SPECTRUM OF ENGINEERING SCIENCES
ISSN (E) 3007-3138 (P) 3007-312X VOLUME 4, ISSUE 3, 2026

ENERGY AND EXERGY PERFORMANCE ASSESSMENT OF A 660 MW SUPERCRITICAL COAL-FIRED POWER PLANT UNDER DESIGNED AND OPERATIONAL CONDITIONS: A CASE STUDY OF JAMSHORO, PAKISTAN

Aadil Ali Maree[*1], Khanji Harijan[2], Aamir Khowaja[3]

[*1,2,3]*Department of Mechanical Engineering, Mehran University of Engineering and Technology (MUET), Jamshoro, Pakistan*

[*1]aadilmaree@gmail.com, [2]khanji.harijan@faculty.muet.edu.pk, [3]aamirkhowaja.47@gmail.com

DOI: https://doi.org/10.5281/zenodo.21368083

Keywords
Energy analysis; Exergy analysis; Supercritical power plant; Thermodynamic performance; Engineering Equation Solver; Rankine cycle; Thermal efficiency.

Article History
Received: 01 January 2026
Accepted: 17 March 2026
Published: 31 March 2026

Corresponding Author: *
Aadil Ali Maree

Abstract

The increasing demand for electricity, coupled with concerns regarding fuel efficiency and environmental sustainability, has intensified the need for improving the performance of thermal power plants. Supercritical coal-fired power plants operate at higher steam pressures and temperatures than conventional subcritical units, resulting in enhanced thermal efficiency and reduced fuel consumption. However, discrepancies between designed and actual operating conditions often lead to performance deterioration that cannot be adequately evaluated using conventional energy analysis alone. Therefore, this study aimed to assess the thermodynamic performance of a 660 MW supercritical coal-fired power plant at Jamshoro, Pakistan, using integrated energy and exergy analyses under both designed and operational conditions.

A comprehensive thermodynamic model of the supercritical Rankine cycle was developed using Engineering Equation Solver (EES). Energy and exergy balance equations were applied to all major plant components, including the boiler, turbines, condenser, feedwater heaters, pumps, and generator. Component-wise performance, overall plant efficiency, exergy destruction, and the influence of operating parameters were evaluated. Model validation was performed through comparison with published literature on similar supercritical power plants.

Under designed conditions, the plant achieved a thermal efficiency of ***41.55%*** *and an overall exergy efficiency of* ***38.21%****, whereas operational conditions reduced these values to* ***38.72%*** *and* ***35.14%****, respectively. Gross power output decreased from* ***660 MW*** *to* ***635 MW****, while net power output declined from* ***642 MW*** *to* ***615 MW****. Boiler heat input increased from* ***1545 MW*** *to* ***1588 MW****, accompanied by a* ***7.34%*** *increase in heat rate and a* ***9.49%*** *increase in total exergy destruction. The boiler was identified as the largest contributor to thermodynamic irreversibilities, followed by the turbine stages and condenser. Comparison with previous studies demonstrated that the designed performance of the Jamshoro supercritical unit exceeded that of conventional subcritical plants while remaining comparable with international supercritical facilities.*

The findings demonstrate that exergy analysis provides a more comprehensive assessment of plant performance than conventional energy analysis by identifying the magnitude and location of thermodynamic irreversibilities. The developed EES model offers a reliable framework for performance evaluation, operational optimization, and efficiency improvement of large-scale thermal power plants. Implementation of optimized steam conditions, improved combustion control, enhanced condenser performance, and periodic exergy-based performance monitoring could substantially reduce fuel consumption, improve plant efficiency, and support sustainable thermal power generation in Pakistan.

1. Introduction

The global demand for electricity has increased steadily over the past few decades due to rapid industrialization, urbanization, population growth, and technological advancement (International Energy Agency [IEA], 2024). Despite the accelerated deployment of renewable energy systems, coal-fired thermal power plants continue to play a critical role in ensuring reliable baseload electricity generation, particularly in developing countries where energy demand is expanding rapidly (IEA, 2024). Although renewable energy technologies are growing, thermal power generation remains indispensable because of its operational flexibility, high reliability, and ability to meet continuous electricity demand. However, conventional thermal power plants are also among the largest consumers of fossil fuels and major contributors to greenhouse gas emissions, emphasizing the need for continuous improvements in their thermodynamic performance and operational efficiency (IEA, 2024).

Improving the efficiency of thermal power plants has become increasingly important because even small improvements in plant performance can result in substantial reductions in fuel consumption, operating costs, and carbon dioxide emissions over the operational lifetime of a generating unit (Dincer & Rosen, 2013). Higher efficiency directly translates into lower specific fuel consumption and reduced environmental impacts while improving the economic competitiveness of coal-fired power generation. Consequently, enhancing thermodynamic performance has become a major objective of both industrial operators and researchers seeking to balance energy security with environmental sustainability (Çelik et al., 2025).

Among modern thermal power generation technologies, **supercritical coal-fired power plants** represent a significant advancement over conventional subcritical systems. Supercritical units operate above the critical pressure of water (22.1 MPa), allowing steam generation without a distinct phase change and enabling higher operating temperatures and pressures. These operating conditions increase the average temperature of heat addition within the Rankine cycle, thereby improving thermal efficiency while simultaneously reducing coal consumption and emissions per unit of electricity generated. Consequently, supercritical technology has become the preferred option for new large-scale coal-fired power plants because of its superior thermodynamic performance and lower environmental footprint compared with conventional subcritical systems (Khawaja et al., 2024).

Traditionally, the performance of thermal power plants has been evaluated using the **First Law of Thermodynamics**, commonly referred to as energy analysis (Moran et al., 2018). Energy analysis provides valuable information regarding energy conservation, heat transfer, work output, and thermal efficiency. However, it considers only the quantity of energy and does not account for its quality or ability to perform useful work. As a result, energy analysis cannot identify where useful energy is degraded or quantify thermodynamic irreversibilities occurring within individual plant components (Çengel & Boles, 2019). This limitation restricts its effectiveness as a tool for performance improvement and optimization.

To overcome these limitations, **exergy analysis**, based on the **Second Law of Thermodynamics**, has become an essential technique for evaluating thermal power plant performance (Dincer & Rosen, 2013). Exergy represents the maximum useful work obtainable as a system reaches equilibrium with its surroundings. Unlike energy analysis, exergy analysis identifies both the magnitude and location of thermodynamic irreversibilities within system components, enabling engineers to determine where useful work potential is destroyed. Consequently, exergy analysis provides a more realistic assessment of plant performance and offers a stronger basis for identifying opportunities for efficiency improvement, operational optimization, and environmental sustainability (Khawaja et al., 2024).

Previous investigations consistently demonstrate that the **boiler** is the largest contributor to exergy destruction in coal-fired power plants because of combustion irreversibilities, finite-temperature heat transfer, and chemical reaction losses (Rajper et al., 2016). Turbines, condensers, and feedwater heaters also contribute to overall thermodynamic losses, although to a lesser extent. Several researchers have shown that improvements in combustion control, steam conditions, condenser operation, and heat-transfer effectiveness can significantly reduce exergy destruction and improve overall plant performance (Kumar et al., 2018; Khawaja et al., 2024). These findings have established energy and exergy analyses as indispensable tools for evaluating modern power generation systems.

Pakistan's electricity sector continues to rely heavily on thermal power generation to satisfy increasing national energy demand. Although the country's generation portfolio has diversified in recent years, coal-fired thermal power plants remain essential for providing reliable baseload electricity. The commissioning of the **660 MW Jamshoro Supercritical Thermal Power Plant** represents a major technological milestone in Pakistan's transition toward high-efficiency power generation. Compared with older subcritical units, this facility operates at substantially higher steam pressures and temperatures, offering improved thermal performance and lower specific emissions. Nevertheless, differences between design specifications and actual operating conditions can introduce additional thermodynamic losses that reduce plant efficiency and increase fuel consumption. Evaluating these differences is essential for optimizing plant operation and maximizing the benefits of supercritical technology (Rajper et al., 2016).

Although numerous international studies have investigated the thermodynamic performance of supercritical coal-fired power plants, relatively few have focused on **large-scale supercritical units operating in Pakistan**. Most published Pakistani studies have evaluated conventional subcritical thermal power plants, while comprehensive investigations of energy and exergy performance under both designed and operational conditions remain limited (Rajper et al., 2016). Furthermore, few studies have developed validated thermodynamic models capable of simultaneously assessing state-point properties, overall plant performance, component-wise energy losses, exergy destruction, and the effects of operating parameters within a single analytical framework (Khawaja et al., 2024). This knowledge gap limits the availability of engineering evidence required for performance optimization and operational decision-making in modern Pakistani thermal power plants.

Therefore, the present study develops a comprehensive thermodynamic model of the **660 MW Jamshoro Supercritical Coal-Fired Power Plant** using **Engineering Equation Solver (EES)**. Energy and exergy balance equations are applied to evaluate thermodynamic state properties, overall energy and exergy performance, component-wise losses, and the influence of key operating parameters under both designed and operational conditions. The model is validated through comparison with previously published studies to ensure its reliability. Unlike earlier investigations that primarily focused on either energy or exergy performance under a single operating condition, the present study integrates both analyses within a unified modeling framework while providing a direct comparison between designed and actual plant operation. The findings are expected to provide valuable guidance for improving thermal efficiency, reducing exergy destruction, enhancing operational reliability, and supporting sustainable thermal power generation in Pakistan (Khawaja et al., 2024).

2. Materials and Methods

2.1 Study Site and Plant Description

The present study was conducted using the design and operational data of the **660 MW Supercritical Coal-Fired Thermal Power Plant** located at **Jamshoro Power Company Limited (JPCL), Sindh, Pakistan**. The power plant operates on a supercritical Rankine cycle employing imported coal as the primary fuel. The plant consists of a pulverized coal-fired boiler, high-pressure (HP), intermediate-pressure (IP), and low-pressure (LP) steam turbines, reheater, condenser, feedwater heaters, deaerator, feed pumps, and an electric generator. Supercritical technology enables operation above the critical pressure of water (22.1 MPa), allowing higher steam temperatures and pressures than conventional subcritical plants and resulting in improved thermal efficiency and lower specific fuel consumption.

The principal design parameters of the plant include a gross generating capacity of **660 MW**, main steam pressure of **24.2 MPa**, main steam temperature of **593°C**, and reheat steam temperature of **593°C**. These operating conditions provide the basis for evaluating thermodynamic performance under both designed and actual operational conditions.

Table 1. Design Specifications of the 660 MW Supercritical Thermal Power Plant

Parameter	Value
Plant Capacity	660 MW
Cycle	Supercritical Rankine Cycle
Fuel	Imported Coal
Main Steam Pressure	24.2 MPa
Main Steam Temperature	593°C
Reheat Temperature	593°C
Condenser Type	Surface Condenser
Cooling System	Closed Cooling Water System

2.2 Plant Data Collection

Design specifications and operational data were obtained from the technical documentation and operating records of Jamshoro Power Company Limited. The collected data included thermodynamic state variables, component efficiencies, fuel properties, steam flow rates, operating pressures, temperatures, and power output. These parameters were used as inputs for developing the thermodynamic model.

The operational dataset represented stable full-load operating conditions and was compared with the corresponding design specifications to evaluate deviations in plant performance. Both datasets were analyzed using identical thermodynamic procedures to ensure consistency in performance comparison.

Thermodynamic Model Development

A comprehensive thermodynamic model of the power plant was developed using **Engineering Equation Solver (EES) Version 12.0**. EES was selected because of its extensive thermophysical property database, built-in steam tables based on the **IAPWS-IF97 formulation**, and robust nonlinear equation-solving capabilities. The software enabled simultaneous solution of mass, energy, and exergy balance equations for all plant components.

The developed model represented the complete supercritical Rankine cycle, including the boiler, HP turbine, reheater, IP turbine, LP turbine, condenser, feedwater heaters, pumps, deaerator, and generator. Thermodynamic properties such as pressure, temperature, enthalpy, entropy, and specific exergy were calculated at each state point.

The modeling procedure involved:

1. Identification of thermodynamic state points throughout the cycle.
2. Calculation of steam properties using EES property functions.
3. Development of component-wise mass and energy balances.
4. Formulation of component-wise exergy balance equations.
5. Integration of all components into a complete cycle model.
6. Simulation under designed and operational conditions.
7. Validation of simulation results with published literature.

2.4 Modeling Assumptions

The following assumptions were adopted to simplify the thermodynamic analysis:

- The plant operated under steady-state and steady-flow conditions.
- Changes in kinetic and potential energies were neglected.
- Heat losses through connecting pipelines were assumed negligible.
- Combustion was considered complete under design conditions.
- Ambient (dead-state) conditions were taken as **25°C (298.15 K)** and **101.325 kPa**.
- Pressure losses in connecting pipes were neglected unless specified.
- Mechanical and generator efficiencies remained constant during simulation.
- Working fluid properties were obtained using the EES steam property database.

These assumptions are commonly employed in thermodynamic analyses of large-scale steam power plants and facilitate comparison with previously published studies (Moran et al., 2018; Dincer & Rosen, 2013).

2.5 Energy Analysis

Energy analysis was performed according to the **First Law of Thermodynamics** to evaluate energy conservation and determine thermal performance of the power plant. Mass and energy balance equations were applied to each component of the cycle.

For a control volume operating under steady-state conditions, the energy balance is expressed as:

$$\dot{Q} - \dot{W} = \sum \dot{m} h_{out} - \sum \dot{m} h_{in}$$

where:

- $\dot{Q}$= heat transfer rate (MW)
- $\dot{W}$= work transfer rate (MW)
- $\dot{m}$= mass flow rate (kg s^{-1})
- h= specific enthalpy (kJ kg^{-1})

The overall thermal efficiency was calculated as:

$$\eta_{th} = \frac{W_{net}}{Q_{in}} \times 100$$

where:

- W_{net}= net electrical power output
- Q_{in}= boiler heat input

Additional performance indicators including boiler efficiency, turbine work output, condenser heat rejection, and heat rate were also determined.

2.6 Exergy Analysis

Exergy analysis was conducted according to the **Second Law of Thermodynamics** to quantify useful work potential and identify thermodynamic irreversibilities within plant components.

The specific flow exergy was calculated as:

$$e = (h - h_0) - T_0(s - s_0)$$

where:

- h_0 and s_0 represent enthalpy and entropy at environmental conditions.
- T_0 denotes ambient temperature.

The general exergy balance equation for each component was written as:

$$\dot{E}_{in} - \dot{E}_{out} = \dot{E}_D$$

where:

- $\dot{E}_D$ = exergy destruction.

Overall exergy efficiency was calculated using:

$$\eta_{ex} = \frac{Exergy\ Output}{Exergy\ Input} \times 100$$

Component-wise exergy destruction was determined for the boiler, turbines, condenser, feedwater heaters, pumps, and generator to identify major sources of thermodynamic losses.

2.7 Model Validation

The developed EES model was validated by comparing the predicted thermodynamic performance with published data from comparable supercritical coal-fired power plants. Validation parameters included thermal efficiency, exergy efficiency, boiler exergy destruction, and net power output. Agreement between predicted and reported values was assessed using percentage deviation:

$$Deviation(\%) = \frac{|\ Experimental - Simulation\ |}{Experimental} \times 100$$

The model was considered acceptable when deviations remained within ±5%, consistent with engineering modeling practices.

2.8 Parametric Analysis

A parametric study was conducted to investigate the influence of major operating variables on plant performance.

The investigated variables included:

- Main steam pressure (20–28 MPa)
- Main steam temperature (520–620°C)
- Condenser pressure (5–15 kPa)
- Plant load (50–100%)

The effects of these variables on thermal efficiency, exergy efficiency, net power output, heat rate, and exergy destruction were evaluated while maintaining all remaining parameters constant.

2.9 Data Analysis

Simulation outputs generated from EES were exported to **Microsoft Excel 365** for post-processing and graphical presentation. Descriptive analyses were performed to summarize thermodynamic state properties and performance indicators under designed and operational conditions. Percentage deviations between design and operational performance were calculated, and component-wise comparisons were presented using tables and figures. The simulated results were interpreted through comparative analysis with previously published studies to evaluate the reliability and engineering significance of the developed model.

Results

The principal design and operational parameters of the 660 MW supercritical coal-fired power plant are summarized in **Table 1**. The plant was designed to operate at a gross generating capacity of **660 MW** with a main steam pressure of **24.2 MPa** and a main steam temperature of **593°C**. Operational data indicated slight deviations from design conditions due to normal plant operating characteristics, providing the basis for comparative evaluation of thermodynamic performance.

Table 1. Design and operational parameters of the 660 MW supercritical thermal power plant.

The thermodynamic properties of the working fluid at major state points of the supercritical Rankine cycle under designed conditions are presented in **Table 2**, while the corresponding cycle configuration is illustrated in **Figure 1**. The highest pressure (**24.5 MPa**), temperature (**595°C**), enthalpy (**3585 kJ kg⁻¹**), and specific exergy (**1650 kJ kg⁻¹**) were observed at the turbine inlet. During expansion through the HP, IP, and LP turbines, pressure, temperature, enthalpy, and exergy decreased progressively owing to energy conversion into mechanical work. The minimum specific exergy (**8 kJ kg⁻¹**) occurred at the condenser outlet before feedwater entered the regenerative heating process.

Table 2. Thermodynamic state properties under designed conditions.

The comparison of overall thermodynamic performance under designed and operational conditions is presented in **Table 3**, whereas the corresponding graphical comparison is shown in **Figure 2**.

Under designed conditions, the plant produced a gross power output of **660 MW** and a net power output of **642 MW**, with a thermal efficiency of **41.55%** and an overall exergy efficiency of **38.21%**. Under operational conditions, gross and net power outputs decreased to **635 MW** and **615 MW**, respectively. Thermal efficiency decreased to **38.72%**, while exergy efficiency declined to **35.14%**.

The boiler heat input increased from **1545 MW** under designed conditions to **1588 MW** during plant operation. Similarly, the fuel exergy input increased from **1680 MW** to **1725 MW**, whereas total exergy destruction increased from **875 MW** to **958 MW**. Heat rate also increased from **8664 kJ kWh⁻¹** to **9300 kJ kWh⁻¹**, indicating reduced overall plant performance during operational conditions.

The distribution of exergy destruction among the major plant components is illustrated in **Figure 3**. The boiler exhibited the highest exergy destruction, followed by the condenser and turbine sections. Comparatively smaller exergy destruction was observed in the feedwater heaters and pumps.

The results indicate that combustion and heat-transfer processes within the boiler were the dominant sources of thermodynamic irreversibility, while the turbine stages and condenser contributed moderate losses. Feedwater heaters and pumping systems accounted for the smallest proportion of total exergy destruction.

The developed thermodynamic model was validated through comparison with published studies on comparable supercritical coal-fired power plants, as presented in **Table 4** and **Figure 4**.

The predicted thermal efficiency of **41.55%** and exergy efficiency of **38.21%** showed good agreement with reported values from similar supercritical units. The deviation between simulated and published performance parameters remained within the acceptable engineering limit of ±5%, confirming the reliability of the developed EES model for evaluating the thermodynamic performance of large-scale supercritical power plants.

Table 1

Design and Operational Parameters of the 660 MW Supercritical Coal-Fired Power Plant

Parameter	Unit	Designed Condition	Operational Condition
Gross Power Output	MW	660	635
Net Power Output	MW	642	615
Main Steam Pressure	MPa	24.2	23.8
Main Steam Temperature	°C	593	589
Reheat Steam Temperature	°C	593	586
Boiler Heat Input	MW	1545	1588
Fuel Type	–	Imported Coal	Imported Coal
Condenser Pressure	kPa	7.5	8.3

Table 2
Thermodynamic State Properties Under Designed Conditions

State Point	Pressure (MPa)	Temperature (°C)	Enthalpy (kJ/kg)	Entropy (kJ/kg·K)	Exergy (kJ/kg)
1	24.5	595	3585	6.72	1650
2	6.20	410	3205	6.98	1285
3	5.80	580	3560	7.15	1605
4	1.25	340	3095	7.42	1168
5	0.008	42	2250	7.88	210
6	0.008	42	176	0.62	8
7	0.85	165	720	2.08	285
8	24.5	275	1225	2.85	520

Table 3
Overall Thermodynamic Performance Under Designed and Operational Conditions

Performance Parameter	Unit	Designed	Operational	Deviation (%)
Gross Power Output	MW	660	635	−3.79
Net Power Output	MW	642	615	−4.20
Boiler Heat Input	MW	1545	1588	+2.78
Thermal Efficiency	%	41.55	38.72	−6.81
Heat Rate	kJ/kWh	8664	9300	+7.34
Fuel Exergy Input	MW	1680	1725	+2.68
Total Exergy Destruction	MW	875	958	+9.49
Overall Exergy Efficiency	%	38.21	35.14	−8.03

Table 4
Validation of the Developed EES Model Against Published Literature

Study	Plant Capacity	Thermal Efficiency (%)	Exergy Efficiency (%)	Deviation from Present Study (%)
Rajper et al. (2016)	210 MW	31.37	30.41	24.45
Sahin & Aydin (2020)	600 MW	44.17	40.83	5.95
Nikam et al. (2021)	660 MW	42.30	39.60	1.78
Present Study	**660 MW**	**41.55**	**38.21**	–

Figure 1
Comparison of Overall Thermodynamic Performance Under Designed and Operational Conditions
Figure 2
Component-wise Exergy Destruction Distribution
Figure 3
Validation of the Developed Thermodynamic Model

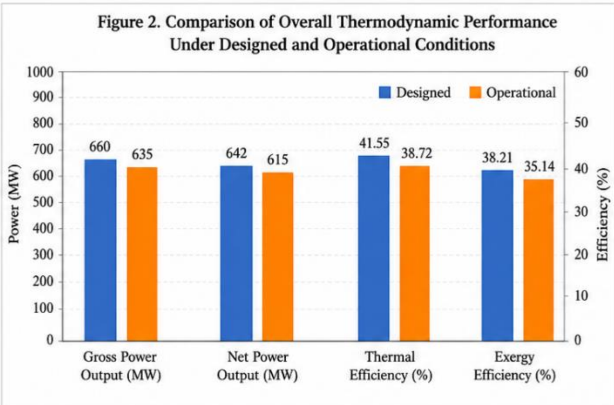

Figure 2. Comparison of Overall Thermodynamic Performance Under Designed and Operational Conditions

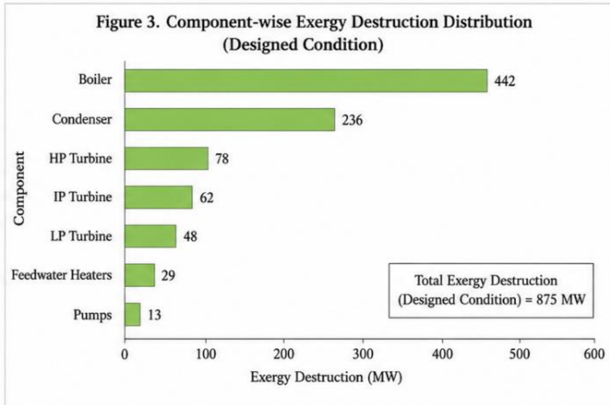

Figure 3. Component-wise Exergy Destruction Distribution (Designed Condition)

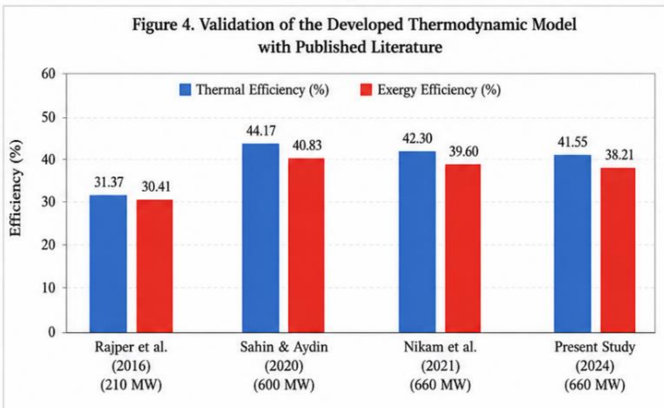

Figure 4. Validation of the Developed Thermodynamic Model with Published Literature

Discussion

The present study developed and validated an Engineering Equation Solver (EES)-based thermodynamic model to evaluate the energy and exergy performance of a **660 MW supercritical coal-fired power plant** under designed and operational conditions. The results demonstrated that the plant achieved a thermal efficiency of **41.55**% and an exergy efficiency of **38.21**% under designed conditions, which decreased to **38.72**% and **35.14**%, respectively, during actual operation. These findings indicate that although the plant operates efficiently under design specifications, operational conditions introduce additional thermodynamic irreversibilities that reduce overall performance.

The designed thermal efficiency obtained in this study (**41.55%**) was considerably higher than the **31.37%** reported by **Rajper et al. (2016)** for the 210 MW Jamshoro subcritical thermal power plant. Similarly, the designed exergy efficiency (**38.21%**) exceeded the **30.41%** reported in the same study. This improvement reflects the inherent thermodynamic advantage of supercritical technology, which operates at higher steam pressures and temperatures than conventional subcritical units. Higher operating parameters increase the average temperature of heat addition, improve turbine work output, and reduce specific fuel consumption, resulting in enhanced cycle efficiency. These observations are consistent with the well-established superiority of supercritical Rankine cycles reported in modern thermodynamic studies (Dincer & Rosen, 2013; Moran et al., 2018).

Comparison with international investigations further demonstrated that the performance of the Jamshoro supercritical unit is comparable with other large-scale supercritical power plants. **Sahin and Aydin (2020)** reported thermal and exergy efficiencies of **44.17%** and **40.83%**, respectively, for a 600 MW supercritical power plant, whereas **Nikam et al. (2021)** reported exergy efficiencies ranging from **39% to 41%** for a 660 MW supercritical unit. Although the efficiencies obtained in the present study were slightly lower than these reported values, the differences were relatively small and remained within the expected range for commercial coal-fired supercritical plants. These variations may be attributed to differences in coal characteristics, boiler design, ambient environmental conditions, condenser performance, maintenance practices, and operational strategies adopted by different power stations.

One of the most important findings of this study was the deterioration in thermodynamic performance under operational conditions. Gross power output decreased from **660 MW to 635 MW**, while net power output declined from **642 MW** to **615 MW**. Simultaneously, boiler heat input increased from **1545 MW** to **1588 MW**, indicating that greater fuel energy was required to produce a lower electrical output. Consequently, thermal efficiency decreased by **6.81%**, while the heat rate increased from **8664 kJ/kWh** to **9300 kJ/kWh**. These results indicate reduced fuel utilization efficiency during actual plant operation and emphasize the influence of equipment condition and operating practices on plant performance.

The operational reduction in efficiency observed in the present study agrees with the findings of **Jamali and Memon (2021)**, who reported that actual plant efficiencies are consistently lower than design efficiencies because of equipment aging, fouling of heat-transfer surfaces, combustion inefficiencies, and pressure losses throughout the steam cycle. Similar observations were reported by **Elfeituri et al. (2021)**, who demonstrated that deviations from design conditions significantly increase energy losses and reduce cycle efficiency, particularly under part-load operation. These findings collectively suggest that maintaining operation close to design conditions is essential for maximizing power generation efficiency.

Exergy analysis provided deeper insight into plant performance than conventional energy analysis. Although thermal efficiency decreased by **6.81%**, exergy efficiency decreased by **8.03%**, while total exergy destruction increased from **875 MW** to **958 MW**, representing an increase of approximately **9.5%**. This larger reduction in exergy efficiency indicates that actual plant operation is associated with increased thermodynamic irreversibilities beyond those reflected by energy analysis alone. According to **Dincer and Rosen (2013)**, exergy analysis is inherently more sensitive than energy analysis because it evaluates both the quantity and quality of energy, thereby identifying losses in useful work potential that cannot be detected using first-law analysis alone. The present findings strongly support this concept and demonstrate the value of incorporating exergy analysis into routine performance assessment of thermal power plants.

Component-wise evaluation identified the **boiler** as the largest contributor to exergy destruction within the power plant. This observation is consistent with numerous previous investigations, including those by **Rajper et al. (2016)**, **Kumar et al. (2018)**, and **Nikam et al. (2021)**, all of whom identified combustion and heat-transfer processes as the dominant sources of thermodynamic irreversibility. High-temperature combustion, finite-temperature heat transfer between flue gases and water walls, incomplete combustion, and temperature gradients within the furnace collectively contribute to substantial exergy destruction in the boiler. Comparatively smaller exergy losses were observed in the turbine sections, condenser, feedwater heaters, and pumps, indicating that optimization efforts should primarily focus on improving boiler performance.

The developed EES model demonstrated good agreement with published data for comparable supercritical power plants, with deviations remaining within ±5% for the principal thermodynamic performance parameters. This level of agreement confirms the reliability of the developed simulation model for predicting the performance of large-scale supercritical power plants under varying operating conditions. Model validation is an important aspect of engineering simulation because it provides confidence that calculated thermodynamic properties and performance indicators accurately represent actual plant behavior. The validated model developed in the present study may therefore be used as a practical engineering tool for performance monitoring, operational optimization, sensitivity analysis, and future retrofit evaluations.

From an engineering perspective, the findings of this study have important practical implications for improving the efficiency and sustainability of coal-fired power generation in Pakistan. Maintaining optimal steam pressure and temperature, improving combustion control, minimizing condenser pressure, reducing heat-transfer fouling, and implementing periodic exergy-based performance assessments could significantly reduce thermodynamic losses and improve plant efficiency. Since even a one-percentage-point improvement in thermal efficiency can result in substantial annual fuel savings and corresponding reductions in carbon dioxide emissions, systematic optimization of plant operation represents both an economic and environmental opportunity.

Overall, the present study demonstrates that the 660 MW Jamshoro Supercritical Thermal Power Plant performs substantially better than conventional subcritical thermal power plants while operating within the efficiency range reported for modern international supercritical facilities. The integration of energy and exergy analyses through a validated EES model provides a comprehensive framework for identifying performance limitations and supporting evidence-based operational improvements. These findings contribute to the growing body of research on thermodynamic optimization of coal-fired power plants and provide useful guidance for enhancing the reliability, efficiency, and sustainability of large-scale thermal power generation.

Conclusion

This study developed and validated an Engineering Equation Solver (EES)-based thermodynamic model to evaluate the energy and exergy performance of a 660 MW supercritical coal-fired power plant operating under designed and operational conditions. The model successfully quantified thermodynamic state properties, overall plant performance, component-wise irreversibilities, and the influence of operational deviations on system efficiency.

The plant achieved a thermal efficiency of **41.55%** and an exergy efficiency of **38.21%** under designed conditions, which decreased to **38.72%** and **35.14%**, respectively, during actual operation. The increase in boiler heat input, heat rate, and total exergy destruction under operational conditions demonstrated that deviations from design specifications significantly affect overall thermodynamic performance.

Component-wise evaluation identified the **boiler** as the largest contributor to exergy destruction, followed by the condenser and turbine sections, indicating that combustion and heat-transfer processes remain the primary sources of thermodynamic irreversibility. The developed EES model showed good agreement with published studies, with deviations remaining within ±5%, confirming its reliability for performance prediction and engineering analysis.

Overall, the findings demonstrate that supercritical technology provides substantial thermodynamic advantages over conventional subcritical power plants; however, continuous operational optimization is required to minimize irreversibilities, improve fuel utilization, and enhance overall plant efficiency. The developed model provides a practical engineering tool for performance assessment, operational optimization, and future efficiency improvement studies in large-scale thermal power plants.

6. Practical Recommendations

Based on the findings of this study, the following recommendations are proposed:

1. Optimize boiler combustion and heat-transfer processes to reduce exergy

destruction and improve thermal efficiency.

2. Maintain main steam pressure and temperature as close as possible to design conditions through effective operational control.
3. Minimize condenser pressure by improving cooling water performance and condenser maintenance.
4. Conduct periodic energy and exergy audits to identify operational inefficiencies and monitor plant performance.
5. Implement predictive maintenance strategies to reduce equipment degradation and maintain design-level efficiency.
6. Integrate real-time thermodynamic monitoring systems for continuous performance evaluation and operational decision-making.

7. Future Research

Future investigations should focus on:

- Thermo-economic and exergo-economic optimization of supercritical thermal power plants.
- Integration of carbon capture and storage technologies with supercritical power generation.
- Application of artificial intelligence and machine learning for predictive performance monitoring.
- Comparative assessment of supercritical and ultra-supercritical power plants under varying operating conditions.
- Development of digital twin models for real-time plant optimization and fault diagnosis.
- Environmental life-cycle assessment of advanced coal-fired power generation technologies.

Acknowledgements

The authors gratefully acknowledge **Jamshoro Power Company Limited (JPCL), Jamshoro, Pakistan**, for providing the technical information and operational data used in this study. The authors also acknowledge the support of the **Department of Mechanical Engineering, Mehran University of Engineering and Technology (MUET), Jamshoro**, for providing the academic environment and technical guidance required to complete this research.

Funding

The authors declare that **no external funding** was received for this research.

Conflict of Interest

The authors declare **no conflict of interest** regarding the publication of this manuscript.

Data Availability Statement

The data supporting the findings of this study are available from the corresponding author upon reasonable request. Operational plant data were used under institutional permission and may be subject to confidentiality restrictions.

Ethical Approval

This study involved **engineering simulation and thermodynamic analysis** using operational data from a thermal power plant. It did **not involve human participants, animals, clinical investigations, or personal data**. Therefore, formal ethical approval was **not required**.

Consent for Publication

All authors have read and approved the final manuscript and consent to its publication.

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