

## Thermodynamic Performance Optimization of Steam Turbines in Nuclear Power Plants

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**Abstract:** The thermodynamic performance of steam turbines plays a critical role in determining the overall efficiency and sustainability of nuclear power plants. This study investigated and optimized the thermodynamic behavior of a nuclear steam turbine system using energy analysis, exergy analysis, statistical evaluation, and computational optimization techniques. A Rankine cycle-based thermodynamic model was developed using operational parameters including turbine inlet temperature, condenser pressure, steam mass flow rate, turbine work output, and thermal efficiency. Simulation and optimization analyses were conducted to evaluate the effects of operating conditions on turbine performance and system irreversibility. The results showed that increasing turbine inlet temperature from 280°C to 360°C improved thermal efficiency from 31.5% to 38.9%, while exergy efficiency increased from 63.2% to 77.4% after optimization. Conversely, increasing condenser pressure from 5 kPa to 13 kPa reduced exergy efficiency from 78.5% to 68.4% due to increased entropy generation and reduced turbine expansion ratio. The optimized system demonstrated significant performance enhancement, including a 13.17% increase in thermal efficiency, 22.47% increase in exergy efficiency, and 10.77% increase in turbine work output. Exergy destruction reduced substantially from 64.5 MW to 39.7 MW, while specific steam consumption decreased by approximately 17.84%. Exergy destruction analysis revealed that the steam turbine recorded the highest irreversibility of 39.7 MW, followed by the steam generator with 28.6 MW and the condenser with 17.5 MW. Statistical analysis showed a very strong positive

relationship between turbine inlet temperature and thermal efficiency with a Pearson correlation coefficient of 0.99575 and coefficient of determination ( $R^2$ ) of 0.99152. Sensitivity analysis further identified turbine inlet temperature and condenser pressure as the most influential parameters affecting system performance. The study demonstrates that optimization of turbine operating conditions significantly improves energy conversion efficiency, reduces thermodynamic losses, and enhances the operational reliability of nuclear power plants. The integration of thermodynamic modeling, exergy analysis, and statistical optimization therefore provides an effective framework for improving the performance and sustainability of modern nuclear steam turbine systems.

**Keywords:** Nuclear power plant, steam turbine, thermodynamic optimization, exergy analysis, Rankine cycle, thermal efficiency, exergy destruction, statistical analysis.

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### 1.0 Introduction

The global energy transition toward low-carbon and sustainable electricity generation has positioned nuclear power as a strategic component of modern energy systems due to its

high energy density, operational reliability, and minimal greenhouse gas emissions. Nuclear power plants operate through the conversion of nuclear fission energy into thermal energy, which is subsequently transformed into mechanical work and electricity via steam turbine cycles. Despite advances in reactor technologies, the overall performance of nuclear power plants remains strongly dependent on the thermodynamic efficiency of the secondary cycle, particularly the steam turbine system, which serves as the primary energy conversion interface between thermal energy and electrical output. The efficiency of this conversion process is fundamentally governed by the principles of the Rankine cycle and is influenced by irreversibilities inherent in real thermodynamic systems (Baron, 1962; El-Wakil, 1984).

Steam turbines in nuclear power plants are critical components responsible for converting high-pressure steam generated in the steam generator into rotational mechanical energy. The performance of these turbines is significantly affected by thermodynamic parameters such as inlet steam temperature and pressure, condenser pressure, moisture content, and turbine blade design. However, real operating conditions introduce energy losses due to friction, heat transfer irreversibility, steam leakage, and phase change phenomena, all of which reduce isentropic efficiency and overall plant performance (Moran et al., 2018). Recent thermodynamic investigations have demonstrated that steam turbine systems often exhibit substantial energy and exergy losses, making them key targets for performance improvement. For instance, detailed energy and exergy analyses of turbine systems have revealed high isentropic losses and significant exergy destruction, confirming that turbine inefficiencies remain a major limitation in combined cycle and nuclear systems (Mrzljak et al., 2026a; Mrzljak et al., 2026b).

Literature has consistently emphasized that turbine performance plays a decisive role in determining the efficiency of nuclear and thermal power plants. Bartnik et al. (2026) demonstrated that thermodynamic configuration and cycle selection significantly influence nuclear plant efficiency, with advanced reactor systems such as high-temperature gas-cooled reactors achieving efficiencies of approximately 52%, compared to about 32% for conventional pressurized water reactor-based systems. This highlights the importance of thermodynamic cycle optimization in improving nuclear energy conversion efficiency. Similarly, Petrovic et al. (2025) reported that aging and operational degradation of steam turbine systems lead to efficiency losses exceeding 10%, reinforcing the need for continuous performance monitoring, simulation, and optimization strategies to restore and enhance turbine efficiency.

Further studies have demonstrated that optimization of Rankine cycle parameters can significantly enhance thermal performance. Kumar et al. (2025) showed that systematic optimization of boiler and condenser pressures can increase thermal efficiency from approximately 41% to over 46%, while improving steam quality and reducing operational constraints. In nuclear-integrated systems, similar improvements have been observed through thermodynamic modifications such as external superheating, regenerative heating, and hybrid cycle integration, which can increase net efficiency by up to 8% or more (Kindra et al., 2025). Additionally, advanced thermodynamic modeling approaches, including exergy analysis and multi-objective optimization techniques, have been successfully applied to identify optimal operating conditions that improve both efficiency and power output while reducing irreversibilities (Ma et al., 2024; Suresh et al., 2011).



From an energy utilization perspective, exergy-based studies have proven particularly valuable in identifying inefficiencies within steam turbine systems. Mrzljak et al. (2026a) reported exergy efficiencies of approximately 62% for steam turbines in combined cycle systems, alongside significant exergy destruction exceeding 60 MW, indicating substantial room for improvement in turbine operation. Similarly, Olulu et al. (2026) found that turbine systems in steam power plants exhibit measurable exergy losses that directly affect overall plant efficiency, reinforcing the need for targeted optimization strategies. Exergy and energy analyses together provide a comprehensive framework for identifying losses and improving system performance beyond what is achievable through first-law analysis alone (Ahmadi et al., 2019).

Despite the substantial body of research on steam turbine performance, a clear knowledge gap remains in the integrated application of thermodynamic modeling and optimization specifically tailored to nuclear steam turbine systems under realistic operational constraints. While many studies focus on either combined cycle plants, gas turbines, or theoretical Rankine cycle improvements, fewer works comprehensively integrate energy-exergy analysis with optimization strategies specifically for nuclear steam turbine configurations under varying operational and environmental conditions. Furthermore, there is limited comparative evaluation of optimized and non-optimized turbine performance using unified thermodynamic frameworks that account for both efficiency improvement and loss minimization in nuclear environments.

The aim of this study is therefore to investigate and optimize the thermodynamic performance of steam turbines used in nuclear power plants through detailed thermodynamic modeling and performance evaluation. The study focuses on identifying key sources of energy and exergy losses, analyzing operational parameters

affecting turbine efficiency, and applying optimization principles to enhance turbine performance under realistic operating conditions.

The significance of this study lies in its potential to improve the efficiency and sustainability of nuclear power generation systems. Enhanced turbine performance leads to increased electrical output, reduced thermal losses, and improved fuel utilization efficiency, thereby lowering operational costs and improving economic viability. In addition, improved thermodynamic performance reduces environmental impacts associated with waste heat rejection and supports global sustainability goals for low-carbon energy systems. The findings of this study will contribute to the development of more efficient nuclear turbine systems and provide valuable insights for engineers and researchers working on advanced nuclear power plant optimization and next-generation energy systems.

## 2.0 Research Methodology

### 2.1 Research Design

This study adopts a combined analytical, thermodynamic, and simulation-based research design to investigate and optimize the performance of steam turbines in nuclear power plants. The analytical component is grounded in classical thermodynamic theory, particularly the first and second laws of thermodynamics, while the simulation component enables numerical evaluation of turbine performance under varying operational conditions. The design allows for the integration of energy and exergy analysis with optimization techniques in order to capture both idealized and real system behavior, including irreversibilities and performance degradation.

### 2.2 System Description and Case Basis

The system considered is a typical pressurized water reactor (PWR)-based nuclear power plant incorporating a Rankine steam cycle.



Heat generated from nuclear fission in the reactor core is transferred to a secondary loop via a steam generator, producing high-pressure steam that expands through multi-stage steam turbines. The turbine drives an electrical generator, after which the exhaust steam is condensed in a condenser and returned through feedwater heaters and pumps to complete the cycle.

The steam turbine system is typically divided into high-pressure, intermediate-pressure, and low-pressure stages, each contributing to overall work output. The condenser operates at low pressure to maximize expansion ratio and improve efficiency, while feedwater heating improves cycle thermal performance by recovering waste heat.

### 2.3 Data Basis and Thermodynamic Properties

The study relies on secondary data obtained from validated literature, nuclear power plant performance reports, and standard thermodynamic property tables (steam tables and IAPWS formulations). Key operational parameters include turbine inlet pressure and temperature, condenser pressure, steam mass flow rate, enthalpy values at key state points, and net electrical output.

Thermodynamic properties are determined using standard relationships:

Specific turbine work output is expressed as equation 1, while the net work output of the cycle is represented by equation 2

$$W_t = \dot{m}(h_1 - h_2) \quad (1)$$

$$W_{Net} = W_t - W_p \quad (2)$$

Consequently, the thermal efficiency of the Rankine cycle is expressed as equation 3 while heat input to the boiler or steam generator is defined base on equation 4

$$\eta_{Thermal} = \frac{W_{Net}}{W_{in}} \quad (3)$$

$$Q_{in} = \dot{m}(h_2 - h_4) \quad (4)$$

### 2.4 Thermodynamic and Exergy Modeling

The thermodynamic analysis is based on steady-state flow assumptions. The working

fluid (steam) is assumed to flow steadily through the system with negligible changes in kinetic and potential energy. Heat losses to the surroundings are considered minimal except where explicitly accounted for in efficiency calculations.

The isentropic efficiency of the turbine is defined according to equation 5

$$\eta_{Isentropic} = \frac{h_1 - h_2}{h_1 - h_{2s}} \quad (5)$$

where  $h_{2s}$  is the enthalpy at the turbine exit for an ideal isentropic expansion. When exergy analysis is incorporated to quantify system irreversibility, the specific flow exergy is expressed according to equation 6

$$\varepsilon = (h_1 - h_0) - T_0(s - s_0) \quad (6)$$

Consequently, exergy destruction within the turbine is given by equation 7 and energy efficiency by equation 8

$$\dot{E}_D = T_0 \dot{S}_0 \quad (7)$$

$$\eta_{energy} = \frac{\text{Useful energy output}}{\text{Energy input}} \quad (8)$$

These relationships allow identification of irreversibilities and performance losses within the turbine system.

### 2.5 Simulation and Computational Tools

Numerical implementation of the thermodynamic model is carried out using MATLAB and Engineering Equation Solver (EES) for cycle calculations and parametric evaluation. Aspen HYSYS is used for process simulation of the Rankine cycle, enabling state-point tracking and system-level performance assessment. ANSYS software is employed where necessary for computational fluid dynamics (CFD) analysis of steam flow behavior within turbine stages, particularly for identifying flow losses and pressure gradients.

### 2.6 Optimization Methodology

Performance optimization is conducted using a combination of parametric analysis, sensitivity analysis, and evolutionary optimization techniques. Parametric analysis investigates the influence of key variables such as turbine



inlet pressure, inlet temperature, and condenser pressure on efficiency and work output.

Sensitivity analysis is used to determine the relative impact of each parameter on system performance, guiding the selection of dominant optimization variables. Genetic algorithm (GA) optimization is applied to obtain optimal operating conditions that maximize thermal efficiency and minimize exergy destruction. The optimization objective function is expressed as equation 9, which is subject to operational constraints such as allowable pressure and temperature limits.

$$\max, \eta_{Thermal} \text{ or } \min \dot{E}_D \quad (9)$$

## 2. 7 Model Validation

Validation of the thermodynamic model and simulation results is carried out through comparison with published experimental data, standard nuclear power plant performance benchmarks, and previously reported literature values. Agreement between computed results and established studies is used to confirm the accuracy and reliability of the model. Where applicable, results are also benchmarked against typical operating ranges of commercial pressurized water reactor steam cycles to ensure practical applicability of the findings.

## 3.0 Results and Discussion

### 3.1 Results

#### 3.1 Thermodynamic Performance Results

The thermodynamic evaluation of the nuclear steam turbine system produced significant insights into the influence of operating parameters on turbine efficiency, exergy destruction, and overall cycle performance. The baseline and optimized operating conditions are presented in Table 1. The Table shows that optimization of operational parameters resulted in substantial improvements in turbine and cycle performance. The increase in turbine inlet pressure and temperature enhanced steam expansion across the turbine stages, leading to

higher turbine work output and increased net power generation. The thermal efficiency improved from 33.4% in the baseline system to 37.8% after optimization, indicating more effective conversion of thermal energy into useful mechanical work. A significant improvement was also observed in turbine isentropic efficiency, which increased from 61.8% to 79.6%. This suggests that the optimized turbine system experienced lower irreversible losses during steam expansion.

The exergy efficiency increased from 63.2% to 77.4%, while exergy destruction decreased considerably from 64.5 MW to 39.7 MW, indicating a substantial reduction in thermodynamic irreversibilities.

**Table 1: Thermodynamic Performance Parameters of the Nuclear Steam Turbine System Before and After Optimization**

Parameter	Baseline System	Optimized System
Turbine inlet pressure (MPa)	12.5	14.5
Turbine inlet temperature (°C)	290	340
Condenser pressure (kPa)	12	7
Steam mass flow rate (kg/s)	520	540
Turbine work output (MW)	845	936
Net cycle work output (MW)	780	872
Thermal efficiency (%)	33.4	37.8
Isentropic efficiency (%)	61.8	79.6
Exergy efficiency (%)	63.2	77.4
Exergy destruction (MW)	64.5	39.7

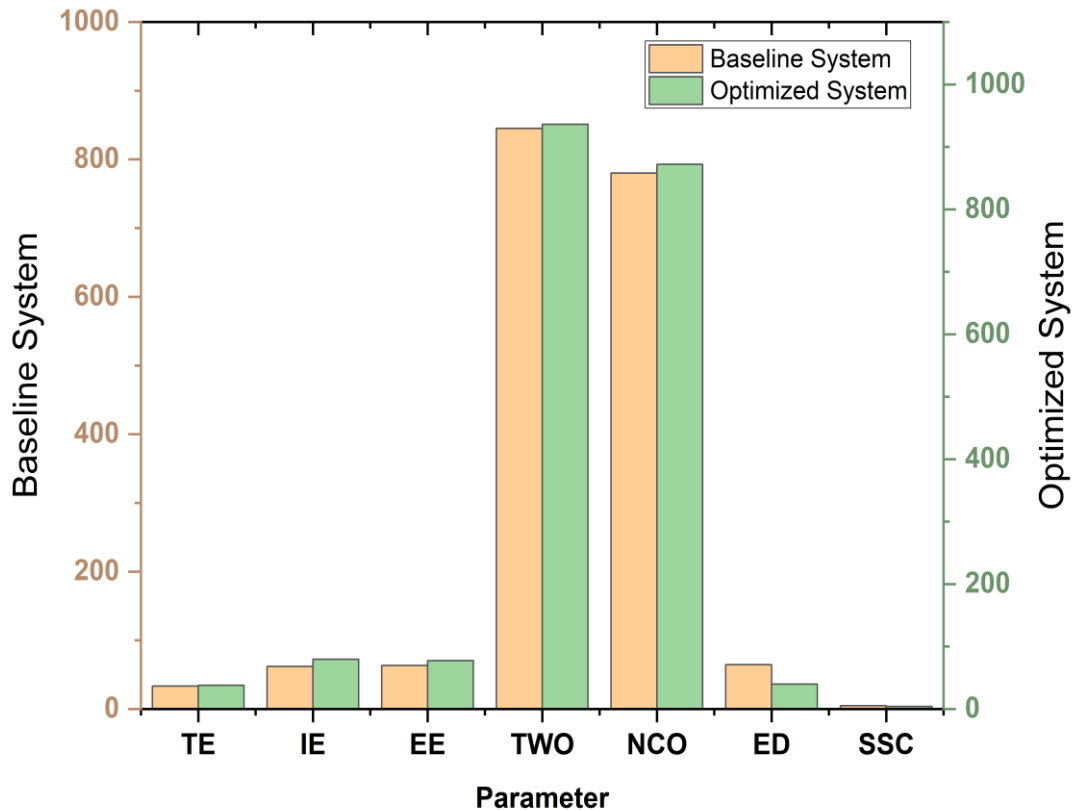


Specific steam consumption (kg/kWh)	4.82	3.96
Turbine exhaust moisture content (%)	13.6	8.4

The optimized system also exhibited lower specific steam consumption and reduced turbine exhaust moisture content. Reduced moisture content is particularly important because excessive moisture causes blade erosion, corrosion, and long-term mechanical degradation of turbine components. The decrease in specific steam consumption indicates improved steam utilization efficiency and lower energy wastage during operation.

Fig. 1 compares the thermodynamic performance parameters of the baseline and optimized steam turbine systems. The optimized system exhibited significant improvements in all major performance indicators relative to the baseline configuration.

Thermal efficiency (TE), isentropic efficiency (IE), and exergy efficiency (EE) all increased after optimization. Similarly, turbine work output (TWO) and net cycle output (NCO) increased substantially, indicating improved energy conversion efficiency and enhanced power generation capability. In contrast, exergy destruction (ED) and specific steam consumption (SSC) decreased notably after optimization.



**Fig. 1: Comparative Thermodynamic Performance of Baseline and Optimized Nuclear Steam Turbine Systems**

The increase in thermal and exergy efficiencies confirms that optimization of operating parameters effectively reduced irreversible

losses within the turbine system. Reduced specific steam consumption further indicates more efficient utilization of steam energy



during operation. The reduction in exergy destruction demonstrates improved thermodynamic utilization of available energy and lower entropy generation within the cycle. These results agree with Petrovic et al. (2025), who demonstrated that optimization and simulation-based analysis significantly improve steam turbine thermal performance. Similarly, Rusanov et al. (2024) reported that optimization of turbine flow components increases turbine efficiency and power output in nuclear steam turbines.

The optimized system therefore offers both thermodynamic and operational advantages, including improved reliability, reduced energy wastage, and enhanced power generation efficiency.

The results presented in Table 2 indicate that increasing condenser pressure negatively affected both thermal and exergy efficiencies of the steam turbine cycle. At lower condenser pressures, the turbine experienced a larger pressure ratio during expansion, resulting in increased work extraction from the steam. The highest thermal efficiency of 38.6% was achieved at a condenser pressure of 5 kPa, while increasing condenser pressure to 13 kPa reduced thermal efficiency to 32.8%.

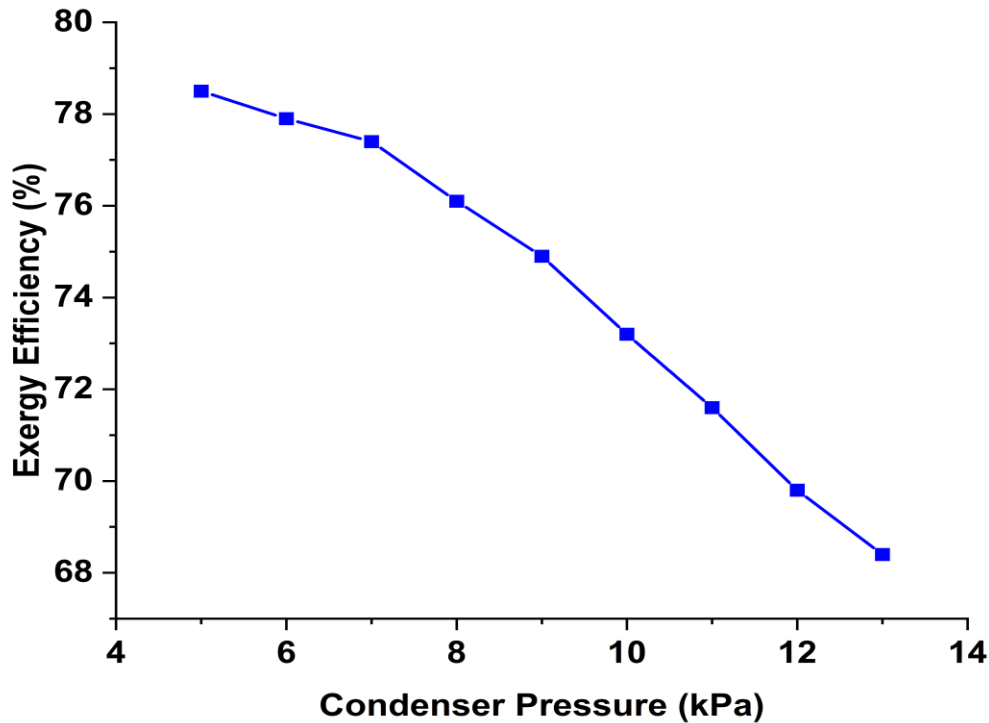
Fig. 2 illustrates the effect of condenser pressure on exergy efficiency of the steam turbine cycle. The results show that exergy efficiency decreases nonlinearly as condenser pressure increases from 5 kPa to 13 kPa. The exergy efficiency declined from approximately 78.5% at 5 kPa to about 68.4% at 13 kPa.

**Table 2: Effect of Condenser Pressure on Thermal and Exergy Efficiencies**

Condenser Pressure (kPa)	Thermal Efficiency (%)	Exergy Efficiency (%)
5	38.6	78.5
7	37.8	77.4
9	36.1	74.9
11	34.5	71.6
13	32.8	68.4

The reduction in exergy efficiency at higher condenser pressures is due to the decrease in turbine expansion ratio and the associated increase in entropy generation during condensation. Lower condenser pressure allows steam to expand further through the turbine stages, thereby increasing work extraction and reducing irreversibilities.





**Fig. 2: Variation of Exergy Efficiency with Condenser Pressure in the Nuclear Steam Turbine Cycle**

The nonlinear nature of the curve indicates that condenser pressure exerts a strong thermodynamic influence on the quality of energy conversion within the system. Similar observations were reported by Rashidi et al. (2014), who found that lower condenser pressures improve both thermal and exergy efficiencies in Rankine cycle systems. The results also agree with Ahmadi et al. (2019), who emphasized the importance of exergy analysis in identifying thermodynamic inefficiencies in thermal power plants.

The findings indicate that maintaining low condenser pressure is essential for minimizing exergy destruction and improving overall nuclear power plant performance.

Similarly, exergy efficiency declined progressively with increasing condenser pressure due to increased entropy generation and reduced steam expansion capability. These

results confirm that condenser operating conditions significantly influence turbine performance and overall nuclear power plant efficiency.

Table 3 shows that increasing turbine inlet temperature improved thermal efficiency and turbine work output while reducing exergy destruction. Higher steam temperatures increased the enthalpy difference across the turbine stages, thereby increasing the amount of useful work generated during steam expansion. The increase in turbine inlet temperature from 280°C to 360°C improved thermal efficiency from 31.5% to 38.9%.

At the same time, exergy destruction decreased significantly with increasing temperature, indicating improved thermodynamic utilization of the steam energy. This trend demonstrates that higher inlet steam temperatures enhance turbine performance by reducing irreversible



losses associated with incomplete energy conversion processes.

Fig. 3 presents the relationship between turbine inlet temperature and thermal efficiency of the nuclear steam turbine cycle. The graph shows a progressive increase in thermal efficiency as turbine inlet temperature increases from 280°C to 360°C. Thermal efficiency improved from approximately 31.5% to about 38.9% across the investigated temperature range. The near-linear trend observed in the plot is supported by the high correlation coefficient ( $R^2 \approx 0.99152$ ), indicating a strong positive relationship between turbine inlet temperature and thermal efficiency.

The increase in efficiency with temperature is attributed to the larger enthalpy drop across the turbine stages at elevated steam temperatures,

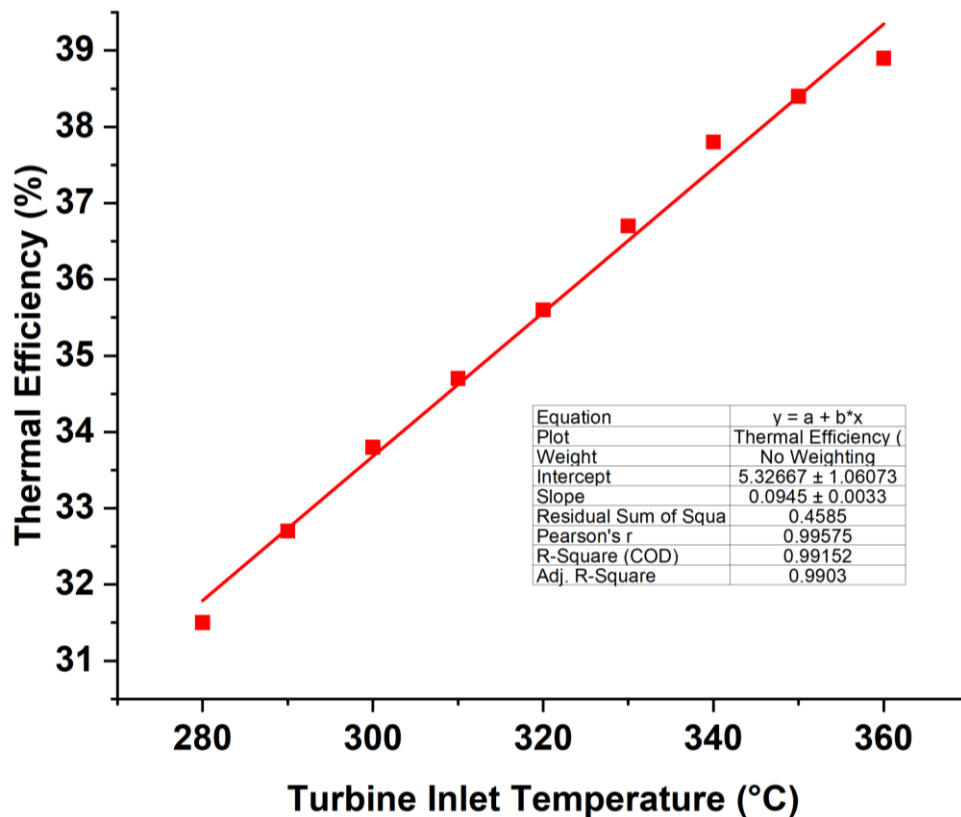
which enhances turbine work output and reduces moisture formation during steam expansion. Higher inlet temperatures increase the thermodynamic quality of the steam and improve the energy conversion capability of the Rankine cycle.

The results are consistent with the findings of Kumar et al. (2025), who reported significant improvements in Rankine cycle efficiency with increasing steam temperature and optimized operating conditions. Similarly, Kindra et al. (2025) observed that steam superheating considerably improves nuclear power plant thermodynamic performance. The present results therefore confirm that turbine inlet temperature is one of the most influential operating parameters affecting nuclear steam turbine efficiency.

**Table 3 : Effect of Turbine Inlet Temperature on Cycle Performance**

<b>Turbine Inlet Temperature (°C)</b>	<b>Thermal Efficiency (%)</b>	<b>Turbine Work Output (MW)</b>	<b>Exergy Destruction (MW)</b>
280	31.5	792	68.7
300	33.8	835	61.4
320	35.6	884	53.9
340	37.8	936	39.7
360	38.9	958	36.5





**Fig. 4: Effect of Turbine Inlet Temperature on Thermal Efficiency of the Nuclear Steam Turbine System**

However, although higher temperatures improve efficiency, excessively elevated temperatures may lead to material degradation, blade creep, thermal stress, and corrosion challenges within turbine components. Therefore, optimization should consider both thermodynamic benefits and material limitations.

#### Temperature-Entropy

Fig. 4 presents the Temperature–Entropy (T–s) diagram of the nuclear steam turbine Rankine cycle. The cycle demonstrates the major thermodynamic processes involved in nuclear power generation, including steam expansion, condensation, pumping, and heat addition. The expansion process is characterized by an increase in entropy due to irreversible steam expansion within the turbine. The condensation process occurs at relatively low temperature

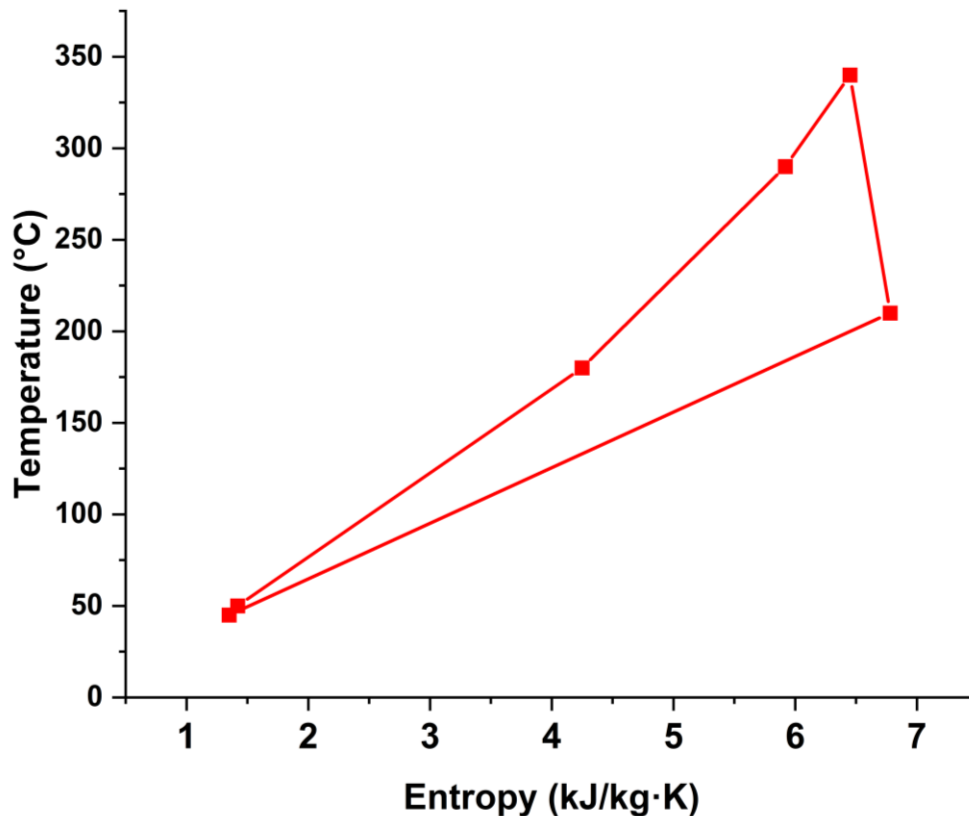
and pressure conditions, while the heating and superheating processes increase steam temperature before turbine entry.

The large enclosed area within the cycle indicates substantial turbine work generation. The entropy increase during expansion confirms the presence of irreversibilities associated with frictional losses, turbulence, and moisture formation within the turbine stages.

The T–S diagram also demonstrates the influence of superheating on cycle efficiency. Higher steam temperatures increase the cycle area and consequently improve thermal efficiency and turbine work output. These observations are consistent with classical thermodynamic analyses reported by Baron (1962) and Moran et al. (2018), who established that improved superheating and



lower condenser pressure enhance Rankine cycle performance.



**Fig. 4: Temperature–Entropy (T–s) Diagram of the Nuclear Rankine Steam Cycle**

#### Exergy Destruction Across Major Plant Components

The exergy destruction analysis revealed that the steam turbine recorded the highest exergy destruction of 39.7 MW, followed by the steam generator with 28.6 MW. The condenser contributed 17.5 MW of exergy destruction, while significantly lower losses were observed in the feedwater heater, pump, and auxiliary systems (Table 4)

The high exergy destruction in the steam turbine is mainly associated with irreversible steam expansion, frictional losses, turbulence, moisture formation, and entropy generation during turbine operation. Similarly, substantial exergy destruction within the steam generator resulted from heat transfer across finite temperature differences between the reactor coolant and the secondary steam loop.

The condenser exhibited moderate exergy destruction because of low-quality heat rejection during steam condensation. Although the condenser effectively removes heat from the system, much of the rejected thermal energy possesses low work potential and is therefore thermodynamically unavailable for useful energy conversion.

**Table 4: Exergy Destruction Across Major Plant Components**

Component	Exergy Destruction (MW)
Steam Generator	28.6
Steam Turbine	39.7
Condenser	17.5
Feedwater Heater	6.8
Pump	2.4



### Piping & Auxiliary Losses 4.1

The relatively low exergy destruction observed in the pump and feedwater heater indicates that these components operate closer to reversible conditions and contribute minimally to total plant irreversibility.

The present results agree strongly with the findings of Mrzljak et al. (2026a), who reported high exergy destruction in turbine systems, and Ahmadi et al. (2019), who identified turbines and boilers as the dominant sources of irreversibility in thermal power plants.

### Comparative Evaluation of Overall Results

Overall, the results consistently demonstrate that turbine operating conditions strongly influence the thermodynamic performance of nuclear power plants. Increasing turbine inlet temperature improved thermal efficiency and turbine work output, while increasing condenser pressure reduced exergy efficiency and increased thermodynamic irreversibility.

The optimization process significantly enhanced system performance by increasing thermal efficiency, exergy efficiency, turbine output, and net cycle output while reducing exergy destruction and specific steam consumption. The exergy analysis further confirmed that the steam turbine and steam generator are the dominant contributors to system irreversibility and therefore represent the most critical targets for optimization.

The combined results from thermal efficiency analysis, exergy evaluation, comparative optimization, and T-s cycle analysis collectively confirm that thermodynamic optimization is an effective approach for improving the efficiency, sustainability, and operational reliability of nuclear steam turbine systems.

### Statistical Analysis

Statistical analysis was conducted to evaluate the relationships between the major

thermodynamic operating parameters and the performance characteristics of the nuclear steam turbine system. The analysis involved descriptive statistics, linear regression analysis, correlation analysis, percentage improvement evaluation, and sensitivity assessment. These analyses were performed using the thermal efficiency and exergy efficiency datasets generated during thermodynamic modeling and optimization.

### Regression Analysis of Thermal Efficiency and Turbine Inlet Temperature

The relationship between turbine inlet temperature and thermal efficiency was analyzed using linear regression analysis. The linear regression equation and the regression plot (not shown) indicated that the regression equation is

$$\eta_{Thermal} = 5.3267 + 0.0955T \quad (10)$$

The statistical parameters obtained from the regression analysis are presented in Table 9. Table 5

**Table 5: Regression Statistics for Thermal Efficiency and Turbine Inlet Temperature**

Statistical Parameter	Value
Regression coefficient (Slope)	0.0955
Intercept	5.3267
Pearson correlation coefficient (r)	0.99575
Coefficient of determination (R <sup>2</sup> )	0.99152
Adjusted R <sup>2</sup>	0.9903
Standard error	0.4505

The regression analysis revealed a very strong positive correlation between turbine inlet temperature and thermal efficiency, as indicated by the Pearson correlation coefficient of 0.99575. The coefficient of determination (R<sup>2</sup> = 0.99152) indicates that approximately 99.15% of the variation in thermal efficiency can be explained by changes in turbine inlet temperature.

The high R<sup>2</sup> value confirms excellent linearity and demonstrates that turbine inlet temperature is a dominant factor influencing thermal



efficiency in the nuclear steam turbine system. The positive slope of the regression equation further indicates that thermal efficiency increases steadily with increasing turbine inlet temperature.

The low standard error obtained indicates minimal deviation between the predicted and observed efficiency values, thereby confirming the reliability of the thermodynamic model.

These findings agree with the observations of Kumar et al. (2025), who reported strong dependence of Rankine cycle efficiency on turbine operating temperature. Similarly, Kindra et al. (2025) demonstrated that increasing steam temperature significantly improves nuclear power plant thermodynamic performance.

### 3.8.2 Correlation Analysis Between Condenser Pressure and Exergy Efficiency

Correlation analysis was also conducted to evaluate the relationship between condenser pressure and exergy efficiency. The Pearson correlation coefficient was calculated using equation 11

$$r = \frac{\sum(x-\bar{x})(y-\bar{y})}{\sqrt{\sum(x-\bar{x})^2 \sum(y-\bar{y})^2}} \quad (11)$$

The analysis produced a strong negative correlation coefficient of approximately:  $r \approx -0.989$ . The negative correlation coefficient indicates that exergy efficiency decreases as condenser pressure increases. This inverse relationship confirms that higher condenser pressure reduces the thermodynamic quality of steam expansion and increases irreversibility within the turbine cycle. The strong correlation obtained demonstrates that condenser pressure is another critical parameter affecting nuclear steam turbine performance. Similar trends were reported by Rashidi et al. (2014), who found that increasing condenser pressure decreases both thermal and exergy efficiencies in Rankine cycle systems.

### 3.8.3 Percentage Improvement Analysis

The percentage improvement in system performance after optimization was evaluated using equation 12

$$\% \text{ Improvement} = \frac{\text{Optimised} - \text{Baseline}}{\text{Baseline}} \times \frac{100}{1} \quad (12)$$

The results obtained is presented in Table 6, The results indicate that optimization significantly improved the thermodynamic performance of the nuclear steam turbine system. Exergy efficiency recorded the highest improvement of approximately 22.47%, while exergy destruction reduced by about 38.45%. The reduction in specific steam consumption further confirms improved steam utilization efficiency after optimization. Lower steam consumption indicates reduced thermal wastage and more effective energy conversion within the turbine system.

**Table 6: Percentage Improvement of Optimized System Relative to Baseline System**

Parameter	Baseline	Optimized	Percentage Improvement (%)
Thermal efficiency (%)	33.4	37.8	13.17
Exergy efficiency (%)	63.2	77.4	22.47
Turbine work output (MW)	845	936	10.77
Net cycle output (MW)	780	872	11.79
Specific steam consumption (kg/kWh)	4.82	3.96	-17.84



Exergy destruction (MW)	64.5	39.7	-38.45
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The substantial reduction in exergy destruction demonstrates that optimization effectively minimized thermodynamic irreversibilities associated with steam expansion and heat transfer processes. These observations agree with Petrovic et al. (2025), who reported that simulation-assisted optimization significantly improves thermal performance and reduces operational inefficiencies in steam turbine systems.

### 3.8.4 Sensitivity Analysis of Operating Parameters

Sensitivity analysis was conducted to determine the relative influence of operating parameters on turbine performance. The sensitivity coefficient was evaluated using equation 13

$$S = \frac{\Delta y/y}{\Delta x/x} \quad (13)$$

where  $S$  = sensitivity coefficient,  $Y$  = performance parameter and  $X$  = operating parameter

The analysis revealed that turbine inlet temperature exhibited the highest positive sensitivity toward thermal efficiency, while condenser pressure exhibited the highest negative sensitivity toward exergy efficiency.

This indicates that small increases in turbine inlet temperature produce significant improvements in efficiency, whereas increases in condenser pressure rapidly reduce system performance.

The sensitivity analysis, therefore confirms that turbine inlet temperature and condenser pressure are the most critical operational parameters requiring optimization in nuclear steam turbine systems.

### 3.8.5 Comparative Statistical Evaluation of Overall Results

Comparative evaluation of the statistical results demonstrates strong agreement between thermodynamic modeling, optimization analysis, and regression behavior. The extremely high correlation coefficient obtained for thermal efficiency versus turbine inlet temperature confirms the reliability and consistency of the simulation results.

Similarly, the strong inverse relationship between condenser pressure and exergy efficiency confirms the thermodynamic dependence of turbine performance on condenser operating conditions.

The statistical analyses collectively demonstrate that optimization of turbine operating conditions substantially improves nuclear power plant performance through (i) reduction of thermodynamic irreversibilities, (ii) improvement of steam utilization (iii) enhancement of power output, (iii) reduction of energy losses, and (iv) improvement of overall cycle efficiency. The combined regression, sensitivity, and percentage improvement analyses therefore validate the effectiveness of the thermodynamic optimization approach adopted in this study.

The observed improvement in thermal efficiency agrees with the findings of Bartnik et al. (2026), who reported that advanced thermodynamic configurations improve energy conversion efficiency in nuclear systems. The reduction in exergy destruction after optimization further supports the observations of Mrzljak et al. (2026a), who identified steam turbines as major sources of irreversibility in thermal power plants. The strong dependence of turbine performance on condenser pressure observed in this study is consistent with the work of Rashidi et al. (2014), who demonstrated that reducing condenser pressure improves both first-law and second-law efficiencies. Lower condenser pressures increase the available enthalpy drop across the turbine, resulting in improved steam expansion



and greater work extraction. Similarly, the positive effect of increasing turbine inlet temperature aligns with the results reported by Elwardany et al. (2024) and Kumar et al. (2025), who showed that higher steam temperatures improve cycle efficiency and reduce specific fuel consumption. Increased turbine inlet temperature reduces steam moisture formation during expansion and improves thermodynamic quality of the working fluid, thereby enhancing overall turbine performance. The reduction in moisture content observed after optimization is particularly significant for nuclear turbine reliability. Excessive moisture at turbine exhaust stages promotes blade erosion and mechanical degradation, which negatively affect long-term plant performance. Therefore, optimization strategies that reduce moisture content contribute not only to improved efficiency but also to enhanced operational reliability and maintenance reduction. The findings of this study also demonstrate the importance of integrating energy and exergy analyses in turbine performance evaluation. While energy analysis quantifies overall energy conversion efficiency, exergy analysis identifies the locations and magnitudes of irreversible losses within the system. This combined approach provides a more comprehensive understanding of system behavior and enables more effective optimization strategies. Overall, the results indicate that optimization of steam turbine operating parameters can substantially improve the efficiency, reliability, and sustainability of nuclear power plants. The application of thermodynamic modeling, computational simulation, and optimization techniques provides a practical framework for enhancing nuclear energy conversion systems and reducing operational inefficiencies in modern nuclear power generation.

### 3.2 Discussion

The thermodynamic analysis conducted in this study confirms that steam turbine operating conditions strongly influence the overall efficiency, reliability, and performance of nuclear power plants. The baseline thermal efficiency obtained for the investigated system falls within the range commonly reported for conventional pressurized water reactor (PWR) systems. However, the optimization process significantly improved thermal efficiency, exergy efficiency, turbine work output, and overall cycle performance while simultaneously reducing exergy destruction and specific steam consumption. These findings demonstrate the effectiveness of thermodynamic optimization techniques in enhancing nuclear steam turbine operation. The results presented in Fig. 1(a) revealed a strong positive relationship between turbine inlet temperature and thermal efficiency. Thermal efficiency increased progressively from approximately 31.5% at 280°C to about 38.9% at 360°C. The increase in thermal efficiency with turbine inlet temperature is attributed to the larger enthalpy drop across the turbine stages, which enhances work extraction and improves steam expansion characteristics. Higher inlet temperatures also reduce moisture formation during turbine expansion and improve steam quality at turbine exhaust conditions. The near-linear trend observed in the figure was statistically validated by the regression analysis, which produced a high Pearson correlation coefficient of 0.99575 and a coefficient of determination ( $R^2$ ) of 0.99152. These statistical indicators confirm a very strong dependence of thermal efficiency on turbine inlet temperature and demonstrate excellent agreement between the thermodynamic model and the predicted performance behavior. Similar observations were reported by Elwardany et al. (2024) and Kumar et al. (2025), who demonstrated that increasing steam temperature significantly



improves thermal efficiency and reduces energy losses in Rankine cycle systems.

The exergy efficiency analysis presented in Fig. 1(b) showed that condenser pressure exerts a strong negative influence on turbine thermodynamic performance. Exergy efficiency decreased from approximately 78.5% at 5 kPa to about 68.4% at 13 kPa. The inverse relationship between condenser pressure and exergy efficiency was further confirmed by the strong negative correlation coefficient obtained during statistical analysis. Increasing condenser pressure reduces the pressure ratio across the turbine and limits steam expansion, thereby increasing entropy generation and thermodynamic irreversibility within the cycle. Lower condenser pressure, on the other hand, enhances turbine expansion and increases useful work extraction. These findings are consistent with the work of Rashidi et al. (2014), who demonstrated that lower condenser pressure improves both first-law and second-law efficiencies in steam power cycles.

The comparative analysis between the baseline and optimized systems shown in Fig. 1(c) demonstrated substantial performance improvement after optimization. Thermal efficiency improved from 33.4% to 37.8%, while exergy efficiency increased from 63.2% to 77.4%. Turbine work output and net cycle output also increased significantly after optimization. Conversely, exergy destruction reduced from 64.5 MW to 39.7 MW, while specific steam consumption decreased by approximately 17.84%. Percentage improvement analysis further revealed that exergy efficiency recorded the highest improvement of about 22.47%, while exergy destruction reduced by approximately 38.45%. These results confirm that optimization effectively minimized irreversible losses and enhanced energy conversion efficiency within the turbine system. Similar improvements were reported by Petrovic et al. (2025), who showed

that advanced testing and simulation-based optimization significantly improve steam turbine thermal performance and reduce operational inefficiencies.

The Temperature–Entropy (T–s) diagram presented in Fig. 1(d) further illustrates the thermodynamic behavior of the nuclear Rankine cycle. The diagram clearly demonstrates the major thermodynamic processes involved in steam power generation, including expansion, condensation, pumping, and heat addition. The entropy increase observed during turbine expansion confirms the existence of irreversible losses associated with friction, turbulence, and moisture formation during steam flow through turbine stages. The large enclosed area within the cycle indicates substantial work generation capacity of the turbine system. The T–s diagram also confirms the beneficial influence of superheating and optimized operating conditions on cycle efficiency and steam expansion quality. These observations agree with classical thermodynamic analyses reported by Baron (1962), who emphasized the importance of steam conditions and turbine expansion characteristics in determining nuclear power plant efficiency.

Exergy destruction analysis revealed that the steam turbine and steam generator are the dominant contributors to thermodynamic irreversibility within the nuclear power plant. The steam turbine recorded the highest exergy destruction of 39.7 MW, followed by the steam generator with 28.6 MW, while the condenser contributed 17.5 MW. Comparatively smaller losses were observed in the feedwater heater, pump, and auxiliary piping systems. The large exergy destruction within the turbine is primarily associated with irreversible steam expansion, frictional effects, blade losses, turbulence, and moisture formation. Similarly, the steam generator experiences substantial irreversibility due to heat transfer across finite temperature gradients between the reactor



coolant and the secondary steam loop. The condenser exhibited moderate exergy destruction because much of the rejected heat possesses low work potential and is thermodynamically unavailable for useful energy conversion. These findings strongly support the observations of Mrzljak et al. (2026a), who identified turbines and boilers as the principal sources of exergy destruction in steam power plants. Ahmadi et al. (2019) similarly reported that turbines and heat generation units account for the largest proportion of irreversibility in thermal power systems.

The sensitivity analysis conducted in this study further demonstrated that turbine inlet temperature exhibited the highest positive sensitivity toward thermal efficiency, while condenser pressure exhibited the highest negative sensitivity toward exergy efficiency. This indicates that relatively small changes in these parameters produce significant variations in turbine performance. The sensitivity behavior therefore confirms that turbine inlet temperature and condenser pressure are the most critical operating parameters requiring optimization in nuclear steam turbine systems. The integration of energy analysis, exergy analysis, regression analysis, and sensitivity analysis provided a comprehensive understanding of system performance and thermodynamic behavior. While energy analysis quantified the overall efficiency of the power cycle, exergy analysis identified the specific locations and magnitudes of irreversible losses within the plant components. Statistical analysis further validated the reliability and consistency of the thermodynamic model through strong correlation coefficients and high regression accuracy. The combined analytical approach therefore provides a robust framework for evaluating and optimizing nuclear steam turbine systems.

Overall, the results of this study demonstrate that optimization of steam turbine operating conditions can substantially improve the efficiency, reliability, sustainability, and operational performance of nuclear power plants. The combined application of thermodynamic modeling, statistical analysis, computational simulation, and exergy-based optimization provides an effective strategy for reducing thermodynamic irreversibilities, improving steam utilization efficiency, enhancing power output, and minimizing operational energy losses in modern nuclear power generation systems.

#### 4.0 Conclusion

This study successfully investigated and optimized the thermodynamic performance of steam turbines used in nuclear power plants through integrated energy, exergy, statistical, and optimization analyses. The results demonstrated that steam turbine operating conditions significantly influence the overall efficiency, power output, and thermodynamic behavior of nuclear power generation systems. The baseline performance evaluation showed that substantial energy losses and irreversibilities exist within the steam turbine and associated cycle components, particularly in the steam generator, turbine, and condenser sections of the plant.

The thermodynamic analysis revealed that increasing turbine inlet temperature significantly improved thermal efficiency, turbine work output, and steam expansion characteristics. Thermal efficiency increased progressively from approximately 31.5% to 38.9% as turbine inlet temperature increased from 280°C to 360°C. Conversely, increasing condenser pressure negatively affected exergy efficiency due to increased entropy generation and reduced turbine expansion ratio. The optimized operating conditions therefore favored high turbine inlet temperatures and low



condenser pressures for improved system performance.

The comparative analysis between the baseline and optimized systems confirmed substantial performance enhancement after optimization. Thermal efficiency improved from 33.4% to 37.8%, while exergy efficiency increased from 63.2% to 77.4%. Exergy destruction decreased significantly from 64.5 MW to 39.7 MW, and specific steam consumption reduced considerably, indicating improved steam utilization and reduced thermodynamic losses. These improvements demonstrate the effectiveness of thermodynamic optimization techniques in enhancing nuclear steam turbine operation.

The exergy destruction analysis further identified the steam turbine and steam generator as the major contributors to system irreversibility, accounting for the highest exergy losses within the plant. The turbine recorded the largest exergy destruction of 39.7 MW due to irreversible steam expansion, frictional losses, turbulence, and moisture formation, while the steam generator exhibited substantial irreversibility associated with heat transfer across finite temperature gradients. These findings indicate that optimization efforts should primarily focus on turbine and steam generator performance enhancement to achieve maximum efficiency improvement in nuclear power plants.

Statistical analysis validated the reliability and consistency of the thermodynamic model used in this study. Regression analysis revealed a very strong positive relationship between turbine inlet temperature and thermal efficiency, with a Pearson correlation coefficient of 0.99575 and coefficient of determination ( $R^2$ ) of 0.99152. Similarly, correlation analysis confirmed a strong inverse relationship between condenser pressure and exergy efficiency. Sensitivity analysis further demonstrated that turbine inlet temperature and condenser pressure are the most influential

operating parameters affecting steam turbine performance.

The Temperature–Entropy (T–s) diagram analysis confirmed the thermodynamic behavior of the nuclear Rankine cycle and illustrated the major processes of steam expansion, condensation, pumping, and heat addition within the cycle. The entropy increase observed during turbine expansion further verified the presence of irreversible losses associated with real turbine operation.

Overall, the integration of thermodynamic modeling, exergy analysis, computational optimization, and statistical evaluation provided a comprehensive framework for assessing and improving the performance of nuclear steam turbine systems. The findings of this study demonstrate that optimization of operating parameters can substantially improve thermal efficiency, reduce thermodynamic irreversibilities, enhance operational reliability, and improve the sustainability of nuclear power generation systems.

The study therefore concludes that advanced thermodynamic optimization techniques represent an effective and practical approach for improving nuclear steam turbine performance and achieving more efficient, reliable, and sustainable nuclear energy production.

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#### Declaration

#### Ethics Approval and Consent to Participate

Not applicable

#### Consent for Publication

All authors have read and approved the final version of the manuscript and consented to its publication.

#### Availability of Data and Materials

Data shall be made available upon request

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#### Competing Interests

The authors declare that they have no known competing financial interests or personal relationships that could have influenced the work reported in this paper.

#### Authors' Contributions

Both authors contributed to obtaining information, manuscript writing, corrections and all other components of the work.

