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Analysis of Sawdust and Coal Biomass Fuel Variations on the Efficiency of 660 MW Multistage Turbine Steam Power Plant

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Abstract

The use of biomass as an alternative fuel in power generation systems is an important strategy in supporting the clean energy transition. This study analyzes the effect of variations in the mixture of biomass fuel in the form of sawdust with coal on the efficiency of a 660 MW multistage turbine in a Steam Power Plant (PLTU). The study was conducted experimentally with six variations of sawdust mixture from 0% to 5%. Data were obtained from direct observation and secondary data, then analyzed quantitatively using calculations of isentropic efficiency, turbine power, turbine heatrate, thermal efficiency, and exhaust emissions. The results showed that increasing the percentage of sawdust caused a decrease in the isentropic efficiency of the three types of turbines, namely High Pressure Turbine (HPT) from 85.90% to 83.20%, Intermediate Pressure Turbine (IPT) 98.01% to 96.89%, and Low Pressure Turbine (LPT) from 88.64% to 88.03%, output power from 639.150 MW to 603.525 MW, and thermal efficiency from 45.16%. to 44.04%, as well as an increase in turbine heatrate from 7971.761 kJ/kWh to 8174.373 kJ/kWh. However, flue gas emissions decreased significantly such as SO_2 from 354.898 mg/Nm³ to 11.507 mg/Nm³ and NO_x from 220.549 mg/Nm³ to 140.324 mg/Nm³, while CO_2 remained relatively stable. The decrease in efficiency is due to the characteristics of sawdust, which has a lower heating value and higher moisture content than coal.

Kata kunci: efficiency; emissions; sawdust; steam turbine

Abstrak

Penggunaan biomassa sebagai bahan bakar alternatif dalam sistem pembangkit listrik menjadi strategi penting dalam mendukung transisi energi bersih. Penelitian ini menganalisis pengaruh variasi campuran bahan bakar biomassa berupa serbuk kayu (sawdust) dengan batu bara terhadap efisiensi turbin *multistage* 660 MW pada Pembangkit Listrik Tenaga Uap (PLTU). Studi dilakukan secara eksperimental dengan enam variasi campuran sawdust dari 0% hingga 5%. Data diperoleh dari pengamatan langsung dan data sekunder, kemudian dianalisis secara kuantitatif menggunakan perhitungan efisiensi isentropik, daya turbin, turbine heatrate, efisiensi termal, dan emisi gas buang. Hasil penelitian menunjukkan bahwa peningkatan presentase sawdust menyebabkan penurunan efisiensi isentropik dari ketiga jenis turbin, yaitu High Pressure Turbine (HPT) dari 85,90% menjadi 83,20% , Intermediate Pressure Turbine (IPT) 98,01% menjadi 96,89%, dan Low Pressure Turbine (LPT) dari 88,64% menjadi 88,03%, daya output dari 639,150 MW menjadi 603,525 MW, dan efisiensi termal dari 45,16%. menjadi 44,04%, serta peningkatan turbine heatrate 7971,761 kJ/kWh menjadi 8174,373 kJ/kWh. Meskipun demikian, emisi gas buang mengalami penurunan signifikan seperti SO_2 354,898 mg/Nm³ menjadi 11,507 mg/Nm³ dan NO_x dari 220,549 mg/Nm³ menjadi 140,324 mg/Nm³, sementara CO_2 relatif stabil. Penurunan efisiensi disebabkan oleh karakteristik sawdust yang memiliki nilai kalor lebih rendah dan kadar air lebih tinggi dibandingkan batu bara.

Keywords: efisiensi; emisi; *sawdust*; turbin uap

1. Introduction

Indonesia's electricity sector is still dominated by the use of fossil energy, especially in the Java-Bali region which is highly dependent on coal-fired Steam Power Plants (PLTU). Meanwhile, the contribution of renewable energy is still relatively low [ ]1 . As a driver of clean energy transition, the government issued Presidential Regulation No. 112 of 2022 which aims to accelerate the development of new renewable energy (EBT) through various sources such as biomass, solar, wind, and geothermal [2]. This commitment is in line with the national target of achieving Net Zero Emissions (NZE) by 2060 as emphasized by the Minister of Energy and Mineral Resources [3].

One of the strategies used to reduce greenhouse gas emissions and reduce dependence on coal is through co-firing technology. Co-firing is a method of burning two types of fuel simultaneously, in this case a mixture of coal and biomass. Biomass such as sawdust has a lower energy content than coal, but can be a sustainable alternative because it produces smaller emissions such as CO_2, NOx, and SOx [4]

The combustion process of a mixture of biomass and coal in a boiler produces high-pressure steam that will be used to drive a steam turbine [5]. The efficiency of the turbine is highly dependent on the inlet steam conditions, particularly pressure and temperature. The characteristics of the steam produced from co-firing combustion can differ from the steam produced by burning pure coal, depending on the type and proportion of biomass used. These variations in fuel composition can affect the mass flow rate, temperature and pressure of the steam produced, ultimately impacting the performance and efficiency of the steam turbine.

Previous research has examined the isentropic efficiency of steam turbines using wood waste from the plywood industry, showing that efficiency is strongly influenced by the difference between the actual work and theoretical work of the turbine [6], which is the energy in the enthalpy entering and leaving the turbine resulting from linear interpolation calculations using the thermodynamic properties of saturated water (liquid-vapor) temperature appendix table [7]. Further research shows that vapor flow rate, pressure, and temperature are the main parameters in influencing turbine power and efficiency[8] . Meanwhile, in another study, turbine power and turbine efficiency experienced increases and decreases caused by the ups and downs of turbine heatrate results, coal combustion that was not maximized, and the characteristics of coal [9].

Based on the literature review, most previous studies on biomass co-firing in coal-fired power plants primarily focus on emission reduction and boiler heat rate performance. Studies that specifically analyze the effect of varying sawdust co-firing ratios on the isentropic efficiency of each steam turbine stage (High Pressure Turbine, Intermediate Pressure Turbine, and Low Pressure Turbine) using actual operational data from large-scale power plants are still limited. Therefore, this study aims to fill this research gap by investigating the relationship between sawdust co-firing variations, steam quality, and multistage turbine performance in a 660 MW coal-fired power plant.

2. Materials and Methodology

This experimental study was conducted at PT PLN Nusantara Power (PLN NP) Paiton Unit, Probolinggo Regency, East Java, from February to March 2025. The study was conducted under typical plant operating conditions, assuming a relatively stable load. Data were obtained by keeping the fuel flow rate constant, while variations were introduced through six fuel mixture compositions, ranging from 0% to 5% sawdust biomass. The analytical approach used included qualitative and quantitative analysis. Qualitative analysis was conducted through field observations, interviews with operators and plant operations managers, and literature review to understand the combustion characteristics and performance of the steam turbine. Quantitative analysis was conducted by processing numerical data from operational measurements and secondary data through mathematical calculations based on thermodynamic principles to evaluate turbine performance. Parameters recorded directly from the Central Control Room (CCR) included fuel composition, mass flow rate, turbine inlet and outlet steam pressures, and turbine inlet and outlet steam temperatures.

This study was conducted based on several operational assumptions to limit the scope of the analysis and focus the discussion on the main research variables. During data collection, the plant was assumed to operate without significant changes to the boiler and turbine configuration. The analysis does not consider the effects of equipment degradation, short-term fluctuations in coal quality, or extreme environmental conditions. These assumptions allow for a more focused evaluation of the direct impact of sawdust biomass cofiring on steam turbine performance. However, this approach also presents limitations as it does not fully represent the dynamic operating conditions of the plant.

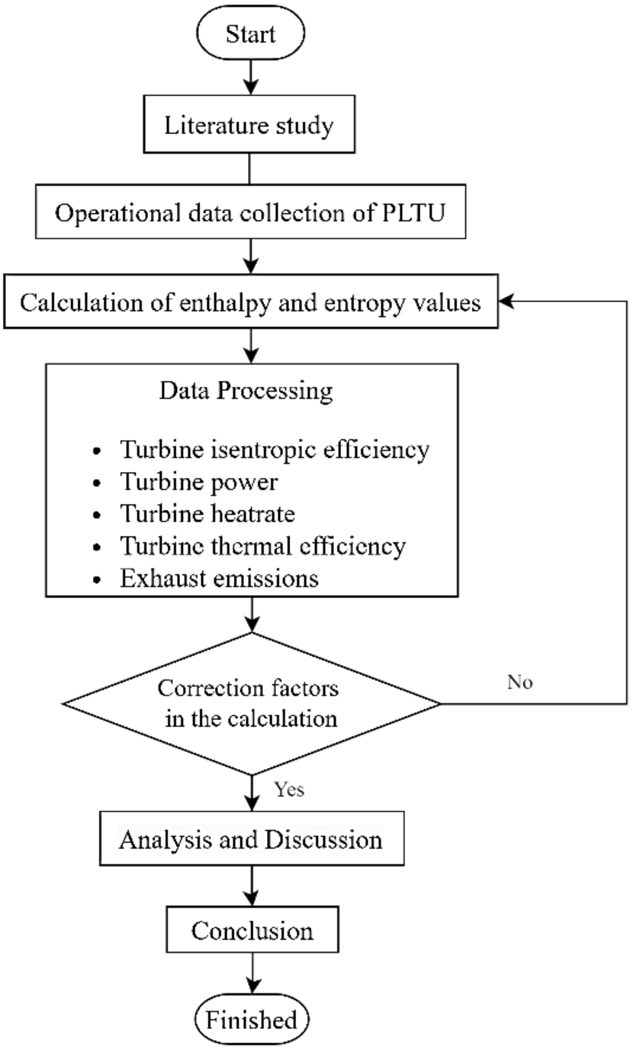

Figure 1 Research flow chart

2.1 Linear Interpolation

Two-point interpolation with a straight line with points (x_0, y_0) and (x_1, y_1). The linear interpolation technique is used to find values in the temperature appendix table A.2 and pressure table A.3 in the form of temperature (T), pressure (P) enthalpy of saturated liquid (h_f), enthalpy of vaporization (h_{fg}), enthalpy of saturated vapor (h_g), entropy of saturated liquid (s_f), entropy of saturated vapor (s_g). In addition, linear interpolation finds the actual vapor enthalpy value (h_2)because vapor enthalpy $h_g = h_2$.

$$p_1(x) = \frac{y_1 - y_0}{x_1 - x_0}(x - x_0) + y_0 \tag{1}$$

Where, $p_1(x)$ is a parameter that is sought based on the boundary values x_0 and $x_1$the pressure before and after the value of x, with x being the known pressure. The values y_0 and y_1 are the limit values before and after $p_1(x)$ [10].

2.2 Turbine Isentropic Efficiency

The efficiency of an isentropic turbine is the ratio of the actual conditions to the ideal conditions of the device in a process. Actual turbines refer to turbines operating under real conditions, where various factors such as energy losses and design imperfections affect their performance [11]. An idealized turbine is a theoretical model used to describe how a turbine would operate under perfect conditions. The efficiency of a turbine in a cycle can be shown on a T-s diagram. Based on Figure 2 below, the isentropic efficiency of the turbine can be formulated using equation 2 as follows:

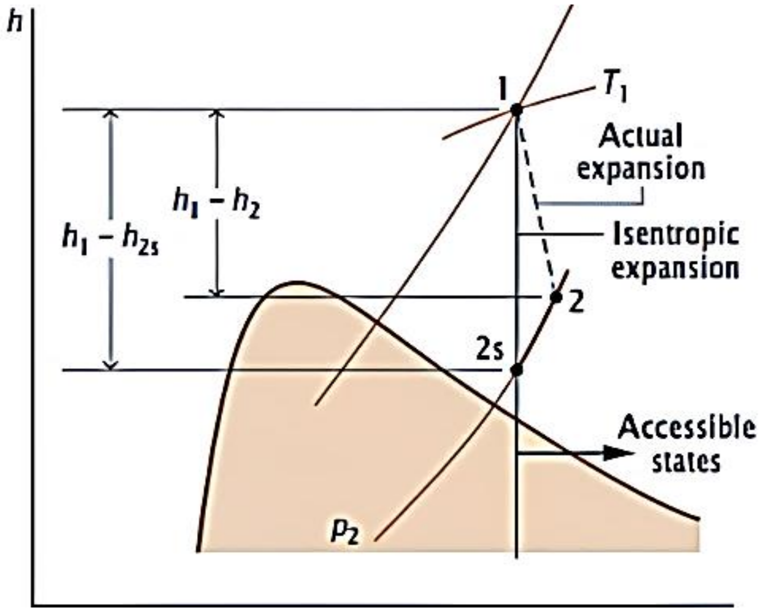

Figure 2. Mollier diagram (comparison between actual and ideal turbine expansion)

$$\eta_{ts} = \frac{\hbar_1 - \hbar_2}{\hbar_1 - \hbar_{2s}} \; x \; 100\% \quad (2)$$

Where, the isentropic efficiency of the turbine is indicated by η_{ts} (%), calculated based on the values of turbine inlet steam enthalpy $\hbar_1$ (kj/kg), actual outlet steam enthalpy $\hbar_2$ (kj/kg), and ideal outlet steam enthalpy $\hbar_{2s}$ (kj/kg) [12]. The numerator and denominator in these formulas are evaluated in the same inlet and outlet states. The ideal enthalpy $\hbar 2s$ is determined by equations 3 - 5 as follows:

- Entropy *outlet* : $\mathcal{S}_1 = \mathcal{S}_2$ (3)

- Vapor fraction : $\mathcal{X}_2 = \frac{\mathcal{S}_2 - \mathcal{S}_f}{\mathcal{S}_g - \mathcal{S}_f} = \frac{\mathcal{S}_2 - \mathcal{S}_f}{\mathcal{S}_{fg}}$ (4)

- Ideal enthalpy : $\hbar_{2s} = \hbar_f + \mathcal{X}_2 \hbar_{fg}$ (5)

Where, the vapor fraction is indicated by $\mathcal{X}_2$, while the entropy is measured at the inlet $\mathcal{S}_1$ and outlet $\mathcal{S}_2$ of the turbine. The entropies of saturated liquid and saturated vapor are denoted by $\mathcal{S}_f$ and $\mathcal{S}_g$, respectively while $\hbar_f$ is the enthalpy of saturated liquid, and$\hbar f$gis the difference between $\hbar_{fg}$ is the difference between $\hbar_g$ and $\hbar_f$, which is also known as the enthalpy of vaporization [13].

2.3 Turbine Power

Turbine power is generated from the conversion of thermal energy contained in steam into mechanical energy through the expansion process in the turbine. The energy formula to determine turbine power using equation 6 is:

$$W_T = \dot{m}\ x\ (\hbar_{\text{in}} - \hbar_{\text{out}})\ x\ \eta_{ts} \quad (6)$$

Where,, W_T T is the turbine power (MW) determined by the enthalpy difference between $\hbar_{\text{in}}$ yaitu uap masuk (kj/kg) dan $\hbar_{\text{out}}$ entalpi keluar (kj/kg), dikalikan dengan $\dot{m}$ yaitu laju aliran massa uap (kg/h) dan efisiensi turbin [14].

2.4 Turbine Heatrate

Turbine heatrate shows the ratio of the total energy used to rotate the turbine to the electrical energy generated by the turbine and is expressed in kJ/kWh, so it can be calculated by equation 7 is:

$$\text{THR} = \frac{(\dot{m}_1\ x\ \hbar_1\ x\ \dot{m}_3\ x\ \hbar_3) - (\dot{m}_f\ x\ \hbar_{fw}\ x\ \dot{m}_2\ x\ \hbar_2\ x\ \dot{m}_{is}\ x\ \hbar_{is} x\ \dot{m}_{ir}\ x\ \hbar_{ir})}{W_T} \quad (7)$$

Where, THR is the heat consumption rate of the turbine measured in kJ/kWh, with mass flow rate parameters such as: $\dot{m}_1$= *main steam*, $\dot{m}_2$ = *cold reheat*, $\dot{m}_3$ = *hot reeheat*, $\dot{m}_{fw}$ = *feedwater*, $\dot{m}_{is}$ = *superheater spray*, $\dot{m}_{ir}$ = *reheater spray* with units (kg/h) and associated enthalpy values such as ,$\hbar_1$, $\hbar_2$, $\hbar_3$, $\hbar_{fw}$, $\hbar_{is}$, $\hbar_{ir}$ with units (kj/kg). The output value of the turbine is expressed as W_T (kWh) [15].

2.5 Turbine Thermal Efficiency

The thermal efficiency of the turbine is a parameter that states the degree of success of the turbine system to convert energy from heat to work. The conversion for every 1 kWh is equal to 3600 kJ, so to find the thermal efficiency of the turbine can use the following equation 8:

$$\eta_t = \frac{3600}{Turbine\ Heat\ Rate}\ x\ 100\% \quad (8)$$

The energy conversion between electrical units and thermal energy follows 1 kWh = 3600 kJ. The overall thermal efficiency of the turbine is symbolized asηt in units of percent (%) [16].

3. Results and discussion

3.1 Hubungan Campuran Presentase *Sawdust* dengan Efisiensi *High Pressure Turbine*, *Intermediet Pressure Turbine*, dan *Low Pressure Turbine*.

Figure 3 shows the results of the graphical analysis of the effect of variations in sawdust percentage on the isentropic efficiency of the three types of turbines, namely High Pressure Turbine (HPT), Intermediate Pressure Turbine (IPT), and Low Pressure Turbine (LPT). The efficiency of the three turbines decreased as the proportion of sawdust increased from 0% to 5%, although with different characteristics. The efficiency of the HPT was recorded to decrease from 86.30% at

0% to 85.96% at 5%, indicating that the high-pressure turbine is severely affected by the decrease in steam quality due to the characteristics of sawdust which has a lower heating value and higher water content than coal, resulting in steam with lower pressure and temperature. Since the HPT works under high pressure and temperature conditions, the decreased steam quality has a significant impact on its efficiency.

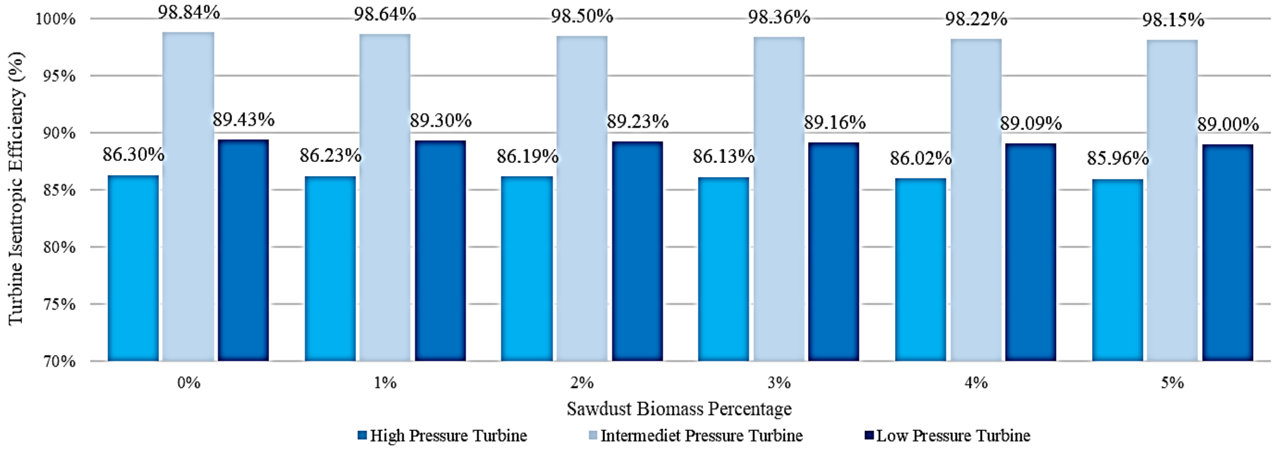

Figure 3 Comparison Chart of Sawdust Percentage to Turbine Efficiency

The observed decrease in isentropic efficiency with increasing biomass proportion is consistent with findings by Danial et al. (2019), who reported that reduced steam quality from biomass combustion leads to lower turbine efficiency. Similarly, Jamaludin and Kurniawan (2017) showed that increased turbine heat rate negatively affects turbine efficiency and power output. The key distinction of this study lies in the use of actual operational data from a 660 MW coal-fired power plant, making the results more representative of commercial-scale power plant conditions compared to previous simulation-based or small-scale studies.

In contrast, the efficiency of the IPT showed the highest and most stable value compared to the other two turbine types. The efficiency of the IPT decreased relatively little from 98.84% to 96.15%. This is due to the IPT operating at intermediate pressures which are more tolerant of variations in steam quality. The IPT is also designed to perform optimally within a more moderate pressure and temperature range, so small changes in steam characteristics do not have a major impact on its performance. Meanwhile, the efficiency of the LPT also decreased from 89.43% to 89.00%, but this decrease was more stable than that of the HPT. This is because the LPT operates at a lower pressure, where the influence of steam quality on efficiency is not as great as that of the HPT, although naturally the efficiency of the LPT is lower because the available steam kinetic energy is also smaller

3.2 Relationship between Sawdust Percentage Mixture and Turbine Generated Power

In Figure 4, the graph shows that the turbine output power decreased consistently from 639.150 MW at 0% sawdust mixture to 603.525 MW at 5% sawdust mixture. This decrease is related to the decrease in heat energy available to produce steam due to the lower heating value of sawdust compared to coal. The water content in sawdust also absorbs most of the energy for the vaporization process so that the remaining energy to generate electricity becomes smaller. In addition, the higher percentage of sawdust causes a decrease in the mass flow rate of steam, especially main steam, cold reheat, hot reheat, as well as temperature, and steam pressure which has a direct impact on the mechanical power generated by the turbine.

The main steam mass flow rate tends to decrease due to a decrease in heat energy production from combustion, which causes the volume of steam produced to decrease. The cold reheat and hot reheat mass flow rates decrease similarly, as less steam leaves the high pressure turbine for the reheater. This decrease in steam flow rate reduces the total kinetic energy available to rotate the intermediate and low pressure turbines, thus decreasing the contribution of each turbine stage to power generation.

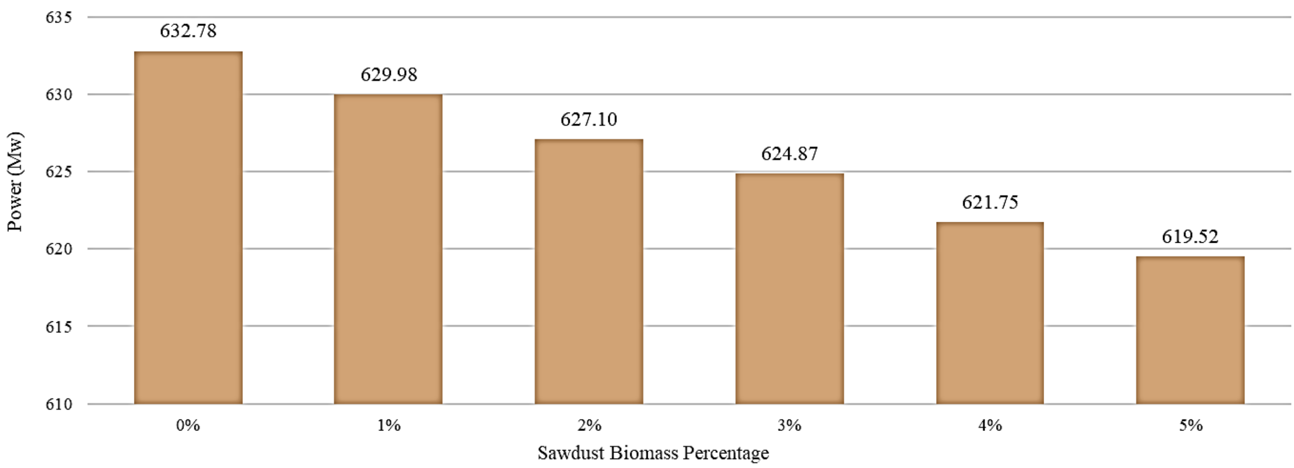

Figure 4 Comparison Chart of Sawdust Percentage to Power

3.3 Relationship between Sawdust Percentage Mixture and Turbine Heat Rate and Turbine Thermal Efficiency

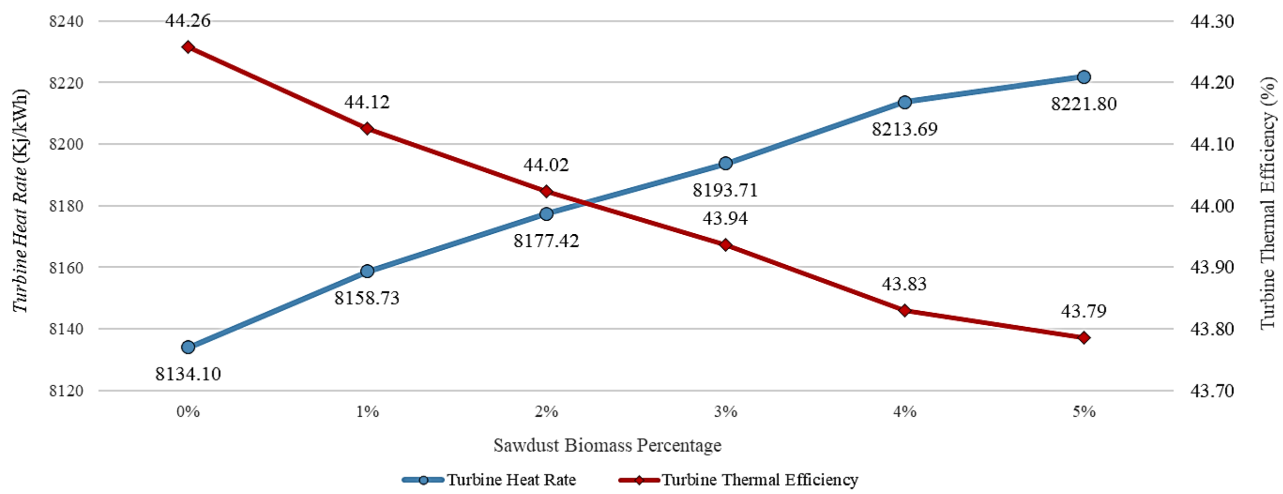

Figure 5 Comparison Chart of Sawdust Percentage to Turbine Heatrate and Turbine Thermal Efficiency

In Figure 5, the graph shows that the heatrate value increases as the percentage of sawdust increases, from 8134.10 kJ/kWh at 0% to 8221.80 kJ/kWh at 5%, while the thermal efficiency decreases. In the 0% sawdust condition, the thermal efficiency of the turbine is at its highest at 44.26%. However, when the sawdust mixture increases gradually until it reaches 5%, the thermal efficiency decreases to 43.79%. This increase in heatrate indicates that the turbine heat consumption required to produce a unit of electrical energy (kWh) becomes greater, thus signaling a decrease in the thermal efficiency of the system. This is due to the characteristics of sawdust which has a low heating value, high moisture and volatile content, and combustion properties that are not equivalent to coal, which can cause minor disturbances in the steam flow system and unstable combustion. The result of unstable combustion can increase the need for water spraying in the superheater and reheater to control temperature, so the system requires more fuel to achieve the same electrical output and a decrease in efficiency

3.4 Relationship between Sawdust Percentage Mixture and Emissions of SO_2, NOx, and CO_2

Figure 6 illustrates the effect of increasing sawdust biomass co-firing from 0% to 5% on exhaust gas emissions, namely SO_2, NO_x, and CO_2. Overall, the results indicate a consistent reduction in all three emission parameters as the proportion of sawdust increases. SO_2 emissions show the most pronounced decline, decreasing steadily from 76.422 mg/Nm³ at 0% sawdust to 36.626 mg/Nm³ at 5%. This trend is primarily attributed to the significantly lower sulfur content of sawdust compared to coal, resulting in reduced sulfur input into the combustion process as coal is progressively displaced. The continuous downward trend across all blending ratios suggests that even small substitutions of coal with low-sulfur biomass can effectively suppress SO_2 formation during combustion.

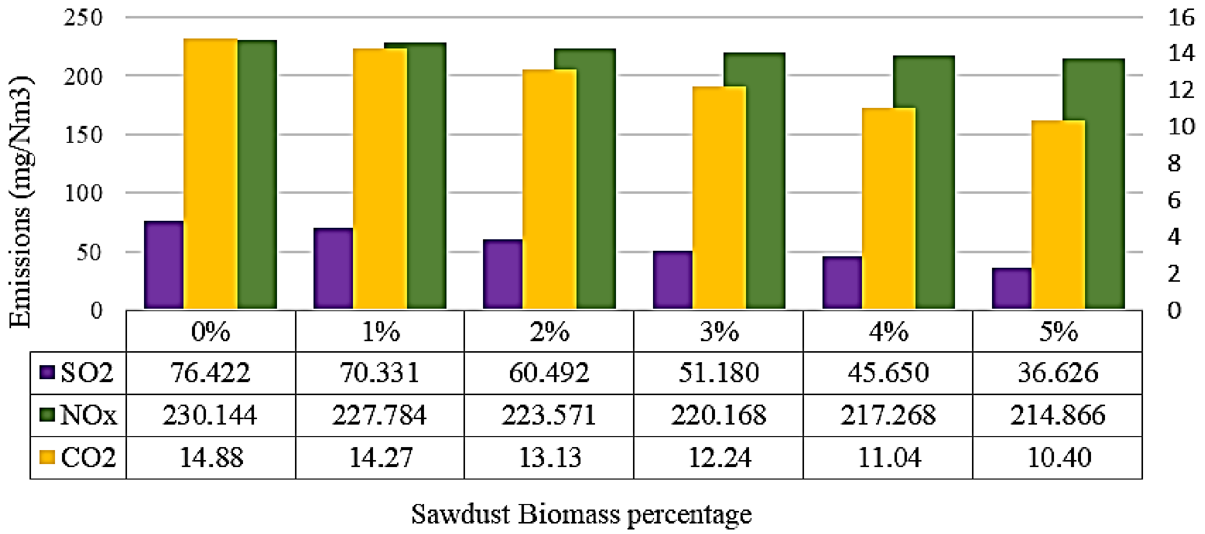

Figure 6 Comparison Chart of Percentage of Sawdust to Flue Gas Emissions

Similarly, NO_x emissions exhibit a gradual decrease with increasing sawdust content, from 230.144 mg/Nm³ at 0% to 214.866 mg/Nm³ at 5%. This reduction can be explained by the lower combustion temperature and higher volatile matter content of sawdust, which tend to suppress thermal NO_x formation. The absence of a sharp increase at higher blending ratios indicates that the co-firing process remains relatively stable within the tested range, without causing significant air–fuel imbalance or excessive temperature rise that could promote NO_x re-formation.

CO_2 emissions also demonstrate a declining trend, although the reduction is less pronounced compared to SO_2 and NO_x. The CO_2 concentration decreases from 14.88% at 0% sawdust to 10.40% at 5%, reflecting the lower carbon content of sawdust relative to coal. This result indicates that partial substitution of coal with biomass contributes to a reduction in carbon-based emissions, supporting the potential role of biomass co-firing as a strategy for mitigating greenhouse gas emissions in coal-fired power plants.

4. Conclusion

The results of this study indicate that increasing the proportion of sawdust co-firing from 0% to 5% leads to a decrease in turbine isentropic efficiency, turbine power output, and overall thermal efficiency, while increasing turbine heat rate. These effects are primarily caused by the lower calorific value and higher moisture content of sawdust compared to coal. However, co-firing sawdust significantly reduces SO_2 and NO_x emissions, while CO_2 emissions remain relatively stable.. This study provides an empirical contribution based on actual operational data by demonstrating the impact of sawdust co-firing on multistage steam turbine performance in a 660 MW coal-fired power plant. The findings offer practical insights for power plant operators in determining optimal biomass co-firing ratios that balance turbine efficiency and emission reduction. Furthermore, this research supports the implementation of biomass co-firing as a transitional strategy toward cleaner energy production in the electricity sector.

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