YTUP

Journal of Thermal Engineering
https://jten.yildiz.edu.tr/
https://doi.org/10.47481/jten.0019

RESEARCH ARTICLE

Investigating the exergy of thermal power plant components

Vikas Kumar[1], Ramesh Kumar Singh[2,*], Vivek Kumar[3]

[1]Trade instructor, Govt. ITI Banka, Bihar, 813103, India
[2]Assistant Professor, Sarala Birla University, Ranchi, Jharkhand, 835103, India
[3]Assistant Professor, Ramgovind Institute of Technology, Koderma, 825409, India

Abstract

Exergy analysis has proven to be an effective approach for evaluating the performance of thermal power plants, offering insights beyond those provided by conventional energy analysis. The present work shows exergy-based performance analysis of the 250-MW unit of the total capacity 500 MW Chandrapura Thermal Power Station in Jharkhand, India. An analysis was performed using Engineering Equation Solver (EES) software to obtain the exergy destruction in major plant components. The results shows that the boiler is identified as the major source of exergy destruction resulting in approximately 80.71% whereas steam turbine and condenser contributes 10.9 % and 2.1 % respectively of total exergy destruction in the in the examined components. The remaining losses are distributed between the feed-water heater and the pump, which together account for less than 4% of the losses. Boiler pressure was varied to study exergy destruction, with optimal results at 167–178 bar, at which efficiency increased and exergy losses decreased; above this range, exergy losses increased. The influence of change in ambient temperature on exergy efficiency was also studied and it is found that, as the ambient temperature increases from 280 K to 310 K, the exergy efficiencies of both boiler and turbine decrease marginally. Whereas, a significant increase in the exergy efficiencies of condenser was detected at similar operating conditions. The exergy efficiency of the power plant as a whole was found to be 34.1%, indicating considerable scope for performance enhancement through optimizing the components and systems level-wise. The results also highlight the role of exergy analysis in detecting the inefficiencies as well as guiding of design trends in the thermal power systems.

Keywords: Coal fired thermal power plant, environmental temperature, exergy, efficiency

Cite this article as: Kumar, V., Singh, R. K., & Kumar, V. (2026). Investigating the exergy of thermal power plant components. Journal of Thermal Engineering, 12(3), 1132–1145. https://doi.org/10.47481/jten.0019

1. Introduction

Energy consumption is a key measure of a country's development and living conditions. Population growth, urbanization, industrialization, and technological development directly increase energy consumption. Now a days, fossil fuels (natural gas, coal, fuel oil and petroleum) provide about 75% of the world's electricity generation. The other 25% is sourced from renewables, like solar, geothermal, biogas, hydro or wind [1]. Assessment for thermal power plants is generally performed using energetic performance indicators based on the first law of thermodynamics, such as electric power and thermal efficiency. Over the past decades, an exergy based analysis in view of second law of thermodynamics has emerged as a powerful tool for designing, assessing and improving thermal power plants. Besides quantifying the size, location and causes of irreversibility within plants, exercise performance analysis provides greater context when assessing the relative efficiency of individual plant components. The performance of a system's components is better characterized by both energetic and exergetic analysis. This helps to find out the areas where improvement is required. Bejan [2] was the first who used the tools of exergy and entropy generation minimization methodologies, and showed the presence of irreversibility phenomena in closed and open systems. Tsatsaronis and Park [3] further enhanced this understanding with ideas like avoidable and unavoidable exergy destruction, enabling the creation of exergoeconomic approaches. Additionally, the work of Kotas [4], Ganapathy et al. [5], and Kamate and Gangavati [6] showed how the exergy could be utilized to quantify performance in operational steam

*Corresponding Author
E-mail Adress: ramesh.singh@sbu.ac.incom

Submitted: 1 December 2025; **Accepted:** 24 December 2025

This paper was recommended for publication in revised form by Editorin-Chief Ahmet Selim Dalkılıç

Published by Yıldız Technical University, İstanbul, Türkiye

and cogeneration plants with a focus on boilers as large inefficient components. Similarly, Datta et al. [7] studied a 210 MW plant in India and showed that the boiler accounts for nearly 60% of total exergy destruction under varying loads and governing modes. Aljundi [8], in his work on the Al-Hussein plant in Jordan, confirmed that the boiler is the major site of irreversibility (≈77%) and analyzed the influence of reference environment conditions. Later, Naterer et al. [9] evaluated a 32 MW subcritical station and linked boiler–turbine losses to sustainability aspects. These studies, however, were limited in plant size and scope and therefore focused mainly on load variation and reference environmental conditions. Dincer and Rosen [10] found that the energy and exergy values provide the information about sustainability of the system. Saidur et al. [11] measured both energy and exergy efficiency. In a boiler, the energy and exergy efficiencies are 72.46% and 24.89%, respectively. The exergy analysis of gas turbine cogeneration system was analyzed by Bilgen [12]. Later, the first and second law efficiencies of an externally fired gas turbine cycle combined with biomass were presented by S. Datta et al. [13]. Exergy analysis signifies the irreversibility of thermal systems which leads to find the components that may limit the performance of system. For combined organic Rankine cycle (ORC) and Brayton cycles, the heat exchangers have the highest share of exergy loss, whereas, turbines have the largest single destruction, provides information to optimize the components for better overall efficiency of plant [14]. Sue and Chuang [15] did an exergy analysis based on load variations and found that the exergy loss is more at part load conditions compared to full load. By adjusting the number of reheat processes, Khaliq and Kaushik [16] demonstrated the Second law efficiency of gas fire thermal power plants. Both number of reheat stages and the pressure ratio increase the exergy destruction in the reheat turbine. According to Habib et al. [17], the reheat pressure plays an important role for optimal efficiency.

In addition, exergy-based evaluations show that the boiler contributes the highest share of irreversibility within steam power plants, followed by notable losses in the low- and intermediate-pressure turbine stages [18]. Reddy and Mohamed [19] found that the main combustion chamber of gas turbines was the primary cause of the rate of exergy destruction. The exergy loss of the boiler is mainly influenced by two key factors: the temperature of the incoming air and the amount of excess air used during combustion [20]. Identifying losses and inefficiencies in wind, solar, and hybrid systems has made exergy analysis an important method for improving efficiency and sustainability of renewable energy system. According to Sunil et al. [21], using a venturi-based windmill helps the propeller rotate more efficiently. As a result, it can generate approximately 12% more power at low wind speeds, while also producing less noise and causing minimal impact on the environment. Further, Sunil Kumar et al. [22] conducted an experiment on wind turbine gearboxes and found that fluctuating wind speeds, high oil temperatures, and vibration-related stresses were the main factors that reduced performance and affected maintenance reliability. The three-stage wind turbine gearbox operated stably within the design of temperature limits. However, the sensor response was limited by the debris particle size, and it can be improved to prevent potential failures and proper analysis [23]. Sunil et al. [24] worked on solar field also and demonstrated that factors such as panel material, tilt angle, regular maintenance, and thermal storage play a significant role in efficiency and informed about government subsidies which help and encourage wider use. Access to modern, clean, and affordable energy is essential for improving socioeconomic development and achieving universal energy access by 2030 [25]. In addition, recent progress in micro-lattice structures and microchannel heat sinks and exchangers (MCHX) has created new opportunities to improve the performance and efficiency of renewable energy systems. Microlattice structures offer a high strength-to-weight ratio, better heat management, and improved energy absorption, so it can be used in turbine blades, heat exchangers, and support structures to reduce exergy losses and produce lighter, stronger, and more thermally efficient components [26]. Similarly, microchannel heat exchangers (MCHX) made from either polymer or from its composites provide compact and efficient thermal solutions and offer good corrosion resistance, cost-effective, and have high thermal conductivity, which helps improve heat dissipation in small-scale energy and electronic systems [27]. With these improvements battery cooling in Formula Student Electric vehicles reduces peak temperatures and keeps the battery pack more even and provide smoother performance, better stability, improved safety and longer battery life [28]. Overall, these developments show that the better materials and improved heat management are key to make the next-generation renewable energy systems more efficient, reliable and sustainable.

Optimizing the performance of thermal power plants has become an emerging research field with a special attention on the use of hybrid systems and smart energy management techniques. Systems that combine power-to-heat with thermal energy storage (P2H–TES), solar-assisted setups and steam/water hybrid storage have shown the strong potential to improve the flexibility, reliability and overall efficiency of power plants. These approaches allow the boiler and turbine to operate more independently with minimum operating load and help to improve the plant's ability to adjust in changing power demands while maintaining grid stability. For example, P2H–TES systems can deliver better round trip efficiency at a lower cost [29] and solar-assisted systems improve energy use when supported by proper control and reduce losses [30]. Steam/water hybrid storage can extend the operating range from approximately 30% to 12.15% of the rated capacity while maintaining an efficiency of approximately 82.24% [31]. Simultaneously, tower-based solar systems help to reduce coal use and lower emissions significantly [32]. The hybrid systems that combine solid oxide fuel cells, solar collectors and coal have shown promising results and provides energy and exergy efficiency of approximately 69.72% and 34.93% respectively but the challenges remain there due to the high energy losses in parts like fuel cells and gasifiers. The type of fuel used has also influence the performance of power plant. For example, changing from lignite to anthracite can increase emissions but reduce the amount of solar support needed [33]. In traditional coal power plants, the studies have shown that the boiler is the largest source of energy and exergy losses followed by the turbines and condenser. Whereas components such as ejectors and heaters generally work more efficiently due to less exergy losses. This shows that we need to improve the fuel burning process, use better materials, and recover more heat from the system to improve the overall performance of plant [34]. Methods such as parametric and exergoeconomic analyses help to improve the input control and make the system more efficient [35]. Simultaneously, data based models and digital twin technologies make the system more reliable and help in reducing the exergy losses [36]. Overall, these studies show that the use of hybrid systems, improvement of heat recovery and application of better control methods can make thermal power plants more efficient, flexible, and eco-friendly.

Earlier work on exergy analysis of thermal power plants have mainly focused on small systems, limited operating conditions or fixed environmental settings. There is very little research on large coal power plants operating under real conditions, especially on how changes in the outside temperature affect the efficiency of powerplant components. Only a few studies have focused on power plants of 250 MW or larger and the effects of boiler pressure and weather conditions on performance are still not clearly understood. The novelty of this study lies in performing a detailed component-wise exergy analysis of a single 250-MW unit at the Chandrapura Thermal Power Station using actual plant data and analyzing the effects of ambient temperature and boiler pressure variation on the exergy and energy performance of each component. The objective of this work is to perform a detailed component wise exergy analysis of a coal fired power unit to identify major exergy destruction sites, evaluate component efficiencies and sensitivities, and provide actionable insights for plant optimization, including retrofit strategies and operational improvements.

2. Methods

A steady-state exergy study was performed on a component of a thermal power plant at full- and part-load conditions. Data on steam pressure, temperature, and flow, feed water temperature, fuel use, and flue gas temperature were recorded at each point. Energy and exergy efficiencies of the components of the power plant were calculated with standard balance equations. Each component was treated as a steady-state system and therefore no energy or exergy was stored in the equipment during operation. The variations in kinetic and potential energies were considered negligible relative to the thermal and chemical exergy of the working fluid. Data was collected for analysis while the plant was running at a steady load, and temporary changes had little effect on the overall exergy balance. The chemical exergy of the fuel was calculated using its composition and higher heating value, based on the method proposed by Bilgen and Kaygusuz [37]. The procedure followed is similar to the methodology described by Kaushik and Singh [38] for thermal power plants. At first, the coal was carefully evaluated through proximate and ultimate analyses before starting the exergy analysis of the Chandrapura thermal power station in India, as these assumptions are commonly used and well accepted in exergy-based thermodynamic studies. Furthermore, the mass balance along with energy and exergy balances was applied to each component of the plant cycle to assess exergetic efficiency and overall system performance. An uncertainty analysis was also carried out following the approaches given by Kilicarslan [39] and Holman [40]. Twice the standard deviation of each experimental measurement was taken as the uncertainty interval; the overall uncertainty was determined using the root-sum-square (RSS) method. The uncertainties in the measuring instruments were ± 0.5 °C for temperature, ± 3 % for pressure, ± 3 % for mass flow rate, and ± 2 % for power.

2.1. An overview of the coal-fired power plant in chandrpura

The Chandrapura Thermal Power Station is run by Damodar Valley Corporation The plant currently has a capacity of 500 MW from its two units, each rated at 250 MW, and it operates on a reheat–regenerative Rankine cycle. The operating conditions are given in Table 1, and Figure 1 shows the layout of the Chandrapura Thermal Power Station cycle.

Table 1. Operating condition of power plant operations.

Power Plant's Operational Condition	Value
Energy production	**250 MW**
Coal mass flow rate	**83.52 kg/s**
Heat rate	**10451.63 kJ/kWh**
Mainline Steam flow rate	**808.74 ton/h**
Mainline Steam pressure	**205 bar**
Mainline Steam temperature	**540°C**
Reheat temperature	**300°C**
Steam flow rate in reheater	**187.7Kg/hour**
Condenser pressure	**0.075bar**
Volumetric flow rate of inlet gas	**1848 ton/h**
Induced and draft fans Number	**PA=2, F.D.=2 , I.D.=2**

2.2. Analysis of energy and exergy

The thermal power plant was assessed for operational efficiency using Engineering Equation Solver (EES). Thermodynamic data were collected at key nodes under defined design conditions (see Figure. 1 and Table 2). Using these data, Engineering Equation Solver calculated the plant's total energy input and output, thereby supporting detailed energy and exergy analyses of the major components. Engineering Equation Solver was used to model the plant with directly measured operational data, including steam and reheat temperatures and pressures, condenser conditions, inlet gas flow rate, and feed water heater configurations. The ambient conditions were also included to analyze the environmental effects on energy and exergy efficiencies of components. The value of total exergy destruction was obtained from the EES software using input data like pressure, temperature, and mass flow rate, which is experimentally measured under steady-state operating conditions. All data were verified for unit consistency and correct scaling within the SI framework before calculations. The combined uncertainty of the component's exergetic efficiencies was determined using the root-sum-square (RSS) method in the EES software. The uncertainties in the input parameters were ±0.5 °C for temperature, ±3 % for pressure, ±3 % for mass flow rate, and ±2 % for power. These uncertainties were propagated through the exergy equations to evaluate their effect on each component's efficiency. The resulting combined uncertainty for the component exergetic efficiencies was within ±0.5–0.8 %, depending on the component sensitivity to the input parameters. The thermodynamic properties were evaluated in Engineering Equation Solver with an accuracy of ±1% compared with standard steam tables which validates the simulation model.

This approach closely represents actual plant conditions and yields reliable and reproducible results. The calculation takes into account the energy produced by coal as well as any losses due to system inefficiencies and the results reflect the overall energy efficiency of the power plant. The energy equation for an open system (steady flow process) is given by [20].

$$\sum Q + \sum m\,(h_i + \frac{C_i^2}{2} + gz_i) = \sum m\,(h_0 + \frac{C_0^2}{2} + gz_0) + \sum W \qquad (1)$$

Where, Q is the heat transferred to the system (J), W is the network output (J), C is the velocity of the working fluid (m/s), Z is the height of the fluid above sea level (m), $\dot{m}$ is the mass flow rate (kg/s), and h is the enthalpy (J/kg). The exergy input and output of the system cycle used in exergy analysis are calculated using the software Engineering Equation Solver. The objective of this study is to understand the quality of energy and how effectively it can be used to do useful work. The results of the exergy analysis help in evaluating the plant's performance more clearly and in identifying areas where improvements can be made.

The equation used for the exergy balance is given by [18]

$$\sum (1 - \frac{T_0}{T})\,Q_K = \sum \dot{m}_1 \psi_1) = \sum \psi_w + \sum \dot{m}_0 \psi_0 + I_{distroyed} \qquad (2)$$

In this equation, Σ represents the sum of all heat, mass and work terms. T_0 is the surrounding (dead state) temperature, and T is the temperature at which heat transfer takes place. Q_k shows the amount of heat transfer at temperature T and $\dot{m}$ is the mass flow rate. The subscripts i and o in the equation indicate the inlet and outlet streams, respectively. ψ is the specific exergy, where ψ_0 is the inlet specific exergy, ψ_i is the outlet specific exergy, and ψ_w is the exergy associated with shaft or electrical work. Finally, $I_{distroyed}$ represents the exergy destroyed inside the system due to irreversibility.

Equations (1) and (2) are equivalent, and the specific flow exergy can be represented as:

$$\psi = (h - h\ ) - T\ \ (S - S\ ) \qquad (3)$$

In Eq. (3), ψ is the specific exergy; h is the specific enthalpy of the stream; ho is the enthalpy at the dead state; T0 is the ambient (dead-state) temperature; S is the specific entropy of the stream; and So is the entropy at the dead state.

In contrast, the total exergy of the flow is equal to:

$$Ex = \dot{m}\psi = \dot{m}\{(h - h_o) - T_0(S - S_o)\} \qquad (4)$$

Exergy destruction in a system is calculated as the difference between the total exergy input and the total exergy output, accounting for work interactions.

$$\textit{Exergy destruction} = [\textit{Exergy in} - (\textit{Exergy out} + w)] \qquad (5)$$

Here, W represents the work interaction. Work done by the system is considered positive, while work done on the system is taken as negative. The percentage of exergy destruction in a component or system is defined as:

$$\%\ \text{Exergy destruction} = \frac{\text{Exergy Destructionin the system}}{\text{Total Exergy Destruction}} \cdot 100 \qquad (6)$$

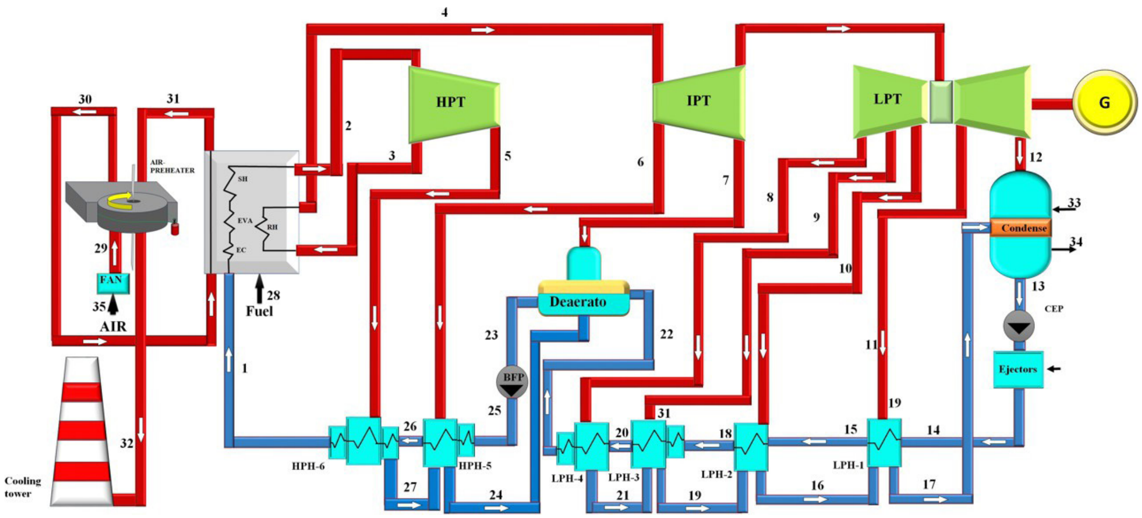

Figure 1. Schematic diagram of chandrapura thermal power station cycle

Table 2. Thermodynamic properties of all node points at the specified reference environmental temperature T=298K (see Figure 1.)

Point.	T ^{0}[C]	P [bar]	m [Kg/s]	h [KJ/Kg]	s[KJ/Kg K]	Exergy (KW)
1	253.14	205.37	205.80	1102.03	2.822	56816.202
2	538.23	189.29	203.8	3369	6.3269	303588.516
3	329.08	47.12	187.70	3016.76	6.3878	209364.516
4	539.12	42.84	187.70	3532.07	7.1655	262839.614
5	327.13	45.23	16.09	3017.01	6.4046	17989.943
6	473.48	26.03	8.65	3401.76	7.2257	10839.077
7	378.82	13.37	9.41	3212.88	7.2557	9927.223
8	289.88	6.589	9.39	3038.84	7.2925	8176.789
9	192.23	2.676	8.94	2851.08	7.3387	5992.531
10	96.7	0.9004	8.48	2667.35	7.3809	3992.504
11	62.22	0.2208	4.78	2475.13	7.4559	1222.452
12	40.32	0.075	138.1	2345.32	7.5226	15041.192
13	40.32	0.075	169.6	168.75	0.5766	259.467
14	40.25	15.105	171.7	169.8	0.5757	518.462

15	58.31	14.69	171.7	245.26	0.8099	1489.710
16	63.31	0.8629	26.8	265.05	0.8726	256.025
17	45.25	0.2116	31.58	189.39	0.6418	85.708
18	90	14.278	171.7	378.06	1.1929	4703.787
19	95	2.565	18.32	398.19	1.2504	552.408
20	122	13.864	171.7	513.13	1.5493	9652.770
21	127	6.315	9.39	533.86	1.6028	571.227
22	154	13.45	171.7	650.17	1.8823	16112.187
23	185.98	13.45	205.8	789.87	2.1971	28728.9
24	196.47	24.95	24.74	837.32	2.2970	3892.394
25	191.47	206.2	205.8	823.55	2.2495	34072.899
26	218	205.79	205.8	940.73	2.4990	43129.4
27	223	43.35	16.09	958.56	2.5454	3297.481
28	25	1.0132	83.52	0	0	707674.06
29	26.55	1.0282	325.4	301.05	6.861	409.221
30	250	1.0207	304.2	527.4	7.43	18034.046
31	326.17	1.0207	397.2	347.47	8.2628	115980
32	179.37	1.0132	418.5	188.33	7.8957	83720
33	25	1.0132	8805.56	104.8	0.3669	0
34	35	1.0132	8805.56	146.7	0.5049	6833.11
35	25	1.0132	325.4	299.64	6.86	0

This formulation quantifies the irreversibility in each component and provides a clear measure of the system's inefficiency. The second law efficiency, or exergy efficiency (η_{II}), of a system is defined as the ratio of the actual useful exergy output to the maximum possible (reversible) exergy output:

$$\eta_{II} = \frac{\text{Actual useful exergy output}}{\text{Maximum possible (reversible) exergy output}} \tag{7}$$

This formulation allows quantification of irreversibility, provides a measure of system inefficiency, and evaluates how effectively the system converts available exergy into useful work. For example, Table S1 in the supplementary material summarizes the energy and exergy formulations for the boiler, steam turbine, and condenser, defined with respect to the points shown in Figure 1 and Table 2.

3. Result and discussions

The thermal power plant was analyzed using equations 1–4, which are provided in the Methods section. The initial environmental pressure and temperature were 101.3 KPa and 298 K, respectively. Table 2. This provides a summary, calculated using Engineering Equation Solver software, of the thermodynamic properties of the various streams at the nodes depicted in Figure. 1. Table 3 displays the second-law efficiency, exergy in, exergy out, and exergy destruction for each component of the power plant. The condenser and boiler appear to have the lowest exergy efficiencies. The boiler has a low efficiency due to irreversible combustion and mixing processes. The condenser's exergy efficiency is also low due to the large amount of heat released outside the cycle.

3.1. Component-wise exergy destruction

Figure 2 shows the percentage of exergy destruction of various components of the power plant. The figure helps us to identify where useful energy is lost and which parts of the system are responsible for most of these losses because exergy destruction indicates a loss in energy quality and helps in finding areas where improvements can be made. As seen in the figure 2, the boiler is the main source of exergy loss which contributes about 80.71% of the total system losses. This high loss is mainly due to combustion occurs at high temperatures which creates large temperature differences and also due to the chemical reactions occurring inside the boiler. The chemical reactions mainly occur due to the presence of coal, as coal contains various chemical elements and compounds.

The coal used in this study has the following composition: carbon 25.32%, hydrogen 1.55%, oxygen 8.81%, nitrogen 0.58%, sulfur 1.29%, moisture 46.38%, and ash 16.07%. Since coal is the main energy source for the plant, the chemical exergy associated with it needs to be quantified to represent the total exergy entering the system. The fuel exergy rate released by coal combustion in the boiler can be calculated using the standard correlation reported by Celik and Aydemir [34], which relates the fuel's heating value to its chemical exergy. The chemical exergy was determined from the measured elemental composition, with the effects of moisture and ash accounted for by the lower heating value calculated on an as-received basis. The lower heating value of the coal is 7773.4 kJ/kg. With a coal flow rate of 83.52 kg/s, the total fuel exergy supplied to the boiler is 707674.06 kW, which corresponds to the values shown in Table 2 and to the point marked in Figure. 1.

Table 3. exergy balance of the chandrapura thermal power station component

Components	Exergy in (KW)	Exergy out (KW)	W (KW)	Exergy destruction (KW)	h*II* (%)	% Exergy destruction
Air fan	0	409.221	550	140.779	74.4	0.0367
Air pre-heater	116389.22	101754.04 6	0	14635.175	54.63	3.816
Boiler	991888.62	682408.13	0	309480.5	49.24	80.71
Steam turbine	566428.13	282546.22	242070	41811.78	85.27	10.9
Condenser	15126.9	7092.577	0	8034.323	46.887	2.095
FWH 6	1996.939	1575.418	0	421.516	69.735	0.107
FWH 5	6034.62	4959.812	0	1074.808	74.94	0.28
FWH 4	11267.545	10205.178	0	1062.367	82.32	0.277
FWH 3	17829.56	16683.341	0	1146.218	84.93	0.298
FWH 2	48209.457	47021.794	0	1187.663	88.41	0.309
FWH 1	61119.343	60113.68	0	1005.66	93.15	0.262
Deaerator	29931.804	28728.9	0	1202.91	95.98	0.3134
Condenser pump	259.467	480.95	430	208.467	51.5	0.054
Circulation pump	28728.9	34072.899	7365.4	2021.4	71.55	0.527

These factors collectively result in considerable entropy generation which shows the presence of thermodynamic irreversibility in the system. Moreover, the combustion process is inherently irreversible which increases the exergy losses in the boiler. In the present analysis, only the physical exergy associated with the temperature and pressure variations of the working fluid was considered for the boiler performance. The fuel's chemical exergy and its corrections for humidity and ash content were not incorporated because the focus was on evaluating the thermodynamic irreversibility within the power plant rather than on the combustion process. This method is consistent with simplified component-level exergy analyses where the fuel composition data are not considered. There are several methods that can help to reduce these losses and for better heat transfer in components like the economizer, air preheater, and combustion chamber, it should be designed in such a way that it improves their heat transfer efficiency. In addition, during the operation a proper fuel–air mixing, maintaining the correct steam temperature and pressure, and effective feedwater preheating can also help in reducing the losses. Some advanced techniques can further improve their performance like real-time combustion control can adjust the fuel and air supply for better combustion. The better heat recovery systems use waste heat to preheat the air, which helps in more complete combustion and reduces the heat needed for burning. The efficient heat transfer surfaces and variable-speed fans also help by adjusting the airflow according to the boiler's requirements. These Advanced options were not included in this study, as the main focus was on identifying current exergy losses and can be considered in future work to reduce losses further. Overall, using a combination of these approaches can lower boiler losses and improve plant efficiency.

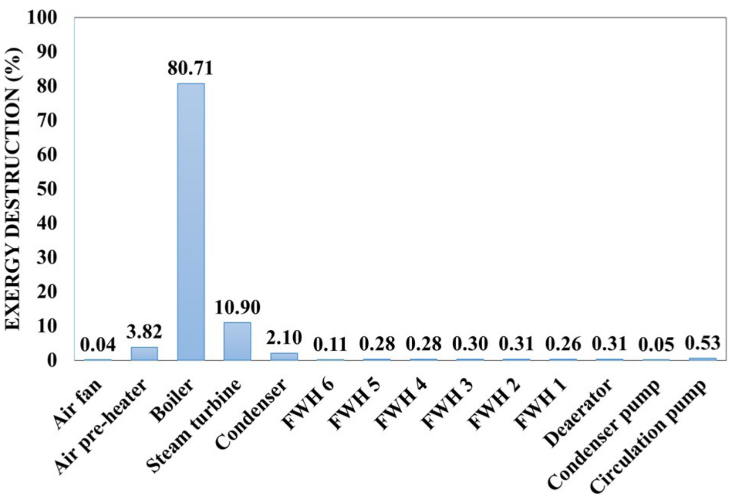

Figure 2. Exergy destruction in different component of power plant

The condenser shows the highest energy loss (approximately 53%) of the total energy input however, its exergy destruction remains limited to just 2.1%. This happens due to the basic difference between the energy and exergy analysis. In a condenser, a large amount of heat is rejected but this heat is low-grade as its temperature is very close to the surrounding condition and hence it cannot be used to produce useful work with these losses. This signifies that the exergy content is very low and even though the condenser shows a big energy losses it is not very important from an exergy point of view. On the other hand, the boiler has highest exergy losses and that is why more attention should be given to the boiler, not the condenser. This idea is often misunderstood when we do the energy analysis. The other components like the turbine, air pre-heater and air fan also cause exergy destruction and each of them contributes around 2–5% of the total loss. These losses happen due to friction, expansion of fluid and heat transfer at small temperature differences. However, their effect is much smaller compared to the losses in the boiler. The remaining parts of the system, such as low-pressure heaters (LPH-1 to LPH-3), high pressure heaters (HPH-4 to HPH-6), the deaerator, boiler feed pump (BFP) and condensate extraction pump (CEP) usually cause less than 1% exergy loss compared to other components which shows that these units are working quite well in both thermal and mechanical terms. These losses are small but still important and even small improvements in these parts can help to improve the overall performance and exergy efficiency of the plant. A schematic flow chart (see Figure 3) shows how exergy destruction is distributed among the main parts of the power plant. It also highlights the areas where efficiency can be improved. The chart makes it easier to understand how each part is performing and helps to increase the overall system efficiency. One important aspect in this study is that the dependence of exergy losses on the surrounding conditions. The exergy values change with temperature, pressure, elevation, speed, and chemical composition. If these conditions do not change then no useful work can be obtained and this state is known as dead state. For example, if the dead-state temperature changes from 280 K to 310 K while the pressure stays at 101.3 kPa, the exergy values change a lot but this change does not affect energy analysis. This again shows that exergy analysis is better for finding where losses really happen in the system. In the whole cycle, almost all the exergy is destroyed and in which the boiler alone be responsible for more than 85% of this destruction. This large amount of irreversibility clearly shows that the boiler is the most important part to improve the performance of plant. If we improve the boiler design, control the combustion process and improve heat transfer, the losses can be reduced and the overall exergy efficiency of the power plant can increase. At the same time, small improvements in the turbine and condenser can also help in improving the overall efficiency of the system.

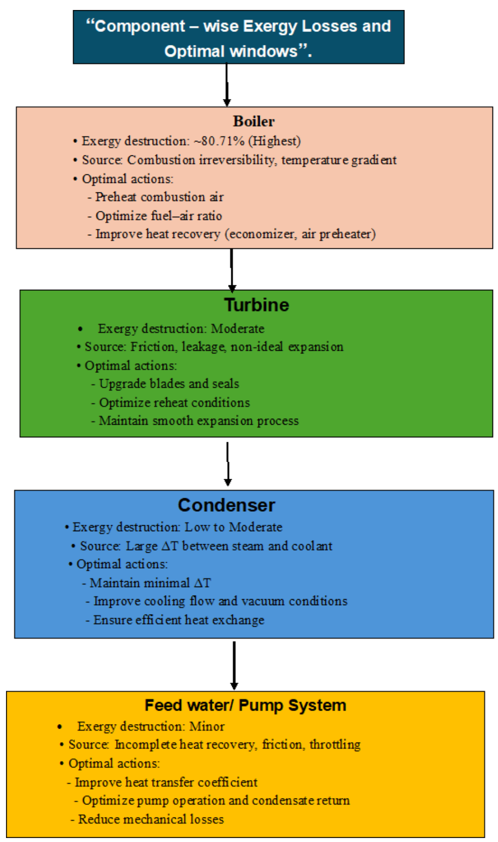

Figure 3. Component-wise exergy losses and optimal operational windows

Figure 4 shows how exergy efficiency changes in the main parts of the plant at 100% load and 80% load. The full details are given in Table S2 which helps to clearly see how the values change at both conditions. The boiler shows the highest exergy destruction at both loads but its efficiency does not change much with load of the plant (49.24% at 100% load and 49.43% at 80% load). The turbine efficiency decreases from 85.27% at 100% load to 83.33% at 80% load. The possible reason for this is that the turbine is not working at its best condition, so the steam expansion becomes less efficient and exergy loss increases. Most of the feedwater heaters show a small drop in efficiency at lower load. This may be occurred due to more irreversibilities causes when flow rate of the feedwater is lower. However, the condenser shows a different trend. Its exergy efficiency increases from 46.89% at full load to 55.20% at 80% load. This is because less heat is rejected and heat transfer becomes more effective under these conditions. The auxiliary components, like feedwater pumps, also show a decrease in efficiency when working at off-design conditions. Overall, the total exergy efficiency of the plant decreases from 34.10% at full load to 31.06% at 80% load. This behavior is normal for thermal power plants when they do not operate at full load.

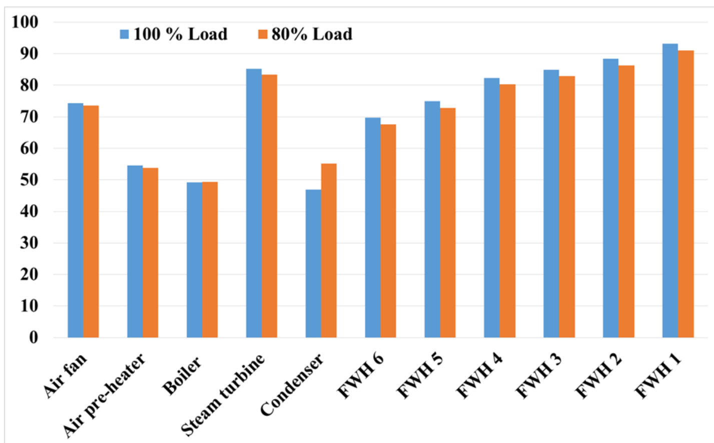

Figure 4. Exergy efficiency of plant components at 100% and 80% load

3.2. Effect of ambient temperature

Figure 5 shows how exergy destruction and exergy efficiency of the three main components i.e. boiler, condenser, and turbine are changing with reference temperature. The condenser shows a clear decrease in exergy destruction when the ambient temperature increases from 280 K to 310 K. This means it is highly affected by environmental conditions. This happens because the temperature of the condensing steam becomes closer to the cooling medium and due to this the temperature difference becomes smaller. As a result, the heat transfer losses are reduced. In contrast, the boiler shows very high exergy destruction, and it remains almost constant even when the ambient temperature changes. This is because the losses in the boiler mainly come from combustion and heat transfer, which do not depend much on the surroundings.

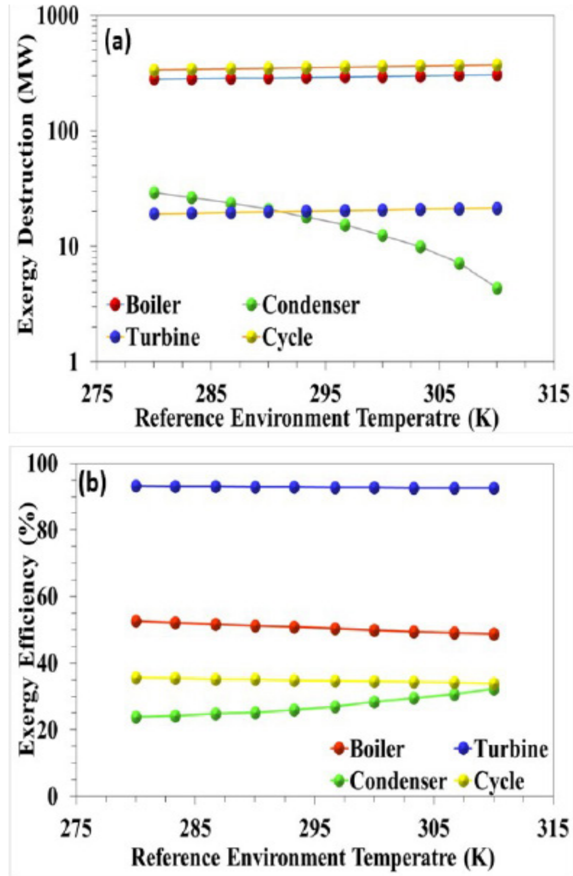

Figure 5. Exergy destruction (a) and exergetic efficiency (b) of main system components with respect to environmental temperature.

However, the turbine works in a stable way. Its exergy efficiency stays above 90%, and there is very little change in its performance with changes in ambient temperature. The overall cycle efficiency shows only a small decrease as the reference temperature increases. This means that higher dead-state temperature reduces the total useful work that can be obtained. The condenser, which has the lowest efficiency at first, improves its efficiency as the reference temperature increases. This shows that its performance can be improved by better use of environmental cooling conditions. These results show that environmental conditions must be considered for proper exergy analysis and it also show that exergy gives a clearer and more practical understanding of system performance compared to energy analysis. The reference temperature of 298 K was chosen because it represents the plant's average ambient conditions and is widely used as a standard dead state in exergy studies. A sensitivity check shows that varying the ambient temperature from 280 to 310 K has a negligible effect on the results. As shown in Figure. 5a, only the condenser shows a small change with temperature, while the major components remain almost constant. The total exergy destruction changes by less than 0.2%, which shows that the overall cycle behaviour remain unaffected. This justifies the use of a fixed reference temperature for the analysis. Future work should focus on using adaptive design strategies that leverage ambient conditions to minimize irreversibility and enhance system efficiency. The uncertainty analysis was carried out using the root-sum-square method in EES software. The calculated uncertainty in exergy destruction is approximately ±350 kW, which mainly

This arises from measurement variations in temperature, pressure, and mass flow rate. When this absolute uncertainty is normalized against the total exergy input to the system (of the order of several hundred megawatts), it results in a relatively small uncertainty of about ±0.7% in exergetic efficiency. The error bars are not visibly distinguishable in Figure 5. due to their negligible scale compared with the plotted data range.

3.3. Boiler pressure sensitivity

Figure 6 shows how exergy destruction in the boiler changes with boiler pressure. It helps to understand how irreversibility changes when the operating pressure is varied. The data shows an opposite trend between pressure and exergy destruction. As the boiler pressure increases from 100 bar to about 200 bar, the exergy destruction decreases from around 297 MW to about 292.8 MW. This means that increasing pressure improves performance from a thermodynamic point of view. At higher pressure, heat is added to the working fluid at a higher average temperature, which reduces irreversibility and improves overall efficiency. Increasing the mean temperature reduces thermal gradients during combustion and heat transfer, thereby minimizing entropy generation and associated irreversibilities. The uncertainty in the calculated boiler exergy destruction was estimated to be ±300 kW, which is very small compared with the total magnitude of exergy loss. Therefore, the error bars are not visible in the figure 6. due to their negligible scale.

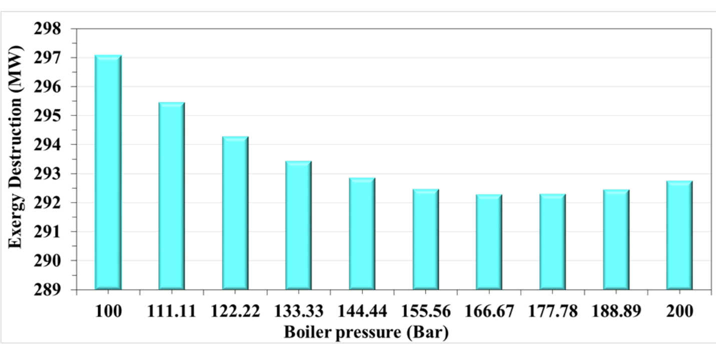

Figure 6. Exergy destruction in boilers varies with boiler pressure

The best operating condition is found when the boiler pressure is between 167 and 178 bar. In this range, the plant gives maximum efficiency and minimum exergy loss. This pressure range is already used in modern supercritical and ultra-supercritical power plants. For example, the Noshiro Thermal Power Station in Japan operates at about 241 bar, and the Alholmens Kraft Power Station in Finland operates at around 165 bar. These powerplants show that such high pressures are practical and achievable. The advanced materials like ferritic steels and nickel-based alloys are used to safely handle under these high pressures and temperatures because these materials have high strength, good corrosion resistance, long life, and can perform well under repeated heating and cooling, which makes them suitable for reliable boiler operation. The exact optimum value may change slightly if we consider economic factors like fuel cost, material limits, and auxiliary power use. However, the best pressure range will still stay close to 167 to 178 bar because at this pressure range, the exergy efficiency is highest and losses are lowest. Operating the plant in this pressure range can improve overall performance and it can increase efficiency, reduce fuel use, lower operating cost and decrease exergy losses. Hence, for better plant efficiency, the boiler should operate at the optimum pressure range aligned with suitable materials. It is also important to consider environmental conditions which helps in reducing maintenance and supports long-term reliable operation. If the boiler pressure goes above about 178 bar, the exergy destruction starts to increase again. This happens because with the increase in pressure increases the temperature and friction inside the boiler and heat exchanger surfaces. As a result the irreversibility increases and there is more stress on materials and pumping systems which reduces the performance of the components. So, the upper limit of around 178 bar is decided by both material strength and flow resistance. At higher pressures, more pump work is needed to overcome pressure losses and long-term reliability can also become a problem. The results show that the best operating range is between 167 and 178 bar. In this range, exergy losses are minimum and the system works efficiently without creating extra load on operation and maintenance. This gives a good balance between efficiency and reliability for both design and operation. This analysis shows that careful selection of boiler pressure is very important in design. Using the right pressure improves thermal performance and reduces irreversibility, which increases the overall exergy efficiency of the power plant. In the next part, the study looks at how exergy is destroyed in different components and gives practical suggestions to improve plant performance and overall operation.

3.4. Practical implications and recommendations for plant optimization

As we already discussed that the boiler is the biggest source of exergy destruction and this mainly happens due to combustion and large temperature differences. These losses can be reduced by preheating the combustion air, controlling the air–fuel ratio properly and improving heat recovery using the economizer and air preheater. The best boiler pressure range is in between 167 to 178 bar where the plant gives maximum efficiency and minimum exergy loss. Modern plants like the Noshiro Thermal Power Station and the Alholmens Kraft Power Station operate in this range, which shows that it is practical for real use. In this range, the plant works efficiently uses less fuel and avoids extra losses and material stress that come with very high pressure. Advanced materials such as ferritic steels and nickel-based alloys ensure reliable performance under these high-pressure and high-temperature conditions.

Table 4. The component-wise exergy efficiencies are compared with similar studies

S.no	Parameter	Present Investigation	Celik and Aydemir [34]	Maghsoudi et. al [41]	Kumar et. al [42]	Mitra & Ghosh [43]
1	Boiler	49.24	53.19	46.24	32.90	59.47
2	Turbine	85.27	86.12	87.78	90.81	84.99
3	Condenser	46.887	42.70	NA	54.764	40.61
4	FWH 1	88.41	64.03	89.71	91.59	44.35
5	FWH 2	93.15	88.16	96.46	90.003	70.47
6	FWH 5	69.735	87.80	97.64	95.839	83.03
7	FWH 6	74.94	96.01	93.52	97.385	92.32

Turbine performance can also be improved by several methods like better reheat conditions, improved blade design and proper sealing. However, the performance of condenser can be improved by maintaining good cooling water flow and stable vacuum. The improvement in feedwater heaters and pumps can be increased by reducing heat and mechanical losses. At the operating level using real-time monitoring and control of pressure, temperature and flow helps the plant work in the best efficiency range. This keeps the system stable and improves overall exergy performance. The component-wise exergy efficiencies in this study are compared with those reported in similar investigations are given in Table 4. The comparison shows that the exergy efficiencies of the main components in this study fall within the typical range reported for thermal power plants and confirming that the model accurately represents real operating performance. The minor

Variations occurs due to the differences in plant design and operating conditions but remain consistent with global trends. The obtained component exergy destruction percentages were also compared with published analyses of similar coal-fired plants in India. The boiler continues to be the dominant source of irreversibility, although its destruction percentage is lower than the 93.07% reported by Kumar et al. [42] and also below the level indicated by Mitra & Ghosh [43], who reported a boiler exergy efficiency of 59.47%, reflecting comparatively improved combustion and heat-transfer conditions. Turbine destruction remains lower than the values documented by Kumar et al. [42] (HPT 1.32%, IPT 0.64%, LPT 2.08%) and closely follows the Mitra & Ghosh [43] turbine exergy efficiency of 84.99%. The condenser shows slightly higher destruction than the 54.76% efficiency reported by Kumar et al. [42] and yet still performs better than the 40.61% value provided by Mitra & Ghosh [43]. The most significant deviation appears in the feedwater heaters. While the high-pressure heaters remain near the published ranges (Kumar et al. [42] 97.38% and 95.83%), the low-pressure heaters show higher destruction when compared to the LPH-2 and LPH-3 efficiencies of 90.00% and 95.54% respectively reported by Kumar et al. [42]. These comparative findings help translate thermodynamic performance into clear operational improvement pathways, which supports higher efficiency and sustainable operation of thermal power plants.

4. Conclusion

A comprehensive study on exergy analysis was carried out for a 250 MW unit at the Chandrapura power plant (total capacity 500 MW). The study showed how ambient temperature and boiler pressure affect the performance of the unit and gives following outcomes:

- The condenser was responsible for about 53% of the total energy loss, but it caused only about 8 MW of exergy destruction, which is around 2.1% of the total. This is because the heat rejected in the condenser is of low quality and cannot be used for useful work.
- The boiler and turbine are the main sources of irreversibility. The boiler alone causes about 309 MW of exergy destruction, which is around 80.7% of the total. The turbine contributes about 41.8 MW, or 10.9%. This shows that these two components need more attention for improvement.
- The total exergy loss in the cycle is about 383 MW, and the overall exergy efficiency of the plant is 34.1%. This indicates

that there are large inefficiencies and a good chance to improve performance.

- When the ambient temperature changes from 280 K to 310 K, the boiler and turbine show only small changes in efficiency, less than 1%. However, the condenser efficiency increases a lot, by more than 50%. This happens because the temperature difference becomes smaller, which reduces irreversibility during heat transfer.
- Increasing boiler pressure was found to reduce exergy destruction and enhance exergy efficiency because it increases the mean temperature of heat addition, thereby reducing entropy generation.
- An optimal pressure range (167–178 bar) was identified, in which exergy losses are minimized without introducing excessive operational complexity, making it a valuable design target for systems engineers.

Acknowledgements

The authors gratefully acknowledge Chandrapura Thermal Power Plant (Jharkhand, India) for providing the technical data used in this paper. The authors would also like to acknowledge the encouragement, motivation, and financial assistance received from the authorities of Govt. ITI Banka, Bihar, and Sarala Birla University, Ranchi, Jharkhand.

Conflict of interest

The authors of this work declare that they have no conflicts of interest.

Copyright and permission statement

All figures included in this manuscript are the authors' original work.

References

[1] Hasan HE, Ali VA, Burhanettin, Ahmet D, Suleyman HS, Bahri S, Ismail T, Cengiz G, Selcuk A. Comparative energetic and exergetic performance analyses for coal-fired thermal power plants in Turkey. International Journal of Thermal Sciences 2009;48:2179–86. https://doi.org/10.1016/j.ijthermalsci.2009.03.007

[2] A. Bejan, "Fundamentals of Exergy Analysis, Entropy Generation Minimization, and the Generation of FlowArchitecture," International Journal of Energy Research, Vol. 26, No. 7, 2002, pp. 545-565. https://doi.org/10.1002/er.804

[3] G. Tsatsaronis and M. Park, "On Avoidable and Unavoidable Exergy Destructions and Investment Costs in Thermal Systems," Energy Conversion & Management, Vol. 43, No. 9-12, 2002, pp. 1259-1270. https://doi.org/10.1016/S0196-8904(02)00012-2

[4] T. J. Kotas, "Exergy Criteria of Performance for Thermal Plant: Second of Two Papers on Exergy Techniques in Thermal Plant Analysis," International Journal of Heat and Fluid Flow, Vol. 2, No. 4, 1980, pp. 147-163. https://doi.org/10.1016/0142-727X(80)90010-7

[5] T. Ganapathy, N. Alagumurthi, R. P. Gakkhar and K. Murugesan, "Exergy Analysis of Operating Lignite Fired Thermal Power Plant," Journal of Engineering Science and Technology Review, Vol. 2, No. 1, 2009, pp.123-130. DOI: 10.25103/jestr.021.23

[6] S. C. Kamate and P. B. Gangavati, "Exergy Analysis of Cogeneration Power Plants in Sugar Industries," Applied Thermal Engineering, Vol. 29, No. 5-6, 2009, pp. 1187- 1194. https://doi.org/10.1016/j.applthermaleng.2008.06.016

[7] A. Datta, S. Sengupta and S. Duttagupta, "Exergy Analysis of a Coal-Based 210 mw Thermal Power Plant," International Journal of Energy Research, Vol. 31, No. 1, 2007, pp. 14-28. https://doi.org/10.1002/er.1224

[8] I. H. Aljundi, "Energy and Exergy Analysis of a Steam Power Plant in Jordan," Applied Thrmal Engineering, Vol. 29, No. 2-3, 2009, pp. 324-328. https://doi.org/10.1016/j.applthermaleng.2008.02.029

[9] Naterer GF, Regulagadda P, Dincer I. Exergy analysis of a thermal power plant with measured boiler and turbine losses. Applied Thermal Engineering 2010;30:970–6. https://doi.org/10.1016/j.applthermaleng.2010.01.008

[10] Dincer I, Rosen MA. Effect of varying dead-state properties on energy and exergy analyses of thermal systems. International Journal of Thermal Sciences 2004;43:121–33. https://doi.org/10.1016/j.ijthermalsci.2003.05.004

[11] Saidur R, Ahamed JU, Masjuki HH. Energy exergy and economic analysis of industrial boilers. Energy Policy2010;38:2188–97. https://doi.org/10.1016/j.enpol.2009.11.087

[12] Bilgen E. Exergetic and engineering analyses of gas turbine based cogeneration systems. Energy 2000;25:1215–29. https://doi.org/10.1016/S0360-5442(00)00041-4

[13] Datta A, Ganguly R, Sarkar L. Energy and exergy analyses of an externally fired gas turbine (EFGT) cycle integrated with biomass gasifier for distributed power generation. Energy 2010;35:341–50. https://doi.org/10.1016/j.energy.2009.09.031

[14] Kaşka, Ö., Bor, O., Tokgöz, N., & Aksoy, M. (2020). First and second law evaluation of combined Brayton-Organic Rankine power cycle. Journal of Thermal Engineering, 6(4), 577-591. https://doi.org/10.18186/thermal.764299

[15] Sue DC, Chuang CC. Engineering design and exergy analyses for combustion gas turbine based power generation system. Energy 2004;29:1183–205. https://doi.org/10.1016/j.energy.2004.02.027

[16] Khaliq A, Kaushik SC. Second-law based thermodynamic analysis of Brayton/Rankine combined power cycle with reheat. Applied Energy 2004;78:179–97. https://doi.org/10.1016/j.apenergy.2003.08.002

[17] Habib MA, Said SAM, Al-Bagawi JJ. Thermodynamic performance analysis of the Ghazlan power plant. Energy 1995;20:1121–30. https://doi.org/10.1016/0360-5442(95)00057-N

[18] Arpit, S., Kumar, P., Prasanta Kumar, D. A. S., & Dash, S. K. (2021). Application of exergy analysis in understanding the performance of a coal-fired steam power plant (120 MW) with single reheat and regenerative configuration. Journal of Thermal Engineering, 9(2), 497-509. DOI: 10.18186/thermal.1285229

[19] Reddy BV, Mohamed K. Exergy analysis of natural gas fired combined cycle power generation unit. International Journal of Exergy 2007;4:180–96. https://doi.org/10.1504/IJEX.2007.012065

[20] Kumar V, Saxena VK, Kumar R, Kumar S. Energy, exergy, sustainability and environmental emission analysis of coal-fired thermal power plant. Ain Shams Engineering Journal. 2024 Feb 1;15(2):102416. https://doi.org/10.1016/j.asej.2023.102416

[21] Sunil Kumar, K., Muniamuthu, S., & Tharanisrisakthi, B. T. (2022). An investigation to estimate the maximum yielding capability of power for mini venturi wind turbine. Ecological Engineering & Environmental Technology, 23. DOI:10.12912/27197050/147150

[22] Kumar, K. S., Muniamuthu, S., Salunkhe, S., Cep, R., & Nasr, E. A. (2025). In-situ analysis on drop in thermal performance of wind turbine gearbox system: global challenges and sustainable ideas. Engineering Research Express, 7(1), 015556. DOI 10.1088/2631-8695/adb4bd

[23] Kumar, K. S., Munıamuthu, S., & Mohan, K. R. (2023). Measurement of temperature flow analysis by condition monitoring system for WTG gear box to evaluate the thermal performance associated with plant load factor. Journal of Thermal Engineering, 9(4), 979-987. https://doi.org/10.18186/thermal.1332437

[24] Kumar, K. S., Surakasi, R., Govindhasamy, K., D'mello, G., & Tharanisrisakthi, B. (2025). Recent trends in the development and growth of solar technologies: a review. Journal of Thermal Engineering, 11(4), 1064-1074. https://doi.org/10.14744/thermal.0000973

[25] Awogbemi, O., Von Kallon, D. V., & Kumar, K. S. (2024). Contributions of artificial intelligence and digitization in achieving clean and affordable energy. Intelligent Systems with Applications, 22, 200389. https://doi.org/10.1016/j.iswa.2024.200389

[26] Gawande, K. R., Sur, A., Tondre, S. M., Raja, N. N., Kale, G., & Razoumny, Y. (2025). Advances and challenges in micro-lattice structures: Properties, applications, and future directions. AIMS Materials Science, 12(3), 649-685. doi: 10.3934/matersci.2025028

[27] Sur, A., & Gulia, V. (2022). A comprehensive review on microchannel heat exchangers, heat sink, andpolymer heat exchangers: Current state of the art. Frontiers in Heat and Mass Transfer (FHMT), 18. DOI: 10.5098/hmt.18.40

[28] Han, Y., Bai, Y., Zhang, W., Cui, S., Zang, L., & Ding, H. (2025). Study of thermal management system for battery box for formula student electric racing car. Frontiers in Mechanical Engineering, 11, 1529633. https://doi.org/10.3389/fmech.2025.1529633

[29] Miao, L., Liu, M., Zhang, K., Zhao, Y., & Yan, J. (2023). Energy, exergy, and economic analyses on coal-fired power plants integrated with the power-to-heat thermal energy storage system. Energy, 284, 129236. https://doi.org/10.1016/j.energy.2023.129236

[30] Yin, H., Jin, Y., Li, L., & Lv, W. (2022). Numerical investigation on the impact of exergy analysis and structural improvement in power plant boiler through co-simulation. Energies, 15(21), 8133. https://doi.org/10.3390/en15218133

[31] Zhou, D., Liu, M., Wang, Z., Fu, Y., Zhang, K., & Yan, J. (2025). Design and performance evaluation of a new steam/water hybrid thermal energy storage system integrated within a coal-fired power plant. Energy, 335, 138324. https://doi.org/10.1016/j.energy.2025.138324

[32] Jiang, Y., Duan, L., Pang, L., & Song, J. (2021). Thermal performance study of tower solar aided double reheat coal-fired power generation system. Energy, 230, 120857. https://doi.org/10.1016/j.energy.2021.120857

[33] Patra, I., Auda AbdulAmeer, S., Khalid, R., Jawad Kadhim, Z., I. Al Mashhadani, Z., & Roohbakhsh, H. (2022). A hybrid fuel cell, solar thermal collector, and coal-fired power plant; energetic, exergetic, and emission analysis. Energy Sources, Part A: Recovery, Utilization, and Environmental Effects, 44(3), 7726-7747. https://doi.org/10.1080/15567036.2022.2116131

[34] Gungor Celik, A., & Aydemir, U. (2025). Energy, Exergy Analysis and Sustainability Assessment of a Thermal Power Plant Operating in Various Environmental Conditions Using Real Operational Data. Sustainability, 17(4), 1417. https://doi.org/10.3390/su17041417

[35] Ashraf, W. M., Uddin, G. M., Tariq, R., Ahmed, A., Farhan, M., Nazeer, M. A., ... & Dua, V. (2023). Artificial intelligence modeling-based optimization of an industrial-scale steam turbine for moving toward net-zero in the energy sector. ACS omega, 8(24), 21709-21725. https://doi.org/10.1021/acsomega.3c01227

[36] Chen, C., Liu, M., Li, M., Wang, Y., Wang, C., & Yan, J. (2024). Digital twin modeling and operation optimization of the steam turbine system of thermal power plants. Energy, 290, 129969. https://doi.org/10.1016/j.energy.2023.129969

[37] Bilgen, S., & Kaygusuz, K. (2008). The calculation of the chemical exergies of coal-based fuels by using the higher heating values. Applied Energy, 85(8), 776-785. https://doi.org/10.1016/j.apenergy.2008.02.001

[38] Kaushik, S. C., & Singh, O. K. (2014). Estimation of chemical exergy of solid, liquid and gaseous fuels used in thermal power plants. Journal of Thermal Analysis and Calorimetry, 115(1), 903-908. https://doi.org/10.1007/s10973-013-3323-9

[39] Kilicarslan, A. (2004). An experimental investigation of a different type vapor compression cascade refrigeration system. Applied Thermal Engineering, 24(17-18), 2611-2626. https://doi.org/10.1016/j.applthermaleng.2004.04.004

[40] Holman JP. Experimental methods for engineers. 8th ed. New York: McGrawHill International Edition; 2012.pp. 65.

[41] K. Maghsoudi, A. Mehrpanahi and M. Tabaraki ; 'Energy and exergy analysis of 250 MW steam power plant', Switzerland Research Park Journal, vol :102, no. :11, Nov2013.

[42] Kumar, A. K. B. A., Nikam, K. C., & Behura, A. K. (2020). An exergy analysis of a 250 MW thermal power plant. Renewable Energy Research and Applications, 1(2), 197-204. https://doi.org/10.22044/rera.2020.9460.1025

[43] Mitra, S., & Ghosh, J. (2015). Energy and exergy analysis of a 250MW coal fired thermal power plant at different loads. International Journal of Research in Engineering and Technology, 9, 54-62. https://ijret.org/volumes/2015v04/i07/IJRET20150407009.pdf