suction (Howell outlet)	12	Superheated Steam to HP Turbine	23	LP Turbine Extraction to LP Heater #8
2	Condensate Water Pump Discharge	13	Cold Steam Return to Boiler	24	LP Turbine Exhaust to Condenser

(Continued)

Table 2 (continued)

Point No.	Description	Point No.	Description	Point No.	Description
3	Outlet of LP Heater #8	14	Reheat Steam to IPT	25	Drain from HP Heater #1
4	Outlet of LP Heater #7	15	IP Turbine Exhaust to LP Turbine	26	Drain from HP Heater #2
5	Outlet of LP Heater #6	16	HP Turbine Extraction #1 to HP Heater #1	27	Drain from HP Heater #3 to Deaerator
6	Outlet of LP Heater #5	17	Cold Steam Extraction #2 to HP Heater #2	28	Drain from LP Heater #5
7	Feedwater Pump Suction (Deaerator outlet)	18	IP Turbine Extraction to HP Heater #3	29	Drain from LP Heater #6
8	Feedwater Pump Discharge	19	IP Turbine Extraction to Deaerator	30	Drain from LP Heater #7
9	Outlet of HP Heater #3	20	LP Turbine Extraction to LP Heater #5	31	Drain from LP Heater #8 to Condensate Line
10	Outlet of HP Heater #2	21	LP Turbine Extraction to LP Heater #6	32	Cooling Water Inlet to Condenser
11	Outlet of HP Heater #1	22	LP Turbine Extraction to LP Heater #7	33	Cooling Water Outlet from Condenser

2.2 Operational Data Collection and Baseline Case

The control room of Unit One at the Wasit Thermal Power Plant was the source of operational data that were used in this study. The data involved recorded parameters such as temperature, pressure, and mass flow rate at main locations of the water-steam cycle. The selected operating data were from 28 October 2025 at 12:00 noon. It was chosen specifically on that day because it offers a stable plant load of 249 MW, which can be used as a reference case for exergy and optimization analyses. Fig. 1 illustrates 33 operating points that were defined to represent the inlet and outlet states for major plant components. At these points, the thermodynamic properties were calculated by using standard water-steam property relations. The analysis was conducted under steady-state conditions, with mass conservation applied to each component, including extraction and drain flows. The water–steam cycle was treated as closed, and each measured point was assumed to represent a uniform thermodynamic state. Changes in kinetic and potential energies, heat losses

from insulated pipes, and pressure drops in short unmeasured lines were neglected. Throttling through control, extraction, and drain valves was assumed to be isenthalpic.

2.3 Exergy Analysis Formulation

Identifying where exergy destruction happens and what its value under the baseline operating condition is a necessary step for thermodynamic performance improvement [25]. For that reason, the exergy analysis has been performed to evaluate the exergy destruction for each component and the overall exergy efficiency of the plant [26]. The general steady-flow energy balance equation for an open system can be expressed as shown in Eq. (1) [7].

$$\dot{Q} - \dot{W} + \sum \dot{m}_{in} h_{in} - \sum \dot{m}_{out} h_{out} = 0 \tag{1}$$

The general exergy balance equation for a steady-state open system is given by Eq. (2) [8].

$$\sum \dot{E}x_{in} - \sum \dot{E}x_{out} + \sum \left(1 - \frac{T_0}{T}\right) \dot{Q} - \dot{W} = \dot{E}x_D \tag{2}$$

For adiabatic components without heat transfer, the exergy destruction can be simplified as [9]:

$$\dot{E}x_D = \sum \dot{E}x_{in} - \sum \dot{E}x_{out} \tag{3}$$

The specific physical exergy was calculated using Eq. (4) [25].

$$ex = (h - h_0) - T_0(s - s_0) \tag{4}$$

The exergy rate at each operating point is expressed as [25]:

$$\dot{E}x = \dot{m} \times ex \tag{5}$$

The fuel exergy rate supplied to the boiler was evaluated using Eq. (6) [27].

$$\dot{E}x_{fuel} = \dot{m}_{fuel}\, \beta\, LHV \tag{6}$$

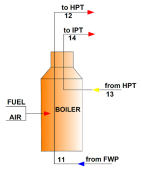
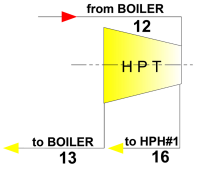
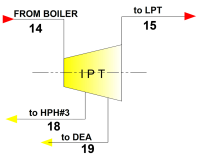
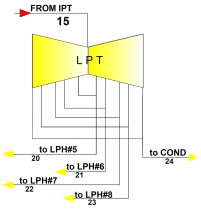
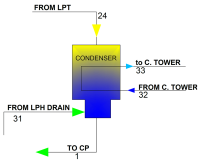
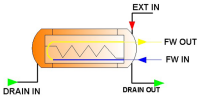
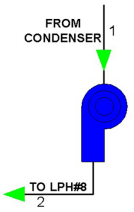
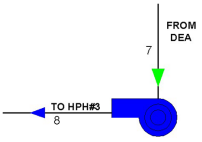
In the present study, the fuel exergy factor, β, for Iraqi crude oil was taken as 1.06 [7]. According to the fuel analysis report issued by Intertek, the crude oil used at the WasitTPP had a net heat of combustion of 40.9 MJ/kg [27]. The exergy destruction of each component was calculated based on the inlet and outlet exergy rates [28]. A summary of the exergy analysis of each component is shown in Table 3.

The total exergy destruction of the unit was obtained by summing up the exergy destruction of all main components, as expressed in Eq. (15):

$$\dot{E}_{D,total} = \dot{E}_{D,boiler} + \dot{E}_{D,HPT} + \dot{E}_{D,IPT} + \dot{E}_{D,LPT} + \dot{E}_{D,cond} + \sum \dot{E}_{D,heater} + \dot{E}_{D,dea} + \dot{E}_{D,CP} + \dot{E}_{D,BFP} \tag{7}$$

The irreversibility of each plant component was quantified by applying the exergy balance to its corresponding control volume, as presented in Table 3. In the boiler, the balance includes the fuel exergy, water–steam exergy streams, and flue-gas exergy. In the condenser, heat rejection is accounted for through the exergy change of the cooling-water stream. Accordingly, heat transfer within the boiler and condenser control volumes is accounted for through the corresponding exergy streams. It is not treated as a separate exergy transfer across the system boundary.

Table 3: Exergy destruction equations for the main components of the Wasit TPP.

Component	Exergy Destruction Equation	Schematic Diagram
Boiler	$\dot{E}_{D,boiler} = (\dot{E}_{fuel} + \dot{E}_{11} + \dot{E}_{13}) - (\dot{E}_{12} + \dot{E}_{14} + \dot{E}_{fg})$ (8)	
HPT	$\dot{E}_{D,HPT} = \dot{E}_{12} - (\dot{E}_{13} + \dot{E}_{16}) - \dot{W}_{HPT}$ (9)	
IPT	$\dot{E}_{D,IPT} = \dot{E}_{14} - (\dot{E}_{15} + \dot{E}_{18} + \dot{E}_{19}) - \dot{W}_{IPT}$ (10)	
LPT	$\dot{E}_{D,LPT} = \dot{E}_{15} - (\dot{E}_{24} + \dot{E}_{20} + \dot{E}_{21} + \dot{E}_{22} + \dot{E}_{23}) - \dot{W}_{LPT}$ (11)	
Condenser	$\dot{E}_{D,cond} = (\dot{E}_{24} + \dot{E}_{31} + \dot{E}_{32}) - (\dot{E}_{1} + \dot{E}_{33})$ (12)	
Feedwater heaters and Deaerator	$\dot{E}_{D,heater} = \sum \dot{E}_{in} - \sum \dot{E}_{out}$ (13)	
Condensate water pump	$\dot{E}_{D,CP} = (\dot{E}_{1} + \dot{W}_{CP}) - \dot{E}_{2}$ (14)	
Boiler feed water pump	$\dot{E}_{D,BFP} = \dot{W}_{BFP} + \dot{E}_{7} - \dot{E}_{8}$ (15)	

The overall exergy efficiency of the plant was then calculated as one minus the ratio of the total exergy destruction to the fuel exergy input:

$$\eta_{ex} = 1 - \frac{\dot{E}_{D,total}}{\dot{E}_{fuel}} \tag{16}$$

The extraction steam flow rates for the feedwater heaters were calculated using mass and energy balances for each heater, including the drain flow from the preceding heater, as given in Eq. (17).

$$\dot{m}_{ext,i} = \frac{\dot{m}_{fw}\left(h_{fw,out} - h_{fw,in}\right) - \dot{m}_{d,in}\left(h_{d,in} - h_{d,out}\right)}{h_{ext,i} - h_{d,out}} \tag{17}$$

The general steady-state energy balance presented in Eq. (1) was applied to each turbine section. Assuming adiabatic operation and neglecting changes in kinetic and potential energies, the turbine power was calculated using Eq. (18):

$$\dot{W}_T = \sum_{\text{in}} \dot{m}_{in} h_{in} - \sum_{\text{out}} \dot{m}_{out} h_{out} \tag{18}$$

2.4 Exergy Optimization Using PSO under Operating Constraints

PSO was presented by Kennedy and Eberhart in 1995 [29]. In the current study, a MATLAB model was developed and linked to an Excel file containing the plant operational data. Table 4 illustrates the actual baseline operating conditions of Unit One recorded from the plant control room on 28 October 2025. Based on these data, 33 state points were defined to represent the main locations of the water–steam cycle, and their thermodynamic conditions are presented in Table 5. The model reads the pressure, temperature, and mass flow rate data, calculates the thermodynamic and exergy properties of each stream, and determines the component exergy destruction and overall exergy efficiency. Three interconnected MATLAB codes were used in the optimization process.

Table 4: Operating and reference conditions of unit one in Wasit thermal power plant.

Parameter	Value	Unit
Operating condition	Partial load	
Turbine load	249	MW
Nominal unit capacity	330	MW
Main steam pressure	14.4	MPa
Main steam temperature	534	°C
Main steam flow rate	780	t/h
Reheat steam pressure	2.5	MPa
Reheat steam temperature	527	°C
Reheat steam flow rate	673	t/h
HPT extraction pressure, E1	4.9	MPa
Cold reheat extraction pressure, E2	2.7	MPa
IPT extraction pressures, E3, E4	1.37, 0.58	MPa
LPT extraction pressures, E5, E6, E7, E8	0.28, 0.12, 0.05, 0.02	MPa
Feedwater flow rate	780	t/h

(Continued)

Table 4 (continued)

Parameter	Value	Unit
Fuel consumption	60	t/h
Fuel LHV	40.9	MJ/kg
Condenser vacuum	−93	kPa
Reference temperature, T_0	32	°C
Reference pressure, P_0	101.325	kPa

Table 5: Operating data and exergy for the 33 state points of Unit One at the Wasit TPP.

Point No.	Temp. (°C)	Pressure (MPa)	Flowrate m· (t/h)	Enthalpy (kJ/kg)	Entropy (kJ/kg·K)	Specific Exergy (kJ/kg)	Exergy (MW)
1	42	0.0083	609	175.893	0.599	0.577	0.098
2	42.5	3	609	180.614	0.604	3.648	0.617
3	60	3	609	253.682	0.8297	7.968	1.348
4	80	3	609	337.363	1.073	17.214	2.912
5	100	3	609	421.345	1.304	30.611	5.178
6	130	3	609	548.233	1.631	57.701	9.761
7	157	0.58	780	662.458	1.912	86.329	18.705
8	160	15.8	780	684.495	1.924	104.568	22.656
9	194	15.8	780	831.909	2.252	152.021	32.938
10	228	15.8	780	984.037	2.566	208.247	45.12
11	262	15.8	780	1143.612	2.874	273.841	59.332
12	534	14.4	780	3413.47	6.494	1439.071	311.799
13	328	2.7	673	3071.162	6.717	1028.802	192.414
14	527	2.5	673	3522.93	7.401	1271.709	237.845
15	330	0.627	609	3123.859	7.459	855.187	144.669
16	399	4.9	56	3196.027	6.655	1172.423	18.456
17	315	2.7	50	3040.128	6.665	1013.694	14.088
18	444	1.37	37	3353.514	7.451	1087.086	11.176
19	332	0.58	27	3129.04	7.503	846.909	6.401
20	254	0.28	30	2976.65	7.566	675.272	5.695
21	186	0.12	19	2846.755	7.690	507.514	2.736
22	85	0.05	19	2652.616	7.613	336.745	1.828
23	61	0.02	13	2610.785	7.912	203.677	0.739
24	42.2	0.0083	526	2457.5	7.833	74.536	10.903
25	233	4.9	56	1004.638	2.633	208.443	3.281
26	199	2.7	106	848.248	2.319	148.009	4.387
27	164	1.37	143	693.268	1.981	96.071	3.835
28	102	0.28	30	427.733	1.329	29.474	0.249
29	82	0.12	49.77	343.465	1.099	15.505	0.214
30	62	0.05	69.31	259.577	0.856	5.74	0.111

(Continued)

Table 5 (continued)

Point No.	Temp. (°C)	Pressure (MPa)	Flowrate m· (t/h)	Enthalpy (kJ/kg)	Entropy (kJ/kg·K)	Specific Exergy (kJ/kg)	Exergy (MW)
31	48	0.02	82.38	200.986	0.677	1.613	0.037
32	27	0.2	35,728	113.373	0.395	0.272	2.702
33	35	0.2	35,728	146.809	0.505	0.160	1.592

The first code (Wasit_TPP_Exergy_core) characterizes the plant exergy model and calculates the performance indicators for a given set of operating variables. The second code (objective_Wasit) evaluates the objective function and verifies the operating constraints. The objective function was defined to maximize the overall exergy efficiency, calculated using Eq. (16), while satisfying the defined operating constraints. Four manageable operating variables were chosen for optimization: main steam pressure, main steam temperature, reheat steam temperature, and condenser pressure. Their operating ranges and the imposed constraints are shown in Table 6. Constraint violations were managed using a quadratic penalty function incorporated into the objective function. The third code (Wasit_TPP_PSO) performs the optimization by updating the particles and searching for feasible operating conditions that provide the highest overall exergy efficiency.

Table 6: Constraints used in the PSO optimization process.

Constraint	Condition	Purpose
LPT outlet steam quality	$0.88 \leq x \leq 0.95$	To reduce moisture and protect turbine blades
Heater TTD	TTD ≥ 1°C	To ensure proper heat transfer
Heater DCA	DCA ≥ 0°C	To maintain realistic heat transfer conditions
Condenser condition	T_{sat} > Cooling water temperature	To ensure proper condensation
Mass balance	Inlet flow = Outlet flow	To maintain realistic operating conditions

The PSO algorithm was implemented using a swarm of 40 particles and a maximum of 100 iterations. The inertia weight was fixed at 0.74, while the cognitive and social acceleration coefficients were both set to 1.5. Particle positions were initialized randomly within the prescribed operating bounds, and the initial particle velocities were set to zero. If a particle exceeded its prescribed operating bounds after an update, its position was clamped to the nearest feasible limit. The optimization process was terminated after completing 100 iterations. To verify the consistency of the obtained solution, the optimization was repeated several times after completion of the algorithm. The obtained results were consistent across the repeated executions. During optimization, the fuel and main steam flow rates were maintained at their baseline values, while only the selected operating variables were varied within their prescribed limits.

Table 5 summarizes the operating data and exergy-related properties at the 33 thermodynamic state points defined along the steam power plant cycle, evaluated with respect to an ambient reference temperature of 32°C.

Four operating variables have been selected for the optimization process, including the main steam pressure at the turbine inlet, main steam temperature, reheat steam temperature, and condenser pressure. operating variables were chosen because of their direct influence on plant performance and exergy destruction. According to the safe operating limits of the Wasit TPP, the lower and upper bounds have been

defined. Several thermodynamic and operational constraints have been imposed to ensure realistic operating conditions during the optimization process. These constraints have been applied to maintain safe plant operation, as shown in Table 6.

3 Results and Discussion

3.1 Baseline Exergy Results

The results of the exergy destruction of the TPP components, presented in Fig. 2, show that the boiler was the largest source of exergy destruction in the plant. The turbine was the second largest source. The condenser was the third, where exergy destruction occurs during the transfer of heat to the cooling water. From a thermodynamic viewpoint, this distribution reproduces the different mechanisms of entropy generation in each component. In the boiler, combustion and heat transfer across large temperature differences produce substantial irreversibility, making it the main source of exergy destruction. In the turbine group, friction, flow losses, and non-isentropic steam expansion change part of the available work potential into irreversibility, but to a lesser extent than in the boiler. In the condenser, though a large amount of heat is rejected, condensation happens at a temperature relatively close to the ambient reference state, where the work potential of the rejected heat is low, resulting in comparatively limited exergy destruction. A similar ranking was stated by Ćehajić [8] for the Tuzla Thermal Power Plant, where the boiler was the main source of exergy destruction, followed by the turbine and condenser. Together, these three components account for nearly 98% of the total exergy destruction in the plant. Therefore, improving the performance of these components can provide the greatest improvement in the overall exergy performance of the plant.

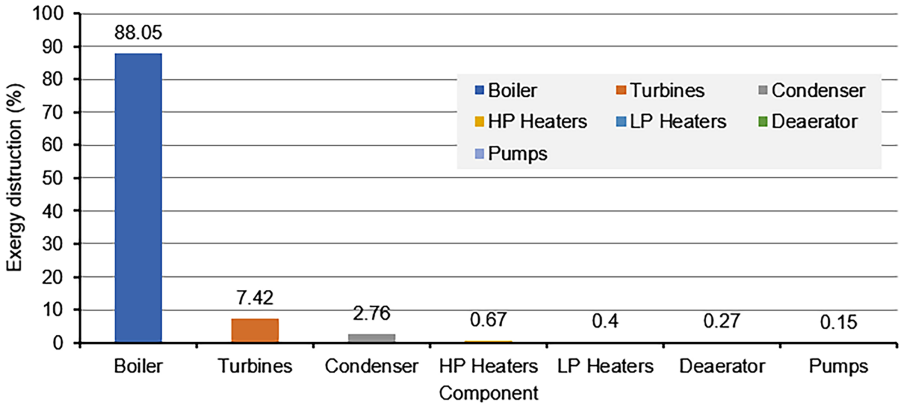


Figure 2: Distribution of exergy destruction among major components of Wasit thermal power plant at baseline condition.

The exergy analysis of Unit One at the Wasit TPP, shown in Fig. 3, showed that the fuel exergy input was 722.567 MW, with a total exergy destruction of 471.81 MW and an overall exergy efficiency of 34.7%. The boiler was the main source of exergy destruction, accounting for 415.978 MW, followed by the turbine group with 35.923 MW and the condenser with 12.846 MW. The distribution of exergy destruction among the major plant components is presented in Table 7. At a constant fuel exergy input, reducing exergy destruction allows more of the fuel exergy to be converted into useful work. Therefore, minimizing exergy destruction provides a direct basis for improving the plant performance through optimization.

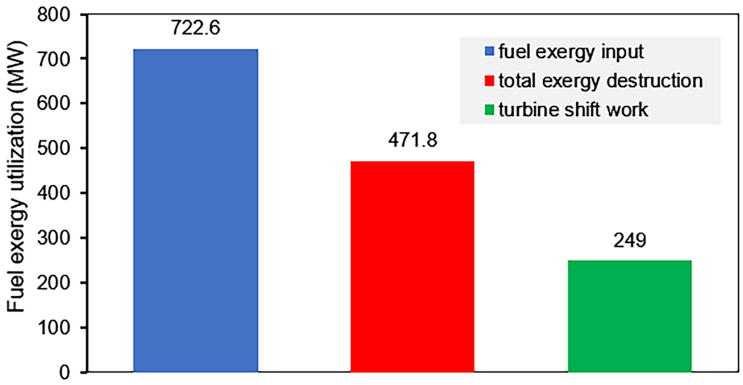


Figure 3: Fuel exergy utilization in the Wasit thermal power plant at baseline condition.

Table 7: Exergy destruction distribution by component—28 October 2025.

No.	Component	Description	Exergy Destruction (MW)	Share of Total Destruction (%)
1	Boiler	Combustion and heat transfer, including reheater and stack	415.9	88.17%
2	HPT	High-pressure turbine	14.477	3.07%
3	IPT	Intermediate-pressure turbine	3.185	0.68%
4	LPT	Low-pressure turbine	18.261	3.87%
5	Condenser	Steam condensation and heat rejection	12.846	2.72%
6	HP1	High-pressure heater 1	0.990	0.21%
7	HP2	High-pressure heater 2	0.808	0.17%
8	HP3	High-pressure heater 3	1.440	0.31%
9	LP5	Low-pressure heater 5	0.862	0.18%
10	LP6	Low-pressure heater 6	0.504	0.11%
11	LP7	Low-pressure heater 7	0.368	0.08%
12	LP8	Low-pressure heater 8	0.178	0.02%
13	Deaerator	Open feedwater heater	1.292	0.27%
14	CP	Condensate pump	0.172	0.04%
15	BFP	Boiler feed pump	0.543	0.12%

3.2 Sensitivity Analysis of the Four Operating Variables

To evaluate the robustness of the baseline results, a parametric sensitivity analysis was conducted before optimization. Each of the four operating variables was varied individually while the remaining parameters were kept constant. The effects on boiler, turbine, and condenser exergy destruction are presented in the following four tables.

As shown in Tables 8–11, increasing the main and reheat steam temperatures reduces exergy destruction in both the boiler and turbines. Reducing the main steam pressure also decreases turbine exergy destruction, while lowering the condenser back pressure produces a slight reduction in condenser exergy destruction.

3.3 Optimization Results Using PSO

The exergy analysis shows that the boiler, turbine, and condenser are the main sources of exergy destruction in the plant. So, the optimization process focused on the operating variables that directly affect the performance of these components. The selected variables are the main steam pressure at the turbine inlet,

main steam temperature, reheat steam temperature, and condenser pressure. The operating ranges used in the optimization process are presented in Table 12.

Table 8: Effect of main steam and reheat steam temperatures on total turbine exergy destruction.

Main Steam Temperature (°C)	Reheat Steam Temperature (°C)	Total Turbine Exergy Destruction (MW)
525	525	38.274
530	530	36.343
535	535	34.430
540	540	32.585

Table 9: Effect of main steam and reheat steam temperatures on boiler exergy destruction.

Main Steam Temperature (°C)	Reheat Steam Temperature (°C)	Boiler Exergy Destruction (MW)
525	525	419.808
530	530	416.673
535	535	413.536
540	540	410.396

Table 10: Effect of main steam pressure on total turbine exergy destruction.

Main Steam Pressure (MPa)	Total Turbine Exergy Destruction (MW)
13.5	33.573
14.0	34.910
14.5	36.204
15.0	37.461
15.5	38.681

Table 11: Effect of condenser vacuum pressure on condenser exergy destruction.

Vacuum Pressure (kPa)	Absolute Condenser Pressure, (MPa)	Saturation Temperature, (T_{sat}) (°C)	Condenser Exergy Destruction (MW)
−86	0.0153	54.38	23.6
−88	0.013325	51.6	20.923
−90	0.011325	48.2	17.845
−92	0.009325	44.4	14.12
−93	0.00832	42.2	12.8

Table 12: Operating variables and their ranges used in the PSO optimization process.

Operating Variable	Lower Limit	Upper Limit	Unit
Main steam pressure at the turbine inlet	13.5	15.5	MPa
Main steam temperature	525	540	°C
Reheat steam temperature	525	540	°C
Condenser pressure	0.007	0.0133	MPa

Figs. 4 and 5 show the convergence behavior of the PSO algorithm. The penalty function decreased during the first iterations and approached zero, indicating that the search quickly moved toward feasible operating conditions. The exergy efficiency increased gradually and reached a stable value after about 35 iterations. This behavior demonstrates the fast convergence and stable performance of the PSO algorithm. A similar rapid convergence behavior was reported by Groniewsky [20], where the PSO solution became nearly stable after approximately 10 iterations. Furthermore, Ni et al. [19] reported that PSO provides reliable and accurate optimization with fast convergence when applied to complex nonlinear energy systems, supporting the convergence behavior observed in the present study.

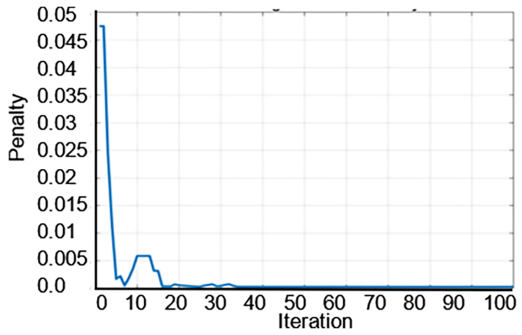


Figure 4: PSO penalty convergence curve for the TPP.

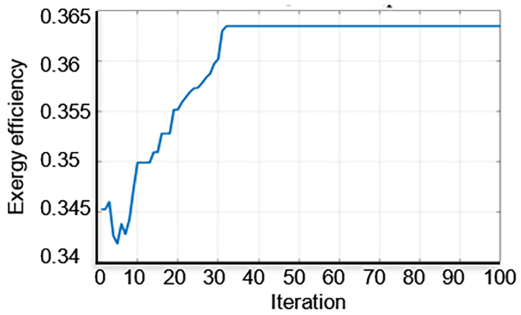


Figure 5: PSO convergence curve of exergy efficiency for Wasit thermal power plant.

Operating conditions selected by the PSO algorithm and corresponding to the highest exergy efficiency and lowest exergy destruction at the same fuel input are presented. Optimal values were a main steam pressure at the turbine inlet of 13.5 MPa, a main steam temperature of 540°C, a reheat steam temperature of 540°C, and a condenser pressure of 0.008219 MPa.

Optimization results showed that the overall exergy efficiency increased from 34.7% to 36.3%, while the total exergy destruction decreased from 471.81 MW to about 460 MW. At the same fuel input, the turbine work output increased to 261 MW. As shown in Figs. 6 and 7 and Tables 13 and 14, a comparison has been made between the baseline and optimized results for the main performance indicators and exergy destruction of the major plant components.

Improvement in exergy efficiency was achieved by increasing the main steam temperature from 534°C to 540°C and the reheat steam temperature from 527°C to 540°C, while reducing the main steam pressure at the turbine inlet from 14.4 to 13.5 MPa. A slight reduction in condenser pressure from 0.0083 to 0.008219 MPa. Grassmann diagrams of exergy flows and component irreversibilities are shown in Fig. 8. The optimal values reflect a thermodynamic balance among the main plant components.

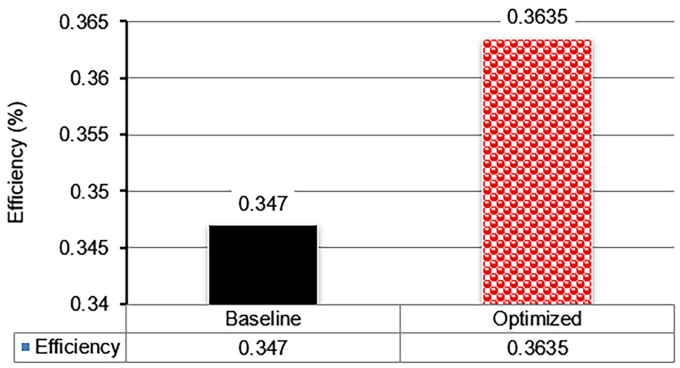


Figure 6: Comparison of exergy efficiency between baseline and optimized conditions using PSO.

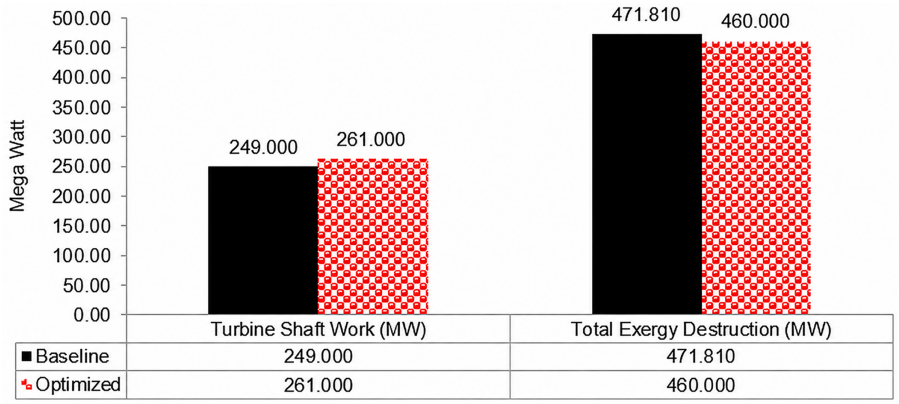


Figure 7: Baseline and optimized comparison of turbine work and total exergy destruction.

Table 13: Comparison of overall performance between baseline and PSO optimized conditions.

Parameter	Baseline	PSO Optimized	Difference
Turbine work output (MW)	249	261	+12
Overall Exergy Efficiency (%)	34.7	36.3	+1.6
Total Exergy Destruction (MW)	471.81	460	−11.81

Table 14: Comparison of component exergy destruction between baseline and PSO optimized conditions.

Group	Baseline (MW)	PSO Optimized (MW)	Difference (MW)
Boiler	415.9	410.8	−5.111
Turbines (HPT + IPT + LPT)	35.923	30.089	−5.834
Condenser	12.846	11.892	−0.954
Heaters + Deaerator (HP1–HP3 + LP5–LP8 + Deaerator)	6.442	6.357	−0.085

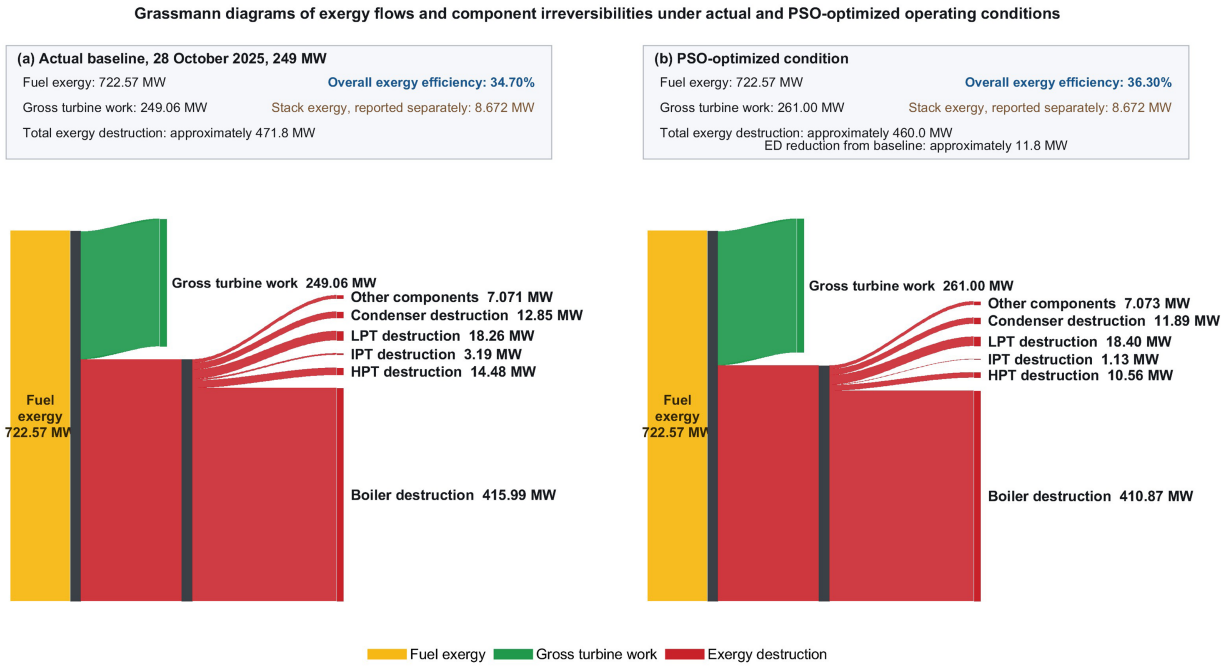


Figure 8: Grassmann diagrams of exergy flows and component irreversibilities under (**a**) Actual baseline operating conditions and (**b**) PSO-optimized operating conditions. Band thickness is proportional to the corresponding exergy flow, with an identical scale used for both **conditions**.

Increasing the main and reheat steam temperatures to 540°C raises the average temperature of heat adding in the boiler and decreases the temperature difference between the hot flue gases and the water-steam streams. This cuts entropy generation throughout heat transfer and therefore lowers boiler exergy destruction. Higher steam temperatures also improve steam quality during expansion and reduce moisture-related losses in the low-pressure turbine.

Lowering the main steam pressure at the turbine inlet from 14.4 to 13.5 MPa also limits steam expansion into the wet region and decreases moisture-related irreversibility in the final turbine stages. The minor decrease in condenser pressure from 0.0083 to 0.008219 MPa reduces the temperature difference between the condensing steam and cooling water, which decreases irreversibility during heat rejection. However, the enhancement is small because the baseline condenser pressure was already close to the optimized value. Overall, these conditions characterize the best thermodynamic balance within the specified operating constraints.

The optimized operating conditions increased the turbine power output by about 12 MW. Assuming 7000 operating hours per year, equal to 292 operating days, while permitting the remaining period for scheduled maintenance and unplanned outages, this enhancement links to an added annual electricity generation of approximately 84,000 MWh (84 million kWh). To account for the uncertainty in electricity generation costs in Iraq, a simple economic sensitivity analysis was made using three representative electricity cost scenarios reported by Al-Rikabi et al. [3], representing subsidized fuel, baseline, and high fuel-cost conditions. The corresponding estimated annual economic benefits for the three scenarios are summarized in Table 15.

Table 15: Sensitivity analysis of the estimated annual economic benefit under different electricity cost scenarios for Iraqi thermal power plants [3].

Operating Assumption	Electricity Generation Cost (USD/kWh)	Additional Annual Electricity Generation (MWh)	Estimated Annual Economic Benefit (Million USD)
Subsidized fuel scenario	0.045	84,000	3.78
Baseline scenario	0.110	84,000	9.24
High fuel-cost scenario	0.150	84,000	12.60

4 Conclusions

This work attempts to analyze and optimize the exergy dilemma in the Wasit thermal power plant using PSO optimization. It is concluded that:

1. The exergy analysis successfully identified the main irreversibilities in Unit One of the Wasit Thermal Power Plant under actual operating conditions. At the baseline turbine work of 249 MW, the fuel exergy input is 722.567 MW, total exergy destruction is 471.81 MW, and the overall exergy efficiency is 34.70%. The boiler, turbine group and condenser account for nearly 98% of the total exergy destruction.
2. Based on the exergy diagnosis, four controllable operating variables, namely the main steam pressure, main steam temperature, reheat steam temperature, and condenser pressure, were selected for optimization. These variables were chosen because they directly influence the components responsible for the largest exergy destruction and can be adjusted during normal plant operation without modifying the existing plant equipment. The parametric analysis successfully established the thermodynamic sensitivity of these variables and provided the physical basis for the subsequent optimization process.
3. The PSO algorithm successfully recognized an improved combination of these operating variables within the specified thermodynamic and operational constraints. Compared with the baseline condition, the main steam temperature rose from 534°C to 540°C and the reheat steam temperature from 527°C to 540°C. In contrast, the main steam pressure at the turbine inlet decreased from 14.4 to 13.5 MPa and the condenser pressure reduced from 0.0083 to about 0.0082 MPa. These modifications reduced exergy destruction in the major components, with the largest reduction occurring in the turbine group, then the boiler and condenser.
4. At constant fuel and main steam flow rates, the optimized operating conditions reduced total exergy destruction from 471.81 MW to about 460 MW and increased the overall exergy efficiency from 34.70% to 36.3%. Reducing irreversibility allowed a greater fraction of the fixed fuel exergy input to be converted into useful turbine work.
5. The results demonstrate that the exergy performance of the existing plant can be improved through proper adjustment of controllable operating parameters without equipment replacement or major design modifications. Identifying and maintaining suitable operating setpoints can therefore provide a practical approach for improving the thermodynamic performance of the plant.

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preparation, or the decision to publish. Its contribution was limited to facilitating access to the plant, providing operational data, and making relevant technical documents available for research purposes.

Author Contributions: The authors confirm contribution to the paper as follows: conceptualization, Tariq A. Saadoun, Abbas J. Jubear Al-Jassani; methodology, Tariq A. Saadoun, Abbas J. Jubear Al-Jassani; software, Tariq A. Saadoun; formal analysis, Tariq A. Saadoun, Abbas J. Jubear Al-Jassani; investigation, Tariq A. Saadoun; data curation, Tariq A. Saadoun, Abbas J. Jubear Al-Jassani; writing—original draft preparation, Tariq A. Saadoun; writing—review and editing, Abbas J. Jubear Al-Jassani; supervision, Abbas J. Jubear Al-Jassani. All authors reviewed and approved the final version of the manuscript.

Availability of Data and Materials: The data that support the findings of this study are available from the corresponding author, Tariq A. Saadoun, upon reasonable request.

Ethics Approval: Not applicable.

Conflicts of Interest: The authors declare no conflicts of interest.

Nomenclature

Term	Interpretation
T	Temperature
P	Pressure
$\dot{m}$	Mass flow rate
h	Specific enthalpy
s	Specific entropy
ex	Specific exergy
E·D	Exergy destruction rate
ηx	Exergy efficiency

References

1. Koeva D, Slavov D. The impact of thermal power plants on the sustainability of the energy system under condi-tions of large-scale RES penetration. Eng Proc. 2026;122(1):18. doi:10.3390/engproc2026122018.
2. Li Q, Ren B, Tang W, Wang D, Wang C, Lv Z. Analyzing the inertia of power grid systems comprising diverse conventional and renewable energy sources. Energy Rep. 2022;8(2015):15095–105. doi:10.1016/j.egyr.2022.11.022.
3. Al-Rikabi IJ, Omara AAM, Ali Abuelnour M, Abdul-Zahra AS, Al Jubori AM, Alsaad H. Energy landscape in Iraq: current status, research review, and policy insights. Energy Sci Eng. 2026;14(1):625–78. doi:10.1002/ese3.70359.
4. Iraqi Ministry of Electricity. Statistics [Internet]. Baghdad, Iraq: Iraqi Ministry of Electricity; 2025 [cited 2026 Mar 31]. Available from: https://storage.moelc.gov.iq/2025/09/11/2025_09_11_12303039504_4195463374479148.pdf.
5. Shanghai Electric. New milestone! Shanghai Electric's overseas projects added life-cycle services to its package [Internet]. Shanghai, China: Shanghai Electric; 2022 [cited 2026 Mar 31]. Available from: https://www.shanghai-electric.com/listed_en/c/2022-06-29/565715.shtml.
6. Science Europe. A common scale for our common future: exergy, a thermodynamic metric for energy. Brussels, Belgium: Science Europe; 2015.
7. Aljundi IH. Energy and exergy analysis of a steam power plant in Jordan. Appl Therm Eng. 2009;29(2–3):324–8. doi:10.1016/j.applthermaleng.2008.02.029.
8. Ćehajić N. Exergy analysis of thermal power plant for three different loads. Teh Glas. 2023;17(2):160–6. doi:10.31803/tg-20211214151555.
9. Kurkus-Gruszecka M, Szabłowski Ł, Dybiński O, Krawczyk P, Badyda K, Kotte G. Exergy analysis of 500 MW power unit based on direct measurement data. Energies. 2025;18(11):2762. doi:10.3390/en18112762.
10. Majed HA, Farhan AA. Energy, exergy, and environmental emission analysis of a crude oil-fired AL-Musayib thermal station in Iraq. Diyala J Eng Sci. 2024:38–55. doi:10.24237/djes.2024.17403.

11. Shaheed HR, Mohammed HN, Radhi RM. Evaluation performance of the steam power plant in Iraq based on energy and exergy analysis. Int J Heat Technol. 2023;41(1):253–8. doi:10.18280/ijht.410128.
12. Talal W, Akroot A. Exergoeconomic analysis of an integrated solar combined cycle in the Al-qayara power plant in Iraq. Processes. 2023;11(3):656. doi:10.3390/pr11030656.
13. Ahmed AH, Ahmed AM, Hamid QY. Exergy and energy analysis of 150 MW gas turbine unit: a case study. J Adv Res Fluid Mech Therm Sci. 2020;67(1):186–92.
14. Ahmed S, Abbas EF, Ali OM. Assessment of the gas turbine unit in Kirkuk gas power station using energy and exergy analysis. NTU J Renew Energy. 2022;2(1):1–8. doi:10.56286/ntujre.v2i1.144.
15. Kareem AF, Akroot A, Abdul Wahhab HA, Talal W, Ghazal RM, Alfaris A. Exergo–economic and parametric analysis of waste heat recovery from taji gas turbines power plant using Rankine cycle and organic Rankine cycle. Sustainability. 2023;15(12):9376. doi:10.3390/su15129376.
16. Kumar R, Bin Queyam A, Singla MK, Louzazni M, Dipak Kumar M. Optimizing efficiency and performance in a Rankine cycle power plant analysis. Energy Eng. 2025;122(4):1373–86. doi:10.32604/ee.2025.058058.
17. Kerdan IG, Raslan R, Ruyssevelt P. Parametric study and simulation-based exergy optimization for energy retro-fits in buildings. In: Proceedings of the 28th International Conference on Efficiency, Cost, Optimization, Simulation and Environmental Impact of Energy Systems (ECOS 2015); 2015 Jun 30–Jul 3; Pau, France.
18. Elahifar S, Assareh E, Nedaei M. Exergy analysis and optimization of the Rankine cycle in steam power plants using the firefly algorithm. Mech Ind. 2018;19(5):505. doi:10.1051/meca/2017065.
19. Ni C, Chen L, Chen X, Zhai J, Mei S, Zhang XP. Exergy analysis and particle swarm optimization of clean energy router based on a solar-thermal-assisted advanced adiabatic compressed air energy storage system. IET Renew Power Gener. 2023;17(9):2302–14. doi:10.1049/rpg2.12758.
20. Groniewsky A. Exergoeconomic optimization of a thermal power plant using particle swarm optimization. Therm Sci. 2013;17(2):509–24. doi:10.2298/tsci120625213g.
21. Valencia Ochoa G, Duarte Forero J, Rojas JP. A comparative energy and exergy optimization of a supercritical-CO_2 Brayton cycle and Organic Rankine Cycle combined system using swarm intelligence algorithms. Heliyon. 2020;6(6):e04136. doi:10.1016/j.heliyon.2020.e04136.
22. Shanghai Electric Power Generation Equipment Co., Ltd. N330-16.7/538/538 330 MW reheat condensing steam turbine thermal performance data. Shanghai, China: Shanghai Electric Power Generation Equipment Co., Ltd.; 2011. 29 p.
23. Jiangsu Pangwo Power Engineering Co. Iraq Wassit power plant boiler equipment and operation training materials. Xuzhou, China: Jiangsu Pangwo Power Engineering Co., Ltd.; 2023. 183 p.
24. Jiangsu Pangwo Power Engineering Co., Ltd. Iraq Wassit power plant turbine training materials. Xuzhou, China: Jiangsu Pangwo Power Engineering Co., Ltd.; 2023. 293 p.
25. Bejan A, Tsatsaronis G, Moran MJ. Thermal design and optimization. New York, NY, USA: John Wiley & Sons, Inc.; 1995. p. 560.
26. Çengel YA, Kanoğlu M. Exergy efficiency of closed and unsteady-flow systems. Entropy. 2025;27(9):943. doi:10.3390/e27090943.
27. Intertek Caleb Brett Germany GmbH. Crude oil test report for Zubidiyah Power Plant. Hamburg, Germany: Intertek Caleb Brett Germany GmbH; 2017. Report No.: 178650.
28. Shamet O, Ahmed R, Nasreldin Abdalla K. Energy and exergy analysis of a steam power plant in Sudan. Afr J Eng Technol. 2021;1(1):4. doi:10.47959/ajet.2021.1.1.4.
29. Kennedy J, Eberhart RC. Particle swarm optimization. In: Proceedings of the IEEE International Conference on Neural Networks (ICNN). Piscataway, NJ, USA: IEEE; 1995. p. 1942–8. doi:10.1109/ICNN.1995.488968.