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Study on the Effect of Coal Blending Quality on the Performance of the XYZ 815 NMW Supercritical Power Plant

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Abstract **- A Supercritical Power Plant with a maximum capacity of 815 NMW faces a shortage of coal supply that meets boiler specifications. Therefore, coal blending with other types of coal is required to maintain operational continuity for one year. This study analyzes the impact of blending three types of coal on the performance of the power generation through laboratory tests, including proximate, ultimate, and ash analysis. Based on the laboratory results, performed coal blending at specific ratios and analyzed for slagging and fouling potential while being filtered against technical limitations. Five coal blending ratios that met the criteria were tested through direct firing in the boiler at a 790 NMW load to assess the impact on environmental, boiler cleanliness, unit efficiency, and cost savings. The results indicate that an increase in silica, and aluminum content in specific blends improved boiler cleanliness by up to 2%, while other blending ratios reduced cleanliness with the increase in ash content. Four coal blends improved boiler efficiency up to 3.1%, attributed to sustained boiler cleanliness and an increase in the blended coal's Gross Calorific Value (GCV), resulting in a reduction of total fuel flow. Consequently, unit efficiency also improved, with a decrease in NPHR of 61.05 kcal/kWh. Cost analysis revealed potential savings of up to IDR 42 billion per year from coal consumption and carbon tax reductions. Additionally, flue gas emissions and wastewater quality from all coal blending ratios remained within the limits set by the Ministry of Environment.**

Keywords: coal blending, silica, aluminum, ash, direct firing test, boiler cleanliness, slagging, fouling, efficiency, cost.

I. INTRODUCTION

Indonesia's coal reserves are estimated at around 36 billion tons, with only approximately 7.87 billion tons meeting the specifications for coal-fired power plants (CFPP), according to detailed data verified by the Geological Agency and the Ministry of Energy and Mineral Resources (ESDM) as of July 2020. Assuming an annual coal production rate of 550 million tons, the lifespan of reserves that meet CFPP specifications is only about 14 years [1].

A Supercritical Coal-Fired Power Plant with a capacity of 815 NMW has now been in operation for 13 years. The volume of coal purchase contracts that align with the boiler design has been decreasing year by year. From the total operational demand of 7 million tons per year, current contracts cover only around 3 million tons annually insufficient to meet the plant's yearly operating requirements. Additionally, the calorific value (GCV) of the coal is steadily declining [2]. To meet annual coal stock requirements and achieve fuel characteristics suitable for boiler design, one effective strategy is coal blending—mixing primary coal with secondary (blending) coal. Coal blending can significantly enhance power plant performance and reduce electricity generation costs [3].

In a previous study, Rasgianti et al. conducted research at the Pacitan Subcritical CFPP using a blend of two coal types: low-rank coal (LRC) and medium-rank coal (MRC), at specific blending ratios. The study found that unit performance improved with a higher proportion of MRC in the blend [4]. However, blending low- and medium-rank coal also introduces the risk of slagging and fouling within the boiler. These risks are generally predictable from the ash composition.

A coal study by Prismantoko et al [5] and Ali at al [6] found that coal with high silica and aluminum content results in less ash deposition due to its high melting point. Testing by Stultz (Babcock & Wilcox) showed that when the combined silica and aluminum (acidic components in coal) content exceeds 60% or when the base-to-acid ratio is less than 0.3, the temperature required to reach 250 poise or lower of ash viscosity increases indicating a lower likelihood of slagging and fouling. This viscosity threshold is where ash begins to

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adhere to boiler tubes, This study also explains that higher ash viscosity indicates a higher melting temperature, particularly when the ash contains high levels of either silica and aluminum or calcium and magnesium. In contrast, lower melting temperatures result from a balanced (intermediate) proportion of these elements. However, in all combinations, iron, sodium, and potassium act as fluxing agents that reduce the ash melting point and increase the potential for slagging [7].

Bhatt reported that ash content exceeding boiler design limits can reduce power plant efficiency, increase maintenance costs, and lead to greater environmental impact. Therefore, coal blending strategies should aim to keep ash content within design specifications [8].

According to Feng Z et al., economizer designs using finned and tube types can exacerbate fouling in boilers [9]. J. Lachman et al. further noted that fouling is influenced by high sodium and potassium content in the ash [10]. Consequently, coal blending at the XYZ Supercritical Power Plant must minimize fouling potential due to the plant's use of finned and tube economizers.

To identify an optimal coal blending strategy, this study aims to:

- Evaluate the characteristics of each coal type through proximate analysis, ultimate analysis, and ash analysis.
- Assess the slagging and fouling potential of each coal blend.
- Conduct direct combustion tests in the boiler to examine the effects of blending on boiler cleanliness, hot flue gas losses, overall plant efficiency, and environmental impacts—including flue gas emissions (SO_2 and NO_x) and pH levels of sea water discharge.
- Analyze potential cost savings from reduced coal procurement costs and reduced carbon tax liabilities.

II. METHOD

The coal types used in this study consist of one primary coal (CMHV), which is compatible with the boiler design, and two blending coals: CHSF and CHHV. The blending ratio for the 2-in-1 mixture (primary coal with one blending coal) begins at 90:10 (CMHV:CHSF/CHHV), with the proportion of primary coal decreased by 10% increments and the blending coal increased by corresponding 10% increments. For the 3-in-1 mixture (CMHV:CHSF:CHHV), the initial ratio is 80:10:10. In subsequent combinations, the proportion of primary coal is reduced by 10% intervals while the total proportion of blending coals is increased accordingly, maintaining the overall 100% blend ratio. This results in a total of 32 coal blending ratios evaluated in the study.

2.1 Proximate Analysis, Ultimate Analysis, and Ash Analysis

To determine the composition of each coal type used in the blending process, an evaluation was carried out based on physical characteristics and chemical composition, confirmed through empirical laboratory testing. The laboratory assessments followed ASTM standards and included proximate analysis, ultimate analysis, and ash analysis.

Proximate analysis is a laboratory procedure used to measure moisture content, volatile matter, fixed carbon, and ash content present in the coal. Calorific Value (CV) analysis measures the energy released when coal is burned, usually expressed in cal/g or kcal/kg. The CV represents the total heat generated from the combustion of a specific amount of coal. The calorific value is determined by the temperature increase during the combustion process, while the heat released is calculated by comparing the initial and final combustion temperatures. A higher CV indicates that the coal feed rate per hour can be lower. Ultimate analysis identifies the chemical composition of the coal, including carbon, hydrogen, nitrogen, sulfur, and oxygen. This analysis demonstrates that coal is composed of these elements, with their total combined composition accounting for 100% of the coal's mass. This analysis includes key elements that relate to its energy characteristics and combustion potential. Ash Fusion Temperature (AFT) analysis refers to the temperature at which ash first begins to soften and become sticky. This test observes changes in the ash cone as it is heated over a temperature range expected in boiler operation. The softening temperature is recorded when the height of the cone equals its width. This analysis is useful for assessing the potential for slagging and fouling in boilers.

Slagging is likely to occur when the combustion chamber temperature exceeds the AFT. Ash chemical composition analysis includes the following components: S, SiO_2, Al_2O_3, CaO, Fe_2O_3, MgO, Na_2O, and K_2O. This analysis is useful for assessing the potential for slagging and fouling in boilers. Chemical compounds that significantly contribute to slagging are CaO and Fe_2O_3, while those that primarily contribute to fouling are Na_2O and K_2O. Compounds that reduce the tendency for slagging and fouling include SiO_2, MgO, and Al_2O_3, due to their high ash fusion temperatures [5][6][7].

Each coal type was tested 10 times to ensure the validity of the laboratory results. The average results of the proximate, ultimate, and ash analyses for each set of 10 samples are presented in Table 1.

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Table 1: Average Values of Coal Laboratory Test Results

Parameter		CMHV	CHSF	CHHV
Total Moisture [AR Basis] %		29,90	28,27	21,21
Inh. Moisture [AD Basis] %		14,57	13,80	12,36
Ash [AR Basis] %		2,03	5,88	4,78
Volatile Metter [AR Basis] %		35,20	32,83	35,91
Fixed Carbon [AR Basis] %		32,87	33,01	38,10
Total Sulfur [AR Basis] %		0,10	0,49	0,16
Calori [AR Basis [kcal/kg]]		4625,70	4701,60	5307,10
Ultimate Analysis [DAF Basis] %	Sulfur	0,15	0,75	0,23
	Hydrogen	5,50	5,38	5,54
	Nitrogen	1,08	1,59	1,43
	Carbon	71,21	74,50	74,12
	Oxigen	22,06	17,78	18,68
HGI		45,40	46,70	45,00
Ash Fusion Temperature [degree C]	ID	1243,00	1183,00	1187,00
	Soft	1255,00	1202,00	1207,00
	Hem	1265,00	1222,00	1227,00
	Fluid	1278,00	1245,00	1248,00
Ash Analysis [DB Basis] %	SiO2	26,90	47,17	38,72
	Al2O3	11,02	20,84	19,23
	Fe2O3	19,17	11,35	11,71
	CaO	23,45	5,48	13,19
	MgO	11,52	3,92	3,11
	Na2O	0,38	1,48	5,27
	K2O	0,83	1,48	1,12
	TiO2	0,65	1,01	0,95

2.2 Research Flow Diagram and Coal Blending Selection Method

The flow diagram of this study is shown in Figure 1. The coal blending process, based on the 32 predetermined blending ratios, was then screened according to the technical specification limits of the XYZ Supercritical Power Plant, as presented in Table 2. The formulas used to calculate the slagging and fouling potential index are shown in Tables 3 and 4.

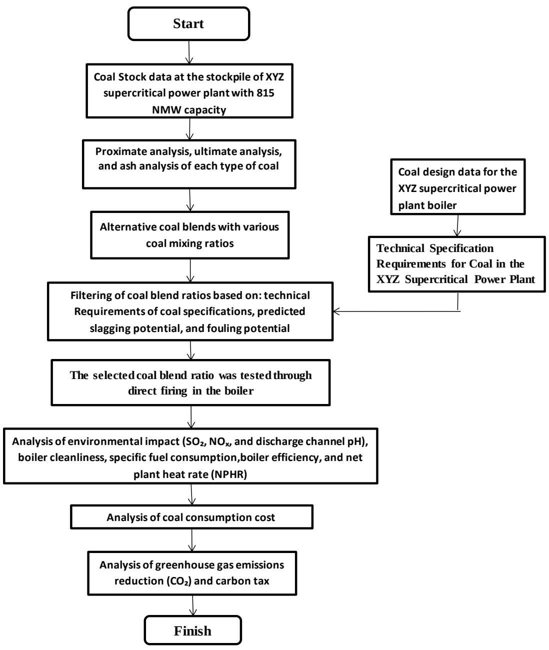

Figure 1: Research Process Flow Diagram

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Table 2: Technical Requirement Limits Based on Power Plant Design

No	Parameter	Nilai	Satuan	Batasan Desain
1	Coal GCV	> 4600	kCal/Kg	Boiler
2	Total ash in coal	≤ 3.5	%	Boiler
3	Total sulphur in coal	< 0.3	%	FGD and Neutralisation basin
4	Total slagging potential score	≤ 5		Boiler
5	Total fouling potential score	≤ 2		Boiler
6	SO2 emissions	< 550	mg/Nm3	Ministry of Environment
7	NOX emissions	< 550	mg/Nm3	Ministry of Environment
8	PH of sea water in the discharge channel	> 6		Ministry of Environment

Table 3: Slagging Potential Index and Risk Criteria

Index	Formula	Kriteria Resiko				Referensi
		Low	Middle	High	Severe	
Base - Acid Ratio (B/A Ratio)	B/A= $\frac{\%Fe_2O_3+\%CaO+\%MgO+\%Na_2O+\%K_2O}{\%SiO_2+\%Al_2O_3+\%TiO_2}$ * for lignitic ash	< 0.4 or > 0.7		0.4 ~ 0.7		Frandsen (1997) Plaza (2013) Li (2017)
	$\frac{B}{A} x\ Sulphur\ in\ coal\ (\%)$ * for bituminous ash	< 0.6	0.6 ~ 2.0	2.0 ~ 2.6	> 2.6	
Slagging Index, ◦C	$\frac{4X(\min IT) + (\max HT)}{5}$	> 1340	1340 ~ 1230	1230~ 1150	< 1150	Frandsen (1997) Rask (1985) B&W (2005) Plaza (2013)
T25, ◦C. Temperature at which the viscosity of ash is equal 25 Pa*s.	$T_{25}°C = [\frac{Mx10^6}{\lg(25)-C}]^{0.5} + 150$ where C =0.0415x$SiO_2 + 0.0192xAl_2O_3 + 0.276xFe_2O_3 + 0.0160xCaO - 3.92$	> 1400	1400 ~ 1245	1230 ~ 1120	< 1120	Plaza (2013) Li (2017)
Iron-Calcium Ratio	$\frac{Fe_2O_3}{CaO}$	< 0.3 or > 3.0		0.3 ~ 3.0		Plaza (2013) Li (2017)
Iron plus Calcium	$Fe_2O_3 + CaO$	< 10%		> 10%		Plaza (2013)
Silica Percentage	$\frac{SiO_2\ x\ 100}{SiO_2 + Fe_2O_3 + CaO + MgO}$	72 ~ 80	65 ~ 72		50 ~ 65	Raask (1985) Plaza (2013)

Note:* Bituminous ash when Fe_2O_3 > (CaO+MgO); Lignitic ash when Fe_2O_3 < (CaO+MgO).

Table 4: Fouling Potential Index and Risk Criteria

Index	Formula	Risk Criteria				Reference
		Low	Middle	High	Severe	
Sodium Content	$\% Na_2O$ * for lignitic ash	< 2	2 ~ 6	6 ~ 8	> 8	Frandsen (1997) Plaza (2013) Li (2017)
	$\% Na_2O$ * for bituminous ash	< 0.5	0.5 ~ 1.0	1.0 ~ 2.5	> 2.5	
Fouling Factor	$\frac{B}{A} xNa_2O$ in the ash (%)	< 0.2	0.2 ~ 0.5	0.5 ~ 1.0	> 1.0	Frandsen (1997) B&W (2005) Plaza (2013) Li (2017)
Total Alkali Content in Ash	%Na_2O+(0.6589x%K_2O)x(% ash/100)	< 0.3	0.3 ~ 0.45	0.45 ~ 0.6	> 0.6	Raask (1985) Frandsen (1997) Li (2017)
Sodium-Potassium Fouling Index	$\frac{B}{A} X\ (Na2O + K2O)$	< 2		> 2		J.L. Miguez (2021) J. lachman (2021) Z. Yu (2020) Ghasidin H. (2023)
Alkali to Silica Ratio	$\frac{Na2O + K2O}{SiO2}$	< 0.1		> 0.1		J. Lachman (2021) Ghasidin H. (2023)

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An assessment (scoring) of the impact of fouling and slagging was conducted, with low risk assigned a score of 0, moderate risk a score of 0.5, and high to severe risk a score of 1. Several coal blending ratios with a total slagging score of ≤ 5 and a fouling score of ≤ 2 were selected and tested through direct firing in the boiler.

2.3 Direct Firing Test

The direct firing experimental methodology was used to test coal blends with specific mixing ratios that met the criteria based on slagging and fouling potential analyses, as well as the technical specification limits of the main equipment at the XYZ Supercritical Power Plant. Coal blending was carried out on the conveyor belt before entering the coal silo, in accordance with the predetermined coal blend ratio. Once a homogeneous mixture was achieved, the blended fuel was fed into the coal silo, passed through the coal feeder and pulverizer, and then transported to the boiler for the firing process. Testing was conducted once daily for each coal blend ratio during operations at a load of 790 NMW, in accordance with the maximum load requested by PLN for the 2024–2025 period. After reaching the 790 NMW load, load stabilization was maintained for 1 hour, followed by data collection over 3 hours of operation, The soot blower operates with the same pattern for each test. Coal samples were taken and analyzed for each coal blending test. Operational parameters were monitored and recorded via the DCS (Distributed Control System) every 5 minutes, with average values calculated for each test parameter. For environmental impact analysis, the maximum or minimum values from the entire data set were taken.

A simplified diagram of the XYZ Supercritical Power Plant is shown in Figure 2, and the boiler specifications of the plant are shown in Table 5.

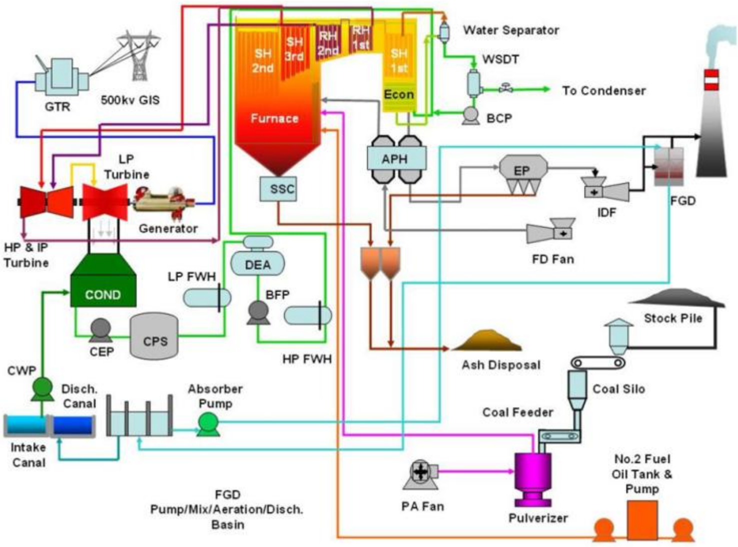

Figure 2: Simplified Diagram of the XYZ Supercritical Power Plant [15]

Table 5: Boiler Specifications of the XYZ Supercritical Power Plant

Parameter	Specification
Unit Nominal Capacity	815 Nett MW
Main steam pressure	25,78 Mpa
Main steam temperature	542 ◦C
Main steam flow	2695 t/h
Re-heater pressure	4,84 Mpa
Re-heater temperature	568 ◦C
Boiler type	Superkritikal sliding pressure operation, once through boiler, single reheat cycle
Coal Feeder type	Gravimetric
Number of Coal Feeder	6 (5 in service, 1 standby)
Coal Feeder capacity	88 t/h
Pulverizer type	Vertikal
Number of Pulverizer	6 (5 in service, 1 standby)
Pulverizer capacity	91,5 t/h

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Boiler cleanliness is calculated using the EtaPRO software developed by Toshiba. The calculation of boiler cleanliness uses equations 1 through 3.

$$HTC_{clean} = HTC_{base}\ x \left(\frac{GIT_{act}+459.67}{GIT_{base}+459.67}\right)^{0.6} \ldots\ldots\ldots\ldots\ldots\ldots\ldots (1)$$

$$BlrSectCleanFact = \left(\frac{HTC_{act}}{HTC_{clean}}\right) \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (2)$$

$$WaterWallCleanFact = \left(\frac{H_{flame}-H_{fegta}}{H_{flame}-H_{fegtc}}\right) \ldots\ldots\ldots\ldots\ldots\ldots\ldots (3)$$

Where:

HTC_{act} = Actual section heat transfer coefficient [Btu/h·ft²·°F]
HTC_{base} = Base section heat transfer coefficient [Btu/h·ft²·°F]
HTC_{clean}= Cleanliness section heat transfer coefficient [Btu/h·ft²·°F]
GIT_{act} = Actual section gas inlet temperature [°F]
GIT_{base} = Base section gas inlet temperature [°F]
BlrSectCleanFact = Boiler section cleanliness factor [%]
WaterWallCleanFact = Water wall section cleanliness factor [%]
H_{flame} = Flue gas enthalpy at adiabatic flame temperature [Btu]
H_{fegta}= Flue gas enthalpy at actual furnace exit gas temperature [Btu]
H_{fegtc} = Flue gas enthalpy at clean furnace exit gas temperature [Btu]

Boiler efficiency is calculated using the direct method according to Equation 4:

$$\eta_{Boiler} = \frac{(m_{MS}\ x\ h_{MS})+(m_{HR}\ x\ h_{HR})-(m_{FW}\ x\ h_{FW})-(m_{CR}\ x\ h_{CR})-(m_{SHS}\ x\ h_{SHS})-(m_{RHS}\ x\ h_{RHS})}{\dot{m}\ batubara\ x\ GCV\ Coal} \ldots. (4)$$

Where:

m_{MS} = Main steam flow (steam exiting the superheater) (kg/h)
h_{MS} = Enthalpy of main steam (kj/kg)
m_{HR} = Hot reheat steam flow (steam exiting the reheater) (kg/h)
h_{HR} = Enthalpy of hot reheat steam (kJ/kg)
m_{FW} = Boiler Feedwater flow entering the economizer (kg/h)
h_{FW} = Enthalpy of boiler feed water entering the economizer (kJ/kg)
m_{CR} = Cold reheat steam flow (steam entering the reheater) (kg/h)
h_{CR} = Enthalpy of cold reheat steam (kJ/kg)

m_{SHS} = spray water flow to superheater (kg/h)
h_{SHS} = Enthalpy of spray water to superheater (kJ/kg)
m_{RHS} = Spray water flow to reheater (kg/h)
h_{RHS} = Enthalpy of spray water to reheater (kJ/kg)
$\dot{m}_{coal}$ = Coal flow rate used in the process (kg/h)
GCV_{coal} = Gross calorific value of coal (kcal/kg)

Calculation of NPHR using the direct method based on equation 5.

$$NPHR \left(\frac{kcal}{kwh}\right) = \frac{mf\ x\ GCV}{Generator\ Output-Auxiliary\ Power} \ldots\ldots\ldots\ldots\ldots (5)$$

Where:

mf = fuel mass flow rate (T/h)
GCV= Gross calorific value of coal (kcal/kg)

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The coal price is calculated in accordance with the Decree of the Minister of Energy and Mineral Resources of the Republic of Indonesia No. 41.K/MB.01/MEM.B/2023, based on the calorific value of coal as specified in Equations 6 and 7. The benchmark price for coal with a calorific value > 5200 – 6000 is as follows:

$$HPB = \left(HBA1 x \frac{K}{5200} x \frac{(100-TM)}{(100-23,12)}\right) - ((TS - 0,69)x4 + (Ash - 6)x\,0,4\,) \;....\;...(6)$$

The benchmark price for coal with a calorific value > 4200 – 5200 is as follows:

$$HPB = \left(HBA2x \frac{K}{4200} x \frac{(100-TM)}{(100-35,29)}\right) - ((TS - 0,2)x4 + (Ash - 4,21)x0,4) \;....\;.(7)$$

Where:

HPB = Benchmark Coal Price (USD/Ton)
HBA 1 = Coal reference price for the first period of March 2025 (USD/Ton) = 82.66 USD/T
HBA 2 = Coal reference price for the second period of March 2025 (USD/Ton) = 50.70 USD/T
K = Calorific value of coal (kcal/kg)
TM = Total moisture in coal (%)
TS = Total sulfur in coal (%)
Ash = Ash content in coal (%)
Exchange rate: 1 USD = Rp 16,300

Calculation of CO_2 emissions is carried out using Equation 8, as issued by the Directorate General of Electricity, to estimate CO_2 emissions from coal-fired power plants.

$$E_{CO_2} = F_{BB}\, x\, [C_{ar} - (A_{ar}\, x\, C_{ub})] x\, 3,6667 \;....\;....\;....\;....\;....(8)$$

E_{CO_2} = Total CO_2 emissions (tons of CO_2)
F_{BB} = Coal consumption (tons)
C_{ar} = Average carbon content as received (%)
A_{ar} = Average ash content as received (%)
C_{ub} = Average unburned carbon content in ash (%)

III. RESULTS AND DISCUSSIONS

3.1 Analysis of Slagging and Fouling Potential

Based on laboratory tests of the three types of coal shown in Table 1, several differences were observed as follows:

a) CMHV Coal: This is the primary coal type designed for boiler operation. Its gross calorific value (GCV) has decreased from the original design value of 4800 kcal/kg to the lowest GCV among the three coal types, approximately 4625 kcal/kg. It has the lowest ash, sulfur, and carbon content, the highest ash fusion temperature, the lowest content of acidic minerals in ash (SiO_2, Al_2O_3, TiO_2), the highest content of base minerals in ash (Fe_2O_3, CaO, MgO), and the lowest sodium content in ash (Na_2O).
b) CHSF Coal: This coal type has the highest sulfur content and the highest content of acidic minerals in ash (SiO_2, Al_2O_3, TiO_2), but the lowest content of base minerals in ash (Fe_2O_3, CaO).
c) CHHV Coal: It has the lowest total moisture, the highest fixed carbon content, the highest gross calorific value (GCV), and significantly higher sodium content in ash (Na_2O) compared to the other two coal types.

Based on the slagging and fouling formulas shown in Tables 2 and 3, the potential for slagging and fouling for each coal type is presented in Table 6.

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Table 6: Predicted Slagging and Fouling Potential for Each Type of Coal

Parameter		CMHV	CHSF	CHHV
Ash type		Lignite	Bituminous	Lignite
Silica ratio	Calculation	33,19	69,46	58,02
	Score	1,00	0,50	1,00
Base to Acid Ratio ($R_{B/A}$)	Calculation	1,44	0,34	0,58
	Score	0,00	0,00	1,00
Ash fusion temperature	Calculation	1247,40	1190,80	1195,00
	Score	0,50	1,00	1,00
Temperature at Ash Viscosity of 25 Pa·s	Calculation	817,13	1223,51	1080,79
	Score	1,00	1,00	1,00
Slagging Index (Rs)	Calculation	0,21	0,26	0,13
	Score	0,00	0,00	0,00
Iron plus calcium (Fe_2O_3+CaO)	Calculation	42,62	16,83	24,90
	Score	1,00	1,00	1,00
Iron - calcium ratio (Fe2O3/CaO)	Calculation	0,82	2,07	0,89
	Score	1,00	1,00	1,00
Total slagging score		**4,50**	**4,50**	**6,00**
Fouling factor	Calculation	0,55	0,51	3,08
	Score	0,50	0,50	1,00
Na_2O	Calculation	0,38	1,48	5,27
	Score	0,00	1,00	1,00
Total alkali in ash	Calculation	0,39	1,54	5,30
	Score	N/A	1,00	N/A
Sodium potasium index	Calculation	1,74	1,02	3,73
	Score	0,00	0,00	1,00
Alkali to silica rasio	Calculation	0,05	0,06	0,16
	Score	0	0	1
Total fouling score		**0,00**	**2,50**	**3,00**

Note: Ash type
Fe2O3 > CaO + MgO = Bituminous
Fe2O3 < CaO + MgO = Lignitic

Based on the predicted slagging and fouling potential in Table 6, only CMHV coal, as the primary coal, meets the criteria with a total slagging potential score ≤ 5 and a total fouling potential score ≤ 2. According to the technical limitations in Table 4, CHSF coal does not meet the criteria because its sulfur and ash content, as shown in Table 1, are significantly higher than the design specifications. Meanwhile, CHHV coal does not meet the criteria due to its ash content exceeding the design limit and its high sodium content, leading to a total fouling score > 2. CMHV coal, while having the lowest calorific value approaching the boiler design limits, causes a reduction in boiler efficiency. Additionally, the annual stock of CMHV coal is insufficient for operation, requiring coal blending.

The analysis of slagging and fouling potential for each coal blend, as shown in Tables 7, 8, and 9, indicates that only the 2-in-1 coal blend, consisting of a mixture of CMHV and CHSF in a 10-50% ratio, meets the slagging and fouling potential criteria. However, the 50% CMHV and CHSF blend does not meet the technical limitations because its ash content is 3.96%, exceeding the boiler design limit (>3.5%). The CMHV and CHHV coal blends do not meet the criteria either, as both the 2-in-1 and 3-in-1 blends in all ratios have a fouling potential > 2, which could lead to severe fouling due to the economizer design using the finned and tube type.

Table 7: Analysis of Slagging and Fouling Potential from the Blend of CMHV and CHSF Coal

Coal Blend Ratio		90:10	80:20	70:30	60:40	50:50	40:60	30:70	20:80	10:90	0:100
Ash Type		Lignitic	Lignitic	Lignitic	Lignitic	Lignitic	Lignitic	Lignitic	Lignitic	Bituminous	Bituminous
Slagging Potential Analysis											
Silica ratio	Calculation	36,28	39,47	42,78	46,19	49,73	53,39	57,19	61,12	65,21	69,46
	Score	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	0,50	0,50
Base to acid ratio *tipe lignitic	Calculation	1,25	1,10	0,96	0,84	0,73	0,64	0,55	0,48	0,41	0,34
	Score	0,00	0,00	0,00	0,00	0,00	1,00	1,00	1,00	NA	NA
Ash fusion temperature (*Fussibility*)	Calculation	1241,74	1236,08	1230,42	1224,76	1219,10	1213,44	1207,78	1202,12	1196,46	1190,80
	Score	0,50	0,50	0,50	1,00	1,00	1,00	1,00	1,00	1,00	1,00
Temperature at Ash Viscosity of 25 Pa*s	Calculation	862,38	906,02	948,35	989,61	1029,99	1069,66	1108,73	1147,34	1185,57	1223,51
	Score	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00
Base to acid ratio (R B/As) tipe bituminous	Calculation	0,26	0,29	0,32	0,33	0,33	0,33	0,32	0,30	0,28	0,26
	Score	NA	NA	NA	NA	NA	NA	NA	NA	0,00	0,00
Iron plus calcium (Fe_2O_3+CaO)	Calculation	40,04	37,46	34,88	32,30	29,73	27,15	24,57	21,99	19,41	16,83
	Score	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00
Iron calcium ratio (Fe2O3/CaO)	Calculation	0,85	0,89	0,93	0,99	1,05	1,14	1,26	1,42	1,67	2,07
	Score	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00
Total Slagging Score		**4,50**	**4,50**	**4,50**	**5,00**	**5,00**	**6,00**	**6,00**	**6,00**	**4,50**	**4,50**
Fouling Potential Analysis											
Fouling factor (B/A x Na_2O)	Calculation	0,62	0,66	0,68	0,69	0,68	0,67	0,64	0,60	0,56	0,51
	Score	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	0,50	0,50
% Na_2O Content (Sodium Oxide Content)	Calculation	0,49	0,60	0,71	0,82	0,93	1,04	1,15	1,26	1,37	1,48
	Score	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	1,00	1,00
Total akali in ash	Calculation	0,51	0,62	0,73	0,85	0,96	1,07	1,19	1,30	1,42	1,54
	Score	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00
Sodium potasium Index	Calculation	1,74	1,72	1,67	1,61	1,53	1,45	1,35	1,24	1,13	1,02
	Score	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00
Alkali to silka ratio	Calculation	0,05	0,05	0,05	0,05	0,06	0,06	0,06	0,06	0,06	0,06
	Score	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00
Total fouling score		**2,00**	**2,00**	**2,00**	**2,00**	**2,00**	**2,00**	**2,00**	**2,00**	**2,50**	**2,50**

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Table 8: Analysis of Slagging and Fouling Potential from the Blend of CMHV and CHHV Coal

Coal Blend Ratio		90:10	80:20	70:30	60:40	50:50	40:60	30:70	20:80	10:90
Ash type		lignitic	lignitic	lignitic	lignitic	lignitic	lignitic	lignitic	lignitic	lignitic
Slagging Potential Analysis										
Silica ratio	Calculation	35,27	37,43	39,67	41,99	44,41	46,92	49,52	52,24	55,07
	Score	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00
Base to acid ratio (R B/A)	Calculation	1,31	1,20	1,10	1,01	0,92	0,84	0,77	0,70	0,64
*tipe lignitic	Score	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	1,00
Ash fusion temperature	Calculation	1242,16	1236,92	1231,68	1226,44	1221,20	1215,96	1210,72	1205,48	1200,24
	Score	0,50	0,50	0,50	1,00	1,00	1,00	1,00	1,00	1,00
Temperature at Ash	Calculation	846,13	874,34	901,87	928,79	955,17	981,07	1006,54	1031,62	1056,36
Viscosity of 25 Pa*s	Score	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00
Base-acid ratio (R B/As)	Calculation	0,20	0,20	0,19	0,18	0,17	0,17	0,16	0,15	0,14
*tipe bituminous	Score	NA	NA	NA	NA	NA	NA	NA	NA	NA
Iron plus calcium	Calculation	40,85	39,08	37,30	35,53	33,76	31,99	30,22	28,44	26,67
(Fe2O3+CaO)	Score	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00
Iron - calcium ratio	Calculation	0,82	0,83	0,83	0,84	0,84	0,85	0,86	0,87	0,88
(Fe2O3/CaO)	Score	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00
Total slagging score		**4,50**	**4,50**	**4,50**	**5,00**	**5,00**	**5,00**	**5,00**	**5,00**	**6,00**
Fouling Potential Analysis										
Fouling factor (B/A x Na_2O)	Calculation	1,14	1,63	2,03	2,35	2,60	2,79	2,93	3,02	3,07
	Score	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00
% Na_2O content	Calculation	0,87	1,36	1,85	2,34	2,82	3,31	3,80	4,29	4,78
	Score	0,00	0,00	0,00	1,00	1,00	1,00	1,00	1,00	1,00
Total alkali in ash	Calculation	0,88	1,37	1,86	2,36	2,85	3,34	3,83	4,32	4,81
	Score	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00
Sodium potasium Index	Calculation	2,27	2,70	3,04	3,30	3,50	3,64	3,72	3,76	3,76
	Score	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00
Alkali to silika ratio	Calculation	0,06	0,08	0,09	0,10	0,12	0,13	0,14	0,15	0,16
	Score	0,00	0,00	0,00	0,00	1,00	1,00	1,00	1,00	1,00
Total score Fouling		**3,00**	**3,00**	**3,00**	**4,00**	**5,00**	**5,00**	**5,00**	**5,00**	**5,00**

Table 9: Analysis of Slagging and Fouling Potential from the Blend of CMHV, CHSF and CHHV Coal

Coal Blend Ratio		80:10:10	70:10:20	70:20:10	60:20:20	50:20:30	50:30:20	40:30:30	30:40:30	30:30:40	20:40:40	10:50:40	10:40:50	0:50:50
Ash type		Lignitic	Lignitic	Lignitic	Lignitic	Lignitic	Lignitic	Lignitic	Lignitic	Lignitic	Lignitic	Lignitic	Lignitic	Lignitic
Slagging Potential Analysis														
Silica ratio	Kalkulasi	38,45	40,71	41,74	44,10	46,54	47,61	50,17	53,92	52,83	56,71	60,74	59,62	63,79
	Score	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00
Base - acid ratio (R B/A)	Kalkulasi	1,15	1,05	1,01	0,92	0,84	0,80	0,74	0,64	0,67	0,58	0,50	0,53	0,45
*tipe lignitic	Score	0,00	0,00	0,00	0,00	0,00	0,00	0,00	1,00	1,00	1,00	1,00	1,00	1,00
Ash fusion temperature	Kalkulasi	1236,50	1231,26	1230,84	1225,60	1220,36	1219,94	1214,70	1209,04	1209,46	1203,80	1198,14	1198,56	1192,90
	Score	0,50	0,50	0,50	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00
Temperature at Ash	Kalkulasi	890,25	917,48	932,97	959,38	985,32	1000,28	1025,62	1065,19	1050,61	1089,73	1128,34	1114,00	1152,28
Viscosity of 25 Pa*s	Score	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00
Base-acid ratio (R B/As)	Kalkulasi	0,25	0,24	0,28	0,26	0,25	0,28	0,26	0,27	0,24	0,25	0,24	0,23	0,22
*tipe bituminous	Score	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00
Iron plus calcium	Kalkulasi	38,27	36,50	35,69	33,92	32,15	31,34	29,57	26,99	27,80	25,22	22,64	23,44	20,87
	Score	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00
Iron - calcium ratio	Kalkulasi	0,86	0,86	0,90	0,90	0,92	0,96	0,97	1,05	0,99	1,07	1,18	1,11	1,23
	Score	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00
Total Slagging Score		**4,50**	**4,50**	**4,50**	**5,00**	**5,00**	**5,00**	**5,00**	**6,00**	**6,00**	**6,00**	**6,00**	**6,00**	**6,00**
Fouling Potential Analisis														
Fouling factor (B/A x Na_2O)	Kalkulasi	1,12	1,54	1,10	1,45	1,74	1,36	1,60	1,46	1,79	1,62	1,45	1,73	1,53
	Score	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00
% Na_2O content	Kalkulasi	0,98	1,47	1,09	1,58	2,07	1,69	2,18	2,29	2,66	2,77	2,88	3,26	3,37
	Score	0,00	0,00	0,00	0,00	1,00	0,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00
Total Alkali in ash	Kalkulasi	1,00	1,49	1,11	1,60	2,09	1,71	2,21	2,32	2,70	2,81	2,93	3,30	3,42
	Score	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00
Sodium potasium Index	Kalkulasi	2,19	2,54	2,09	2,39	2,62	2,23	2,42	2,22	2,55	2,32	2,09	2,38	2,12
	Score	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00
Alkali to silika ratio	Kalkulasi	0,06	0,08	0,06	0,08	0,09	0,08	0,09	0,09	0,10	0,10	0,10	0,11	0,11
	Score	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	1,00	1,00	1,00	1,00	1,00
Total Fouling Score		**3,00**	**3,00**	**3,00**	**3,00**	**4,00**	**3,00**	**4,00**	**4,00**	**5,00**	**5,00**	**5,00**	**5,00**	**5,00**

3.2 Direct Firing Test

The second phase of this study involved conducting direct combustion tests at the XYZ Supercritical Power Plant at a unit load of 790 NMW (in accordance with the maximum load requested by PLN during 2024 - 2025), using a blend of CMHV and CHSF coal in ratios ranging from 10% to 50%, which met the criteria of being non-slagging and non-fouling. This was carried out to evaluate the impact on environmental performance, boiler cleanliness, and unit efficiency

3.2.1 The Impact of CMHV and CHSF Coal Blending on Environmental Effects

Based on the SO_2 emission data collected, an increase in SO_2 and NO_x emissions was observed in line with the rising percentage of CHSF coal in the blend, as shown in the graph in Figure 3. This is attributed to the higher sulfur and nitrogen content in CHSF coal compared to CMHV coal. However, NO_x emissions are influenced not only by the nitrogen content in the coal but also by heat distribution within the boiler, the configuration of the pulverizers in service, and the calorific value (GCV) of the coal [5]. Despite the increase, all maximum recorded emission values for SO_2 and NO_x remained well below the regulatory limits set by the Ministry of Environment (KLH), which is 550 mg/Nm³.

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Higher SO_2 absorption by seawater in the flue gas desulfurization (FGD) system leads to a decrease in the pH of the seawater discharge. This trend is evident in the graph in Figure 5, where the discharge water pH decreases as the CHSF coal blending ratio increases to 50%. The lowest recorded pH was 6.32, which is close to the critical safety threshold of <6.3, at a 50% CHSF blending ratio where the total sulfur content reached 0.3%, exactly at the design limit of the FGD and neutralization basin. According to KLH regulations, the pH in the discharge canal must not fall below 6. Therefore, blending CHSF coal at ratios between 10% and 40% is considered environmentally safe. A 50% blending ratio can still be used, but precautionary measures must be taken to ensure the discharge water pH does not drop below 6, which would constitute a violation of KLH regulations.

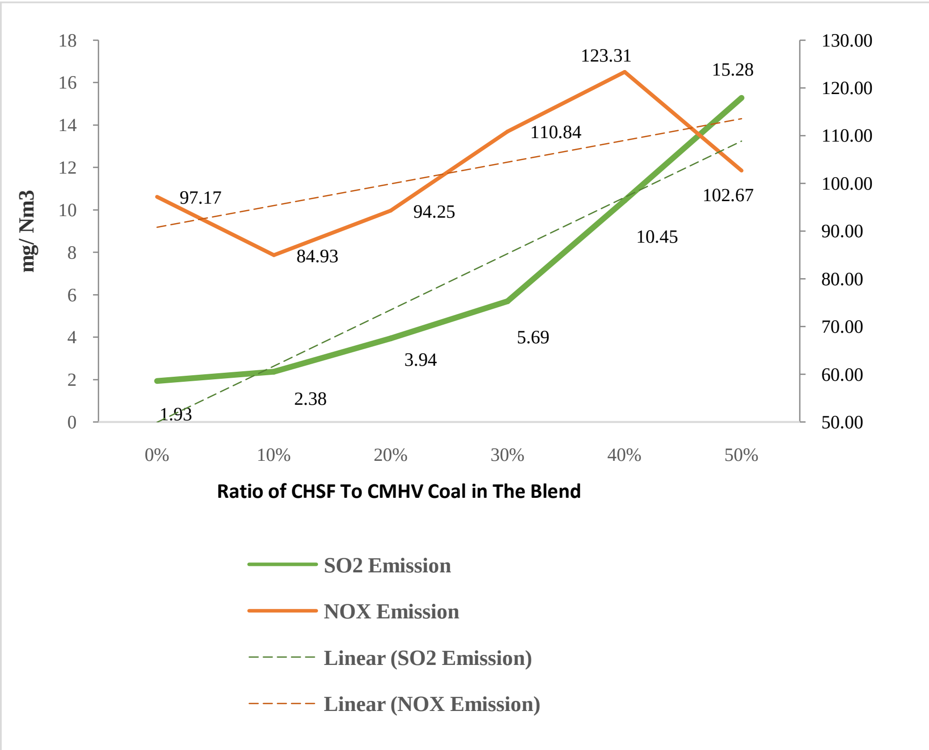

Figure 3: SO_2 and NO_x Emission Graph for CMHV and CHSF Coal Blends at 790 NMW Load

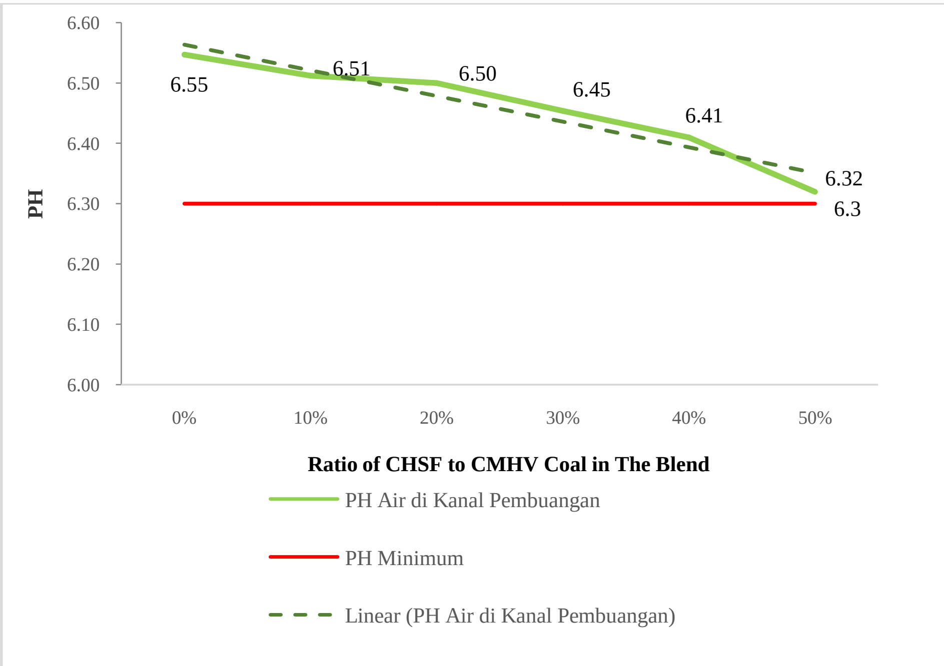

Figure 4: Graph of the Impact of CMHV and CHSF Coal Blending on Seawater pH in the Discharge Canal

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3.2.2 Effect of CMHV and CHSF Coal Blending at 10–50% Ratios on Boiler Cleanliness and Hot Flue Gas Losses

Based on the graph in Figure 5, at CHSF coal blending ratios of 10 – 40%, the distribution of boiler cleanliness percentages remains stable, consistent with the slagging and fouling potential scores shown in Table 7. This is due to the increase in ash content which can promote slagging and fouling being offset by higher levels of silica and aluminum, and a decrease an iron content which help reduce slagging and fouling effects [5][6][7]. At coal blend ratios of 10–20% CHSF, the ash fusion temperature remains above 1230 °C. In fact, an improvement in average boiler cleanliness is observed at the 10 – 20% CHSF blending ratio.

A decline in the distribution percentage of boiler cleanliness begins at a CHSF blending ratio of 30%, corresponding with a rise in ash content. A sharp drop in boiler cleanliness is seen at the 50% CHSF blending ratio, where the ash content reaches 4.08%, exceeding the boiler's design limit of 3.5%. This finding aligns with previous research which showed that increasing ash content leads to higher levels of ash forming minerals responsible for slagging and fouling, particularly sodium and potassium [5][6][7]. Moreover, increasing the CHSF coal blend ratio tends to balance the proportion of basic and acidic ash minerals, further enhancing the potential for slagging [7][11][12][13]. The average boiler cleanliness and cleanliness of each boiler area is illustrated in the graph in Figure 6.

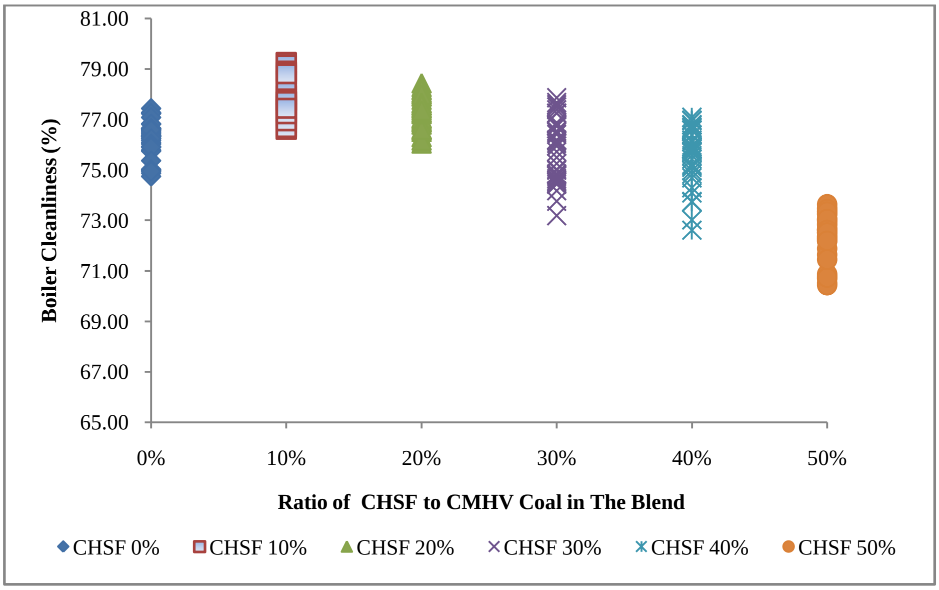

Figure 5: Graph of the Effect of CMHV and CHSF Coal Blending on the Distribution of Boiler Cleanliness Percentage

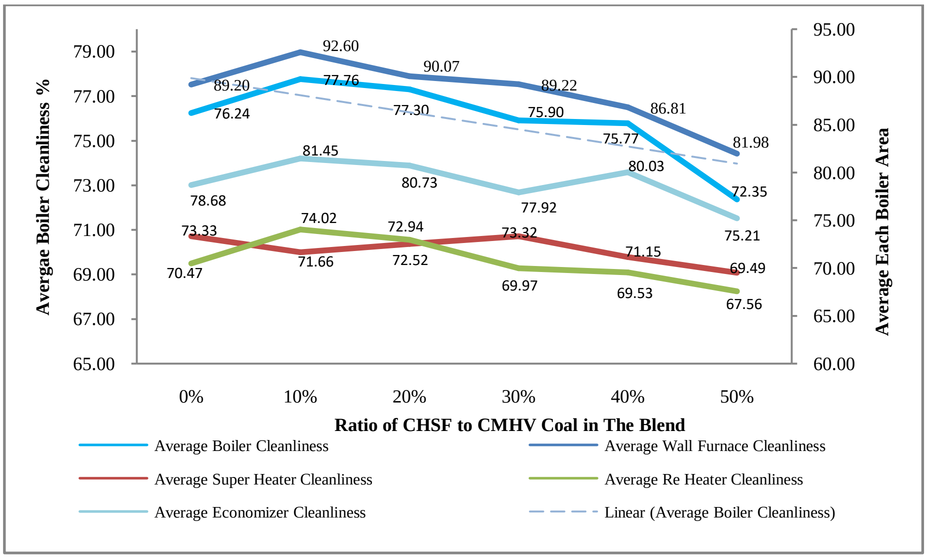

Figure 6: Graph of the Effect of CMHV and CHSF Coal Blending on Average Boiler Cleanliness and Cleanliness of Each Boiler Area

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The flue gas temperature at the air heater (AH) inlet is influenced by the ash content of the coal and the cleanliness of the boiler. Lower boiler cleanliness due to slagging and fouling, combined with higher ash content, leads to an increase in flue gas temperature at the AH inlet. This indicates higher energy losses in the flue gas (hot flue gas losses), caused by less effective heat transfer within the boiler [8]. This trend is illustrated in Figures 4.8 and 4.9, where improved boiler cleanliness associated with CHSF coal blends at a 10–20% ratio results in lower AH inlet temperatures compared to 100% CMHV coal, despite a slight increase in ash content. The lowest flue gas temperature is observed at the 20% CHSF blend. In contrast, blends of CMHV with CHSF at 30–40% show a slight increase in AH inlet temperature, though it remains relatively stable. This is primarily due to the increased ash content, while boiler cleanliness shows a slight decreased. However, with a 50% CHSF blend, where ash content in coal exceeds the boiler's maximum design limit (>3.5%), the AH inlet flue gas temperature rises sharply to 424.15°C, nearing the safety threshold of 425°C. This suggests rapid formation of slagging and fouling within the boiler, thus causing the highest heat loss in the flue gas.

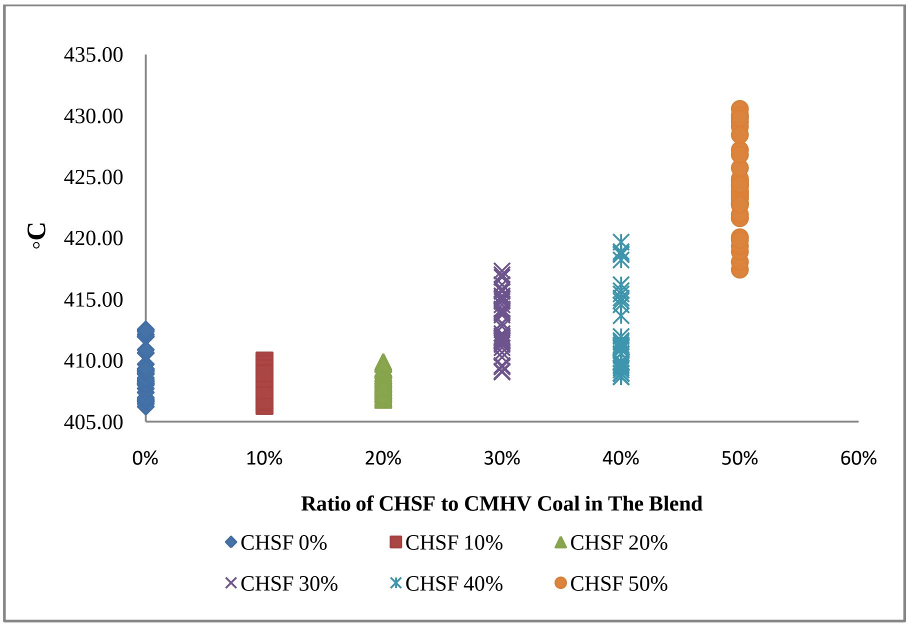

Figure 4.8: Graph of the Effect of Coal Blending on the Distribution of Flue Gas Temperature at the Air Heater (AH) Inlet

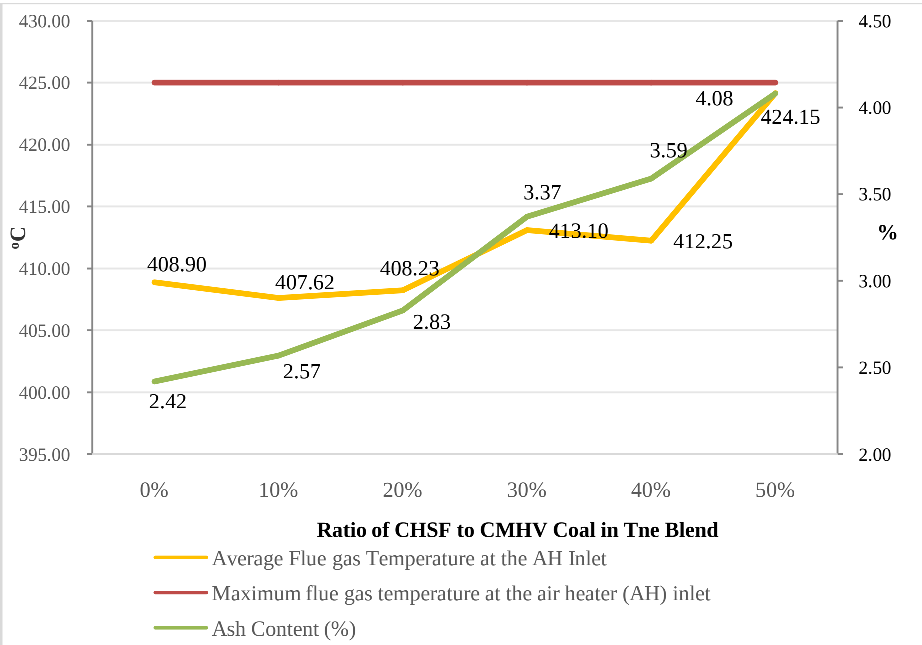

Figure 4.9: Graph of the Effect of Coal Blending on the Average Flue Gas Temperature at the Air Heater (AH) Inlet and the Ash Content of the Coal Blend

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3.2.3 Effect of CMHV and CHSF Coal Blending at 10–50% Ratios on Power Plant Efficiency

The blending of CMHV and CHSF coals positively affected boiler efficiency. As shown in the graph in Figure 7, boiler efficiency increased with CHSF blending up to 40%. This improvement was influenced by the gross calorific value (GCV) of the coal as the CHSF ratio increased and by the maintained boiler cleanliness, which reduced the required coal flow to generate the same amount of electricity. However, at a 50% CHSF blending ratio, where ash content exceeded the boiler's design limit, boiler cleanliness deteriorated, leading to reduced heat transfer efficiency. As a result, total coal flow increased significantly, causing a sharp decline in boiler efficiency.

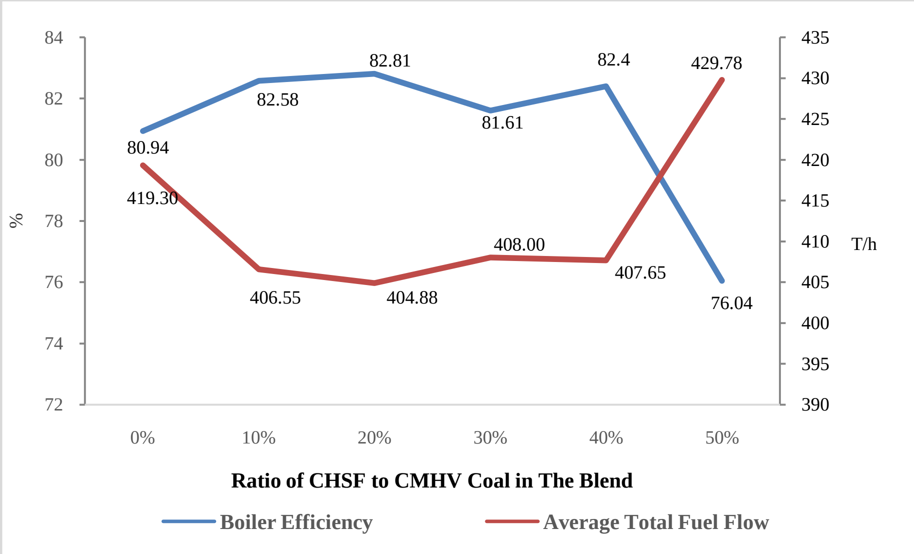

Figure 7: Graph of the Effect of CMHV and CHSF Coal Blending on Boiler Efficiency and Total Fuel Flow

From Figure 8, blending CHSF coal up to 40% results in a decrease in Net Plant Heat Rate (NPHR), indicating an improvement in power plant efficiency, with the highest efficiency observed at a 20% CHSF blend. The decrease in NPHR corresponds to an increase in boiler efficiency and a reduction in coal flow. At a 50% CHSF ratio, the significant increase in ash content is not offset by a substantial rise in the actual coal GCV, leading to a notable increase in total fuel flow, which in turn causes a sharp rise in NPHR or a significant drop in unit efficiency.

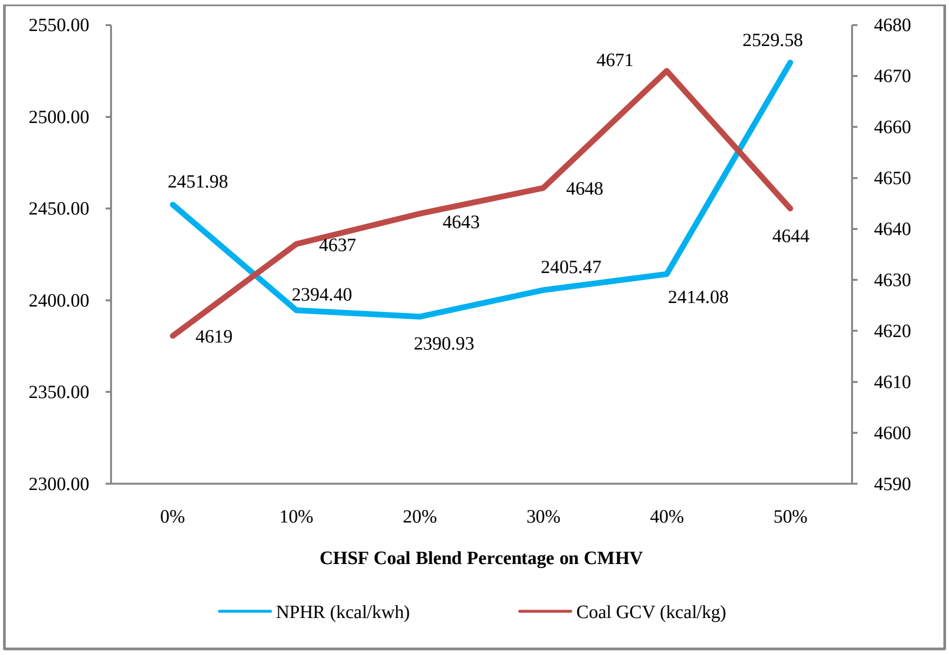

Figure 8: Graph of the Effect of CMHV and CHSF Coal Blends on NPHR

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3.2.4 Effect of Coal Blending on Potential Cost Savings from Coal Procurement and Carbon Tax Reduction at a 790 NMW Load

The coal prices per ton were calculated using Equations 6 and 7, in accordance with the Decree of the Minister of Energy and Mineral Resources of the Republic of Indonesia No. 41.K/MB.01/MEM.B/2023. The resulting prices for each type of coal are presented in Table 10, based on the coal reference price set by the Ministry of Energy and Mineral Resources for March 2025

Table 10: The Prices for Each Type of Coal per Ton

Coal Name	Coal Price
CMHV	Rp1.006.719
CHSF	Rp995.360
CHHV	Rp1.451.578

Coal consumption savings were calculated using the Specific Fuel Consumption (SFC) equation, which represents the amount of coal used in the combustion process within the boiler to produce one kilowatt-hour of electrical energy (kg/kWh), as follows:

$$SFC_{netto}\ \left(\frac{kg}{kWh}\right) = \frac{NPHR\ \left(\frac{kcal}{kWh}\right)}{GCV\ batubara\ \left(\frac{kcal}{kg}\right)} \ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (9)$$

Where:

SFC = Specific fuel Consumption (kg/kWh)
NPHR = Nett Plant Heat Rate (kcal/kWh)
Coal GCV = Coal Gross Calorific Value (kcal/kg)

The SFC values were obtained from the graph in Figure 9. Based on 2023 operational data, the supercritical power plant operated at a 790 NMW load for a total of 2,891 hours. Therefore, the total annual coal consumption savings at a 790 NMW load can be calculated using Equation (10).

$$Annual\ Coal\ Savings\ (ton) = SFC\ x\ 790\ x\ 2891 \ldots\ldots\ldots\ldots \quad (10)$$

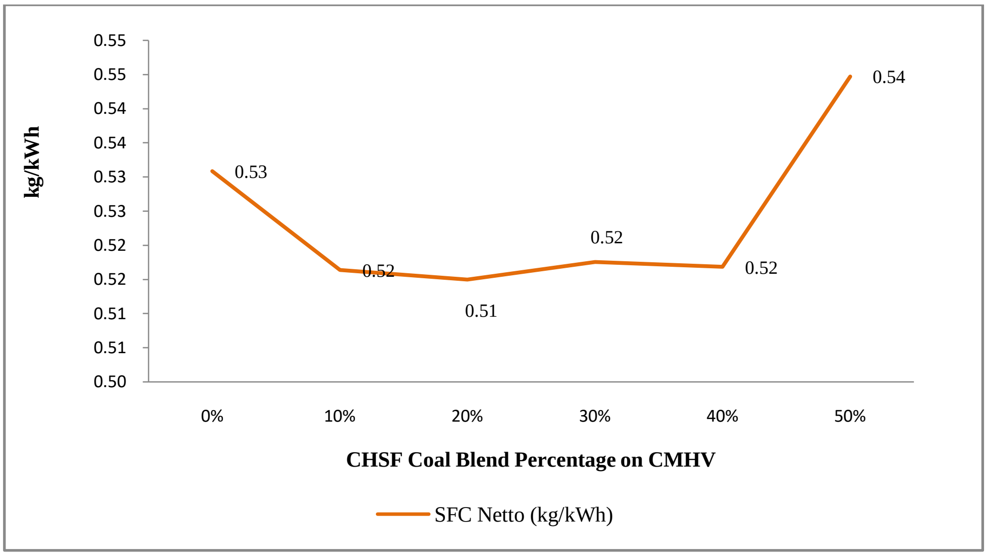

Figure 9: Graph of the Effect of CMHV and CHSF Blending on SFC

The annual coal consumption savings are shown in the graph in Figure 10, and the cost savings from annual coal consumption are shown in Table 11. From the table and graph, the greatest savings are obtained from the CMHV and CHSF coal blend at a CHSF ratio of 20%, resulting in an annual coal consumption reduction of 36,296 tons and an annual cost savings of IDR 39 billion.

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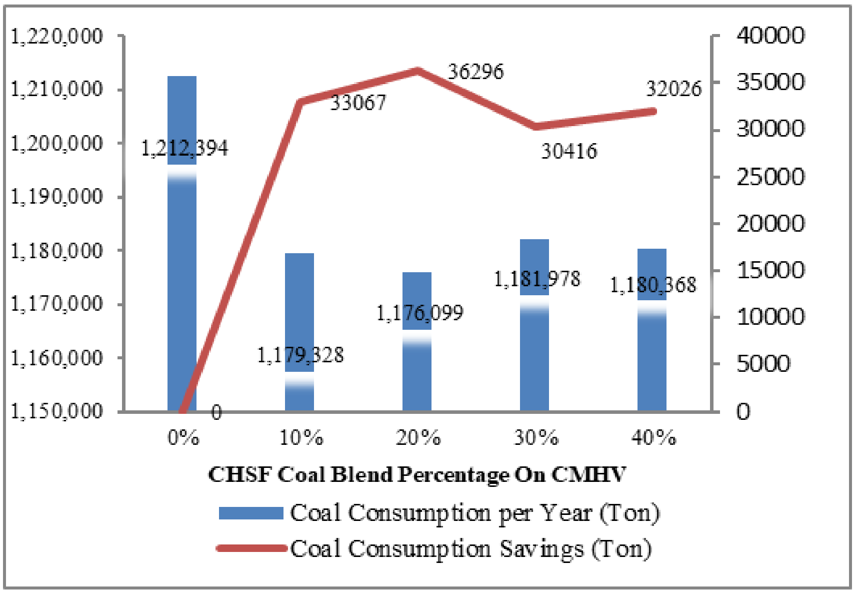

Figure 10: Coal Consumption and Annual Coal Consumption Savings at 790 NMW Load

Coal Blend	Annual Coal Consumption at 790 NMW Load (Ton)	Coal Base Price (Rp/Ton)	Annual Coal Cost at 790 NMW Load	Annual Cost Savings at 790 NMW Load
100% CMHV	1.212.394	Rp1.006.719	Rp1.220.540.070.457	-
10%CHSF+90%CMHV	1.179.328	Rp1.005.412	Rp1.185.710.311.681	Rp34.829.758.776
20%CHSF+80%CMHV	1.176.099	Rp1.004.265	Rp1.181.114.748.920	Rp39.425.321.537
30%CHSF+70%CMHV	1.181.978	Rp1.003.126	Rp1.185.672.610.538	Rp34.867.459.919
40%CHSF+60%CMHV	1.180.368	Rp1.001.994	Rp1.182.721.670.384	Rp37.818.400.073
50%CHSF+50%CMHV	1.244.031	Rp1.000.869	Rp1.245.111.829.855	-Rp24.571.759.398

Table 11: Coal Consumption and Cost Savings from Coal Procurement at 790 NMW Load per Year

By determining the potential annual coal consumption savings, the potential annual reduction in carbon emissions can be calculated using Equation (8). When multiplied by the carbon tax rate of Rp 30,000 per ton of CO_2e, the potential savings from carbon tax reduction are shown in Table 12.

Table 12: Total Annual Cost Savings from Carbon Tax Reduction and Coal Procurement at 790 NMW Load

Coal Blend	Coal Consumption Savings (Tons)	Ash Content (%)	Carbon Content (%)	Average Unburned Carbon (%)	Carbon Emission Savings (Tons)	Potential Savings from Carbon Tax Reduction	Total Savings from Carbon Tax Reduction and Coal Procurement
10%CHSF+90%CMHV	33066,74282	2,4142	71,5412	2,33	79920,53681	Rp2.397.616.104	Rp37.227.374.880
20%CHSF+80%CMHV	36295,82095	2,7994	71,8694	2,33	86967,36554	Rp2.609.020.966	Rp42.034.342.503
30%CHSF+70%CMHV	30416,17187	3,1846	72,1976	2,33	72244,3677	Rp2.167.331.031	Rp37.034.790.950
40%CHSF+60%CMHV	32025,92521	3,5698	72,5258	2,33	75399,30259	Rp2.261.979.078	Rp40.080.379.150

IV. CONCLUSION

This study shows that coal blending is an effective strategy to meet the operational requirements of PLTU Supercritical XYZ while optimizing performance and cost efficiency. Among the 32 tested coal blending ratios, the CMHV–CHSF combinations within the 10%–40% CHSF range were found to be the most technically and economically feasible. These blends met slagging and fouling criteria, maintained emissions within regulatory limits, improved boiler and unit efficiency, and reduced overall operating costs. The optimal blend was identified at 20% CHSF, driven by higher silica, aluminum, and gross calorific value (GCV), while ash content remained low. This blend provided the highest benefits in boiler cleanliness (increase 2%), boiler efficiency (increase 2.3%), and unit performance (2.5% NPHR reduction), along with the greatest cost savings of up to IDR 42 billion per year from coal consumption and carbon tax reductions. Blends containing CHHV, in both 2-in-1 and 3-in-1 configurations, were deemed unsuitable due to high fouling

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risks caused by elevated Na_2O content, potential damage to economizer components, and higher procurement costs. Additionally, CHSF ratios above 40% especially at 50% exceeded technical limits for ash content, leading to reduced boiler performance, increased slagging and fouling, and environmental parameters nearing regulatory thresholds. Therefore, this study recommends limiting CHSF content to a maximum of 40%, with 20% as the optimal blend for operational, environmental, and economic performance.

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