Optimization of Biomass and Coal Mixtures on Co-firing Systems at Power Plants Using Deterministic Algorithm

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Abstract. Co-firing is a combustion system that involves two or more types of fuel in one combustion chamber. The abundant availability of biomass and the depletion of availability are the background for this co-firing. This study aims to determine the optimum composition of coal and biomass and to optimize the mixture. Optimization begins by modeling the objective and constraint functions. The variables used are HHV which represents the calorific value of the fuel, S as a parameter of exhaust emissions, RB as a parameter for preventing incidents, and HBB as a parameter of fuel prices. Then proceed with optimization using Matlab software and using SQP and Interior Point algorithms. The objective function value obtained from the optimization using the SQP method has met all the specified constraints, while in the optimization using the Interior Point method there is one variable that does not meet the constraints.

Keywords: Co-firing · Optimization · Deterministic · SQP · Interior Point

1 Introduction

Electrical energy is a type of energy that is the main need of society. Electricity is a type of energy which every year has increased in consumption. According to PLN's statistical data since 2012 until 2020, electricity consumption has increased by 39.9% [1]. As consumption increases, production must also be increased. Currently, to obtain electrical energy, processing is required from primary energy in the form of natural products such as oil, gas, and coal. As a non-renewable energy source, one day the non-renewable energy source will run out if its use continues to increase [2]. Indonesia

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itself has coal availability of only 2.2% of world reserves, but the production level is relatively large, which is around 450 million tons per year, so it is estimated that coal reserves can last around 60 years [3]. In addition to the impact on the depletion of the availability of natural resources, the increasing use of natural resources has an impact on environmental conditions [4]. One way to overcome this is by implementing coal-biomass co-firing combustion. Biomass can be an energy reserve as well as a balance to minimize dependence on fossil fuels mixed with coal through a co- firing system.

Biomass, which is a renewable energy source has considerable potential, therefore the combination of two sources of biomass energy and coal through a co-firing combustion system is a solution to overcome these problems [5]. Therefore, an optimization process for the co- firing combustion is needed so that the co-firing process becomes more optimal by considering all the existing constraints. In this study, a deterministic optimization method was used using two algorithms, namely the SQP algorithm and Interior Point, both of which are contained in the Matlab software toolbox.

The target of this optimization is to optimize financial aspects, environmental impacts (emissions), power plant performance, and operational constraints that will be caused when conducting Co-firing at the power plant [6].

2 Methodology

2.1 Data Collection

Based on this description, it is determined that the optimized criteria are sulfur content (S) which is minimized, calorific value (HHV) is maximized, the Base Ratio (RB) and the price of coal and biomass (HBB) is minimized. There are four types of fuel used with different properties as shown in Table 1.

2.2 Calculation of HHV Variable Constraints

In the modeling of this variable constraint, it refers to the regulation of the Minister of the Environment of the Republic of Indonesia No. P.15 Year 2019 which is 550 mg/Nm3 for plants that have been established before 2019. There is data on the report on the results of the burn test at Power Plant "X" in 2014 which is shown in Fig. 1 which displays a graph of the relationship between sulfur content and exhaust SOx gas emissions.

Based on the Fig. 1, we get the equation y = 1.442,12x + 131,32 where y is SOx and X is Sulfur that contained in fuel.

Table 1. Natural gas composition.

Parameter	Coal 1	Coal 2	Wood Pellet	Sawdust
Sulphur Content (%)	0,16	0,27	0,07	0,07
Fuel Price (Rp/kg)	709,47	709,47	1400	450
Plant Heat Rate (kCal/kg)	4047	4552,42	4487	2694
Ratio Basa (%)	27,9	34,0	47,5	50,5

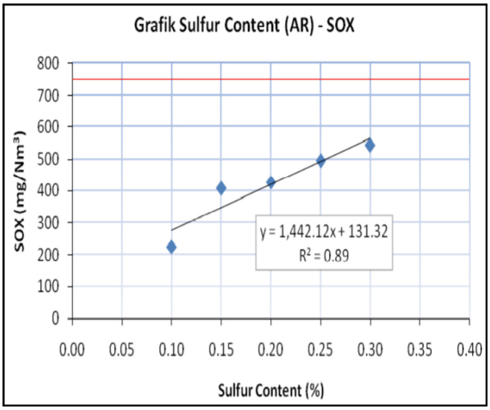

Fig. 1. Graph of SOx against Sulfur content on Power Plant "X" (PT PJB UP Paiton, 2014)

From these equations it can be calculated the maximum limit of the value of x if using the value constraint of y is ≤ 550 mg/Nm^3.

$$y = 1.442, 12x + 131, 32 \tag{1}$$

Substitute y ≤ 550, and the equation become

$$550 \leq 1.442, 12x + 131, 32 \tag{2}$$

$$x \leq \frac{(550 - 131, 32}{1.444, 12} \tag{3}$$

$$x \leq 0, 290 \tag{4}$$

Thus, the limit for the variable sulfur content (S) must be less than 0,290% (S ≤ 0,29%).

2.3 Calculation of RB Variable Constraints

TO minimize the occurrence of operational problems, the potential for slagging-fouling is to use the parameter, namely the ash base ratio of the fuel. The ash base ratio of the fuel itself affects the Ash Fusion Temperature (AFT) value of fuel ash. The AFT value must be higher than the boiler furnace temperature so that the potential for slagging-fouling will be smaller. Power Plant "X" has a maximum furnace boiler temperature of 1200 °C with a safety factor in the range of 60 °C. Then the AFT of coal ash should be ≥ 1260 °C. In Fig. 2, the greatest potential for the occurrence of slagging-fouling is at the base percentage of 35% to 63%. For the coal ash AFT to be ≥ 1260 °C, the base ratio must be less than or equal to 35% or it must be greater than or equal to 0.63 (x ≤ 0.35; x ≥ 0.63). So that the operating constraint on the potential for slagging fouling with the base ratio parameter (RB) must be below 0.35 or more than 0.63 (RB ≤ 0,35; RB ≥ 0,63).

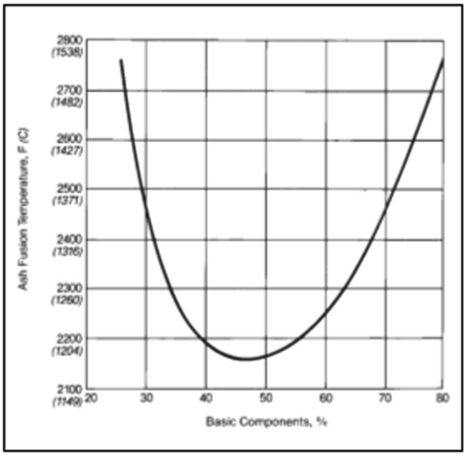

Fig. 2. Graph of Relationship Between % Base and AFT (J.B Kitto and S.C. Stultz, 2005)

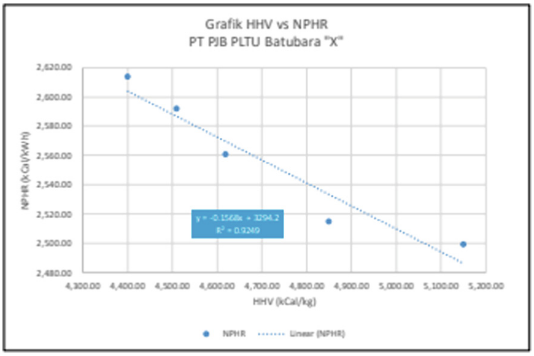

Fig. 3. Graph of NPHR against HHV Power Plant "X" (PT PJB UP Paiton, 2017)

In this study, the parameters for the NPHR constraint were determined based on the NPHR performance contract value of Power Plant "X" in 2017 with a target of 2642.64 kcal/kWh. So, the NPHR value must be smaller than the target number. To get a limit on the value of the NPHR input variable, the HHV value of fuel is calculated based on the graph of the results of the coal burning test at power plant "X" as shown in Fig. 3 and the results of the Heat Rate test for PPA by PLN Research and Development Center at power plant "X" as shown in the Fig. 4.

The equation in Fig. 3 is used to calculate the HHV value of fuel to know the impact of Power Plant load (GGO) on NPHR, where "y" is NPHR, and "x" is GGO.

$$y = 0,0074x^2 - 5,8079x + 3738,1 \tag{5}$$

$$\Delta y = y1 - y2 \tag{6}$$

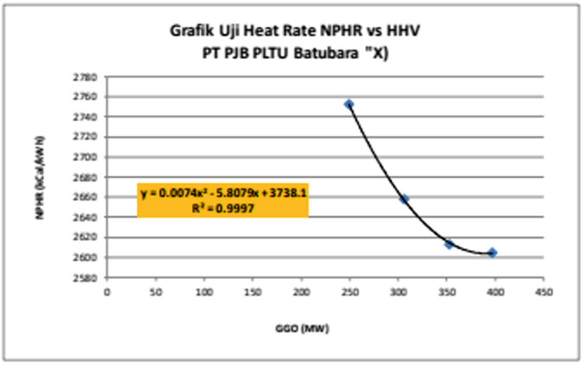

Fig. 4. Graph of NPHR against GGO Power Plant "X" (PT PJB UP Paiton, 2015)

If on y1 the Capacity Factor (CF) value of Power Plant "X" is 80% and GGO is 400 MW, then the GGO value is obtained, namely GGO = 400 MW x 80% = 320 MW and y2 is when the CF condition is 100% then GGO = 400 MW. Then the value of GGO is substituted in Eq. (5), then the values of y1 and y2 are substituted into Eq. (6), then the value of Δy is obtained as follows.

$$y1 = 0,0074\,x\,(320)^2 - (5,8079\,x\,320) + 3738,1$$

$$y1 = 2637,33\,kCal/kWh$$

$$y2 = 0,0074\,x\,(400)^2 - (5,8079\,x\,400) + 3738,1$$

$$y2 = 2598,94\,kCal/kWh$$

The value of Δy is substituted into the equation in Fig. 3 to determine the effect of fuel HHV on NPHR where "y" is NPHR of 2642.64 kcal/kWh and "x" is HHV. So that the value of x is obtained as follows

$$y = -0,1568x + 3294,2 + \Delta y$$

$$y = -0,1568x + 3294,2 + 38,39$$

$$y = -0,1568x + 3332,59$$

$$2642,64 = -0,1568x + 3332,59$$

$$x = 4400,19\,kCal/Kg$$

So, for the NPHR value used a variable in the form of HHV which must be greater than 4400.19 kcal/kg (HHV $\geq$ 4400.19 kcal/kg).

2.4 Calculation of HBB Variable Constraints

Then for modeling the HBB value, it is obtained from the calculation of the BPP component C value from Power Plant "X" data on the Java Bali electricity system in June 2020. The target of this merit order is that the BPP Component C must be lower than Rp. 436.8/kWh. Then the following equation is used which is the equation to calculate the value of HBB.

$$BPP\ component\ C = NPHR \times \frac{fuel\, prise}{HHV\, of\, fuel} \tag{7}$$

It is known that the BPP value of component C is 436.8 Rp/kWh with fuel HHV of 4400.19 kcal/kg, and NPHR of 2642.64 kcal/kWh. Then the data is substituted into Eq. (7) to get the value of the fuel price variable as follows

$$436,8 = 2642,64 \times \frac{fuel\, prise}{4400,19}$$

Based on the above calculation, it is found that the price of mixed fuel between biomass and coal must be less than Rp. 727.3 for each kilogram (BB Price 727.3 Rp/kg).

2.5 Calculation of HBB Variable Constraints

This optimization there are also constraints that must be met in the calculation, namely the total fuel flow should not be greater than the maximum volumetrix capacity boiler capacity of 220 tons/hour, so that if it is assumed that each type of fuel comes from each storage, the flow of each type of the fuel that comes out of each storage in one hour should not be more than 55,000 tons/hour.

Another constraint that must be met is the generator output power (GGO) in this co-firing optimization must be greater than the generator installs capacity (GGO = 400 MW). Then, in the application of co-firing, there is a limit to the ability of the installed equipment, namely the maximum percentage of biomass from the total fuel that can be used is 5%.

2.6 Determination of Objective Function

$$\sum_{i=1}^{5}\sum_{j=1}^{5} Sij.\left(\frac{Xij}{Q}\right) = S \tag{8}$$

$$\sum_{i=1}^{5}\sum_{j=1}^{5} HBBij.\left(\frac{Xij}{Q}\right) = HBB \tag{9}$$

$$\sum_{i=1}^{5}\sum_{j=1}^{5} HHVij.\left(\frac{Xij}{Q}\right) = HHV \tag{10}$$

$$\sum_{i=1}^{5}\sum_{j=1}^{5} RBij.\left(\frac{Xij}{Q}\right) = RB \tag{11}$$

With:
S = Sulfur Content (%).
HBB = fuel price (Rp/kg).
HHV = Calorific value of fuel (kCal/kg).
RB = Ratio of fuel ash base (%).
Q = Total Flow of fuel (kg/hour).
x = amount of fuel flow.
i = type of fuel “i”.
j = boiler silo "j".

3 Co-firing Optimization

OptiMization was carried out using Matlab software. This optimization is carried out to determine the mixture of biomass and coal for combustion carried out in the boiler. Optimization is carried out using a deterministic optimization method because there are predetermined constraints. There are two optimization algorithms used, namely SQP and Interior-Point. If the results of the optimization carried out do not meet the set constraints, the optimization will be carried out again.

3.1 Optimization Results with the SQP Method

Optimization is carried out using the variables HHV, RB, HBB, and S. Obtained a graph of the change in the value of the objective function as the number of iterations increases. Optimization will stop if the difference in the value of the last 2 iterations is less than a certain value. The change in value can be seen in Fig. 5 to Fig. 8.

The objective function values obtained from the optimization results for each variable are as shown in Table 2. In the optimization using the SQP method, the ratio of the amount of fuel used in combustion is as shown in Table 3.

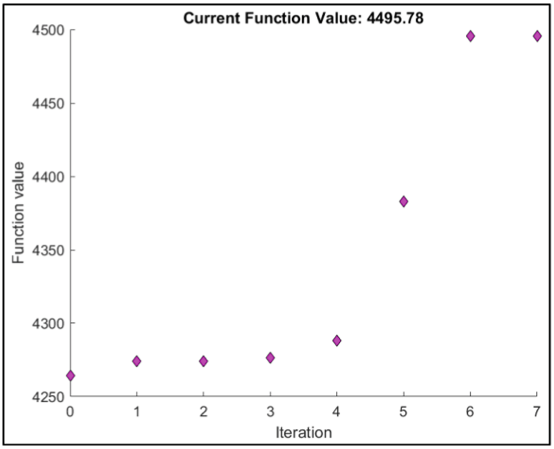

Fig. 5. Graph of Changes in the Value of the Objective Function of the HHV Variable Using SQP Method

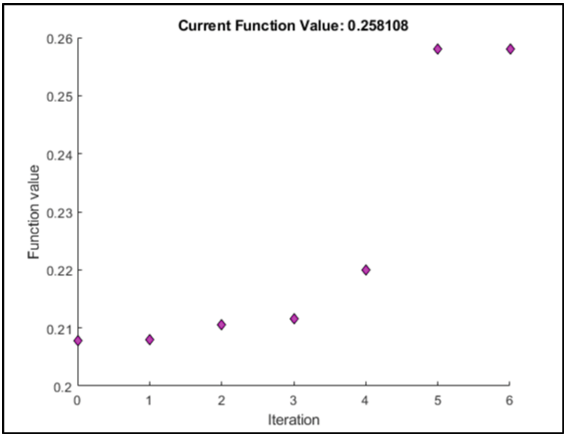

Fig. 6. Graph of Changes in the Value of the Objective Function of the S Variable Using SQP Method

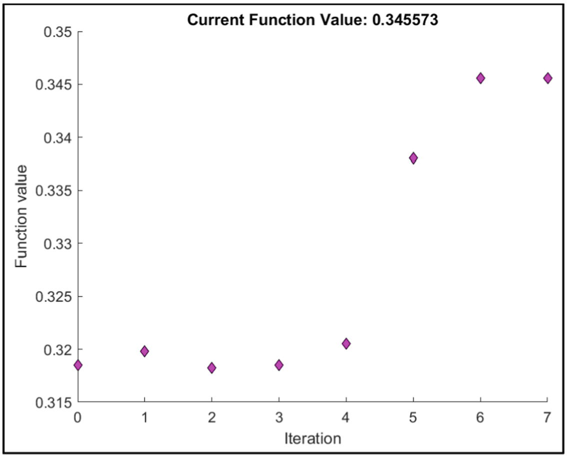

Fig. 7. Graph of Changes in the Value of the Objective Function of the RB Variable Using SQP Method

3.2 Optimization Results with the Interior Point Method

The equations are an exception to the prescribed Optimization is carried out using the variables HHV, RB, HBB, and S. Obtained a graph of the change in the value of the objective function as the number of iterations increases. Optimization will stop if the difference in the value of the last 2 iterations is less than a certain value. The change in value can be seen in Fig. 9 to Fig. 12.

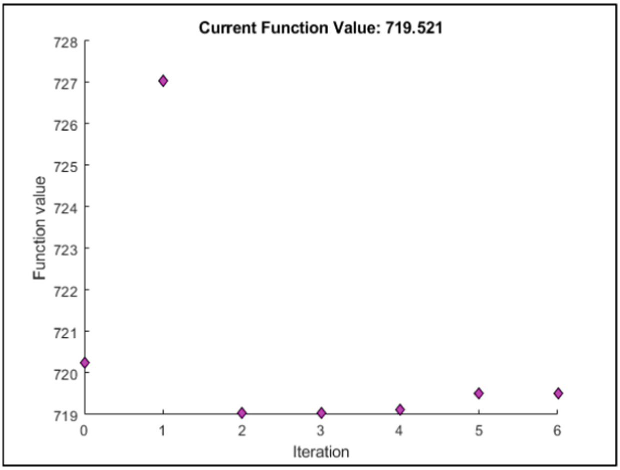

Fig. 8. Graph of Changes in the Value of the Objective Function of the HBB Variable Using SQP Method

Table 2. The objective function of the optimization result using SQP

Optimization Variable	Objective Function
HHV	4.495,78 kcal/kg
S	0,258108%
RB	34,56%
HBB	Rp. 719,521

Table 3. Mixture amount of each fuel using SQP Method

Fuel Types	Lots of Mixes (kg/hour)
Coal 1	5.250
Coal 2	209.407,87
Wood Pellet	5.250
Sawdust	5.250

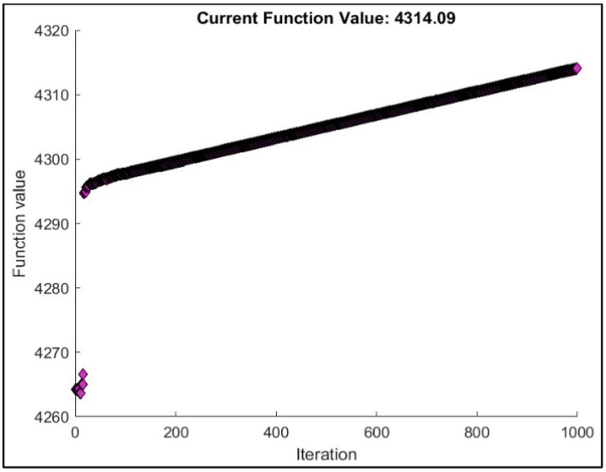

Fig. 9. Graph of Changes in the Value of the Objective Function of the HHV Variable Using Interior Point Method

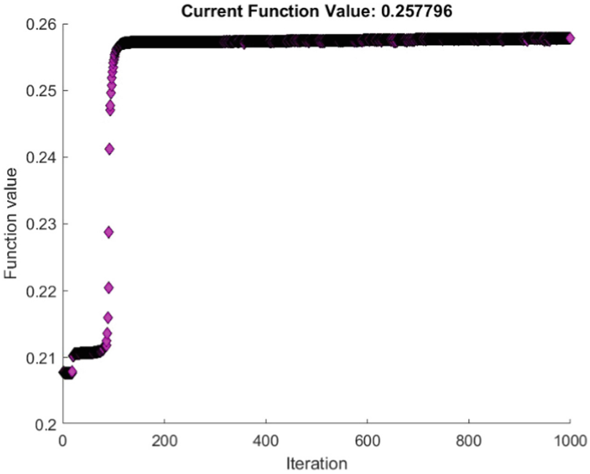

Fig. 10. Graph of Changes in the Value of the Objective Function of the S Variable Using Interior Point Method

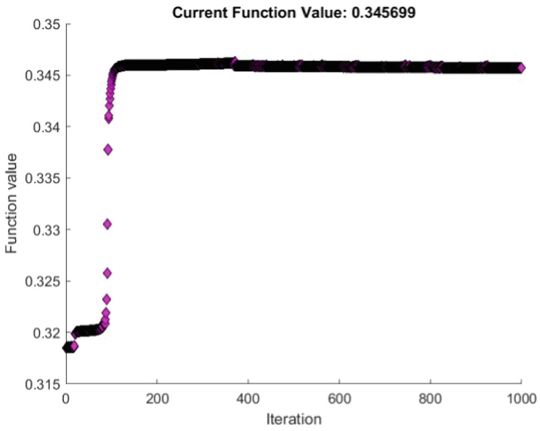

Fig. 11. Graph of Changes in the Value of the Objective Function of the RB Variable Using Interior Point Method

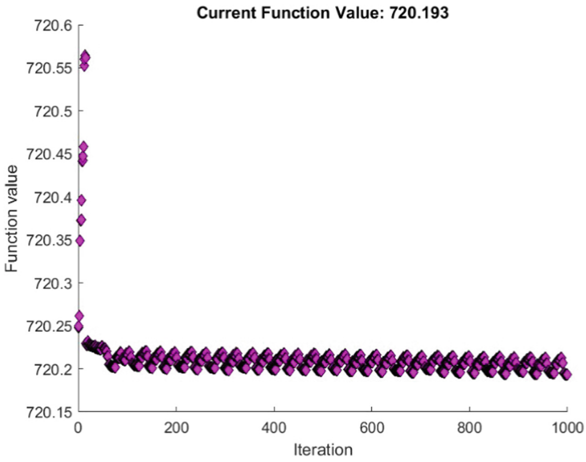

Fig. 12. Graph of Changes in the Value of the Objective Function of the HBB Variable Using Interior Point Method

Table 4. The objective function of the optimization result using Interior Point

Optimization Variable	Objective Function
HHV	4.495,78 kcal/kg
S	0,258108%
RB	34, 56%
HBB	Rp. 719,521

Table 5. Mixture amount of each fuel using Interior Point Method

Fuel Types	Lots of Mixes (kg/hour)
Coal 1	5.250,21
Coal 2	206,646,67
Wood Pellet	5.266,60
Sawdust	5.250

Table 6. Comparison before and after optimization

Emission (mg/Nm^3)	Before Optimized	After Optimized	
		SQP	Interior Point
SO_2	509,595	503,386	SO2

4 Results and Analysis

4.1 Power Plant Performance Analysis Result of Co-firing Optimization on HHV Variable

Based on the data in Table 2 and Table 4, it is found that the optimization results on the HHV variable which has a maximum objective function and has a value of 4,495.78, where the optimization result is 2% greater than the constraint. This means that the HHV variable which symbolizes the calorific value of the fuel optimized using the SQP method has met the limits in accordance with the predetermined constraints, while the HHV variable optimized using the Interior Point method has an objective function that is less than the specified constraint. Because the HHV variable is a variable that has a maximized objective function, it is necessary to use the SQP variable.

4.2 Environmental Impact Analysis Result of Co-firing Optimization on S Variable

THEN for the variable S which symbolizes SOx exhaust emissions, where the sulfur content produced in this optimization process is 11% lower than the predetermined constraint. If the optimization results are substituted back into the previous equation, the exhaust gas emission figures derived from the optimization results are 503.4 mg/Nm^3 for the SQP method and for the Interior Point method, which is 501.9 mg/Nm^3, both of which are still below the threshold. The quality standard that has been set by the Ministry of Environment and Marine Affairs of the Republic of Indonesia is 550 mg/Nm^3.

The implementation of the Co-firing system is carried out with the main objective of reducing the resulting exhaust emissions. When compared with the conditions before the optimization was carried out, which used pure coal as fuel. The variable that represents the exhaust emission is S with the parameter sulfur content. The coal used has sulfur content of 0.16 and 0.27. If it is substituted into the previous equation using the percentage of Coal 2 used is the same as the optimization results, then the SOx exhaust emission is 0.262 which if converted to the form of mg/Nm^3 has a value of 509.595 mg/Nm^3. This reduction in exhaust emissions is because biomass has lower exhaust emissions. The following is a comparison of exhaust gas emission data carried out in this study.

4.3 Analysis of Potential Constraints at Power Plant Result of Co-firing Optimization on RB Variable

The RB variable which symbolizes the safe limit to prevent potential operational constraints is slagging-fouling. The objective function for this RB variable is the minimum, where as much as possible the value of this RB is smaller than the predetermined constraint so that there are no operational constraints. The results of the optimization show a number that is smaller than the set constraint. The constraint on the RB variable is less than 0.35, while the optimization results using the SQP method show an objective function of 0.34 and for the Interior Point method, the objective function is 0.3457, both of which have shown numbers below the constraint. This means that the potential for operational constraints that occur will be smaller and of course there will still be a risk of technical problems and will incur costs for maintenance and repairs if damage occurs.

4.4 Economic Impact Analysis of Co-firing Optimization Results on HBB Variables

The last variable is HBB which symbolizes the price of fuel used. The limit that has been set is Rp. 727.3 for every kilogram of it. In the optimization results, the objective function value of the HBB variable is slightly lower than the set constraint. This means that there is a slight decrease in production costs that will be incurred by the plant in implementing Co-firing. Even though the difference is only 1% of the constraint, the value is for every kilogram. The combustion in a power plant requires hundreds of tons of fuel, of course, the price difference will have a big impact if it happens many times over.

Although the implementation of Co-firing is primarily aimed at reducing exhaust emissions, if based on the results of the optimization, it is in accordance with the established limits, if it results in operational problems and increases costs significantly, it is necessary to re-optimize the Co-firing system. Can run optimally.

This study also reviews the economic impact. Where in the condition before optimization has a price of Rp. 709.47 for each kilogram. The initial price is also lower than the existing constraint, which is 727.3 IDR/kg. The optimization results for fuel prices show the figure of 719,521 Rp/kg, which indicates that the price is below the constraint and above the initial price. However, the increase in costs is due to the use of fuel in the form of biomass which has a price almost 2x the price of coal.

In the ratio of coal and biomass optimization results, it is substituted with the price of the fuel. For the composition of the optimization results using the SQP method, the required cost per hour is Rp. 162,005,819, and for the optimization results using the Interior Point method, the cost required for each hour in the Co-firing process is Rp. 160,070,219. Although the costs required for the optimization results with the SQP method are higher, the four optimized variables have met the existing constraints, so the ratio used is based on the results of the optimization using the SQP method.

5 Conclusion

After going through the optimization process, the optimum mixture ratio between biomass and coal is obtained by considering the constraints that have been set. The composition of the fuel used based on optimization using the SQP method is 5,250 kg of type 1 coal, 209,407.47 kg of type 2 coal, 5250 kg of Wood Pellet biomass, and 5,250 kg of Sawdust biomass so that the total cost required for each hour is IDR 162,005,819.

Then for the composition of the fuel used based on optimization using the Interior Point method, for type 1 coal as much as 5,250.21 kg, type 2 coal as much as 206,646.67 kg, WoodPellet biomass as much as 5,266.60 kg, and Sawdust biomass as much as 5,250 kg so that the total the cost required for each hour is Rp 160,070,219.

The optimization process begins with modeling the objective function based on data from PT. X. Then, the constraint modeling is used as a constraint in the optimization process. After getting the optimization variables, namely the objective and constraint functions, then proceed with optimization using two deterministic algorithms, namely SQP and Interior Point. The objective function values for each variable are as follows: HHV of 4495.78 kcal/kg, S of 0.258%, RB of 0,3456, and HBB of 719.521 for the SQP method. Meanwhile, using the Interior Point method, the objective function values for each variable are as follows: HHV of 4,306.84 kcal/kg, S of 0.257539, RB of 0.3457, and HBB of 720.208. The optimization results using the Interior Point method have one variable, namely HHV which does not meet the constraints, so the optimization results used are those using the SQP method.

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