

Heat Rate and Efficiency Evaluation of Cofiring Biomass in CFB Boiler Coal-Fired Power Plant

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Abstract. Cofiring activity is an effort to carry out fuel switching in stages at the existing coal power generation. This is done to accelerate the implementation of renewable energy in 2025 by 23% according to the government's target. However, implementing biomass cofiring in coal power generation also has challenges, such as selecting the appropriate type of biomass, modifying the combustion system, and handling potential side effects such as the formation of slagging, fouling and agglomeration. This paper reviews the effect of cofiring on the CFB boiler performance and the effect on flue gases emissions. It is hoped that the results of this paper will provide a better understanding of the potential for utilizing biomass in electricity generation, as well as recommendations for larger scale implementation in the future. In addition, the effects of incorporating biomass, considering factors such as the type, proportion, particle size, and method of injection, as well as the burner's design and operational mode, on flame characteristics and emissions have been extensively studied. The findings indicated that the integrated system could offer a favorable approach to electricity generation. To enhance the overall efficiency of the process and minimize exergy destruction, an enhanced process integration technique was implemented.

Keywords: *cofiring, biomass, CFB boiler, heat rate, efficiency*

1 Introduction

The Indonesian government plans to gradually stop using fossil fuels, especially for electricity generation, until net zero emissions are achieved by 2060. In the RUPTL of PT. Perusahaan Listrik Negara (PLN) (Persero) 2021 - 2030, the government is targeting a renewable energy mix of 23% by 2025[1]. In line with this, PLN is implementing a fuel switching strategy from fossil energy to more environmentally friendly energy such as biomass. Referring to the document "Guidelines for National Greenhouse Gas Inventories Volume 2 Energy" published by the Intergovernmental Panel on Climate Change (IPCC) in 2006, Greenhouse Gas (GHG) emissions from burning biomass are not accounted for in the electricity generation sector within the national GHG emissions inventory. Instead, they are attributed to the forestry sector, specifically under land use, land-use change, and forestry (LULUCF)[2].

Cofiring at a coal power generation is an activity of mixing coal with biomass. The cofiring activity is an effort to carry out fuel switching in stages at the existing coal power generation. This is done to accelerate the implementation of new and renewable energy in 2025 by 23% according to the government's target. Economic evaluations further support the viability of cofiring. The investment cost per kilowatt (kW) of installed capacity for building thermal power plants exclusively fueled by biomass is about ten times higher than the investment cost per kW required to retrofit existing coal power plants for cofiring coal and biomass[3].

However, implementing biomass cofiring in coal power generation also has challenges, such as selecting the appropriate type of biomass, modifying the combustion system, and impacts on plant performance metrics such as heat rate and efficiency. By considering these benefits and challenges, in this paper, the effect of cofiring on the circulating fluidized bed (CFB) boiler plant's heat rate and efficiency will be performed. It is hoped that the results of this paper will provide a better understanding of the potential for utilizing biomass in electricity generation, as well as recommendations for larger scale implementation in the future.

2 Research Method

2.1 Fluidized Bed Combustion

Fluidization is the process of converting solid fuel particles into a fluid suitable for combustion. This technology has various advantages, including a high rate of heat transfer, a boiler design that is compact, and the ability to utilize a variety of fuels, the combustion of low-grade fuel, and lower emissions of pollutants such as sulfur oxides (SO_x) and nitrogen oxides (NO_x). Figure 1 depicts the principle of fluidization. Solid particles are suspended in a gas to achieve a fluid-like condition suitable for burning. The gas, which is uniformly distributed for fluidization, enters the bed through a distributor orifice and ascends through finely divided bed materials, such as sand, limestone, or ash[4].

At low speeds, the solid particles remain immobile, resulting in a fixed bed. As the gas velocity steadily increases, the pressure decrease within the bed equals the bed's weight per unit area at that height. At this point, individual particles dissolve in the airstream, generating what is described as a "fluidized bed"[4]. As air velocity increases, bubbles form, causing the solid particle bed to behave like a boiling liquid. This stage is known as a "bubbling fluidized bed". Because of the greater velocities, bubbles form and vanish quickly, blowing particles out of the fluidized bed. To maintain a stable system, a certain number of particles must be recirculated, resulting in a "circulating fluidized bed"[4].

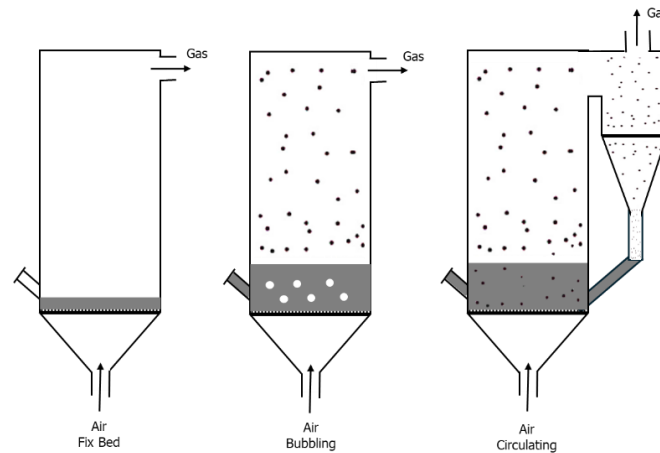


Figure 1. Type of Fluidized Bed Boiler[4]

The bed material, fuel, and sorbent are fluidized by air provided by fan systems. This fluidization occurs in a hot and dynamic environment within the fluidized bed, where the concentration of combustibles is relatively low (approximately 2%). At an optimal temperature range of 850-900°C, the sorbent reacts with sulfur compounds, like SO_2 , present in the fuel within the combustor. This temperature range is carefully maintained to effectively control SO_2 emissions. Additionally, the use of a lower combustion temperature and staged air supply results in significantly lower nitrogen oxides (NO_x) levels compared to those typically observed in conventional pulverized-fuel boilers.[5].

The effect of fuel composition on furnace size in fluidized bed boilers is of lesser significance than in pulverized coal powered boilers. While fluidized bed boilers are noted for their fuel flexibility, it is crucial to note that the fuel composition has an effect on furnace size. However, this effect is not as dominant as in the case of pulverized coal-fired boilers[6]. Currently, combining coal and renewable fuels has emerged as a viable and sustainable option to reduce heavy reliance on fossil fuels in the industrial sector[7]. Combustion in a fluidized bed is typically known for its efficient operation, even when using fuel mixed in varying proportions, effectively handling the characteristics of the mixture[8]. However, knowledge gaps remain regarding the combined burning technology of low-rank coal and renewable fuels, such as biomass[9]. The combination of low-grade coal and pine chip has been examined in both circulating fluidized bed burners and bubbling fluidized bed burners. The findings of this study indicate the technical success of fluidized bed technology as an environmentally friendly approach for burning low-grade coal/biomass mixtures[10].

Circulating fluidized bed (CFB) boilers have become popular in Asia and Eastern Europe due to their fuel flexibility. These boilers can burn low-quality fuel

without significantly reducing performance. This adaptability is enabled by the distinctive combustion and heat transfer conditions offered by CFB furnace. Figure 2 presents the view of the transverse section of a CFB boiler furnace. The furnace is constructed from the riser of CFB loops, where coal is combusted in a suspension of hot, non-combustible granular solids. These solids are retained in a state of rapid fluidization. Crushed coal, sized below 6-10 mm, is introduced into the furnace via a feeder from the side[11].

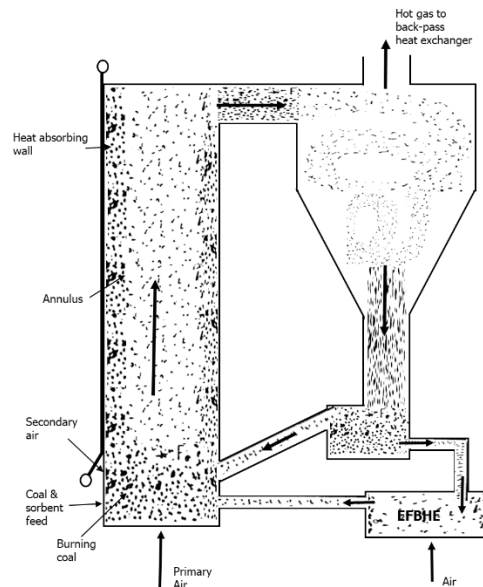


Figure 2. Diagram of a CFB Boiler Furnace[11].

The hot surface solids, which outnumber the coal particles by a ratio of at least 98 to 2, are swiftly blended with fresh coal particles as a result of the vigorous mixing within the CFB furnace. Consequently, regardless of the fresh coal's physical condition or heat content, the efficient surface solids elevate the temperature of the coal particles above the combustion threshold without substantial temperature drop. Following combustion, the coal particles efficiently transfer heat back to the surface solids[11].

When fresh coal particles are placed in a bed, it initiates a series of events. Initially, it undergoes heating and drying, followed by devolatilization and volatile combustion. In certain types of coal, there is an additional stage of swelling and primary fragmentation. Finally, the remaining charcoal undergoes combustion.

2.2 Cofiring in Circulating Fluidized Bed (CFB) Boilers

Air Anyir Coal-Fired Power Plant (CFPP) located in Air Anyir Village, Merawang District, Bangka Regency. It has a power capacity of 2 x 25 MW and is connected to the Sumatra grid via transmission line 150 kV to the Sumatra-Bangka sea cable. This CFPP using the Circulating Fluidized Bed (CFB) boiler and has been implementing rubber woodchip (WC) for cofiring since November 2022. The schematic model of CFPP has shown in Figure 3 below.

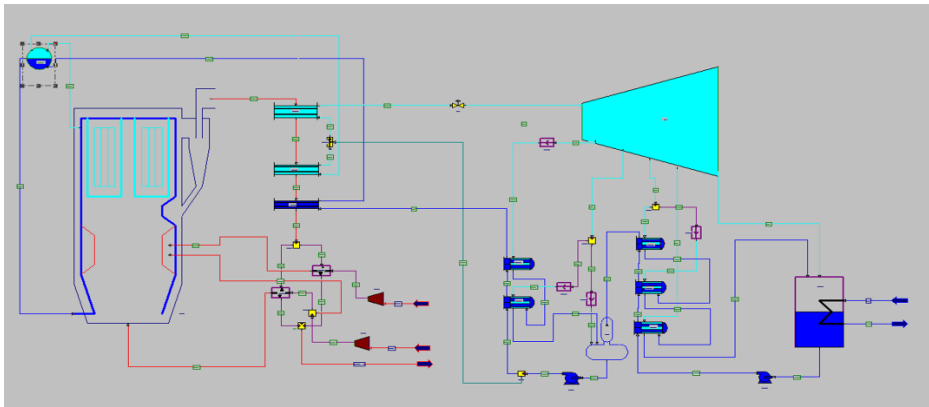


Figure 3. Schematic Model of Air Anyir CFPP.

Cofiring percentage varies between 5% and 20% that data used in this study is derived from monthly performance tests. The performance test lasted two hours, with data collected every 30 minutes, after which the average was calculated. Data was collected from October 2022 until October 2024 and observing cofiring variations of 0%, 5.04%, 7.83%, 11.45%, 14.46%, and 18.97%, as shown in Figure 3 below.

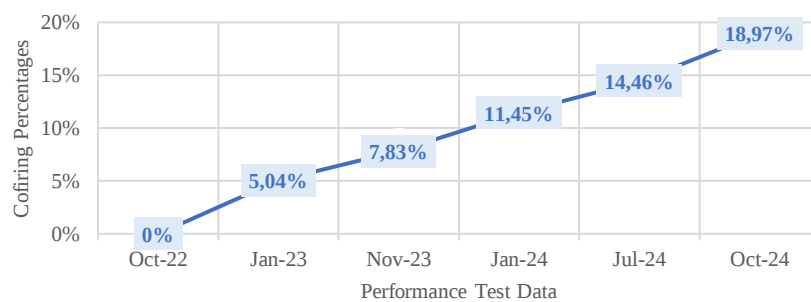


Figure 4. Cofiring Variations.

The fuel used is a mixture of coal and woodchips with proximate and ultimate analysis based on as-received (Ar) conditions as shown in Table 1.

Table 1. Proximate and Ultimate Analysis of Fuel.

ANALYSIS	COFIRING VARIATIONS											
	0%		5,04%		7,83%		11,45%		14,46%		18,97%	
	COAL	WC	COAL	WC	COAL	WC	COAL	WC	COAL	WC	COAL	WC
GCV (kcal/kg)	4.261	-	4.192	2.538	4.064	3.939	4.186	3.049	3.990	3.476	4.096	3.968
<i>Proximate Analysis</i>												
Total Moisture (%)	37,55	-	35,07	49,98	35,43	23,08	36,97	36,21	34,78	22,96	35,15	19,73
Ash Content (%)	3,26	-	4,12	0,69	4,30	0,61	4,90	2,08	5,61	1,18	4,00	1,33
Volatile Matter (%)	29,79	-	31,41	-	31,82	60,24	29,37	50,33	32,19	62,68	32,60	64,18
Fixed Carbon (%)	29,40	-	29,40	-	28,45	16,07	28,76	11,39	27,42	13,19	28,25	14,76
Total Sulfur (%)	0,28	-	0,19	0,07	0,22	0,10	0,51	0,05	0,26	0,11	0,13	0,04
<i>Ultimate Analysis</i>												
Carbon (%)	44,30	-	43,47	-	43,77	39,37	41,40	30,65	42,42	43,14	43,53	40,24
Hydrogen (%)	3,18	-	3,11	-	3,20	6,86	2,98	7,79	3,07	7,20	3,14	6,71
Nitrogen (%)	0,85	-	0,66	-	0,78	0,24	0,63	0,31	0,64	0,41	0,68	0,38
Oxygen (%)	10,58	-	13,38	-	12,29	52,82	12,61	59,13	13,18	47,96	13,37	51,29

2.3 Performance of Coal-Fired Power Plant (CFPP)

The performance of Coal-Fired Power Plant (CFPP) can be evaluated using several parameters. In this study, three parameters will be examined: specific fuel consumption (SFC), heat rate, and efficiency. As a baseline, data from the initial commissioning will be used, as shown in the following Table 2.

Table 2. Initial Commissioning Parameters

No	Parameter	Unit	Initial Commissioning
1	Generator Active Power	MW	32,10
2	GCV	kCal/Kg	4.210,00

Table 2. (continuation)

No	Parameter	Unit	Initial Commissioning
3	Specific Fuel Consumption (SFC)	t/h	22,51
4	NPHR (Input - Output)	kCal/kWh	3.446,77
5	NPHR (Heat Balance)	kCal/kWh	3.178,50
6	Efisiensi Thermal	%	27,06
7	Turbine Heat Rate (Gross)	kCal/kWh	2.488,23
8	Efficiency Boiler (Heat Loss)	%	86,09

2.3.1 Specific Fuel Consumption (SFC)

Specific Fuel Consumption (SFC) is one of the performance parameters that is relatively easy to calculate. SFC can be calculated by dividing the total fuel consumption by generator power output. SFC can be calculated using the following formula:

$$SFC \left(\frac{kg}{kWh} \right) = \frac{\text{Total Fuel Consumption (kg)}}{\text{Generator Power Output (kWh)}} \quad (1)$$

2.3.2 Heat Rate

Heat rate is defined as the ratio of heat energy input to the electrical energy output of a system, measured in units such as kcal/kWh or Btu/kWh. This value is affected by the performance of the boiler's heat exchanger. Typically, the actual heat rate is higher than the value observed during initial commissioning[12]. A lower rate value indicates better system performance.

Plant heat rate is a method for calculating the performance of a power plant that involves operational data parameters from the boiler, turbine, and generator. The value of the plant heat rate provides an overall efficiency of a power plant. Therefore, if a power plant experiences a decrease in efficiency compared to its design conditions, identifying the location of this efficiency decrease, whether it is from the boiler, turbine, or generator, becomes easier through this calculation method. The calculation method for plant heat rate is divided into two categories:

2.3.2.1 Input-Output Energy Methods

The input-output energy method is a simple method to determine plant performance through heat rate values because it only involves the parameters of the calorific value of coal, the amount of coal entering the boiler and the energy generated. This method is generally used by control room operators or operation control planners for the purpose of commercial transactions for the purchase of electrical energy. The disadvantage of this method is that it cannot determine the part of the plant that is the source of inefficiency. This method also cannot be used as a reference for the performance standards of individual components such as boilers, turbines and generators.

The calculation of heat rate using this method can be done through the following equation:

$$GP\text{HR} \left(\frac{\text{kcal}}{\text{kWh}} \right) = \frac{\text{Total Fuel Consumption (kg)} \times \text{GCV of Fuel} \left(\frac{\text{kcal}}{\text{kg}} \right)}{\text{Generator Power Output (kWh)}} \quad (2)$$

To calculate Net Plant Heat Rate (NPHR), subtract the self-consumption (auxiliary power) from the generator power output, as shown in the following equation:

$$NPHR \left(\frac{\text{kcal}}{\text{kWh}} \right) = \frac{\text{Total Fuel Consumption (kg)} \times \text{GCV of Fuel} \left(\frac{\text{kcal}}{\text{kg}} \right)}{\text{Generator Power Output (kWh)} - \text{Auxiliary Power (kWh)}} \quad (3)$$

2.3.2.2 Heat Balance Methods

Heat balance method is used to identify the reasons for an increase or decrease in heat rate in a power generation unit. The advantage of the heat balance method is that primary data measurements, such as exhaust gas analysis and exhaust gas temperature, can be made in more detail, allowing the sources of losses in the power plant to be identified. Calculations heat balance method can be performed using the following equation:

$$NPHR = \frac{\text{Total Heat Consumption}}{\left(\frac{\text{Eff.Boiler}}{100} \right) \times \left(\frac{\text{Eff.Gen.Transformer}}{100} \right) \times (\text{Gen.Net Power Output})} \quad (4)$$

Turbine heat rate is an indicator that shows the performance of the steam cycle in the turbine. The value of the turbine heat rate can be calculated by subtracting the incoming and outgoing heat energy of the turbine, then dividing it by generator power output, as shown in the following equation:

$$THR \left(\frac{kcal}{kWh} \right) = \frac{Q_{in} (kcal) - Q_{out} (kcal)}{Generator Power Output (kWh)} \quad (5)$$

2.3.3 Boiler Efficiency

Boiler efficiency refers to The American Society of Mechanical Engineers (ASME) Performance Test Code (PTC) 4 of 2008 [13]. In this method, it is used with a heat loss method approach. The equation for this method can be shown in the following equation:

$$Boiler Efficiency = \left\{ 1 - \frac{\sum_{i=0}^n Li \left(\frac{kcal}{h} \right)}{Fuel Flow Rate \left(\frac{kg}{h} \right) \times GCV \left(\frac{kcal}{kg} \right)} \right\} \quad (6)$$

Li is the amount of heat losses that occur in the boiler. The heat losses in the boiler in question include:

- L1: Heat Loss from Heat in Dry Flue Gas
- L2: Heat Loss from Moisture in Fuel
- L3: Heat Loss from Moisture from Burning of Hydrogen in Fuel
- L4: Heat Loss from Moisture in Air
- L5: Heat Loss from Combustible in Refuse
- L6: Heat Loss from Sensible Heat in Bottom Ash
- L7: Heat Loss from Sensible Heat in Fly Ash
- L8: Heat Loss from Formation Carbon Monoxide
- L9: Heat Loss from Formation of NO_x
- L10: Heat Loss from Surface Radiation and Convection (ABMA Chart)
- L11: Heat Loss from Uncounted Losses
- L12: Heat Loss from Calcination
- L13: Heat Loss from Water in Sorbent

Thermal efficiency can be calculated by converting units from NPHR where NPHR has units of kcal/kWh while thermal efficiency has units of kWh/kWh in percent (%). Thermal efficiency calculations can be calculated using the following equation:

$$\text{Therma Efficiency (\%)} = \frac{860}{NPHR} \times 100 \quad (7)$$

3 Results and Discussions

3.1 Effect of Cofiring on Specific Fuel Consumption (SFC)

From the variation of cofiring carried out on each active power generator, the specific fuel consumption (SFC) increased along with the increase in the cofiring percentage as seen in Figure 5. As a baseline, the initial SFC commissioning is 0.70 kg/kWh on a 32.10 MW active power generator. The higher the percentage of cofiring, the larger SFC will be. This is because woodchip have a lower calorific value compared to coal. Therefore, to produce the same amount of energy, a greater amount of fuel is required.

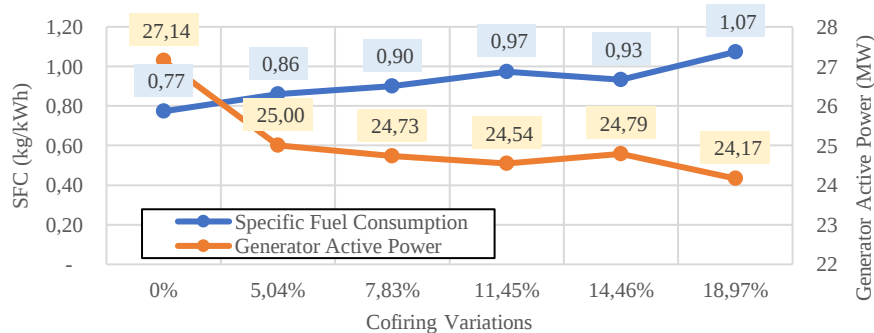


Figure 5. Specific Fuel Consumption.

3.2 Effect of Cofiring on Heat Rate

Heat rate calculation uses both heat loss method and the input-output method. The net plant heat rate (NPHR) is calculated using the channeled energy and the turbine heat rate is calculated using an active power generator. The results of the heat rate calculation can be seen in the following figure 6. As a baseline, the heat rate using heat balance method during initial commissioning was 3,178.50 kcal/kWh for net plant heat rate (NPHR) and 2,488.23 kcal/kWh for turbine heat

rate. Whereas, for NPHR using the input-output method during initial commissioning was 3,446.77 kcal/kWh.

The heat rate increases with the increase in cofiring percentage. For the heat balance method, the heat rate tends to rise gradually up to 7.83% cofiring, with a significant increase occurring from 7.83% to 11.45% cofiring, and then gradually decreasing again up to a cofiring percentage of 18.97%. The highest NPHR for heat balance method in this study is for 11.45% of cofiring that 4,187.56 kcal/kWh the difference is 1,009.06 kcal/kWh from the initial commissioning. The highest turbine heat rate is 3,101.75 kcal/kWh for 11.45% cofiring which results in a 613,52 kcal/kWh difference from the initial commissioning.

For the input-output method, NPHR increases gradually from 0% to 11.45% cofiring, slightly down at 14.46%, and then significantly up to 4,875.91 kcal/kWh in 18.97% cofiring.

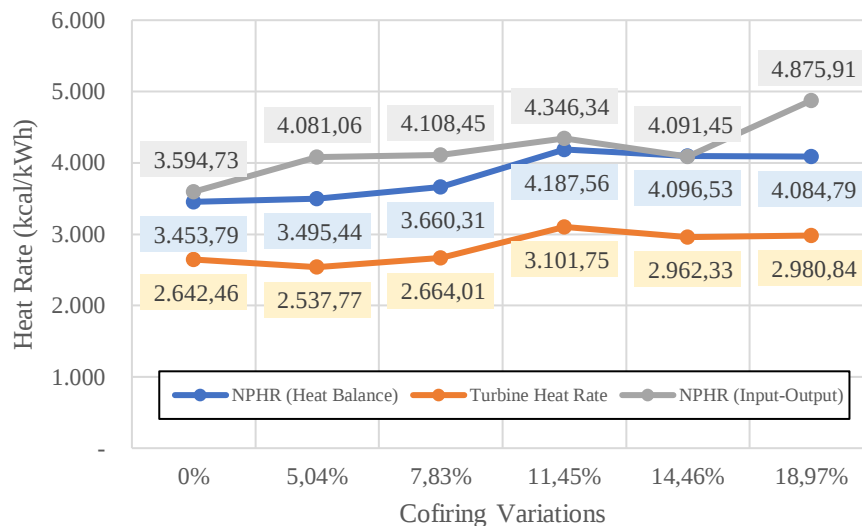


Figure 6. Heat Rate.

From the heat rate trend in Figure 6, there is an upward trend in heat rate corresponding to the increase in cofiring percentage. This is due to the lower calorific value of woodchip compared to coal. The proximate analysis in Table 1 shows that the total moisture and volatile matter content of woodchip tends to be higher than that of coal. This indicates that the fuel heat will be utilized to remove total moisture and volatile matter first before it can be absorbed in the boiler.

3.3 Effect of Cofiring on Efficiency

3.3.1 Boiler Efficiency

Boiler efficiency calculated by energy balance method. This method calculates efficiency by subtracting the heat losses from the total energy input. The calculated by ASME PTC 4-2008[13] that heat losses includes due to heat in dry flue gas, moisture in fuel, moisture from burning of hydrogen in fuel, moisture in air, combustible in refuse, sensible heat in bottom ash, sensible heat in fly ash, formation carbon monoxide, formation of NO_x , surface radiation and convection, calcination, water in sorbent and uncounted losses. For the baseline, boiler efficiency at initial commissioning was 86,09%. Calculation of boiler efficiency in any variations of cofiring percentage in this study shows in Figure 7.

Boiler efficiency starts at 83.57% for 0% cofiring and slightly rise to 84.01% for 5.04% cofiring. Subsequently, efficiency decline gradually from 83.77% for 7.83% cofiring to 82.75% for 14.46% cofiring. Boiler efficiency climb back up to 83.19% for 18.97% cofiring. The trend line indicates an overall slight decrease in efficiency with increasing cofiring, but specific cofiring levels show distinct efficiency behaviors. Understanding these patterns helps in optimizing fuel mixes and operational strategies for better efficiency.

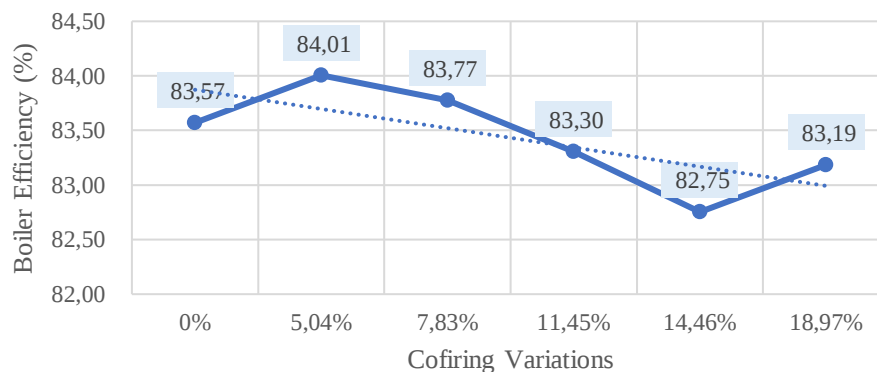


Figure 7. Boiler Efficiency.

3.3.2 Thermal Efficiency

Thermal efficiency is obtained from the calculation of heat energy consumption divided by the net electrical energy produced in generators. For the baseline, thermal efficiency at initial commissioning was 27.06%.

In this study, Figure 8. shows initial thermal efficiency starts at 24.90% and gradually decreases during increased cofiring, hitting the bottom at 20.54% for 11.45% cofiring. Thermal efficiency gently rises to 21.05% for 18.97% cofiring. In this research, the higher percentage of cofiring, thermal efficiency tends to decrease.

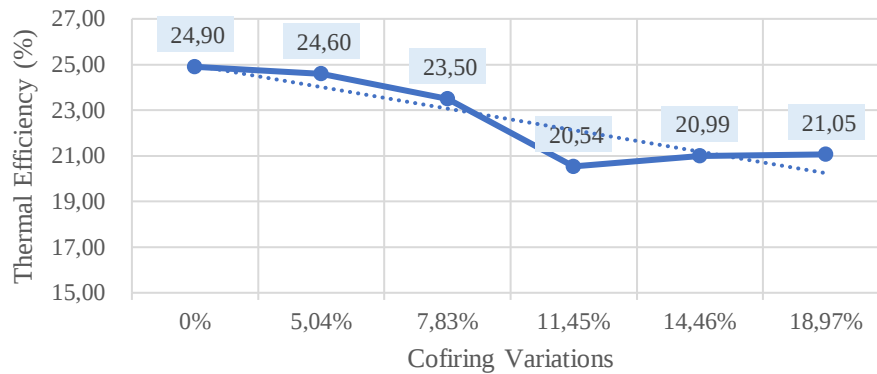


Figure 8. Thermal Efficiency.

4 Conclusion

The study investigates the impact of cofiring on SFC, heat rate and efficiency of CFPP. SFC increases with the increase in cofiring percentage. Heat rate calculation uses both heat loss method and input-output method. The heat rate increases with the increase in cofiring percentage, with the highest NPHR and turbine heat rate at 11.45% cofiring using heat loss method. For input-output method, the highest NPHR at 18.97% cofiring.

Boiler efficiency is determined by subtracting heat losses from the total energy input. The study indicates a slight decrease in efficiency as cofiring increases, although certain levels of cofiring exhibit unique efficiency patterns. Understanding these patterns helps optimize fuel mixes and operational strategies for better efficiency. Thermal efficiency is obtained by calculating heat energy consumption divided by the net electrical energy produced in generators. The study shows the lowest thermal efficiency was 20.54% for 11.45%.

From this research, the use of woodchips as cofiring material in CFPP can be continuously utilized. In terms of CO₂ emission load, biomass combustion in power plants is not considered as emissions from the plant according to IPCC 2006. To assess the balance between woodchip usage and still acceptable

performance, a study related to biomass availability and efficiency loss should be conducted.

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