Jurnal Rekayasa Mesin
p-ISSN: 1411-6863, e-ISSN: 2540-7678
Vol.20, No.2, Agustus **2025**, hal. 319-328

Analysis of The Effect of Co-Firing of Coal and Sawdust Fuel on Boiler Efficiency Values With the Direct and Indirect Calculation Methods at PT PLN Nusantara Power Unit 2

M. Daru Fathur Rizki, Radissa Dzaky Issafira*, M Ausin Al Qoroni, Vrischo Candra
Mechanical Engineering, Universitas Pembangunan Nasional Veteran Jawa Timur, Jl. Rungkut Madya, Gn. Anyar, Kec. Gn. Anyar, Surabaya, Jawa timur 60294, Indonesia
*E-mail: radissa.d.tm@upnjatim.ac.id

Submitted: 02-06-2025; Accepted: 30-08-2025; Published: 31-08-2025

Abstrak

Meningkatnya kebutuhan listrik di Indonesia menyebabkan peningkatan konsumsi bahan bakar fosil, yang berdampak negatif terhadap lingkungan. Sebagai bentuk komitmen terhadap target *net zero emission* pada tahun 2060, pemerintah mulai mendorong penerapan teknologi co-firing dengan memanfaatkan biomassa sebagai bahan bakar alternatif. Salah satu jenis biomassa yang potensial digunakan adalah serbuk gergaji (*sawdust)*, yang dapat dicampurkan dengan batubara dalam proses pembakaran. Penelitian ini bertujuan untuk menganalisis pengaruh pencampuran sawdust terhadap efisiensi boiler menggunakan metode perhitungan langsung (*direct method*) dan tidak langsung (*indirect method*). Hasil menunjukkan bahwa campuran 55% batubara peringkat rendah (LRC), 40% batubara peringkat menengah (MRC), dan 5% sawdust mampu menghasilkan efisiensi sebesar 86,8% secara langsung dan 85,2% secara tidak langsung, serta menghasilkan emisi yang lebih rendah dibandingkan campuran 80% LRC dan 20% MRC. Hal ini menunjukkan bahwa sawdust melalui teknologi *co-firing* berperan dalam meningkatkan efisiensi pembakaran sekaligus menurunkan emisi dari pembangkit listrik tenaga uap.

Kata Kunci : Emisi, *Sawdust*, Batubara, *Direct*, *indirect*

Abstract

The increasing demand for electricity in Indonesia has led to a rise in fossil fuel consumption, resulting in negative environmental impacts. As part of its commitment to achieving net zero emissions by 2060, the Indonesian government has begun promoting the application of co-firing technology that utilizes biomass as an alternative fuel. One promising type of biomass is sawdust, which can be blended with coal in the combustion process. This study aims to analyze the effect of sawdust blending on boiler efficiency using both direct and indirect calculation methods. The results show that a fuel composition of 55% low-rank coal (LRC), 40% medium-rank coal (MRC), and 5% sawdust produces a boiler efficiency of 86.8% using the direct method and 85.2% using the indirect method. Additionally, this blend generates lower emissions compared to a mixture of 80% LRC and 20% MRC. These findings indicate that sawdust, when applied through co-firing technology, contributes to improved combustion efficiency and reduced emissions in coal-fired power plants.

Keywords: *Emissions, Sawdust, Coal, Direct, indirect*

1. Introduction

Based on the 2024 report of the Indonesian Environment & Energy Center, the energy sector in Indonesia—especially power plants that use fossil fuels such as coal—are still one of the main contributors greenhouse gas (GHG) emissions. The report states that Indonesia contributes around 2.3% of total emissions. globally, with coal-fired power plants being the largest contributor of emissions due to the process burning fossil fuels for energy needs.[1]

Biomass is a renewable energy source that is getting more and more attention, because it has potential. major role in reducing carbon emissions and dependence on fossil fuels [2]. Biomass comes from materials organic materials such as agricultural waste, wood, and crop residues, which can be converted into energy through the process combustion or chemical reactions. In the steam power generation sector, biomass energy can be utilized as an alternative to reduce coal consumption, one of which is through the use of sawdust [3] However, the application of biomass faces a number of challenges, including the tendency of sawdust to cause slagging. on boiler pipes and reduced combustion efficiency. In addition, high water content in sawdust can causing the combustion process to be imperfect [4]. Therefore, appropriate technology is needed. accommodate the characteristics of biomass, one of which is through co-firing technology, namely the technique of burning two types of fuel. fuel simultaneously in one combustion cycle.[5].

Previous research has examined the use of rice husk as fuel through the co-firing method with ratio of 0.5–1%, which is applied directly to steam power plants. This research was conducted with direct experimental approach to evaluate the performance of the generating plant as well as the resulting boiler efficiency. Results research shows that boiler performance increases slightly, accompanied by a reduction in emissions if compared to the use of pure coal. In addition, no significant effect was found on the equipment boiler [6]. Other research was also conducted using palm shell materials through experimental simulation methods. with a biomass content variation of 5–7%. However, due to the relatively low calorific value of palm shells, boiler efficiency decreased, as did the overall performance of the plant. However, The resulting emissions were successfully reduced from 580.5 tons to 538.7 tons [7].

This article aims to comprehensively evaluate the effect of biomass mixing in the form of sawdust. (sawdust) with coal on boiler efficiency in steam power plants, using the approach direct and indirect method calculations. This study is also intended to assess The potential of sawdust as an environmentally friendly alternative fuel in efforts to reduce greenhouse gas emissions without sacrificing the thermal performance of the generating system. In addition, this study attempts to compare the effects of variations coal quality in the mixture to identify the optimal fuel configuration to support clean and efficient energy transition.

2. Materials and Methodology

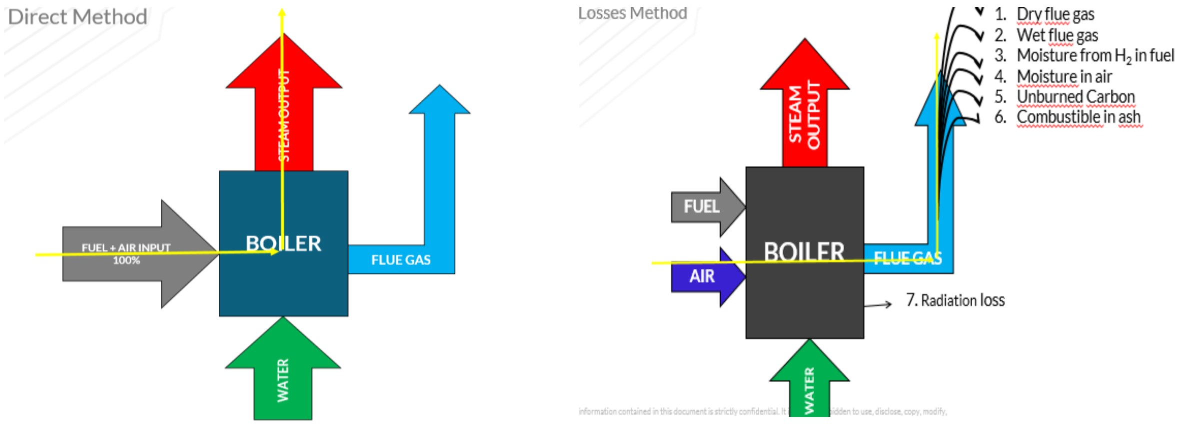
This research is an experimental study conducted at PT PLN Nusantara Power Unit 2, which is located on Jl. Raya Surabaya–Situbondo Km. 142, Bhinor Rice Field Area, Paiton District, Probolinggo Regency, East Java 67291. The research activities were carried out from August to September 2024. The limitations of this research include data collection during performance testing, with the generator operating at load full capacity of 400 MW. The fuel mixture variations used include: 75% Low Rank Coal (LRC) + 20% Medium Rank Coal (MRC) + 5% sawdust; 55% LRC + 40% MRC + 5% sawdust; as well as 80% LRC + 20% MRC as comparator.

The data analysis method used in this study consists of two approaches, namely the direct method (direct method) and indirect method. The direct method is used to analyze the comparison between the incoming heat energy and the outgoing heat energy from the boiler system. Meanwhile, the indirect method is used to calculate efficiency by considering the amount of energy lost due to the combustion process. The formulas used in each method are explained in the following sections.

2.1 Direct Method

This method analyzes the input energy calories and output energy calories that occur during boiler combustion, where For illustration of this method can be seen in Figure 1 with the formula used for this method with Equation (1), as follows

$$\eta = \left(\frac{Qout}{Qin}\right) \times 100 \tag{1}$$



(a) (b)

Figure 1. Illustration of: (a) Direct method and (b) Illustration of indirect method

$$\eta Q_{in} = mcoal \times HHV \quad (2)$$

The input heat variable (Qin) is calculated using the fuel flow rate entering the boiler (mcoal) in kg/s units, multiplied by the high heating value of the fuel (High Heating Value/HHV) in kJ/kg units as in Equation (2). Next, the heat output (Qout) is calculated based on the sum of the energy supplied to the various (1) B (2) system components, which include: main steam, superheater spray water, reheater steam, reheater spray water, and water blowdown. As in Equation (3).

$$Qout = Qms + Qpsw + Qrs + Qrsw + Qblw \quad (3)$$

The energy supplied to the main steam (Q.ms) is obtained from the difference between the mass rate of the main steam (mms) and the mass rate of water. feeder (mpsw), multiplied by the difference in the specific enthalpy of the main steam (hms) and the specific enthalpy of the feed water (hfw) as in Equation (4). Meanwhile, the energy supplied to the superheater spray water (Qpsw) is calculated based on superheater spray water mass rate (mpsw) multiplied by the difference in the primary steam specific enthalpy (hms) and the water enthalpy superheater spray (hpsw). In Equation (5).

$$Qms = (mms - mpsw) \times (hms - hfw) \quad (4)$$

$$Qpsw = mpsw \times (hms - hpsw) \quad (5)$$

The energy supplied to the reheater steam (Qrs) is calculated from the result of multiplying the mass rate of the reheater steam (mrs) by The difference in specific enthalpy of the reheater steam at the heater outlet (hrso) and heater inlet (hrsi) as in Equation (6). reheater spray water, the energy supplied (Qrsw) is calculated based on the mass rate of the reheater spray water (mrsw) multiplied by with the difference in specific enthalpy of reheater inlet steam (hrsi) and specific enthalpy of reheater spray water (hrsw) as in Equation (7).

$$Qrs = mrs \times (hrso - hrsi) \tag{6}$$

$$Qrsw = mrsw \times (hrsi - hrsw) \tag{7}$$

$$Qblw = mblw \times (hblw - hrw) \tag{8}$$

Finally, the energy supplied to the blowdown system (Qblw) is calculated from the blowdown mass rate (mblw) multiplied by with the difference in specific blowdown enthalpy (hblw) and feed water enthalpy (hrw) as in Equation (8).

2.2 Indirect Method

Next, the calculation of boiler efficiency using the indirect method is carried out by taking into account the energy losses that occur during the combustion process. This method involves a number of variables calculated using predetermined equations (Equation (9)).

$$\eta = \frac{output}{input} = \frac{(input - heat\ loss + credit)}{input} \tag{9}$$

An illustration of the indirect method calculation can be seen in Figure 1, which emphasizes identification and quantification of the energy lost during the combustion process in the boiler. In addition, this method also takes into account additional energy in the form of water credit that contributes during the combustion process. Total energy loss (total losses) is formulated as the sum of several loss components, as explained below.

$$L = Luc + LG + Lmf + LH + LmA + Lco + Ld' \tag{10}$$

Equation (10) is the equation for the calculated energy loss components which include: losses due to unburned carbon (symbolized as Luc in Equation (11)), losses due to flue gas (LG) in Equation (12), losses due to water content in fuel (Lmf) in Equation (13), losses due to hydrogen content (LH) in Equation (14), losses due to auxiliary air humidity (LmA) in Equation (15), losses due to carbon monoxide gas (Lco) in Equation (16), as well as losses due to fly ash which still carries heat (Ld') in Equation (17).

$$Luc = 33727 \times Wdp \times Hdp \tag{11}$$

Heat loss due to unburned carbon occurs because there is still carbon content in the fuel that fails to burn completely in the boiler. The variables used in this calculation includes the symbols Wdp, which indicates the total weight of dry ash from combustion (kg/kg), and Hdp, which is the value mean unburned carbon in the combustion process (kg/kg).

$$LG = Wg \times Cpg \times (Tg - Tr) \tag{12}$$

The next heat loss is due to dry exhaust gas, which still contains heat energy. even though it has left the boiler system. Ideally, the heat energy can be reused, for example for heating other units in the generating system. The variables used in this calculation include: Wg (heating rate) dry gas flow at the outlet of the air heater in units) (kg/kg), Cpg (specific heat capacity of the gas in units kJ/kg·K), Tg (air heater outlet temperature), and Tr (reference temperature).

$$Lmf = 0{,}01 \times War \times (Hg - Hrv) \tag{13}$$

Further heat loss comes from the water content (moisture) in the fuel, which during the combustion process will absorb heat and come out in the form of steam. The variables that are taken into account in this loss include: water content in coal is symbolized by War, steam enthalpy at the outlet of the air heater (Hg), and enthalpy water at reference temperature (Hrv).

$$LH = \frac{8{,}963 \times Har \times (Hg - Hrv)}{100} \tag{14}$$

This heat loss occurs due to the evaporation of water which absorbs heat energy from the combustion process, then released in the form of vapor. The variables used in this calculation include the hydrogen content in fuel (Har), enthalpy of steam at the air heater outlet (Hg), and enthalpy of water at reference temperature (Hrv).

$$Lma = Wma \times Wa \times (Hg - Hr) \tag{15}$$

Next, the next heat loss comes from the water vapor contained in the auxiliary air, both primary air and secondary air. and secondary air, which is supplied by the PA fan and FD fan. The variables taken into account include the mass of water vapor (Wma), dry air mass (Wa), steam enthalpy at the air heater outlet (Hg), and enthalpy at reference temperature (Hr).

$$Lco = \frac{23632 \times Cb \times CO}{CO2 + CO} \tag{16}$$

The next heat loss is related to the presence of carbon monoxide (CO) gas produced as a result of combustion. not perfect on the boiler. A high CO content indicates the presence of carbon in the fuel which is not completely burned. The variables used in the calculation include the mass of carbon burned (Cb), the content carbon monoxide (CO), and carbon dioxide (CO_2) content at the air heater output.

$$Ld = 0{,}9 \times \frac{Tg - Tr}{Wfc} \times Wdp \tag{17}$$

The final heat loss comes from fly ash and bottom ash produced during coal burning. Very fine ash particles will be absorbed by the electrostatic precipitator (ESP). If the amount excessive ash produced, this can be an indicator of imperfect combustion. The variables that used include the outlet gas temperature from the air heater (Tg), reference temperature (Tr), coal flow rate (Wfc), and mass total dry ash (Wdp)

After calculating the total energy losses , additional energy (credit) calculations are also carried out . transferred into the boiler system. This additional energy consists of two categories, namely energy from dry air that enters to the boiler and the energy from the water vapor contained in the incoming air. The air is supplied by the PA fan and FD fan. The variables calculated include the enthalpy of air entering the air heater (Hah), dry air mass (Da), water vapor content in air (Ba), as well as the enthalpy of dry steam at the air heater inlet (Hvh). Which can be seen in Equations (18) and (19), which will then be totaled with Equation (20).

$$Bah = Hah \times Da \tag{18}$$

$$Bma = Hvh \times Ba \tag{19}$$

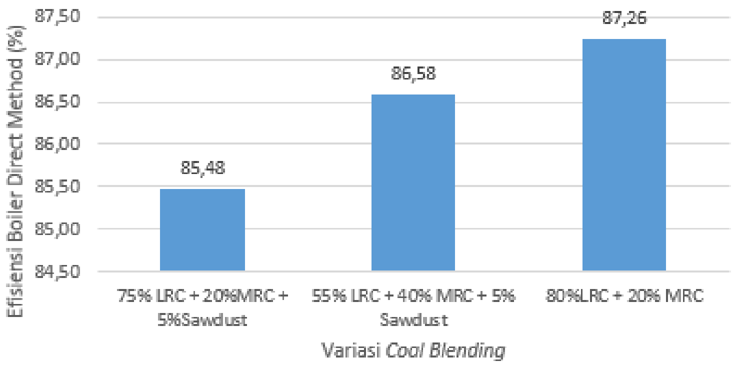
$$Total\ Credit\ Air = Bma \times Bah \tag{20}$$

3. Result and Discussion

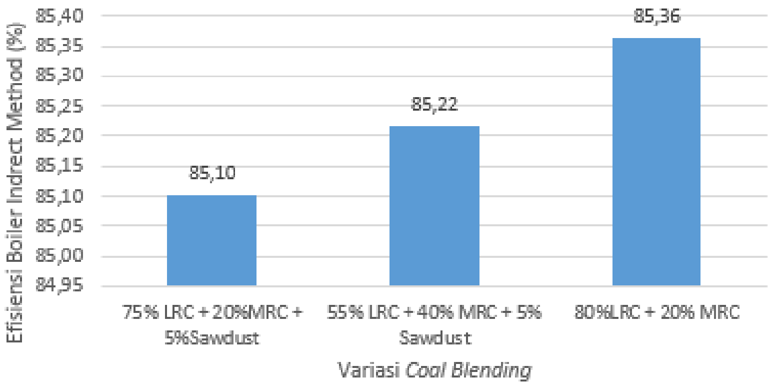
3.1 Relationship Between Biomas Mixture Variations and Boiler Efficiency Parameter Using Direct and Indirect Method

Figure 2 presents a comparison of boiler efficiency based on the direct calculation method and indirect method. The results of the analysis show that the highest efficiency is obtained in the mixture of materials fuel consisting of Low Rank Coal (LRC) and Medium Rank Coal (MRC), without the addition of sawdust biomass. This high efficiency value is due to the relatively high calorie content and low water content in the stone. coal, so that the combustion process in the boiler takes place optimally and produces steam output. maximum [8]. On the other hand, the addition of sawdust as much as 5% in the fuel mixture resulted in a decrease boiler efficiency. This is due to the characteristics of sawdust which has a lower calorific value than coal. embers, as well as a fairly high water content if it doesn't go through a drying process first. these conditions causes the combustion process to be less than perfect, thus producing steam with lower quality. low compared to the use of pure coal [9].

From the indirect method point of view, it is seen that the combustion of fuel mixed with sawdust tends to resulting in higher levels of losses , particularly due to high water content and carbon combustion. This is in line with research conducted by Chayalakshmi 2020, which stated that boiler efficiency decreases as losses due to hydrogen increase, more heat will be used to burn the hydrogen content and produce steam in the form of H20 which will increase the temperature of the flue gas [10]. is not perfect. This shows that although sawdust has the potential to be used as an alternative fuel, its efficiency still depends on the preprocessing conditions and the mixture proportions used [11].



(a)

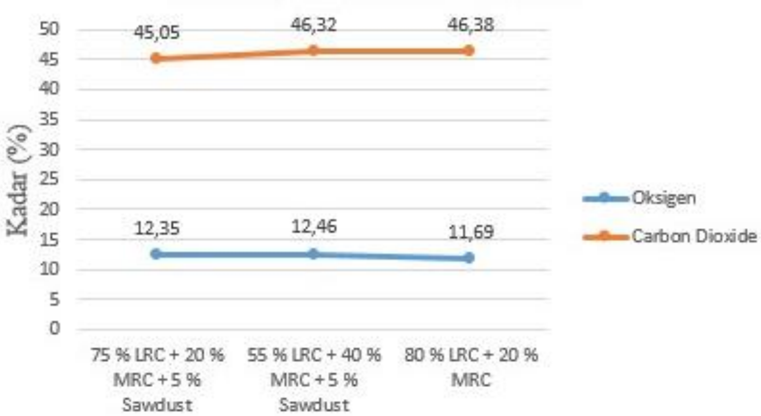


(b)

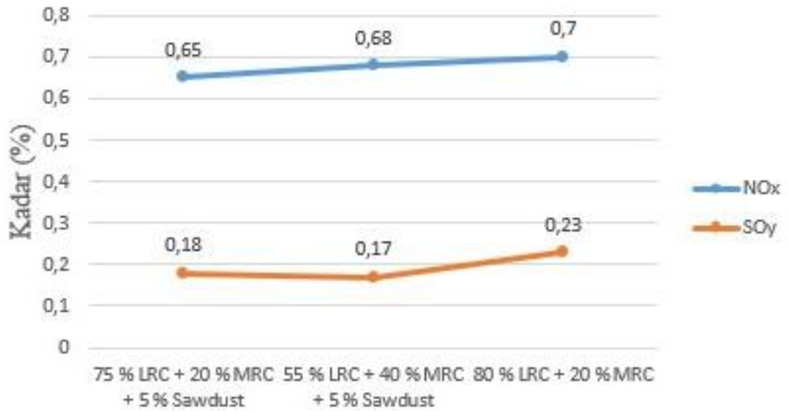
Figure 2. (a) Direct boiler efficiency and (b) Indirect boiler efficiency

3.2 Relationship between variations in coal and sawdust mixtures and oxygen, carbon dioxide, NOx and SO_2

The measured emission results reflect the composition of elements in the fuel used. Based on the graph on Figure 3 shows that carbon dioxide (CO) levels increase as the proportion increases. coal in the fuel mixture. This is caused by the high carbon content in coal compared to sawdust, so that the combustion process of a mixture of coal and sawdust produces CO emissions. higher in the exhaust duct (stack) [12]. On the other hand, the oxygen content (O_2) in emissions from coal combustion Pure coal was recorded lower. This indicates that combustion was more perfect, so that it did not much oxygen remains in the exhaust gas [13]. On the other hand, in a mixture with sawdust, which has a combustible nature, burning, additional air supply is needed so that combustion remains stable in the boiler combustion chamber [14]. This phenomenon also has an impact on increasing levels of nitrogen oxide (NOx) and sulfur oxide (SOx) emissions, as illustrated on the same graph. This difference can occur because the biomass fuel content has a total sulfur and nitrogen content that is less than coal. This occurs because during the biomass manufacturing process it is not buried in the ground so it does not absorb much sulfur and nitrogen content. This is in line with research conducted by (Visang Farda, 2023) [15], The content of these compounds is influenced by the chemical composition of the fuel and the conditions combustion, so that the combination of fuels becomes an important factor in controlling greenhouse gas emissions from electric steam power plant.



(a)

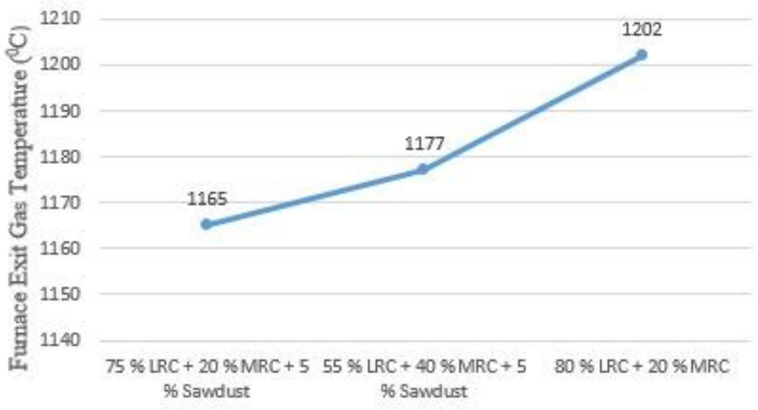


(b)

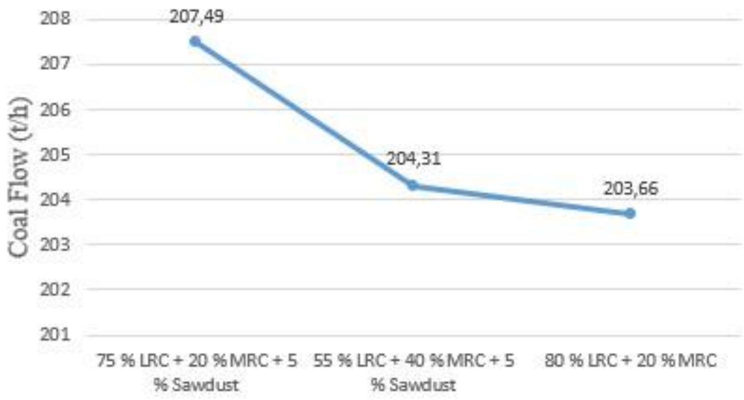
Figure 3. (a) Effect of variation to O_2 and CO and (b) Effect of variation to NOx and Soy

3.3 Relationship Between Coal and Sawdust Mixture Variations and FEGT and Coal Flow Values

Based on the graph in Figure 4, there is a significant relationship between variations in biomass mixture and coal to the temperature of the gas exiting the combustion chamber (Furnace Exit Gas Temperature). Pure coal mixture shows a higher temperature increase after the combustion process, which indicates that combustion has occurred. which is more perfect. This is due to the relatively high calorific value of coal, so that the heat energy that The results are larger and more stable [16]. Meanwhile, on the coal flow graph , the variation using pure coal shows the rate lower fuel flow. This is due to optimal combustion efficiency, so the need fuel to reach the specified operating temperature becomes smaller. On the other hand, in mixtures with sawdust content, the fuel flow rate tends to increase. This is due to the higher calorific value of sawdust. low, high water content, and low carbon content, so more fuel is needed large enough to maintain the combustion temperature according to system requirements [17]. And also this can happen because the fixed carbon and carbon content affect the combustion temperature, if the temperature decreases it causes the need for fuel to increase to maintain combustion conditions, so that the fuel flow rate (coal flow) tends to increase along with the addition of biomass, and for the FEGT temperature it can decrease due to the higher volatile matter content of sawdust than ordinary coal, high volatile matter will burn faster during the combustion process. As a result, heat is absorbed directly by the walls adjacent to the FEGT area without having time to rise to the upper area or spread to other areas [18].



(a)



(b)

Figure 4. (a) Effect variation to FEGT and (b) Effect variation to coal flow

4. Conclusion

Based on the results of the analysis of variations in the mixture of coal and sawdust using the method direct and indirect calculations , it can be concluded that the composition of the material fuel has a significant effect on the boiler efficiency value. The addition of 5% sawdust in the mixture proven to moderately reduce boiler efficiency, which is due to the relatively low calorific value of sawdust and high water content. This condition causes the combustion process to be less than perfect, so that impact on the reduction of thermal energy produced. However, efficiency can still be maintained at relatively stable levels when the mixture is combined with medium quality coal (MRC). Apart from the efficiency aspect, the use of sawdust also shows a positive impact on reducing greenhouse gas emissions. greenhouse gas (GHG), which is reflected in the reduction in NO_x and SO_2 emission levels compared to pure coal mixtures This can happen because biomass has a lower nitrogen and sulfur content than coal, thus reducing the potential for NO2 and SO2 formation, and with an increase in biomass up to 100%, it can achieve zero emissions, but biomass requires better handling at the beginning, such as being dried first, such as being burned elsewhere and using only the gas as fuel to reduce the possibility of mixing moisture content into the coal which will later inhibit the combustion process. Therefore, sawdust can be considered as a more environmentally friendly alternative fuel solution in energy generation system. To support the increased utilization of sawdust, it is recommended to use wood types or plants with a calorific value close to coal, such as calliandra plants. This use is considered allows for low generator loads, but for high load generators and boiler designs Specifically for coal, further studies are needed to ensure its technical compatibility.

References

[1] R. M. Ariefianto and R. A. Aprilianto, “Peluang Dan Tantangan Menuju Net Zero Emission (NZE) Menggunakan Variable Renewable Energy (VRE) Pada Sistem Ketenagalistrikan Di Indonesia,” *J. Paradig.*, vol. 2, no. 2, pp. 1–13, 2021, [Online]. Available: https://www.researchgate.net/publication/357448042

[2] D. S. Nawawi *et al.*, “Chemical Characteristics of Biomass for Energy,” *J. Ilmu Teknol. Kayu Trop.*, vol. 16, no. 1, pp. 44–51, 2018.

[3] M. F. Ilham and N. Sinaga, “Pengaruh Cofiring Menggunakan Serbuk Gergaji Terhadap Emisi Gas Buang di Pembangkit Listrik Tenaga Uap Batubara,” *Rekayasa Energi Manufaktur) J.* |, vol. 7, no. 2, pp. 2528–3723, 2022, [Online]. Available: http://doi.org/10.21070/rem.v7i2.1644

[4] A. V. Febriani, F. F. Hanum, and A. Rahayu, "Review : Analisis Potensi dan Tantangan Biomassa Sebagai Bahan Bakar pada PLTU dan PLTBm," no. April 2024, pp. 1–11, 2024.

[5] I. Aufi, J. Wintoko, and N. A. Masruroh, "Evaluasi pemilihan teknologi Co-firing Biomassa pada PLTU batu bara dengan Metode Analytical Hierarchy Process (Studi Kasus: PLTU XYZ)," *Angkasa J. Ilm. Bid. Teknol.*, vol. 15, no. 1, p. 88, 2023, doi: 10.28989/angkasa.v15i1.1641.

[6] Y. C. Dwiaji, "Analisis Pengaruh Co-Firing Biomassa Terhadap Kinerja Peralatan Boiler PLTU Batubara Unit 1 PT. XYZ," *J. Appl. Mech. Eng. Renew. Energy*, vol. 3, no. 1, pp. 7–15, 2023, doi: 10.52158/jamere.v3i1.445.

[7] G. N. Tampubolon and B. A. Dwiyantoro, "Studi Pengaruh Rasio Co-firing Bahan Bakar Batubara dan Biomassa Tertorefaksi Terhadap Performa Boiler," *J. Tek. ITS*, vol. 12, no. 3, pp. 3–8, 2023, doi: 10.12962/j23373539.v12i3.128337.

[8] M. F. Ilham and S. W. A. Suedy, "Effect of Cofiring Using Sawdust on Steam Coal Power Plant Heat Rate Value," *J. Energi Baru dan Terbarukan*, vol. 3, no. 2, pp. 121–127, 2022, doi: 10.14710/jebt.2022.13828.

[9] W. Sulaiman, Sugiyarto, and E. Mahajoeno, "Biodelignification Of Coconut Wood Sawdust Using Pleuratus Sapidus," *Semin. Nas. Edusainstek FMIPA UNIMUS*, pp. 37–45, 2018.

[10] C. L. Chayalakshmi, D. S. Jangamshetti, and S. Sonoli, "Boiler efficiency estimation from hydrogen content in fuel," *2015 Int. Conf. Adv. Comput. Commun. Informatics, ICACCI 2015*, no. April, pp. 1107–1110, 2020, doi: 10.1109/ICACCI.2015.7275758.

[11] F. Tri Putra, Y. I. Basir, and M. . Ir H M Nefo Alamsyah, "Analisa Bahan Bakar Biomassa PLTU Asam-Asan Sebagai Pengganti Bahan Bakar Batubara," *J. Tek. mesin*, pp. 1–10, 2019.

[12] D. Putri and K. Umma, "Variasi Rasio Co-Firing Batubara Dan Sawdust (Serbuk Gergaji) Terhadap Pembangkit Listrik Tenaga Uap," vol. 06, no. 01, pp. 28–36, 2025.

[13] K. A. Margawadi, Widayat, and S. W. A. Suedy, "Co-firing simulations with blending of low range coal and medium range coal on the performance of 615 MW capacity steam power plant and Indonesia carbon trading review," *E3S Web Conf.*, vol. 605, 2025, doi: 10.1051/e3sconf/202560501005.

[14] A. N. Sidiq, "Pengaruh Co-Firing Biomassa terhadap Efisiensi Boiler PLTU Batubara," *Kilat*, vol. 11, no. 1, pp. 21–31, 2022, doi: 10.33322/kilat.v11i1.1553.

[15] Z. Arifin, V. F. S. Insani, M. Idris, K. R. Hadiyati, Z. Anugia, and D. Irianto, "Techno-Economic Analysis of Co-firing for Pulverized Coal Boilers Power Plant in Indonesia," *Int. J. Renew. Energy Dev.*, vol. 12, no. 2, pp. 261–269, 2023, doi: 10.14710/ijred.2023.48102.

[16] E. Gultom, D. Angga, F. Muzhoffar, and E. Ari, "Pengaruh Cofiring Menggunakan Variasi Biomassa untuk Menjaga Feedstock Biomassa di Pembangkit Listrik Tenaga Uap Batubara," vol. 9, no. 2, 2024.

[17] R. F. Meditama, I. M. Fitriani, and F. K. Asshidiqi, "G-Tech : Jurnal Teknologi Terapan Analysis of Heat Rate Co-firing Pacitan PLTU," vol. 9, no. 1, pp. 410–416, 2025.

[18] F. Tanbar *et al.*, "Analisa Karakteristik Pengujian Co-Firing Biomassa Sawdust Pada Pltu Type Pulverized Coal Boiler Sebagai Upaya Bauran Renewable Energy," *J. Offshore*, vol. 5, no. 2, pp. 2549–8681, 2021.