

Coal Blending Effect in Coal Fired Power Plant Performance

Fransiskus Xavierius Adeodatus Alfa Febriant¹, Willy Adriansyah,² Mochamad Soleh³

¹PT PLN Indonesia Power

²Faculty of Mechanical Engineering and Aerospace, Institut Teknologi Bandung

³PT PLN (Persero) Pusat Penelitian dan Pengembangan

Abstract. Coal is one of most favorable energy source due to its high calorific value and easily processed. In 2022 until 2024, coal price rose significantly, leading to energy crisis because some CFPP need to stop operating due to lack of coal supply, especially CFPP with high rank coal as its primary fuel designed. Coal blending with LRC is one of best method to maintain CFPP sustainability in the middle of coal crisis. A simulation using GateCycle as a tool is conducted to study change of boiler operating parameter and boiler performance while using coal blending method in 100 MW Ombilin CFPP. From the simulation and study, increased LRC composition will result in increasing of coal flow from 38.45 ton/h using 0% LRC to 63.78 ton/h using 100% LRC. The incremental increase of coal flow is 0.253 t/h for every 1% LRC composition and FDF electrical load by 18.48% due to increased combustion air flow. Boiler efficiency also reduced from 91.94 % to 86.20% due to high moisture content by increasing LRC Composition. With maximum mill capacity as its constraint, in order to produce 100 MW, maximum allowable LRC composition of coal blending in Ombilin CFPP is 37%.

Keywords: *capacity, coal, efficiency, simulation,*

Nomenclature

$\%X_{LRC}$	=	LRC composition in blending (%)
A_{corr}	=	Surface Area Correction Factor
AFR	=	Air to Fuel Ratio (kg-air / kg-coal)
Ash	=	Ash Content (%)
A_t	=	Heat Transfer Surface Area (m ²)
C	=	Carbon Content (%)
C_b	=	Carbon Content Burned (%)
CF	=	Coal Flow (t/h)
H	=	Hydrogen Content (%)
HHV_b	=	Blended High Heating Value (kcal/kg)
HHV_{HRC}	=	HRC High Heating Value
HHV_{LRC}	=	LRC High Heating Value (kcal/kg)
K_{rad}	=	Heat Transfer Coefficient (kW/kg m ²)

L_1	=	Losses due to dry gas (%)
L_2	=	Losses due to Moisture Content in Fuel (%)
L_3	=	Losses due to H ₂ O Formation from burning Hydrogen (%)
L_4	=	Losses due to Combustible in Refuse (%)
L_5	=	Losses due to Radiation (%)
N	=	Nitrogen Content (%)
O	=	Oxygen Content (%)
Q	=	Radiation Heat Transfer (kcal/h)
S	=	Sulphur Content (%)
$T_{g,eff}$	=	Effective Gas Temperature (°C)
TM	=	Total Moisture Content (%)
$T_{w,eff}$	=	Effective Wall Temperature (°C)
U_b	=	Blended coal element (%)
U_{HRC}	=	HRC coal element (%)
U_{LRC}	=	LRC coal element (%)
η_b	=	Boiler Efficiency (%)
σ	=	Boltzman Number

1 Introduction

W. Jia et al define that Coal is one of the main energy sources worldwide, which is known as the “black gold” and “industrial food” [1]. Coal is a combustible black or brownish-black sedimentary rock with a high amount of carbon and hydrocarbons. Coal is classified as a non-renewable energy source because it takes millions of years to form. Coal is one of most favourable hydrocarbons for energy source due to its high calorific value and easily to processed. Ria Setiawan stated that coal can be classified into four grades from its calorific value Air Dried Basis (Dab), fixed carbon content and Volatile Matter based on ASTM shown in table 1 [2].

Table 1 Coal Classification Based on Calorific Value (referensi2)

No	Grade	Calorific Value (kcal/kg)
1	Low Rank Coal (LRC)	< 5,100
2	Medium Rank Coal (MRC)	5,100 – 6,100
3	High Rank Coal (HRC)	6,100 – 7,100

Indonesia Ministry of Mineral and energy released a statistic that In Indonesia, coal is still used as primary fuel for power generation, due to its abundant resource. Indonesia has 42,495.10 MW total capacity of power plant installed and

Coal Fired Power Plant (CFPP) still dominated with 36.85% composition from Indonesia total capacity power plant [3]. Low Rank Coal, Medium Rank Coal, and High Rank Coal are still used as fuel in existing Indonesia CFPP. Indonesia energy source sustainability mostly still depends on coal availability.

In 2022, World coal price rose significantly which led to insufficient coal domestic supply and energy crisis due to some CFPP must stop due to lack of coal supply. In 2024, World coal price is lower than in 2022 with \$131.17 / metric ton, but it is still higher than Indonesian Electric Company (PLN) caping price in \$70 / metric ton for 6,322 kcal/kg High Heating Value (HHV) [4]. This price phenomenon will have a huge impact on CFPP operational sustainability especially CFPP with HRC as its fuel design.

From Indonesia Ministry of Mineral and Energy, In the other hand, Indonesia also still has 31,713.55 million metric ton coal potential, but it is still dominated by LRC Supply with 23,700.14 million metric ton or 74.73% from total potential. High Rank Coal supply is only 3,548.85 million metric ton or 11.19% from total coal supply [5]. CFPP with HRC fuel design will not sustain for a long time with those 2 phenomenon. In order to maintain its sustainability, CFPP with HRC fuel must be converted using LRC as its fuel by using coal switching method or coal blending.

Lowering Calorific value as CFPP primary fuel will affect its performance. Co-combustion method can be used to analyze CFPP performance using coal having lower calorific value. An experiment was conducted by Cahyo, et al in 16.5 MWe Circulated Fluidized Bed CFPP, reduced the calorific value of the fuel using higher LRC Blending composition, Nett Plant Heat Rate (NPHR) increased slightly by 3.65% [6]. Increasing LRC blending composition also increase coal consumption from 11.53 kg/h to 12.35 kg/h or increased by 7.11% from nominal value.

Another experiment by Tontu, et al in some Pulverized Coal CFPP, concluded that combustion of low rank coal is feasible. Using low rank coal as primary fuel, CFPP can produce 100% boiler load with two types of coal (lignite and bituminous coal) pulverized in one mill with 22.5% lignite from total coal flow [7]. Arief, et al also conducted experiment, by using low rank coal discover that using LRC will reduce furnace temperature and by varying Primary Air (PA) / Pulverized Coal (PC) has an effect on increasing average temperatures in furnace [8]. Vuthaluru, et al also experimented using some blending ratio between lignite and sub-bituminous coal can reduce agglomeration at 800°C [9]. Alfian et, al conducted an experiment, lowering heating value in fuel combustion will tend to increase coal feeder working level and auxiliary power consumption due to increasing of combustion air flow [10]. Veatch, et al also stated that by using lower calorific value coal, there will be some effect in boiler and plant such as

plant derating, change in load pattern, higher auxiliary power, higher nett plant heat rate [11].

From the experiments that have been conducted previously, it only state the effect of using lower coal calorific value on a specified condition using field experiment this paper study and predict the effect of coal blending / coal downgrading in CFPP with HRC as its fuel design to its performance, and the change in operational parameter using heat balance simulation. Heat balance will also give another perspective about effect of using coal with lower calorific value outside allowable range of calorific value on CFPP equipment and performance.

2 Methodology

The CFPP used in this study is Ombilin Coal Fired Power Plant with rated power 100 MW. Ombilin CFPP is a pulverized coal type boiler with tangential firing burner. From manual book and design, Ombilin CFPP uses 6,300 kcal/kg coal as its design fuel. GateCycle software is used as tool for simulation in this study. Off-design simulation is used as its running method. Simulation steps and analysis can be seen in fig 1.

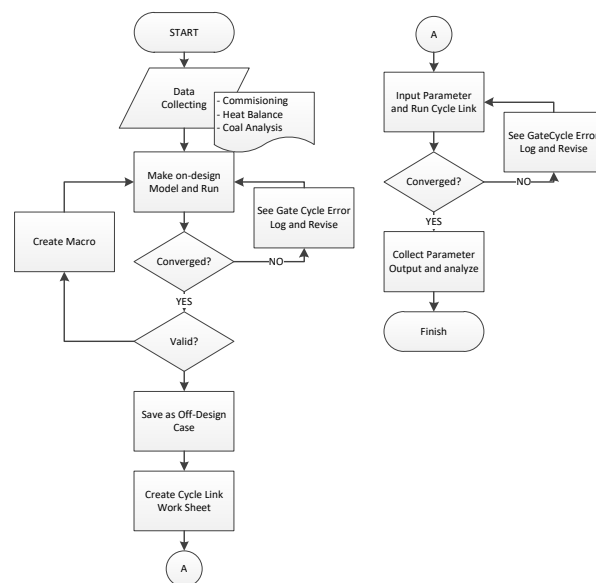


Figure 1 Modelling Simulation Flow Chart

2.1 Plant Modelling

Commissioning data and Heat Balance diagram will be the main basis for creating on-design plant model. Ombilin CFPP use non-reheat turbine, 5 heater (2 Low

Pressure Heaters, 1 Deaerator and 2 High Pressure Heaters), 1 Low Temperature Superheater (LTSH), 1 High Temperature Superheater (HTSH), and 1 Economizer. Heat balance model in gate cycle software can be seen in fig 2.

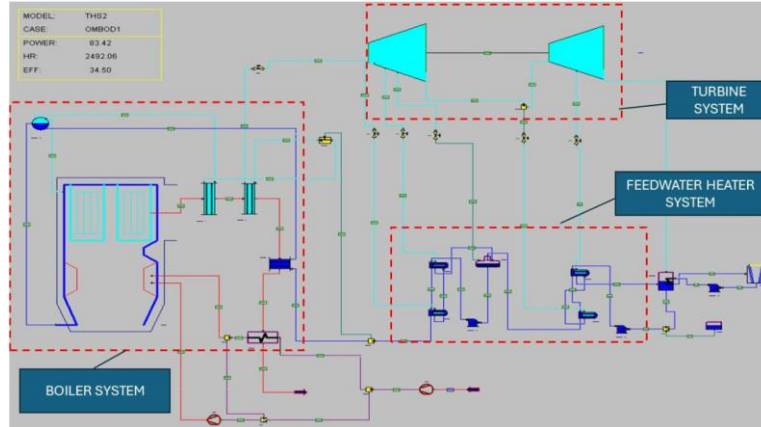


Figure 2 Ombilin Heat Balance Model

On-Design modelling required fluid properties as its main input, and GateCycle will calculate the equipment design, such as surface area, length, etc. Off-design modelling is different from on-design modelling. Off-design modelling is the opposite of on-design, in off-design modelling, fluid properties will be the main output. Parameter validation is required in order to make sure that the model that had been built resemblance the real one. A validation will compare between some parameters from the result of GateCycle simulation and commissioning or heat balance (Data Source). ASME PTC PM standard stated that deviation below 10% is categorized as valid [12]. Validation will also compare in 3 load variation as seen in table 2.

Table 2 Model Validation

Load	Parameter	Unit	Gate Cycle	Actual	Deviation
100%	Gross Generator Load	MW	101.65	101.90	-0.25%
	Coal Flow	Kg/hr	39,191	36,482.40	6.91%
	Main Steam Temperature	°C	510.43	510.22	0.04%
	Main Steam Pressure	Bar-a	107	102.1	4.58%
	Main Steam Flow	Kg/hr	382,389	385,840	-0.90%
	Feedwater Temperature	°C	222.40	219.90	1.12%
	Boiler Efficiency	%	91.91	89.23	2.92%
	Nett Plant Heat Rate	Kcal/kwh	2,459.29	2,469	-0.39%
75%	Gross Generator Load	MW	75.66	75.94	-0.37%

Load	Parameter	Unit	Gate Cycle	Actual	Deviation
60%	Coal Flow	Kg/hr	29,096	27,007.2	7.18%
	Main Steam Temperature	°C	507.71	510.45	-0.54%
	Main Steam Pressure	Bar-a	103.01	103.01	0.00%
	Main Steam Flow	Kg/hr	285,552	279,930	1.97%
	Feedwater Temperature	°C	210.22	205.6	2.20%
	Boiler Efficiency	%	92.61	90.03	2.79%
	Nett Plant Heat Rate	Kcal/kwh	2,489.72	2,538	-1.94%
	Gross Generator Load	MW	60.46	60.71	-0.41%
	Coal Flow	Kg/hr	24,531	22,266	9.24%
	Main Steam Temperature	°C	507.2	509.95	-0.54%
	Main Steam Pressure	Bar-a	103.76	103.77	-0.01%
	Main Steam Flow	Kg/hr	229,664	226,840	1.23%
	Feedwater Temperature	°C	200.79	195.5	2.63%
	Boiler Efficiency	%	92.04	90.07	2.14%
	Nett Plant Heat Rate	Kcal/kwh	2,558.43	2,586	-1.08%

Table 2 shows that the deviation between GateCycle simulation result and actual is still less than 10% which concluded that the model is valid and can be used for simulation. This simulation used fixed load simulation and coal quality as free variable. In order to connect GateCycle simulation and worksheet program in excel, GateCycle has a feature to simulate the model by running in the background. This feature is called cycle link. Cycle link excel worksheet will be used to further simulation.

2.2 Coal Blending Scenarios

In coal blending simulation, one specimen of high rank coal with 6,456 kcal/kg of HHV and one specimen of low rank coal with 4,168 kcal/kg of HHV will be used in simulation. The ultimate analysis of those specimens can be seen in table 3.

Table 3 Ultimate Analysis

Coal Specimen	HHV (Kcal/kg)	C (%)	H (%)	O (%)	N (%)	S (%)	Ash (%)	TM (%)
Low Rank Coal	4,168	44.04	3.36	12.61	0.72	0.12	3.24	35.91
High Rank Coal	6,456	63.52	4.54	10.27	1.04	0.53	11.10	9.00

In this simulation, there will be 11 blending scenarios ranging from 0% composition of LRC to 100% composition of LRC with 10% interval. The blended ultimate analysis and blended calorific Value can be determined using eq (1) and (2)

$$HHV_b = \%X_{LRC} \times HHV_{LRC} + (1 - \%X_{LRC}) \times HHV_{HRC} \quad (1)$$

$$U_b = \%X_{LRC} \times U_{LRC} + (1 - \%X_{LRC}) \times U_{HRC} \quad (2)$$

The blended ultimate analysis and blended HHV is required for further simulation. Higher percentage means higher LRC Composition. Final blended ultimate analysis and HHV per scenario can be seen in table 4 as follows.

Table 4 Blended Ultimate Analysis and HHV

Blend Scenario	HHV (Kcal/kg)	C (%)	H (%)	O (%)	N (%)	S (%)	Ash (%)	TM (%)
0%	6,456	63.52	4.54	10.27	1.04	0.53	11.10	9.00
10%	6,227	61.57	4.42	10.50	1.01	0.49	10.31	11.69
20%	5,998	59.62	4.30	10.74	0.98	0.45	9.53	14.38
30%	5,769	57.68	4.19	10.97	0.94	0.41	8.74	17.07
40%	5,540	55.73	4.07	11.21	0.91	0.37	7.96	19.76
50%	5,312	53.78	3.95	11.44	0.88	0.33	7.17	22.46
60%	5,083	51.83	3.83	11.67	0.85	0.28	6.38	25.15
70%	4,854	49.88	3.71	11.91	0.82	0.24	5.60	27.84
80%	4,625	47.94	3.60	12.14	0.78	0.20	4.81	30.53
90%	4,396	45.99	3.48	12.38	0.75	0.16	4.03	33.22
100%	4,168	44.04	3.36	12.61	0.72	0.12	3.24	35.91

2.3 Boiler Simulation

Boiler is one of the main component in CFPP system. Boiler is used to convert high pressurized feed water into superheated steam to roll the turbine. Boiler consists of 4 main equipment : Furnace, Convection zone, Air Heater, and Mill [13]. In order to maintain perfect combustion, boiler needed more combustion air known as excess air.

Combustion air can be determined by using stoichiometric calculations. Kenneth, et al stated that the amount of combustion air flow depends on the element of carbon, hydrogen, oxygen, nitrogen, and sulphur in coal [14]. Combustion air flow can be calculated by using empirical formula or using mass and element balance. Combustion air flow can be calculated using equation (3) and (4).

$$AFR = 11.51 \times C_b + 4.31 \times S + 34.3 \times H - 4.32 \times O \quad (3)$$

$$CAF = AFR \times CF \quad (4)$$

Boiler energy performance indicators can be determined from boiler efficiency, there are 2 methods to calculate boiler efficiency, direct method and indirect method [15]. ASME PTC 4 conducted, there are five heat losses from boiler calculation of indirect method as follows in equation (5) to (10)

$$\eta_b = 1 - (L_1 + L_2 + L_3 + L_4 + L_5) \quad (5)$$

$$L_1 = \frac{W_{fg} \times (h_{fg} - h_{air})}{CF \times HHV} \quad (6)$$

$$L_2 = \frac{TM \times CF \times (h_v - h_f)}{CF \times HHV} \quad (7)$$

$$L_3 = \frac{H \times CF \times (h_v - h_f)}{CF \times HHV} \quad (8)$$

$$L_4 = \frac{UBC \times Ash}{1 - UBC} \times CF \times HHV_{ash} \quad (9)$$

$$L_5 = L_{econ} + L_{ww} + L_{LTSH} + L_{HTSH} \quad (10)$$

Previous experiment stated that using lower coal calorific value reduced furnace temperature. Sarofim, et al stated that furnace temperature can be calculated using radiation heat transfer formula [16]. Furnace temperature formula can be described in equation (11).

$$Q = A_{corr} \times A_t \times K_{rad} \times \sigma \times (T_{g,eff}^4 - T_{w,eff}^4) \quad (11)$$

3 Result and Discussion

This section presented the results of simulation that had been done to observe the effects of using coal blending method on plant effect and performance. Boiler operating parameters and performance also become the content of this part.

3.1 Boiler Parameter – Coal Flow

Increasing LRC composition in blending ratio will reduce final calorific value entering furnace. With lower coal calorific value, in order to generate equal steam flow to produce same generator load will require higher coal flow as seen in fig 3.

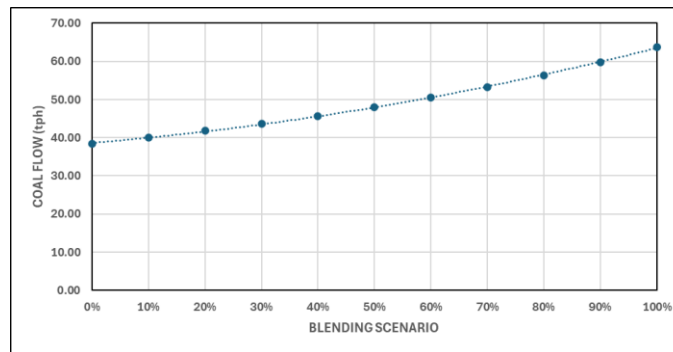


Figure 3 Coal Flow vs Blending Scenario

From figure 3, it is shown that by increasing LRC in blending composition, Ombilin CFPP needed higher coal flow to produce 100 MW. In 100% blending scenario, it need 63.78 ton/h of coal flow while in 0% blending scenario, it only need 38.45 ton/h of coal flow. By increasing 1% of LRC Composition in blending scenario will increase coal flow by 0.253 ton/h.

From figure 3, maximum coal blending allowed should be determined in order to maintain plant sustainability. Ombilin CFPP has 4 mills with 3 operating mills and 1 mill in stand by phase as redundant. Maximum coal flow allowed in Ombilin CFPP mill is 45 ton/h in all 3 mills or 15 ton/h each mills. Maximum coal blending scenario can be seen in fig 4.

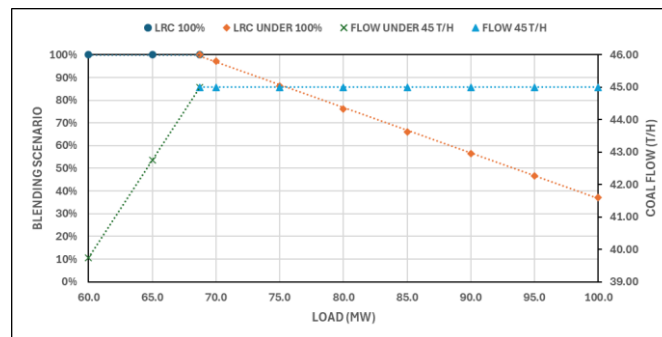


Figure 4 Maximum Allowed Coal Blending

Figure 4 showed that in order to produce 100 MW in Ombilin CFPP, maximum coal blending allowed with 3 mills operate is 37% LRC composition. Higher LRC composition will result in reduced plant load by 0.498 MW for every 1% rise of LRC. When using 100% LRC Composition, Ombilin CFPP can only produce 100 MW.

3.2 Boiler Parameter – Combustion Air Flow

Other parameters which is affected by using lower calorific value other than coal flow is combustion air flow. LRC has lower carbon content than HRC, increasing LRC composition will reduced blended carbon content entering the furnace. Lower carbon content will reduce the Air Fuel Ratio (AFR) needed for perfect combustion. Since Combustion flow is the function of AFR and coal flow, hence lower AFR does not mean lower combustion air flow as seen in figure 5.

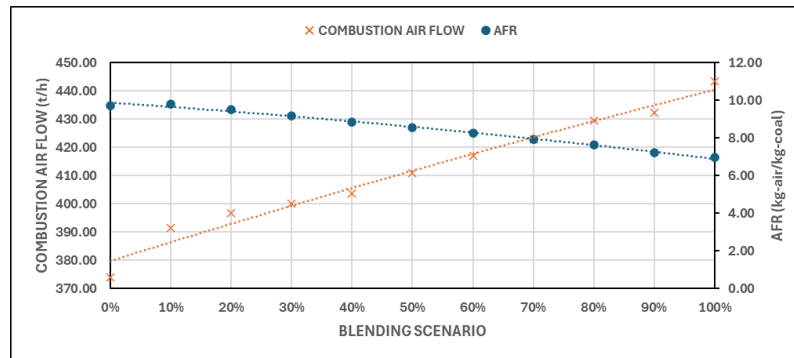


Figure 5 Air to Fuel Ratio and Combustion Air Flow vs Blending Scenario

Fig 5 shows that by using 100% LRC composition to produce 100 MW will result in increased total combustion air flow to 443.25 t/h with 6.95 kg-air/kg-coal AFR. Since Ombilin CFPP can only use 37% LRC composition, hence Ombilin CFPP will need 403.75 t/h combustion air flow and 8.95 kg-air/kg-coal AFR. Increased combustion air flow will also affect in Force Draught Fan (FDF) electrical load. Assumed that FDF operates with constant pressure ratio and 95% electrical efficiency from its design, then by using 37% LRC composition increased FDF electrical load from 217.68 kW to 257.91 kW. FDF electrical load increased by 18.48% from its original value.

3.3 Boiler Parameter – Furnace Temperature

Using lower calorific value will also have impact in furnace temperature and stack temperature. Lower calorific value slightly reduced furnace temperature but increased stack temperature significantly. Furnace and stack temperature change can be seen in fig 6.

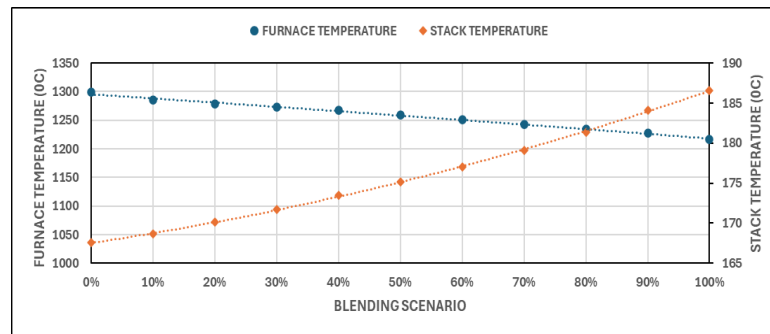


Figure 6 Furnace and Stack Temperature Change

Figure 6 shows that highest furnace temperature is 1,299 °C and the lowest is 1,216 °C. Furnace temperature slightly drops by 83 °C from using 0% LRC composition and 100% LRC composition. Stack temperature increased by 19.02 °C from 0% LRC composition to 100% LRC composition. Since using lower calorific value tends to increase combustion air flow, then the flue gas energy released from boiler will also increase. With constant flow, water and steam will not absorb more energy to produce a 100 bar-a and 510 °C. This phenomenon will result in higher stack temperature when using lower calorific value.

3.4 Boiler Performance

Lower calorific value will also result in boiler performance degradation. Low rank coal has significantly higher total moisture than the high rank coal. By increasing LRC composition in coal blending will increase blended total moisture of coal entering the furnace. Change of boiler performance can be seen in fig 7.

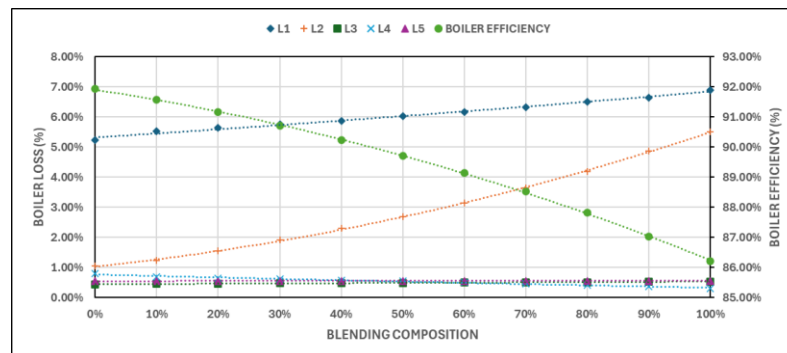


Figure 7 Boiler Performance vs Blending Composition

Figure 7 showed that by increasing LRC composition will reduce boiler efficiency from 91.94% to 86.20%. Reduced boiler efficiency mostly is

contributed from increasing of losses due to dry gas and losses due to moisture in fuel. Losses due to dry gas increased from 5.24% to 6.89%, it happened because higher LRC composition will increase stack temperature and flue gas flow due to higher combustion air flow. Losses due to moisture content increase from 1.04% to 5.51%. Losses due to moisture content define how much water in fuel entering the furnace. Moisture tends to absorb heat produced from combustion reaction until it convert into steam. Higher moisture will require more heat to evaporate into steam, which leads to increasing of losses due to moisture content.

4 Conclusion

From the entire study, simulation and result, it can be concluded that coal blending method using LRC as its composition in HRC design boiler will affect its performance significantly. Coal flow increased by 0.253 ton/h for every 1% increase of LRC composition. With maximum mill capacity as its constraint, in order to produce 100 MW, allowable LRC composition in coal blending ranging from 0 – 37%. Higher LRC composition will also result in combustion air flow rise which affect increasing of FDF electrical load by 18.48% from its original load. More LRC composition will also increase total moisture content entering the furnace and reducing boiler efficiency from 91.94% to 86.20%. This result can be applied to typical CFPP with 100 MW capacity. For larger capacity and different design, another simulation is required.

5 Acknowledgement

We thank PLN Indonesia Power, PT PLN (Persero) Pusat Penelitian dan Pengembangan and Institut Teknologi Bandung for supporting in arranging this paper. We also thank to PLN Indonesia Power UBP Ombilin for data supporting and UBP Teluk Sirih for GateCycle modelling simulation running.

REFERENCES

- [1] W. Jia *et al.*, “Co-combustion of carbon-rich fraction from coal gasification fine slag and biochar: Gas emission, ash sintering, heavy metals evolutions and environmental risk evaluation,” *Chem. Eng. J.*, vol. 471, no. April, p. 144312, 2023, doi: 10.1016/j.cej.2023.144312.
- [2] M. Riasetiawan *et al.*, “Coal rank data analytic for ASTM and PSDBMP classification,” *Int. J. Innov. Res. Sci. Stud.*, vol. 6, no. 2, pp. 374–380, 2023, doi: 10.53894/ijirss.v6i2.1469.
- [3] ESDM, “72F25-Web-Publish-Statistik-2022,” *Stat. Ketenagalistrikan*

Pln, vol. 36, pp. 1–114, 2022.

- [4] E. Ditjen Minerba, “Harga Acuan - Ditjen Minerba 2023-12-24.” 2024.
- [5] Menteri Energi dan Sumber Daya Mineral Republik Indonesia, “Keputusan Menteri Energi dan Sumber Daya Mineral Republik Indonesia No. 77 Tahun 2022 tentang Kebijakan Mineral dan Batubara Nasional,” *Kepmen ESDM*, pp. 1–46, 2022.
- [6] N. Cahyo, R. B. Sitanggang, H. H. Alif, and C. Hudaya, “Co-combustion Characteristics of Low- And Medium-Rank Coal of the Circulating Fluidized Bed Boiler Coal Power Plant,” *2019 IEEE 2nd Int. Conf. Power Energy Appl. ICPEA 2019*, pp. 282–285, 2019, doi: 10.1109/ICPEA.2019.8818503.
- [7] M. Tontu, “Feasibility Study on the Combustion of Low-Rank Coal in the Pulverized Coal-Fired Power Plant in Turkey,” 2021.
- [8] A. L. Putra, W. A. Widodo, and A. Nugroho, “Numerical Study Effect Using Low Rank Coal on Flow Characteristics, Combustion, and Furnace Exit Gas Temperature on Tangentially Fired Pulverized Coal Boiler 350 MWe,” *Lect. Notes Electr. Eng.*, vol. 876, no. January 2022, pp. 281–287, 2022, doi: 10.1007/978-981-19-1581-9_31.
- [9] D. Zhang, “Effect of coal blending on particle agglomeration and defluidisation during spouted-bed combustion of low-rank coals,” *Fuel Process. Technol. - FUEL Process TECHNOL*, vol. 70, pp. 41–51, 2001, doi: 10.1016/S0378-3820(01)00130-8.
- [10] A. M. Reza, M. A. Susetyo, and F. B. Juangsa, “Biomass Co-firing Effect on Coal Feeder and Draught Plant for 50 MW Class CFB Boiler Type CFPP,” *ICT-PEP 2021 - Int. Conf. Technol. Policy Energy Electr. Power Emerg. Energy Sustain. Smart Grid, Microgrid Technol. Futur. Power Syst. Proc.*, pp. 113–118, 2021, doi: 10.1109/ICT-PEP53949.2021.9601047.
- [11] V. Black, *Power Plant Engineering*. SPRINGER, 2021. doi: 10.1201/9780429069451.
- [12] ASME PTC PM, *Performance Monitoring Guidelines for steam power plants. Performance test codes*, vol. 2010. 2013.
- [13] J. Kitto and S. Stultz, *Steam: Its generation and use*, 41st ed., vol. 51,

14 Fransiskus Xaverius Adeodatus Alfa Febriant, Willy Adriansyah,
Mochamad Soleh

no. 1. 2005.

- [14] K. W. Ragland and K. M. Bryden, *Combustion Engineering, Second Edition*. 2011. doi: 10.1201/b11548.
- [15] ASME, *Asme Ptc 4.1 1-B 64*, vol. 1, no. 3. 1999.
- [16] H. C. Hottel and A. F. Sarofim, *Radiative transfer*.