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Original Article

Coal Consumption Optimization through Performance Gap Analysis and Heat Rate Improvement in Thermal Power Plants

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Abstract *- India coal fired thermal power is still playing an important role in electricity generation in the country. To enhance plant performance, economic competitiveness and environmental sustainability, therefore, the efficient use of coal is essential. Coal is the major component of the generation cost, and it plays a significant role in the plant heat rate and plant efficiency in Sri Damodaram Sanjeevaiah Thermal Power Station (SDSTPS). There have been several studies on heat-rate analysis, energy audit, and auxiliary power optimization, but little focus has been paid to the plant-level approach to optimize coal consumption with actual plant data. The present work is to optimizing coal consumption by considering technical and operational performance of the plant, in particular combustion efficiency and turbine heat rate, which are important parameters of specific consumption of coal. The study utilizes performance gap analysis, evaluation of operational data, energy audit and heat-rate analysis to determine the significant performance deviations and set appropriate optimization parameters to increase plant efficiency. The analysis indicates that optimizing the coal use systemically can lead to improved efficiency and reliability and reduce coal consumption overall. The results indicate that streamlined operational practices together with advanced energy management systems can significantly enhance plant performance. Such an approach will help SDSTPS operate more efficiently and serve as an example of sustainable and high-performance thermal power plant operation.*

Keywords *- Coal consumption, Energy efficiency optimization, Heat rate improvement, Sustainable power generation, Thermal power plant.*

1. Introduction

The installed power generation capacity in India was about 441.97 GW in March 2024, of which almost 67% of the electricity generation was due to coal-fired thermal power plant [1, 2]. Although renewable energy has been growing faster, coal still plays a central role in the provision of base-load power, which has led to the need to enhance the level of operation of the current units to meet demand. The increase in cost of fuel, fluctuation in the quality of coal, and the tightening of the environment laws have further forced efficiency improvement in thermal power plants.

According to thermodynamic studies, the effectiveness of large-scale coal plants is highly affected by the energy losses and irreversibilities in large parts of the plant in the form of boilers and turbines [3]. The energy and exergy studies of supercritical units indicate that the boiler subsystem contributes a large portion of exergy destruction to the total, which points to a significant potential of efficiency enhancement [4].

The heat rate is one of the main indicators of the power plant performance in coal-based power plants, and changes in operating parameters and coal properties greatly affect fuel consumption and overall efficiency [5]. Minor variations of design heating rate may result in significant changes in specific coal use and generation cost.

Another important factor that is critical to the net plant efficiency is auxiliary power consumption. Investigations of Indian coal-fired units have indicated that the auxiliary consumption is between 8 and 12 percent of gross generation and that significant decreases can be measured by optimization of larger auxiliary equipment and better plant load factor [6].

The auxiliary systems of the plants, like feed pumps, draft fans, are energy-consuming, and hence their systematic optimization provides opportunities to immediately optimize the performance of the plants and minimize emissions.

Previous studies mainly focused on individual areas such as thermodynamic analysis, heat-rate evaluation, auxiliary power optimization, and energy audits separately. However, only limited studies have combined performance gap analysis, operational observations, combustion improvement, auxiliary system optimization, maintenance practices, and technological interventions together using actual operating data from coal-fired thermal power plants. Therefore, the present study attempts to provide a practical plant-level approach for improving coal consumption and heat-rate performance at SDSTPS under real operating conditions.

A data-guided and systematic methodology is therefore needed for achieving a sustainable reduction in coal consumption. This gap is particularly important because simultaneous deviations in boiler performance, turbine operation, coal quality, and auxiliary power consumption can collectively increase heat rate and coal usage under actual plant conditions. Hence, there is a need for an integrated framework that can identify these interacting performance losses and prioritize suitable operational and technological improvement measures.

The case analysis of the current paper concerns the Sri Damodaram Sanjeevaiah Thermal Power Station (SDSTPS) and suggests a coordinated coal consumption optimization model. Assessing the operational deviations, performing comprehensive energy audits and applying means like combustion optimization and use of variable frequency drives, the study shows that the heat rate and use of fuel in plants can be significantly improved.

The present study addresses this gap by integrating operational performance evaluation, energy audit findings, performance gap analysis, and practical optimization measures using actual operating data from SDSTPS. Unlike studies that primarily examine individual subsystems, the present work adopts a coordinated plant-level approach to identify interacting performance losses and evaluate their influence on heat-rate performance, coal consumption, and auxiliary energy use. The main contribution of the study is the combined application of these established methods within a single practical framework to quantify heat-rate improvement, coal-saving potential, and auxiliary energy reduction under real operating conditions.

The novelty of the present study lies not in introducing a new individual technology or analytical method, but in the coordinated plant-level application of established performance assessment and energy-management approaches using actual operating data from SDSTPS. Previous studies have generally examined individual aspects such as boiler efficiency, turbine heat rate, auxiliary power consumption, thermodynamic losses, or predictive heat-rate modelling separately. In contrast, the present work combines performance-gap analysis, energy-audit findings, turbine and boiler assessment, coal-quality evaluation, auxiliary-system analysis, and desirability-based optimization within a single practical framework. This integrated approach enables simultaneous identification of interacting performance losses and quantification of their effect on heat rate, coal consumption, and auxiliary energy use under real operating conditions.

2. Literature Review

Thakare and Daspute (2024) conducted a comprehensive energy audit of a 1050 MW coal-fired thermal power plant and demonstrated that structured plant-level interventions can produce measurable reductions in coal consumption and auxiliary power usage. Their findings reported annual savings of 12.098 million kWh and 25,832.80 MT of coal through measures such as arresting air preheated leakage, insulation up gradation, and installation of variable speed drives.

The study established that an energy audit serves as a practical tool for achieving grassroots-level energy conservation in thermal power plants [7].

Sivageerthi et al. (2022) modelled and analysed the operational performance of a coal fired thermal power plant through heat rate performance and the operational performance. The experiment found that the variations in turbine cycle parameters, conditions of condenser vacuum and the ability of regenerative heating to be effective have a substantial impact on overall unit heat rate and specific fuel consumption.

The authors also pointed out that systematic performance monitoring and diagnostic analysis is critical in determining inefficiency and enhancing thermal efficiency. They emphasize on the significance of systematic heat rate test as a starting point towards the optimization of fuel use in coal based power plants [8].

Gavirineni and Gundabattini (2022) assessed the extent of energy efficiency enhancement in one of the 660 MW supercritical thermal electricity power plants in terms of the load factor in the power plant and the performance of auxiliary equipment used to enhance performance. The experiment revealed specific auxiliary power consumption is decreased through operation close to maximum load and enhances the overall plant efficiency. The authors emphasized that systematic control over the auxiliary systems and optimal operation of the load can play a significant role in reducing the internal losses and increasing fuel use among coal fired thermal power stations [9].

Jang et al. (2024) have performed a thermodynamic analysis of a 500 MW coal fired thermal power plant to determine the changes in efficiency under varying operating conditions. The paper concentrated in the analysis of the cycles, such as boiler performance, the expansion stages of the turbine, and the regenerative feed water heating, in order to conclude on the effect of the three on the total performance of the entire plant and heat rate. The findings showed that increased efficiency of turbine operating conditions and the enhancement of the feed water heating process could lead to significant steps in improving the efficiency of the cycle and lowering the specific consumption of fuel.

The authors underscored that full thermodynamic evaluation gives a systematic platform of determining performance variations and fuel use improvements in large scale thermal power plants that operate on coal as the input fuel source [10].

Chen et al. (2025) carried out a comprehensive energy-saving potential analysis of a 660 MW ultra-supercritical coal-fired power plant using thermodynamic and exergy analysis. The study revealed the major source of energy losses in the boiler, turbine and Regenerative feed water system and proved that thermal efficiency could be increased considerably by optimizing the operating condition of the system and further reduction in fuel consumption. The authors found that the comprehensive assessment of loss at the component level is an effective means to improve the whole plant energy efficiency of large-scale coal-fired power generation systems [11].

Sindhu et. al. (2014) studied various energy saving techniques in coal fired thermal power plants and concluded that optimum operation of the boiler feed pump, condenser performance and optimization of auxiliary systems can save a significant amount of heat rate, auxiliary power consumption and coal consumption, which will optimize the energy efficiency of thermal power plant generation [12].

Vinchurkar et al. (2015) highlighted the significance of energy management practices in thermal power plants and concluded that proper monitoring of Auxiliary power consumption, heat rate, Specific coal consumption and Plant load factor can help to increase the thermal efficiency of a thermal power plant, which ultimately results in a reduction of generation cost. The authors highlighted that energy auditing, maintenance activities and optimisation of auxiliary equipment are important aspects to increase the plant performance [13].

Patel and Agrawal (2017) carried out an energy audit analysis of the 250 MW coal fired thermal power plant with various operating load conditions and analyzed the performance improvement of the plant. The study has concluded, reduction in plant load reduces the overall thermal efficiency of the power plant, and it has been concluded that the most prominent areas of energy loss are turbine-generator section and the condenser section, and it has been stated that it is necessary to achieve heat rate improvement and better operational efficiency of the power plant [14].

Thakre et al., 2017 presented a review of the energy management techniques for the reduction of auxiliary power consumption in 500 MW thermal power plants, where it was observed that optimum utilization of auxiliary systems, energy auditing and improvement of plant load factor can significantly improve plant efficiency and fuel consumption [15].

To achieve the goal of energy efficiency and operation flexibility in coal-fired thermal power plants under different operational conditions, Zhang et al. (2025) developed a direct exergy balance control strategy. The study showed that the exergy-based control will lead to better coordination of the boiler and turbine operation, resulting in better reduction of energy losses and overall plant performance. The authors pointed out that advanced operational control strategies can contribute much to fuel utilization optimization and increasing efficiency of the thermal power plants [16].

Vinchurkar et al. (2014) investigated energy management strategies for enhancing the performance of thermal power plants and cited that an energy audit, periodic review, process optimization and monitoring of energy indicators like heat rate, boiler efficiency and auxiliary power consumption can significantly lower energy losses and boost plant efficiency [17].

Nulhakim and Irawan (2025) designed an Artificial Neural Network (ANN) based predictive model for optimizing the Net Plant Heat Rate (NPHR) of coal fired thermal power plants. It was shown that the proposed method successfully simulated different heat-rate changes under various operating conditions and that the data-driven optimization methods can be used to enhance fuel utilization and overcome operational inefficiencies. The study revealed the increasing potential of intelligent predictive models to assist performance optimization and energy-efficient operation of modern thermal power plants [18].

Setyawan and Sudiarto (2024) examined how the application of machine learning techniques can predict heat rate and CO_2 emission from 468 performance-test records for coal-fired steam power plants. Random Forest, Gradient Boosting, Neural Network and Extra Trees Regression were tested as regression models.

Extra Trees Regression model showed the best heat-rate prediction result with R^2= 0.946, MAE= 136.884 and RMSE= 187.225 among these models. Additionally, the study determined the following to be factors that greatly affected the heat rate: installed capacity, boiler type, load percentage, excess air, and operating duration. The results showed that machine-learning-based prediction can assist in the enhancement of energy efficiency and reducing CO_2 emissions from the operation of coal-fired power plants [19].

Mittal et al. (2012) have estimated CO_2, SO_2 and NO emissions from coal and lignite fired thermal power plants in India. A total of 86 thermal power plants were studied, and the following parameters were taken into consideration: Coal quality, Coal consumption, Operating condition of the plants. The reported emission levels were about 0.91-0.95 kg/kWh for CO_2, 6.94-7.20 g/kWh for SO_2, and 4.22-4.38 g/kWh for NO. The study also revealed that the quantity of emissions is different among the power plants primarily due to the difference in the quality of coal, fuel consumption, operating conditions and plant efficiency. The possibility of reducing emissions from thermal power plant by improving the efficiency of coal use was also noted.

Overall, the reviewed literature shows that coal-fired thermal power plant performance has been extensively investigated through energy auditing, heat-rate assessment, thermodynamic analysis, auxiliary power optimization, and data-driven prediction. However, these aspects are generally examined independently, with limited attention to their combined influence under actual plant operating conditions.

In particular, the simultaneous effects of coal quality, boiler and turbine performance, auxiliary power consumption, and operational deviations are seldom evaluated within a single plant-level framework. The present study addresses this gap by integrating performance gap analysis, energy audit findings, and operational optimization using actual operating data from Sri Damodaram Sanjeevaiah Thermal Power Station (SDSTPS).

3. Objectives of Energy Management Implementation

- Optimize Heat Rate and Operational Parameters: Improve thermal efficiency by minimizing steam cycle and combustion losses, ensuring maximum energy output from each unit of fuel.
- Identify Equipment Efficiency Gaps: Conduct detailed assessments for locating underperforming components and implementing corrective actions by maintenance, repair or upgrades of the Turbine and Boiler.
- Adopt Energy Efficiency Improvement Measures: Implement modern solutions such as VFDs and advanced pump coatings for saving energy, enhance auxiliary efficiency and also for boosting operational flexibility.

4. Problem statement

The problem addressed in this study is the excessive coal consumption and suboptimal heat-rate performance of SDSTPS, caused by operational deviations, equipment inefficiencies, and auxiliary system losses, and the lack of an integrated plant-level optimization framework using actual operating data to diagnose these gaps and improve overall thermal efficiency.

5. Methodology

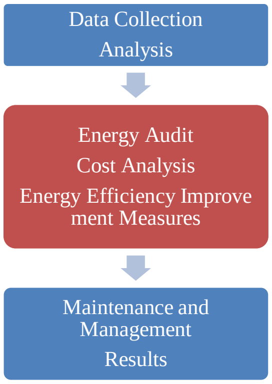

Fig. 1 Flow chart for energy management system

The methodology adopted in the present study includes collection of operational data from SDSTPS for evaluating plant performance under actual operating conditions. Parameters such as gross heat rate, turbine heat rate, boiler efficiency, coal consumption, auxiliary power consumption, condenser vacuum, and coal quality were collected from plant operational records and energy audit observations. The collected data were compared with design values to identify performance deviations and major loss areas. Based on the observed deviations, combustion optimization, auxiliary system improvement, turbine performance assessment, and technological interventions were analyzed for improving heat-rate performance and reducing coal consumption.

The effectiveness of the proposed optimization measures was evaluated through key performance indicators, including boiler efficiency, turbine heat rate, auxiliary power consumption, and specific coal consumption under actual operating conditions. The optimization trends and interaction behaviour between heat rate, ash content, and coal consumption were evaluated using desirability-based optimization analysis.

MCDM and machine-learning methods were not adopted in the present study because the objective was to evaluate actual plant performance using available operational and energy-audit data rather than to develop a predictive or decision-ranking model. The available dataset was therefore used for performance-gap assessment, interaction analysis, and desirability-based response optimization. Advanced MCDM or machine-learning approaches may be considered in future studies with larger and more structured datasets covering a wider range of operating conditions.

6. Data Collection

The proposed capacity installation of Sri Damodaram Sanjeevaiah Thermal Power Station (SDSTPS) is 1600 MW. At present, 2400 MW is the total installed capacity of the existing thermal power plants. The major energy sources of power generation by thermal power plants are coal, furnace oil, as well as light diesel oil. Coal is the primary fuel (99.545%) for producing electricity. The data for the present study was collected for eliciting the level of energy consumption in a thermal power plant for implementing advanced techniques for energy management to improving the performance of the thermal power plant.

7. Study of Gap Analysis and Review of Energy

The parameters of the plant performance have been analyzed basing on design and operating values. From the following given data, a deviation exists between the design and operating values of indicators' general performance and is shown in the Table 1.

Table 1. Hiatus between the design and parameters' general operating performance

S. No	Indicators of Performance	Indicators Design Performance	Indicators Operating Performance
1.	Efficiency of Boiler(%)	89.26	87.24
2.	Heat Rate of Plant (Kcal/KWh)	2228	2418
3.	Heat Rate of Turbine Kcal/KWh)	1989	2110
4.	Consumption of Specific Coal (Kg/KWh) or MT/Day	0.656(Kg/KWh) or 10296.6 MT/Day	0.653(Kg/KWh) or 10,265 MT/Day
5.	Auxiliary Power Consumption (%)	6.50	7.244

Table 1 portrays that the input factors, such as planning as well as procedures of operation, policy pertaining to energy, objectives, and the maintenance for good management, are immensely influencing performance indicators of this research and also have high positive impact on the immense improvement of the thermal plants' profuse performance, consumption level of fuel energy, as well as efficiency of the auxiliaries of the plant. For an operating load of 655 MW (approximately 80% MCR), the daily coal consumption is estimated as 655 MW × 15.72 t/day per MW = 10,296.6 t/day, corresponding to a specific coal consumption of approximately 0.656 kg/kWh.

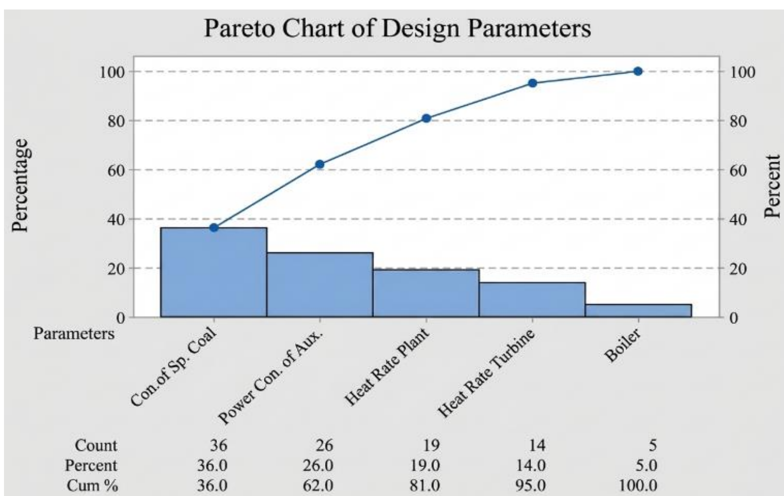

Fig. 2 Design parameters

Table 2 presents the source-wise energy consumption data collected from July 2024 to November 2024 for evaluating plant operational performance and energy management practices. The monthly energy input data show that the average energy input from coal is 273,541 TOE, compared with 191 TOE from LDO and 43 TOE from FO, indicating that coal is the principal contributor to greenhouse gas emissions and environmental impacts.

Table 2. Source-wise monthly consumption of the energy by thermal power plants

S.No.	Description	Units	July 20 24	Aug 20 24	Sep 20 24	Oct 20 24	Nov 20 24
1.	Coal	MT/day	6786	5695	7051	7183	6984
2.	Light Diesel Oil	kL	65	66	60	72	70
3.	Furnace Oil	kL	553	690	675	543	582

4.	Coal Calorific Value	Kcal/Kg	4137	3828	3961	4125	3968
5.	Light Diesel Oil Calorific Value	Kcal/Kg	10612	10668	10619	10537	10409
6.	Furnace Oil Calorific Value	Kcal/Kg	10122	10166	10206	10076	10056
7.	Input Energy by Coal	TOE	214927	239197	358652	279178	275754
8.	Energy Input by Furnace Oil	TOE	41	42	42	45	48
9.	Energy Input by Light Diesel Oil	TOE	19	193	195	190	190
10.	Total Energy Input	TOE	215158	239432	358889	279413	275992
11.	Net Energy Generated	MUS	300	312	290	287	290
Input of Mean Energy by Coal (TOE)			273541				
Input of Mean Energy by Furnace Oil (TOE)			43				
Input of Mean Energy by Light Diesel Oil (TOE)			191				

Table 3. Comparison of alternative fuels for sustainability and emissions

Fuel	CO_2 Emissions	SO_x Emissions	NO_x Emissions	Particulate Matter	Renewable	Sustainability	Applicability to Existing Thermal Plants	Fuel	CO_2 Emissions
Coal	Very High	Very High	High	Very High	No	Low	Existing primary fuel	Coal	Very High
Furnace Oil (FO)	High	High	Moderate	Low	No	Low	Start-up/support fuel	Furnace Oil (FO)	High
Light Diesel Oil (LDO)	Moderate-High	Low	Moderate	Very Low	No	Low	Ignition and emergency fuel	Light Diesel Oil (LDO)	Moderate-High
Natural Gas	40-50% lower than coal	Negligible	Low	Negligible	No	High	Suitable with gas infrastructure	Natural Gas	40-50% lower than coal
Biomass Pellets	Near carbon-neutral	Very Low	Low	Low	Yes	Very High	Excellent for 5-20% co-firing	Biomass Pellets	Near carbon-neutral
Refuse-Derived Fuel (RDF)	Lower than coal	Moderate	Moderate	Moderate	Partly	High	Suitable after fuel processing	Refuse-Derived Fuel (RDF)	Lower than coal
Green Hydrogen	Zero direct CO_2	Zero	Very Low	Zero	Yes	Excellent	Long-term option	Green Hydrogen	Zero direct CO_2
Green Ammonia	Zero carbon	Zero	Moderate (requires NO_x control)	Zero	Yes	Excellent	Future co-firing technology	Green Ammonia	Zero carbon

Table 4. Estimation of emissions for CO_2, SO_2, NO. FY 2023-24 &2024-25.

Parameter / Pollutant	Specific Emission Factor	FY 2023-24 Emissions	FY 2024-25 Emissions	Net Change
Net Generation	-	10000-12500MU	13000-14500MU	+15 % to + 30%
Carbondioxide(CO_2)	0.70-0.80kg/kWh	7.00-10.00 MT	9.10-11.60 MT	+16 % to + 30%
Sulfur Dioxide(SO_2)	0.005-0.006 kg/kWh	50000-75000 Tonnes	65000-87000 Tonnes	+16 % to + 30%
Nitric Oxide(NO)	0.003-0.004 kg/kWh	30000-50000 Tonnes	39000-58000 Tonnes	+16 % to + 30%

7.1. Sustainability Assessment

The data clearly indicate that coal remains the dominant fuel source throughout the study period (July-November 2024), accounting for nearly all of the thermal energy supplied to the plant. Monthly coal consumption ranges from 5,695 to 7,183 MT, whereas LDO consumption ranges only from 60-72 kL and FO consumption from 543-690 kL. Consequently, reductions in coal consumption will have the greatest impact on lowering emissions and improving sustainability.

7.2. Recommended Sustainable Fuel Strategy

Based on the attached operational data, the following phased strategy is recommended:

Short-term (Immediate)

- Improve combustion efficiency.
- Optimize boiler operation and heat rate.
- Reduce auxiliary fuel (LDO and FO) consumption during start-up.

Improve coal quality management.

Long-term (5-15 Years)

- Evaluate natural gas where pipeline infrastructure is available.

Consider green ammonia or green hydrogen co-firing as these technologies mature.

Energy consumption data for the last five months has been harnessed to evaluate the mean energy consumption levels of different sources. The Figure 3 presents that the prime source of energy source is coal, contributing to 98.67 per cent, whereas the light diesel oil contributes at 1.2 per cent, and the rest is by the consumption of furnace oil. The status of monthly and yearly coal consumption of light diesel oil and furnace oil is furnished in the Figures 3-7, respectively.

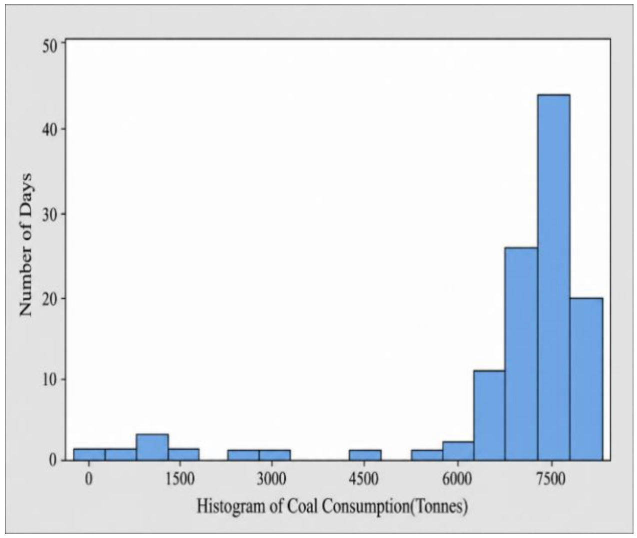

Fig. 3 Every day power plant coal consumption in 2024

8. Data Analysis

The present research availed and analyzed both the present as well as fuel data (Plant) energy consumption Power by coal and oil. Moreover, the data on the consumption of coal and oil was collected for five months from July 2024 to November 2024. The collected data include gross heat rate, efficiency of boiler and turbine, and the data is collated in Tables (2,5-8).

Table 5. Actual plant parameters of design

S.No.	Description	Unit	Design(A)	Actual As fired Coal(B)	Variation (A-B)/A in %
1.	Load	MW	800	793	0.875
2.	Gross Heat Rate	Kcal/kwh	2228	2418	-8.52
3.	Turbine Heat Rate	Kcal/kwh	1989	2110	-6.08
4.	Boiler Efficiency	%	89.26	87.24	2.26
5.	GCV	Kcal/kg	4600	4272	7.13
6.	Consumption of Specific Coal	Kg/kwh	0.655	0.653	0.30
Main Stream Parameters					
7.	Flow	Kg/kwh	3.45	3.63	-5.21
8.	Temp	^0C	559	562.2	-0.57
9.	Pressure	kg/cm^2	139.9	130.58	6.66
10.	Condenser	Ksc	0.9585	0.815	14.97
11.	DM Water Flow	t/h	624	657	-5.288
Efficiency of Turbine Cylinder					
12.	Heat, Pressure and Temperature	%	89.24	86.21	3.39
13.	Input Pressure and Temperature	%	91.48	92.31	-0.907
14.	Load, Pressure, and Temperature PT	%	88.6	78.65	11.230

Table 6. Total unit's performance

	Load	Heat Rate of TG	Net Heat of Rate	Performance of Unit(Gross)	Performance of the boiler	Coal Flow
Units	mw	kcal/kwh	kcal/kwh	%	%	MT
Design (100%)	800	2235	2264	36.69	69.45	7256
80%	640	1788	1811.2	29.352	55.56	5804.8
60%	480	1341	1358.4	22.01	41.67	4353..6

Table 7. Total unit's performance on 768 MW loads

Units	Load MW	Heat Rate of TG	Heat of Rate Unit	Unit Efficiency(Gross)	Boiler Efficiency%	Coal Flow t/h
Actual	768	2418	2563	35.54	67.51	6739.8

Table 8. Unit's overall performance deviation

	Load	Heat Rate of TG	Heat Rate of Unit	Unit Efficiency(Gross)	Boiler of Efficiency	Coal Flow
Units	mw	kcal/kwh	kcal/kwh	%	%	t/h
Design(A)	800	2235	2264	36.69	69.45	7256
Actual(B)	768	2418	2563	35.54	67.51	6739.8
Deviation(A-B)/A%	-4	-8	-132	3.13	2.79	7.12

The results indicate noticeable deviations in heat-rate performance, boiler efficiency, and turbine operating parameters under actual plant conditions compared to design values. The deviation was more significant in turbine heat rate and low-pressure turbine performance.

Load: The plant was operating at 793 MW, slightly below its 800 MW design load, a deviation of -3.048 per cent.

Gross Heat Rate: The operating gross heat rate was 2418 kcal/kwh compared to the design of 2228 kcal/kwh, with a deviation of 190.1 kcal/kwh.

Turbine Heat Rate: Measured at 2110 kcal/kwh against a design of 1989 kcal/kwh, a deviation of 120.9 kcal/kwh.

Boiler Efficiency: The operating efficiency of 87.24 per cent was lower than the design of 89.26%, a deviation of 2.26 per cent.

Gross Calorific Value (GCV): The actual GCV of coal was 4272 kcal/kg, lower than the design of 4600 kcal/kg, indicating a 2.850 per cent deviation in fuel quality.

Specific Coal Consumption: Operating at 0.653 kg/kWh, slightly lower than the design of 0.655 kg/kWh, a deviation of 0.002.

Turbine Cylinder Efficiency: The Low-Pressure Turbine (LPT) exhibited a substantial efficiency drop, operating at 78.65 % compared to a design of 88.6 per cent, a severe 11.230 % deviation. High-Pressure Turbine (HPT) efficiency was 86.21 per cent vs. 89.24 per cent design (3.395% deviation), while Intermediate-Pressure Turbine (IPT) showed a slight improvement at 92.31 % vs. 91.48 % design (-0.907% deviation).

Table 9. Proximate analysis of coal

Variables	Unit	Design	Actual
Fixed Corbon	%	38.96	35.06
Volatile Matter	%	14.8	19.88
Content of Moisture	%	10	8.49
Ash Concentration	%	28.35	36.57
GCV	Kcal/Kg	4000	3886

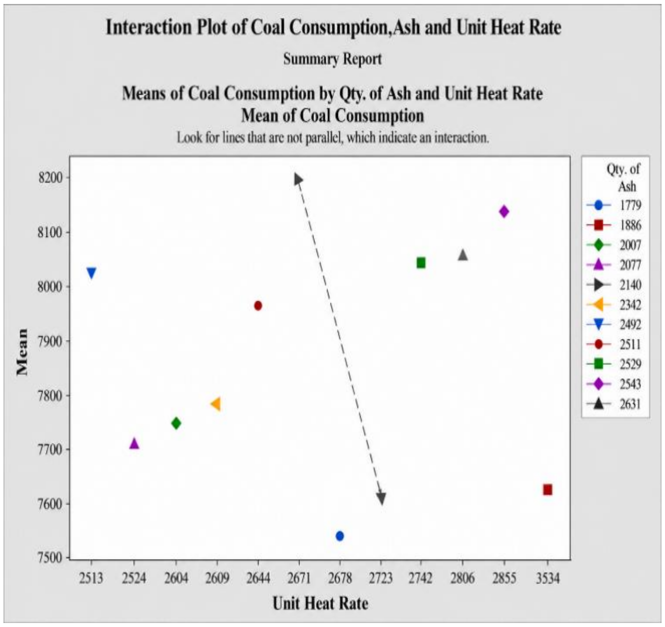

Fig. 4 Interaction behaviour between coal consumption, ash quantity, and unit heat rate

Graph shows non-parallel lines and ash line, sharply downward so indicates a strong relation between them, hence coal consumption depends ash quantity.

The major reasons include low calorific value of coal and variation in heat-rate performance.

9. Response Optimization

The optimization objective was to minimize coal consumption by considering unit heat rate and ash production as the principal operating variables.

The desirability-based response optimization method was applied using the observed operating ranges of these parameters as constraints.

Coal consumption was assigned a minimization goal, while the corresponding desirability settings were used to identify the operating combination that produced the highest composite desirability.

The optimum condition was evaluated by comparing the predicted response with the observed plant operating range and the interaction trends obtained from the actual operating data.

Coal Consumption Parameters

Response	Goal	Lower	Target	Upper	Weight	Importance
Coal Consumption	Minimum		650	7758	1	1

Solution

Solution	Unit Heat Rate	Qty of Ash Production	Coal Consumption Fit	Composite Desirability
1	4143	617	144.415	1

Multiple Response Prediction

Variable	Setting
Unit Heat Rate	4143
Qty of Ash Production	617

Response	Fit	SE Fit	95% CI	95% PI
Coal Consumption	144	4680	(-10283, 10571)	(-10855, 11144)

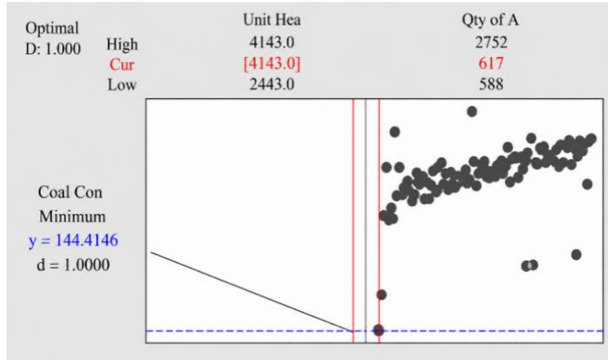

Fig. 5 Regression analysis of optimization of coal consumption

- Performance gap analysis finds deviation between design and actual performance and Regression, Predicts expected heat rate and explains which variables cause the gap.
- Heat-rate assessment Quantifies thermal efficiency ANN, SVR, and AutoML predict heat rate from plant inputs with high accuracy.

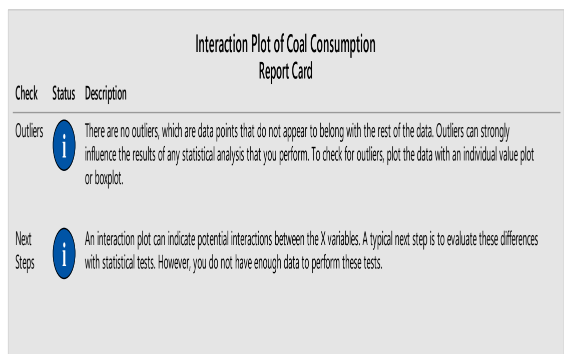

Fig. 6 Report card analysis of interaction plot for coal consumption

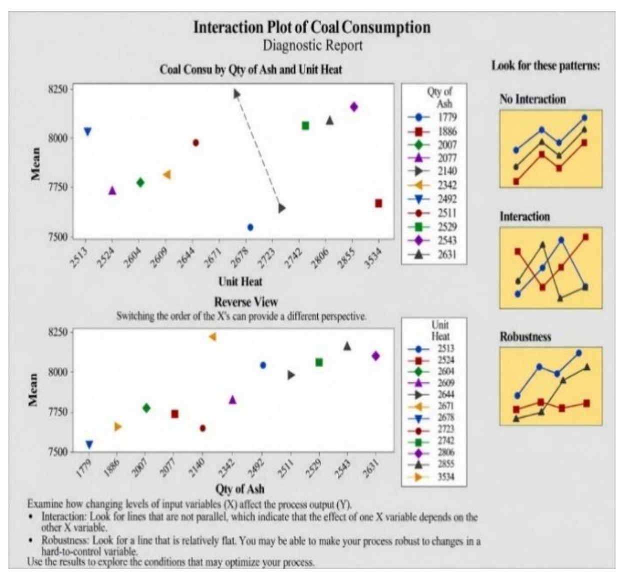

Fig. 7 Diagnostic analysis of coal consumption optimization behaviour

By observing the two graphs above Figure 7 find that optimum heat rate 2723 kcal/kwh which indicates bottom triangle of the dotted line at min. Coal consumption 7650 tonnes/day (Graph of Heat rate vs Min. coal consumption) for minimum ash production 2140 tonnes/day, which indicates a corresponding value circle shape in the graph is quantity of ash vs coal consumption.

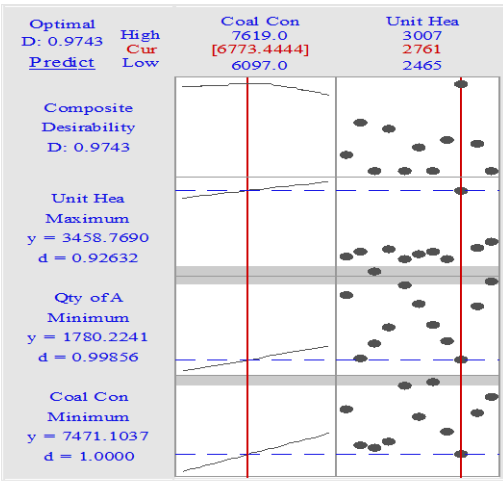

Fig. 8 Response optimization of coal consumption, ash production, and unit heat rate

The heat-rate value of 2723 kcal/kWh was identified from the interaction analysis, while the minimum coal consumption of 7471.1037 was obtained from the desirability-based response optimization using the actual plant operating data.

From the graph, there are no outliers beyond the limits; hence, the process can be controlled within specification limits. By the desirability function approach, coal consumption was minimized by satisfying both heat-rate and ash-quantity constraints. Reduction in ash quantity and improvement in heat-rate performance contributed to lower coal consumption.

The estimated coal saving range of 8-15% was determined based on the observed improvement trends in heat-rate performance, combustion optimization, auxiliary power reduction, and operational efficiency.

The optimization analysis was carried out using interaction plots and desirability-based response optimization to evaluate the combined effect of heat rate and ash content on coal consumption under actual operating conditions.

9.1. Benchmarking with Recent Studies

To evaluate the performance of the present study in relation to recent developments in coal-fired thermal power plant performance assessment and optimization, the obtained results were benchmarked against recent energy-audit, thermodynamic, and machine-learning-based studies, as presented in Table 10.

Table 10. Quantitative benchmarking of the present study with recent coal-fired power plant studies

Study	Plant / approach	Performance indicator	Quantitative result	Present-study comparison
Thakare and Daspute (2024)	Energy audit of a coal-fired thermal power plant	Boiler efficiency	84.10% and 82.84%	Present study: actual boiler efficiency of 87.24%
Khawaja et al. (2024)	660 MW supercritical coal-fired power plant	Overall cycle energy/exergy efficiency	40.77% / 39.69%	Contextual comparison only, as the present study evaluates component-level boiler and turbine performance rather than overall cycle/exergy efficiency
Setyawan and Sudiarto (2024)	Machine-learning model using 468 plant records	Heat-rate prediction performance	R^2 = 0.946, MAE = 136.884, RMSE = 187.225	Contextual comparison only, as the present study uses an actual measured heat rate of 2418 kcal/kWh rather than a prediction model

Direct quantitative comparison was made only where similar performance indicators were available; studies using different modelling approaches or efficiency definitions were included only for contextual benchmarking.

10. Sensitivity/Uncertainity Analysis

Sensitivity analysis was carried out to determine the relative influence of major operating parameters on plant heat rate, turbine performance, and coal consumption using the actual operating data collected from Sri Damodaram Sanjeevaiah Thermal Power Station (SDSTPS). The analysis was based on observed deviations between design and operating conditions rather than on simulated data. To provide quantitative evidence of parameter influence, the sensitivity contribution was calculated from the observed heat-rate improvement associated with each operating parameter.

The relative sensitivity contribution was determined using:

$$Si = \frac{\Delta HR_i}{\sum \Delta HRi} \times 100$$

Where Si represents the sensitivity contribution (%), and ΔHRi represents the observed heat-rate improvement associated with the corresponding operating parameter.

Table 11. Sensitivity analysis of parameters

Parameter	Heat-rate improvement (kcal/kWh)	Contribution (%)
Condenser vacuum	25.00	61.55
Reheat/HRH temperature	6.00	14.77
Main steam pressure	4.14	10.19
Feedwater temperature	3.00	7.39
RH spray/heat pickup	2.475	6.09

The results indicate that condenser-vacuum improvement had the highest quantitative influence on heat-rate reduction, contributing 61.55% of the total observed improvement.

10.1. Uncertainty Analysis

The uncertainty associated with the present investigation primarily originates from normal operating variations of the thermal power plant and measurement limitations of field instrumentation.

The major sources of uncertainty include:

- Variation in coal quality (gross calorific value and ash content).
- Instrumentation accuracy for pressure, temperature, steam flow, and condenser vacuum.
- Boiler combustion variability.
- Measurement uncertainty in fuel flow and coal weighing systems.

Table 12. Uncertainity analysis of parameters

Measured Parameter	Instrument	Instrument Accuracy	Standard Uncertainty	Effect on Calculated Heat Rate
Main steam pressure (bar)	Pressure transmitter	±0.10% FS	0.10%	Moderate
Main steam temperature (°C)	RTD	±0.5°C	0.5°C	Moderate
Feedwater flow (t/h)	Flow transmitter	±0.50% of reading	0.50%	High
Coal flow (t/h)	Belt weigher	±0.50% of reading	0.50%	Very High
Electrical power (MW)	Energy meter	±0.20% of reading	0.20%	Moderate
Condenser vacuum (kPa)	Vacuum transmitter	±0.25% FS	0.25%	High
Feedwater temperature (°C)	RTD	±0.5°C	0.5°C	Moderate

11. Energy Audit

11.1. Boiler Efficiency

Calculations of the boiler efficiency are detailed in Table 13 since unit has been established in 2015 by considering its age and deviations. Table 13 shows that about 2.11 per cent of the deviation is observed in the efficiency of the boiler according to the Performance Guarantee Test (as tested without correction) [7]. Moreover, the present unit has been established in 2015 and also by considering its age, the deviation is observed in the efficiency of the boiler, rather at higher side. Nevertheless, the boiler efficiency deviation can be partly recovered by immediately implementation of short-range measures, best operation, as well as maintenance strategies and practices. The boiler efficiency values presented in Tables 5 and 13 correspond to different evaluation conditions. The values reported in Table 5 represent overall operating boiler performance under actual plant conditions, whereas the values presented in the energy audit section correspond to Performance Guarantee (PG) test and energy audit-based efficiency assessment.

Table 13. Boiler efficiency calculations

SNo.	Parameters	Design Efficiency(%)	PG Test Efficiency(%)	Efficiency as Tested in Energy Audit	Deviation w.r.t.PG Test Value($)
1.	Boiler Efficiency	67.51	68.11	66	2.11

11.2. Calculations of Heat Rate of Turbine

The heat rate of turbine cycle was evaluated by the test data at 100 per cent rating condition continuously. The calculation results are furnished as shown in Tables 13 and 14.

Regarding the design values, a heat rate deviation of 113.37 Kcal /KWh is observed at 100 per cent MCR load. The dearth is retained partially by implementing measures at both short-term as well as long-term, and also by the implementation of both optimum operating and maintenance modes [8]. Owing to poor vacuum, the consumption of steam for unit is on higher side. Proposed boiler and turbine optimization measures showed measurable improvement in heat rate performance, reduction in coal consumption, and annual energy savings under actual plant operating conditions.

Table 14. Performance of turbine (heat rate)

S.No.	Parameters	Heat Rate Tested Kcal/KWh	Heat Rate Corrected Kcal/KWh	Heat Rate by PG Test Kcal/KWh	Shortfall Kcal/KWh
1.	Heat Rate	2236	2073	1986.37	113.37

Table 15. Performance of turbine (efficiency)

Load		Efficiency			Shaft Power		
		Heat Pressure & Temp.	Input Pressure & Temp	Load Pressure & Temp	Heat Pressure & Temp.	Input Pressure & Temp	Load Pressure & Temp
Units	MW	%	%	%	MW	MW	MW
Design(A)	800	89.24	91.46	88.6	59.91	66.8	86.48
Actual(B)	768	86.21	92.31	78.65	61.29	71.92	76.32
Deviation% (A-B)/A*100	-4	3.395	-0.907	11.230	-0.02	-0.076	11.74

Table 16. Boiler and turbine performance improvement: Energy and cost savings analysis (2023-25)

S.No.	Suggestions for Boiler and Turbine			Energy Savings	Savings Rs.Lakhs
1.	Performance of Boiler	2023-2024	2024-2025		
a.	Due to Optimization of Combustion then decrease in unburnt coal, fine tuning of mill and renovate	5525MT/y	3016MT/yr	Saving of Coal 2509.01MT/yr	2067
b.	Outlet temperature of Flue gasreduced due to designing the value by Boiler/Super Heater/Re-Heater cleaning, and Air pre-heater service/ substitute of element	8292.8MT/yr	7795.2MT/yr	Coal Savings of 497.568MT/Year	24.8
Total				3006.578MT/y	2091.8
2.	Heat Rate of Turbine	Kcal/KWh	Kcal/KWh	Heat Rate Improve	-
a.	Prime steam pressure improvement	2324.14	2320	4.14	37
b.	Improve heat pick up in water by reducing RH spray	2332.476	2330	2.475	184
c.	Arresting air ingress/cleaning of tubes to improve vacuum of the condenser	2345	2320	25	3725
d.	Reinstallation of Low Pressure Heater-3 and modification of High Pressure heater problem by increasing HP heater Feed outlet temp	2323	2320	3	223
e.	Operational practice & RH spray valve passing to improve the HRH temperature	2326	2320	6.0	446
Total				40.615Kcal/Kwh	Rs.4615

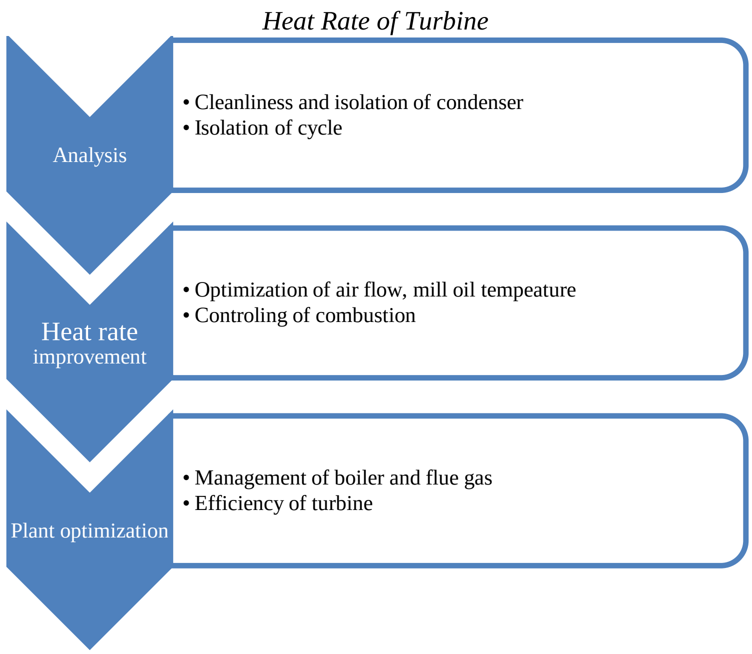

Fig. 9 Process flow diagram for heat rate

11.3. Performance of the Boiler

- The consumption of coal reduced by 5-6%, hence fuel saves and thermal performance improves.
- By regular maintenance of heating surface of boiler, superheater and tubes of reheater, including with timely service and periodical replacing of air pre-heater elements, improves heat rate and optimized air preheating, hence it improves efficiency of boiler by 5% and minimizes consumption of coal.

11.4. Heat Rate of Turbine

- The high pressure increases thermal energy of steam entering into the turbine, it leads improving expansion efficiency and heat consumption decreases per kWh of generation. Hence, heat improvement is 4.14 kcal/kwh.
- Controlled reheated steam temperature reduces excessive spray water consumption improved outlet steam temperature, and enhances thermal energy utilization, thereby improving turbine expansion efficiency and reducing heat consumption per unit power generation. Hence, the heat-rate improvement was 2.476 kcal/kWh.
- These actions decreases condenser back pressure, enhance transfer of heat rate, and achieve steam expansion in the turbine, which causes reduction of specific heat consumption and improves unit efficiency in overall. Heat rate improvement 25kcal/kwh.
- Technical Causes for boiler: Whenever feed water temperature is high, it reduces boiler heat input. Cycle efficiency regeneration Improves. In order to raise water to steam conditions, less fuel is required. Rate of heat of the plant reduces in overall. From the above technical reasons turbine heat rate improvement is 3 kcal/kwh.
- Technical Causes for heat rate of the turbine, slow cooling of HRH steam minimizes the spray water**.** Steam enthalpy improved because of high HRH temperature. Better expansion in turbine stages**.** Per unit power generation heat input optimized. From the above technical reasons quality of steam improves, which increases turbine efficiency; decreases heat consumption results in improving the overall performance of plant and heat rate improvement is 6 kcal/kwh.

12. Energy Efficiency Improvement Measures

The following established energy-efficiency measures were evaluated for their potential to reduce auxiliary power consumption and improve overall plant performance.

12.1. Seal Air Fan and Installation of Variable Frequency Drive (VFD)

Analysis of Technology and Finance: Large energy is wasted across the damper wastage. Thus, a conclusion has been decided for immediate installation the fan by changing drive frequency. Impact due to Implementation: Secondary Flow of Air with 100 % energy saving of Damper open position while application of Variable Frequency Drive (VFD).

Without application of VFD: 500KW

Fan consumption with application of VFD: 232KW

Owing to VFD application, the net energy saving 500-232=268 KW

Annual Energy Savings: 268X 24 hrs X 350 days= 2,251,200Kwh/year =22.512 Lakhs Units /Year

Annual Estimated Savings of Energy: 2,251,200X3.8=Rs. 8,554,120 = Rs. 85.55 Lakhs(Tarrif Rs.3.8/Kwh)

VFD Cost: Rs.15 Lakhs /- per unit

Period of Payback =15/ 85.55=0.175 years=0.1753X12Months= 2.10 Months.

12.2. For Heavy Fuel Oil (HFO) Pump using Variable Frequency Drive(VFD)

Background: A boiler of coal-based direly needs for firing oil for supporting the combustion of coal. An HFO firing pump is readily provided as the supporting fuel with a minimum recirculation valve for minimizing the oil flow from pump.

Inspection: While the general function of both units, the consumption of Heavy fuel oil is nil and is obtained further re-circulated by both small and major re-circulation line of both boilers for maintaining the Heavy Fuel Oil temperature. The small and major re-circulation flow is rather extremely low, but by Pressure Control Valve (PCV), the maximum quantity of HFO is re-circulated nearby its burning pumps to Heavy Fuel Oil tank. Moreover, it controls the Heavy Fuel Oil releasing pressure of the header is 21-23 Kg/cm2, and 50 % is open while regular process of the units.

Technological and Financial Analysis: It was strongly suggested for installing variable frequency drive for Heavy fuel oil firing of a pump motor rated at 415v and 37 kw for controlling as well as maintaining the optimum flow as well as pressure of HFO by changing motor’s speed.

Implementation’s Impact: After installation of VFD, the energy consumption by pump will decrease optimally. The period of the proposed payback is below one year, and hence it is the need of the hour for installing as well as commissioning required variable frequency drive for the 37kw, 415v. Heavy fuel oil pumps saving energy considerably. Whereas an average power measurement in regular re- flow mode is

Excluding variable frequency drive @ 29.25KW

Including variable frequency drive @ 22.75KW

Variation @ 6.5 Reduction in kwh = kw*hr *no.days = 6.5*24*365 kwh = 56,940 kwh

Value of savings @ Rs. 3.80 = 216372/ year

Variable frequency drive Cost = Rs.4,00,000

Repayment period is 674 days or 22.18 months.

12.3. Replacing the Present Feed-Pumps: By Automatic Recirculation Control (ARC) Valves with the Drag Valves of Multi-Stage Pressure Reduction

Replace existing ARC valves by the drag valves of multi-stage pressure reduction. These valves can reduce pressure in multiple stages by minimizing erosion, extending valve life and also reducing energy consumption. Many plants have already adopted this technology with measurable energy savings.

Implementation Plan

1. Replace one ARC valve in Unit-1 as a pilot.
2. In operation process, replace all the ARC valves of feed pumps gradually.

Energy Saving Potential

Power consumption of one BFP pump = 12,000 kW

Expected reduction = 4% → 480 kW saved per pump

Annual saving = 480 kW × 8000 hrs ×3.8/kWh =146 Lakhs

Financial Analysis

Investment per valve = 50 lakhs

Annual saving = 145 lakhs

Payback period = 4 months.

Replacing existing ARC valves with multi-stage drag valves ensures significant energy savings, reduced erosion, improved valve longevity, and a very short payback period, making it a highly viable energy efficiency measure.

13. Management of Maintenance

Management of maintenance is a primary factor for energy management of plant, load factor of plant, power generation cost, as well as power from the grid. The major components, viz. boiler, turbine, as well as generator, along with their components, are immensely significant to achieve the maximum load factor of the plant, including minimum power consumption of the auxiliaries.

Thus, plant maintenance is crucial in improving the efficiency of the plant as well as reducing the consumption of both electrical and fuel energy. The failure of the observation of tube of boiler is quoted below.

13.1. Minimizing Failures of Tube of Boiler

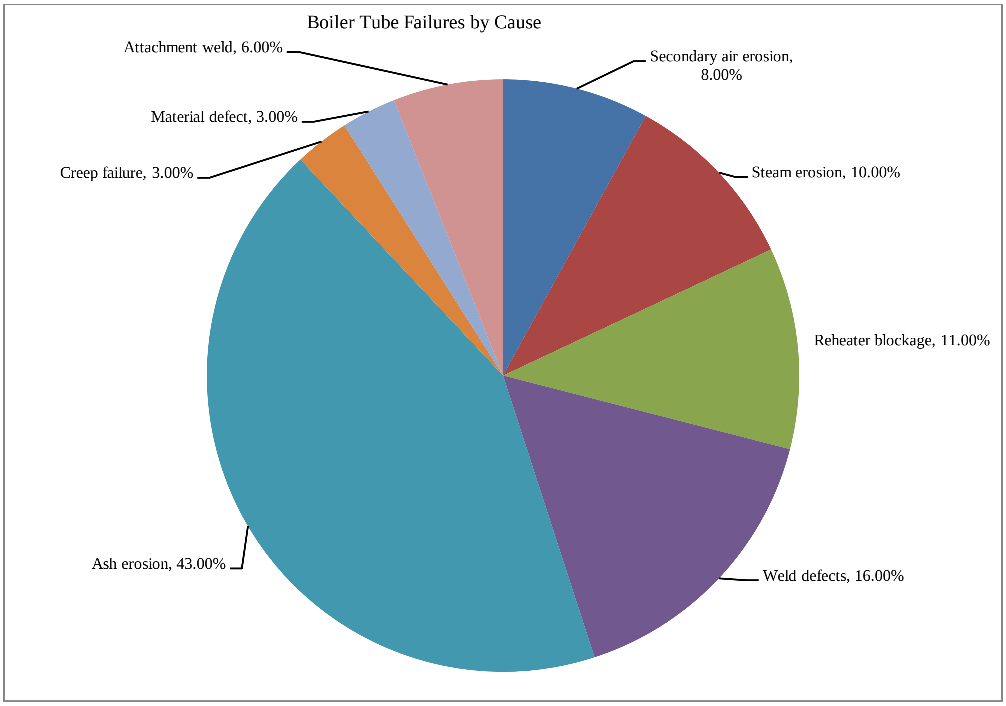

Fig. 10 Failures of tube of boiler by cause

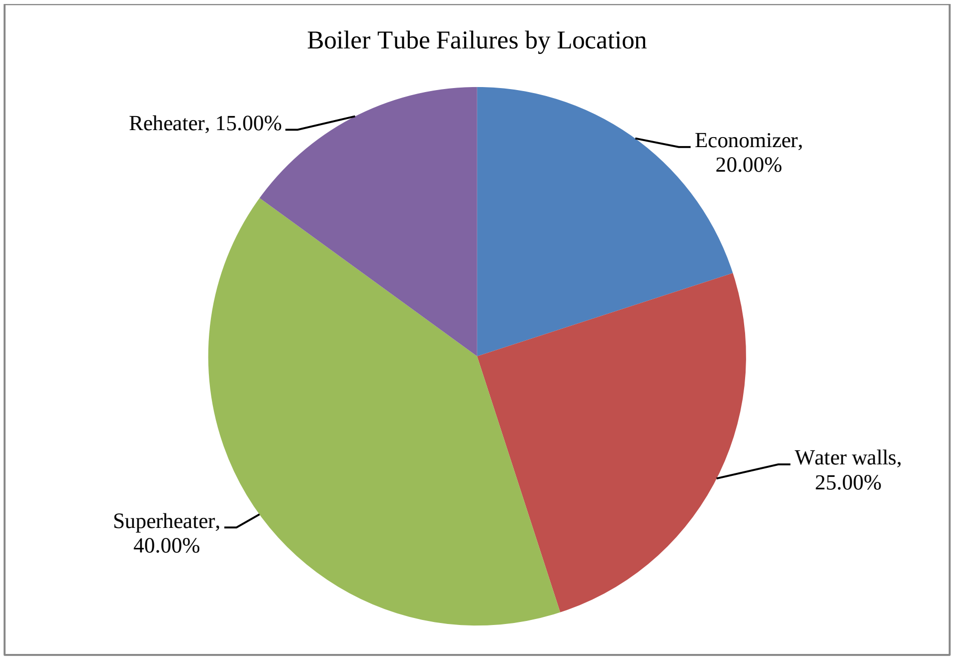

Fig. 11 Boiler tube failures by location

These visuals clearly highlight ash erosion as the leading cause and the super heater zone as the most failure-prone area.

14. Results and Conclusion

Sri Damodaram Sanjeevaiah Thermal Power Station (SDSTPS) had conducted a comprehensive performance evaluation to measure the nonconformance to the design conditions and to find ways to optimize coal consumption. The analysis incorporated thermodynamic considerations, operational diagnostics, energy audit results, and technological interventions as the means of enhancing the plant efficiency and decreasing the specific fuel consumption.

- The gross heat rate under operating conditions was higher than the design value of 2228 kcal/kWh by 2418 kcal/kWh, showing that it had an approximate variance of 8.5 per cent.
- The deviation in the heat rate of the turbines was almost 6%, and losses were seen to be massive in the low-pressure turbine section through losses in the deterioration of the condenser vacuum and operation loss in the sprays.
- Improved efficiency of the boiler by 89.26 (design) to 87.24 (operating), which was mainly due to combustion inefficiencies, ash deposition, and degradation of heating surface.
- Higher ash content and lower gross calorific value of coal were directly related to high specific consumption of coal.
- The effectiveness of the proposed optimization measures was also influenced by variations in coal quality and plant operating load conditions. Higher ash content and lower calorific value of coal affected heat-rate performance and specific coal consumption. Similarly, varying operating loads influenced boiler efficiency, turbine performance, and auxiliary power consumption.
- The cumulative turbine heat rate deficit at 100% MCR was determined to be 113.37 kcal/kWh, and the corrective action produced a reduction of 40.615 kcal/kWh.
- Combustion optimization, maintenance of air preheater and minimization of unburnt carbon led to annual coal saving of about 3006.58 MT, which was estimated.
- Installation of Variable Frequency Drives (VFDs) on seal air fans saved power usage of 500 kW to 232 kW that saved about 9 million units of energy per year with a payback period of about two months.
- Substitution of traditional ARC valves with multi-stage drag valves in boiler feed pump systems proved to have extra potential in terms of energy saving and with low payback time.
- The total auxiliary power consumption was minimized by systematic optimization of the significant auxiliary equipment and better load factor in the plants.

The findings reveal that optimization of coal-fired thermal power plants consumption needs a global plant-level structure, which integrates performance gap analysis, energy audit, combustion control, turbine cycle optimization, auxiliary system optimization, and maintenance interventions. Individual corrective actions can only have partial benefits, but co-ordinated thermodynamic and operating action can have quantifiable effects on removing heat rate, specific coal consumption, and overall economic performance.

The methodology adopted at SDSTPS provides a practical framework for improving fuel consumption and operational reliability; however, its wider applicability should be validated using longer-term data and additional thermal power plants. The present observations are also in agreement with earlier studies on coal-fired thermal power plants, particularly regarding the influence of coal quality, heat-rate variation, condenser losses, and auxiliary power consumption on overall plant performance.

The proposed optimization approach can also be applied to other coal-fired thermal power plants operating under similar load and fuel quality conditions. Systematic performance monitoring, energy audit practices, combustion optimization, and auxiliary system improvement can help improve heat-rate performance and reduce coal consumption in large-scale thermal power stations.

14.1. Validation Findings

Table 17. Validation for given parameters

Item	Reported in document	Validation view
Gross heat rate	2228 design vs 2418 actual	Reasonable trend: actual is worse than design.
Turbine heat rate	1989 design vs 2110 actual	Reasonable trend: actual is worse than design.
Boiler efficiency	89.26 design vs 87.24 actual	Reasonable trend: efficiency dropped.
Specific coal consumption	0.655 design vs 0.653 actual	Reasonable trend: slight decrease in specific coal consumption.
Auxiliary power consumption	6.50 design vs 7.244 actual	Reasonable trend: auxiliary use increased.
LPT efficiency	88.6 design vs 78.65 actual	Significant and credible degradation signal.

The findings reveal that optimization of coal-fired thermal power plants consumption needs a global plant-level structure, which integrates performance gap analysis, energy audit, combustion control, turbine cycle optimization, auxiliary system optimization, and maintenance interventions.

Individual corrective actions can only have partial benefits, but co-ordinated thermodynamic and operating action can have quantifiable effects on removing heat rate, specific coal consumption, and overall economic performance.

The type of methodology adopted at SDSTPS offers a viable and generalizable measure of improving the fuel consumption and reliability of operations in such thermal power plants.

The present observations are also in agreement with earlier studies on coal-fired thermal power plants, particularly regarding the influence of coal quality, heat-rate variation, condenser losses, and auxiliary power consumption on overall plant performance.

The proposed optimization approach can also be applied to other coal-fired thermal power plants operating under similar load and fuel quality conditions.

Systematic performance monitoring, energy audit practices, combustion optimization, and auxiliary system improvement can help improve heat-rate performance and reduce coal consumption in large-scale thermal power stations.

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Nomenclature

TOE :Tonners of Oil Equivalent
GCV : Gross Calorific Value
DM : Decentralized Water
PT : Pressure Temperature
MT : Metric Tonne
ARC : Automatic Recirculation Control
VFD : Variable Frequency Drive
HFO : Heavy Fuel Oil
HRH : Hot Re-Heat
PCV : Pressure Control Valve
LPT : Low-Pressure Turbine
HPT : High-Pressure Turbine
IPT : Intermediate-Pressure Turbine
MCR : Maximum Continuous Rating

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Author Contributions

S. Lingamaiah: Conceptualization performance analysis, energy audit evaluation, methodology development, investigation, and manuscript preparation.

Dr. R. Ramachandra: Supervision, technical guidance, validation of results, review and editing of the manuscript.

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