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Maximum Biomass Co-Firing Percentage Mixture on 100 MW Pulverized Coal Boiler Using GateCycle Simulation Modelling

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Abstrak
Dalam rangka mencapai target *Net Zero Emission (NZE)* Indonesia pada tahun 2060, penerapan *co-firing* biomassa pada Pembangkit Listrik Tenaga Uap (PLTU) eksisting berbahan bakar batu bara merupakan salah satu metode terbaik dan paling memungkinkan untuk diterapkan. Makalah ini menunjukkan persentase maksimum biomassa yang dapat digunakan pada PLTU tipe *Pulverized Coal (PC) Boiler* berkapasitas 100 MW melalui simulasi menggunakan perangkat lunak GateCycle. Berdasarkan hasil simulasi, peningkatan campuran biomassa yang masuk ke dalam *furnace* akan meningkatkan total aliran bahan bakar untuk mempertahankan daya keluaran sebesar 100 MW. Campuran biomassa lebih dari 8% cenderung menyebabkan kebutuhan total aliran bahan bakar melebihi kapasitas maksimum *coal mill* sebesar 45.000 kg/jam, atau mengurangi beban generator apabila aliran bahan bakar total dibatasi pada kapasitas maksimum tersebut. Setiap peningkatan 1% campuran biomassa di atas 8% akan menurunkan *Gross Generator Load* sebesar 0,7505 MW. Selain itu, peningkatan campuran biomassa juga berpotensi meningkatkan laju *slagging*, karena suhu tungku hasil simulasi GateCycle berada pada kisaran 1.258,11 °C hingga 1.276,07 °C, sementara titik leleh abu (*ash fusion temperature*) biomassa adalah 1.185 °C. Setiap kenaikan 1% campuran biomassa juga akan meningkatkan *Specific Fuel Consumption* (SFC) sebesar 0,0028 kg/kWh. Berdasarkan hasil simulasi, persentase maksimum biomassa yang direkomendasikan untuk digunakan pada *PC Boiler* adalah sebesar 8%.

Kata kunci: *Biomassa, Beban, Suhu, Campuran, Kapasitas.*

Abstract
Abstract—For establishing Indonesia's NZE target in 2060, biomass co-firing in existing Coal Fired Power Plant (CFPP) is one of the best and applicable method. This paper shows maximum biomass percentage on 100 MW scaled PC Boiler CFPP can handle by using GateCycle simulation. From the simulation, by increasing biomass mixture entering the furnace, it will increase total fuel flow in order to produce 100 MW. Biomass mixtures higher than 8% will tend to required total fuel flow exceeding maximum mill capacity which is 45,000 kg/hour, or reduced Generator Load while setting total fuel flow entering furnace same with maximum mill capacity. For every 1% increasing biomass mixture above 8%, it will reduced Gross Generator Load by 0.7505 MW. Increasing will also potentially increase slagging rate as the furnace temperature calculated from GateCycle simulation is 1,258.11 0C to 1,276.07 0C, while the ash fusion temperature of biomass is 1,185 0C. Also, increasing 1% of biomass mixture will increase the Specific Fuel Consumption by 0.0028 kg/kwh. From the simulation it is stated that maximum biomass percentage allowed for PC Boiler is 8%.

Keywords: *Biomass, Load, Temperature, Mixture, Capacity.*

1. INTRODUCTION

Energy and power generation are the most important sectors which drive nation's economy growth. Electricity which is produced from power generation is needed in any level of aspects to maintain economy sustainability, especially in Indonesia. In 2020, the energy and electricity supply of Indonesia is still dominated 67% by coal fired power plant, which means the sustainability of coal fired power plant is still needed in national scale (PLN, 2021). The large amount of coal fired power plant usage will also has a huge impact on climate change knowing that the result of combustion progress from fossil fuels mostly Carbon Dioxide (CO2) which can accelerate global warming, and CO2 is one of the greenhouse gasses classified by the United Nation Convention alongside with Dinitrogen Oxide (N2O), Methane (CH4), Sulphur Hexafluoride (SF6) and Perfluorocarbons (PFCS) (Rahmadania, 2022). In 2019, Indonesia already produced 638,452 Tons CO2, contributed from energy sector mainly from power generation sector (43.83%), transportation sector (24.64%), manufacturing and construction industry sector (21.46%), other sectors (4.13%). Indonesia government set a commitment to reduce 29% green house or 834 million tons of CO2 equivalent in 2030 from Business as Usual (BaU) condition. Energy sector has target for reducing 314 million tons CO2 equivalent. CO2 Emissions can be reduced by implementing CCUS, and Biomass Co-Firing. CCUS method costs a lot of investment and needs a large amount area, while biomass co-firing method costs less investment, because it can be implemented without modifying equipment if the mixture applied is below allowance (Destalia *et al.*, 2024). With the dominance of Coal Fired Power Plant (CFPP) in composition of power generation, Biomass Co-firing is the best method for reducing CO2 emissions and achieving goal of reducing greenhouse gases, because it is cheaper and easier to implement than applying CCUS. Biomass combustion will still produce CO_2; however, it is assumed that the amount of CO2 produced by biomass combustion has the same amount of CO2 that was absorbed within the life cycle of plants, and it is defined as "carbon neutral". However, all installed CFPP in Indonesia are designed to use specified coal as their main fuel.

Various Studies and manufacture states that PC Boiler, which typically has ratios maximum of 3%, actually it can use 3% - 20% mass basis ratio of biomass, but it will have issue in slagging, fouling, and efficiency loss. Circulating Fluidized Bed (CFB) Boiler covers a wider range of co-firing mass basis mixture up to 30%, as high as 60%, while stocker boiler can completely convert 100% biomass, but stocker boiler only be used for small scale power generation (Lou *et al.*, 2023). Mixing biomass and coal will reduce fuel calorific value and need more total fuel flow needed for generating same generator load than using as designed coal. Increased total fuel flow will increase secondary and primary air flow. Reduced input energy in furnace will affect change in Furnace Exit Gas Temperature (FEGT) and stack temperature. In PC Boiler. Maximum total fuel flow is limited by the specification of coal feeder and pulverizer / coal mill for PC Boiler. From those facts, authors want to study the maximum percentage of co-firing mass basis mixture and operating parameters with various constraints such as maximum total fuel flow from coal mill specification, Furnace Exit Gas Temperature (FEGT).

The study will start with heat balance modelling using Gate Cycle V5.61 Simulation application using designed fuel and operating parameters from commissioning test then author will run the simulation with off-design method using biomass mixture from 1% to 30% and determined maximum percentage of biomass mixture and create optimized operation parameter. This Study will also give a perspective for engineers about Maximum and limitation of biomass co-firing mixture due to several specific power plant parameters related to the constraint.

2. METHODOLOGY

In off-design simulation method, GateCycle will compute the resulting state of working fluid using the geometries calculated from the On-Design running method. Properties and condition of fluid are no longer the inputs, but they will become the outputs. Simulation running methodology can be seen in Figure 1.

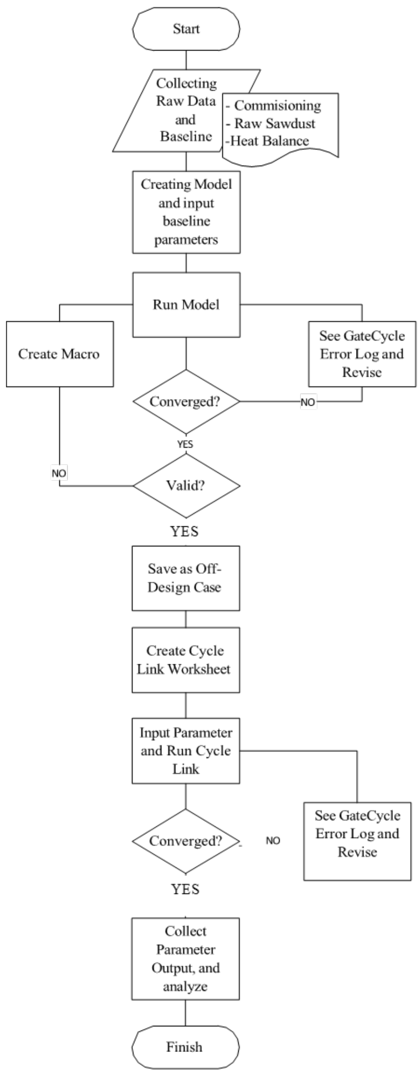

Figure 1. Flowchart Modelling Simulation Usin GateCycle

This study will use a 100 MW non- Reheat, Pulverized Coal (PC) type boiler, using 5 water heaters (2 Low Pressure Heaters, 2 High Pressure Heaters and 1 Deaerator) using off- Design GateCycle ver 5.61. Commissioning data and heat balance are required to make a valid power plant model. Sawdust ultimate analysis will be used in off-design method for biomass co-firing heat balance simulation. In some case a macro is needed to acquire desired parameters which are not provided as an input in GateCycle, such as power generated, feedwater temperature outlet heater, etc.

Table 1. Design fuel specification

Parameters	Unit	Worst	Design	Commissioning
Carbon	%Wt	59.53	68.03	63.52
Hydrogen	%Wt	4.09	4.91	4.54
Oxygen	%Wt	7.03	9.39	10.27
Nitrogen	%Wt	1.13	1.18	1.04
Sulphure	%Wt	0.82	0.91	0.53
Ash Content	%Wt	13.00	10.97	11.1
Total Moisture	%Wt	14.40	4.61	9.00
Total	**%Wt**	100	100	100
High Heating Value	Kcal/kg	5953	6876	6456

This Pulverized Coal boiler is typically designed for using high calorific value which is shown in Table 1. Coal Calorific Value, ultimate analysis are essential parameters in calculating plant performance. Fuel calorific value of coal is determined by testing using calorimeter bomb, with as Received basis as its results using ASTM D5865 Standart. The analysis will use worst coal as its basis due to the high price and insufficient supply of High Rank Coal, and sawdust as biomass material specification can is shown in Table 2.

Table 2. Ultimate anlysis of sawdust

Parameters	**Unit**	**Value**
Carbon	%Wt	19.71
Hydrogen	%Wt	4.19
Oxygen	%Wt	30.95
Nitrogen	%Wt	0.33
Sulphure	%Wt	0.03
Ash Content	%Wt	0.92
Total Moisture	%Wt	43.87
Total	**%Wt**	100
High Heating Value	Kcal/kg	2508

GateCycle modelling will require mixed ultimate analysis and mixed Calorific Value from sawdust and coal, which can be determined by using equation (1) and equation (2).

$$\%U = (\%Ub \times \%Xb) + (\%Uc \times (1 - \%Xb)) \quad (1)$$

$$HHV = (HHVb \times \%Xb) + (HHVc \times (1 - \%Xb)) \quad (2)$$

where:
%U = Mixed Fuel element content (%Wt)
%Ub = Biomass element content (%Wt)
%Uc = Coal element content (%Wt)
%Xb = Biomass mass mixture
HHV = Mixed High Heating Value (Kcal/kg) HHVb = Biomass High Heating Value (Kcal/kg)
HHVc = Coal High Heating Value (Kcal/kg)

A. Boiler Equipment Simulation

Boiler Model can be used to design and analyze the performance of the furnace of conventional, radiant fossil- fueled boilers. The main operating parameters are the total fuel flow or heat input, fuel mixture specifications, and excess air specifications, which are used in both design and off-design mode. In Boiler Modelling combustion calculations, all combustible matter is assumed to be converted into combustion products (CO2 and H2O) consuming oxygen from the combustion air. To ensure complete combustion of all combustibles in a real combustion environment, it is normal practice to provide slightly more combustion air than is required theoretically (stoichiometrically). For calculating dry gas losses, as combustion product can be determined by Eqs. (3) and (4) based on ASME PTC 4.1 Standart (Terranova, 1999).

$$W_{dg} = \left(\frac{11\times CO_2+8\times O2+7\times(N_2+CO)}{3\times(CO_2+CO)}\times C_b+\frac{3}{8}\times S\right) \quad (3)$$

$$\dot{m}_{air} = w_{dg}\times\dot{m}_f \quad (4)$$

Where:
C_b = Carbon Burned (%Wt)

CO = Carbon Monoxide in Flue Gas (%Wt)
CO_2 = Carbon Dioxide in Flue Gas (%Wt)
m_{air} = Combustion Air Flow (kg/hr)
m_f = Total Fuel Flow (kg/hr)
N_2 = Nitrogen in Flue Gas (%Wt)
S = Sulphur Content in Fuel (%Wt)
W_{dg} = Dry gas ratio (kg-drygas/kg-fuel)

GateCycle cannot provide Heat Loss Method Boiler Efficiency as its output, the amount of Boiler Efficiency can be determined using ASME PTC 4.1 standard with direct and indirect method.

- Direct Method

This method compares the amount of steam energy produced with the amount of fuel energy entering boiler and can be calculated using Eq. (5),

$$\eta_{b-io} = \frac{\dot{m}_s \times h_s - \dot{m}_{fw} \times h_{fw}}{\dot{m}_f \times HHV} \times 100\% \quad (5)$$

Where :
η_{b-io} = Boiler Efficiency (%)
h_{fw} = Feedwater Enthalpy (kcal/kg)
HHV = High Heating Value (kcal/kg)
h_s = Main Steam Enthalpy (kcal/kg)

- Indirect Method

This method is based on accurate and complete information which will make possible the calculations to determine all accountable losses. There are 6 losses occurred in Boiler, since GateCycle assumed a perfect combustion which there is no Carbon Monoxide product in Flue Gas, hence Losses due to Incomplete Combustion can be neglected. Indirect method boiler efficiency can be expressed in equation (6) to (10).

$$\eta_{b-hl} = 100\% - (L_1 + L_2 + L_3 + L_4 + L_5) \quad (6)$$

$$L_1 = \frac{w_{dg} \times (h_{fg} - h_{air})}{HHV} \times 100\% \quad (7)$$

$$L_2 = \frac{\%TM \times (h_v - h_a)}{HHV} \times 100\% \quad (8)$$

$$L_3 = \frac{9 \times \%H_2 \times (h_v - h_a)}{HHV} \times 100\% \quad (9)$$

$$L_4 = \frac{(U_{ba} \times F_{ba} + U_{fa} \times F_{fa}) \times HHV_a}{HHV} \times 100\% \quad (10)$$

where:
η_{b-hl} = Boiler Efficiency (%)
$\%H_2$ = Hydrogen Content in Fuel (%Wt)
%TM = Total Moisture Content in Fuel (%Wt)
F_{ba} = Fraction of Botom ash (%Wt)
F_{fa} = Fraction of Fly Ash (%Wt)
h_a = Enthalpy of Vapor at 1 Psi-a and Ambient Temperature (kcal/kg)
h_{air} = Enthalpy of Ambient Air (kcal/kg)
h_{fg} = Enthalpy of Flue Gas (kcal/kg)
HHV_a = Ash Heating Value (kcal/kg)
L_1 = Heat Loss Due to Dry Gas (%)
L_2 = Heat Loss Due to Moisture in Fuel (%)

L_3 = Heat Loss Due to H_2O from combustion of H_2 (%)
L_4 = Heat Loss Due to Combustible in Refuse (%)
L_5 = Heat Loss Due to Radiation (%)

GateCycle can calculate the amount of radiant loss in all equipment, hence ABMA chart for calculating L5 is not needed.

B. Overall Performance

GateCycle cannot provide Efficiency and Heat Rate as its performance result, manual formula computation is required to determine NPHR (Net Plant Heat Rate), GTHR (Gross Turbine Heat Rate), and SFC (Specific Fuel Consumption). Plant Performance indicator can be calculated using ASME PTC 46 (ASME, 2013) standard shown in equation (11) to (13).

$$GTHR = \frac{\dot{m}_s \times h_s - m_{fw} \times h_{fw}}{P_g} \quad (11)$$

$$NPHR = \frac{\dot{m}_s \times h_s - m_{fw} \times h_{fw}}{\eta_b \times (P_g - P_{aux})} \quad (12)$$

$$SFC = \frac{\dot{m}_f}{P_g} \quad (13)$$

Where:
GTHR = Gross Turbine Heat Rate (kcal/kwh)
NPHR = Nett Plant Heat Rate (kcal/kwh)
P_{aux} = Auxiliray Power (kW)
P_g = Gross Generated Power (kW)
SFC = Specific Fuel Consumption (kg/kwh)

After model was created, as seen in Figure 2, a running test is needed to check whether the model is converged or not. If the model is not converged or converged with an error, a troubleshooting action is needed by revising input parameters or setting. A validation will be used after plant model is converged. A validation will compare between actual parameters (heat balance and commissioning) with parameters provided by GateCycle after converged. Deviation exceeding 10% means that the heat balance model is not valid, a revision is needed. Modelling validation of 100 MW CFPP will be shown in Table 3, deviation which is below 10% is considered as valid.

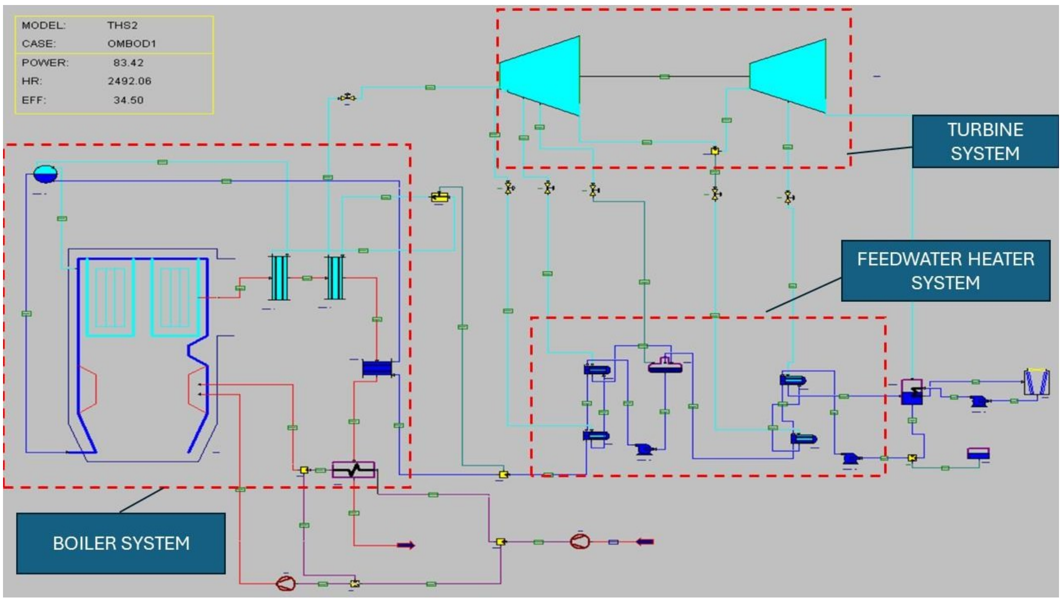

Figure 2. Heat Balance Model of 100 MW PC CFPP

Table 3. Modelling validation

Parameters	Unit	Actual	GateCycle	Deviation
Gross Power Output	MW	102.03	99.64	2.34%
Fuel Flow	Kg/hr	36482	38778.18	-6.29%
Main Steam Temp.	0C	510.22	509.94	0.05%
Main Steam Press.	Bar-a	102.097	108.416	-6.19%
Vaccuum Press.	Bar-a	0.091	0.0954	-4.84%
Feedwater temp.	0C	225.67	222.054	1.60%
Boiler Efficiency	%	89.29	92.45	-3.54%
GTHR	Kcal/kwh	2178.13	2271.28	-4.28%
NPHR	Kcal/kwh	2469	2456.76	0.50%

3. RESULTS AND DISCUSSION

Increasing biomass mixture will tend to decrease final calorific value of fuel entering the furnace and it will have many impacts on many aspects. Using lower calorific value In order to produce constant load will require more total fuel flow as shown in Figure 3.

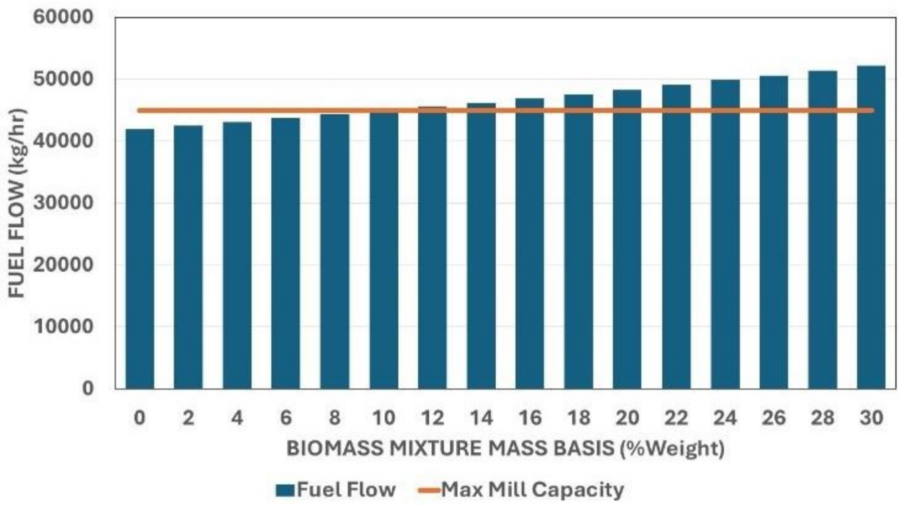

Figure 3. Total Fuel Flow Required

In PC Boiler, fuel will be pulverized using mill in order to reduce its size to 200 mesh. Increased fuel flow entering mill will have impact on increasing mill and feeder load. If total fuel flow exceeds maximum mill capacity, it will reduce mill and feeder reliability. In 100 MW scale PC Boiler, maximum mill capacity is 45,000 kg/hr as its constraint for total fuel flow. From GateCycle off-design result, in order to produce 100 MW under maximum mill capacity allowed, maximum mixture should not exceed 8%. To increase mixture exceeding 8%, lowering Generator Output is required, so that total fuel flow entering furnace will not exceed maximum mill capacity.

Increasing mixture of biomass with lower calorific value will have impact on producing lower energy of combustion which can be seen in Furnace Temperature (Cahyo *et al.*, 2019). The furnace temperature from gatecycle off-design method can be seen in Figure 4.

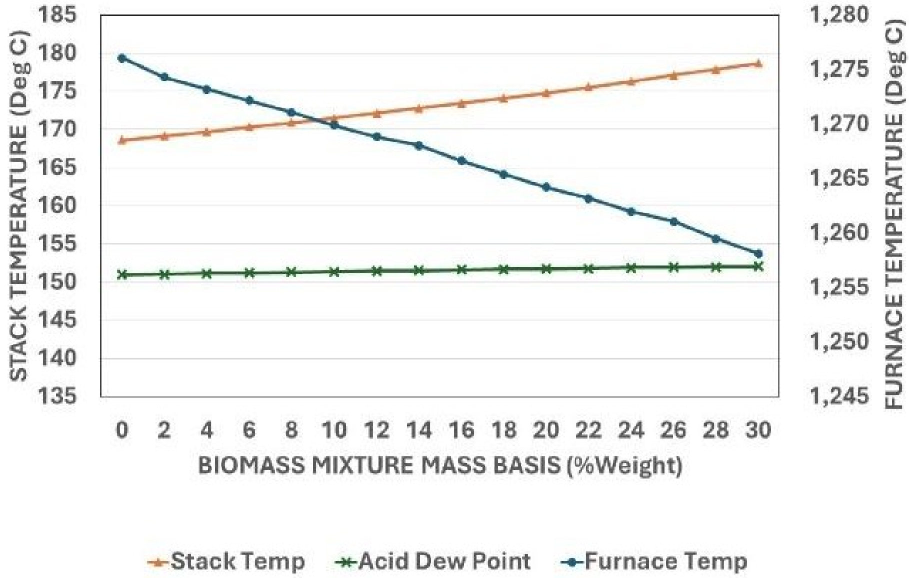

Figure 4. Furnace Temperature from GateCycle Modelling

Based GateCycle simulation, furnace temperature is still in a range of 1,258.11 to 1,276.07 ^{0}C, in order to generate 100 MW with the lowest furnace temperature occurred in 30% mixture with 1,258.11 ^{0}C and the highest furnace temperature occurred in 0% mixture with 1,276.07 ^{0}C since 0% mixture has higher heating value than 30% mixture as shown in Table III. Furnace temperature will always correspond to slagging formation, when ash fusion temperature of fuel entering the furnace is lower than furnace temperature, it will tend to form slagging outside boiler tube. Due to its own characteristic, coal has different ash fusion temperature with sawdust, 1292.4 ^{0}C for coal (Sianipar *et al.*, 2019), and 1185 ^{0}C for sawdust (Adi Sasongko *et al.*, 2023). From simulation results, it is shown that furnace temperature is higher than biomass ash fusion temperature, hence using biomass co- firing will increase slagging rate in boiler tube, increasing mixture of biomass will increase slagging rate formation in boiler. Increasing mixture of biomass will also increase stack temperature, with maximum temperature occurring for 30% mixture is 178.69 ^{0}C, but it is still higher than acid dew temperature using verhoff-banchero method.

Increasing biomass mixture which has impact on lowering final calorific value will also tend to decrease boiler efficiency due to increasing of stack temperature as shown in figure 5 and increasing of combustion air flow (Cahyo *et al.*, 2019). Impact of increasing biomass mixture to Boiler performance and losses can be seen in Figure 5.

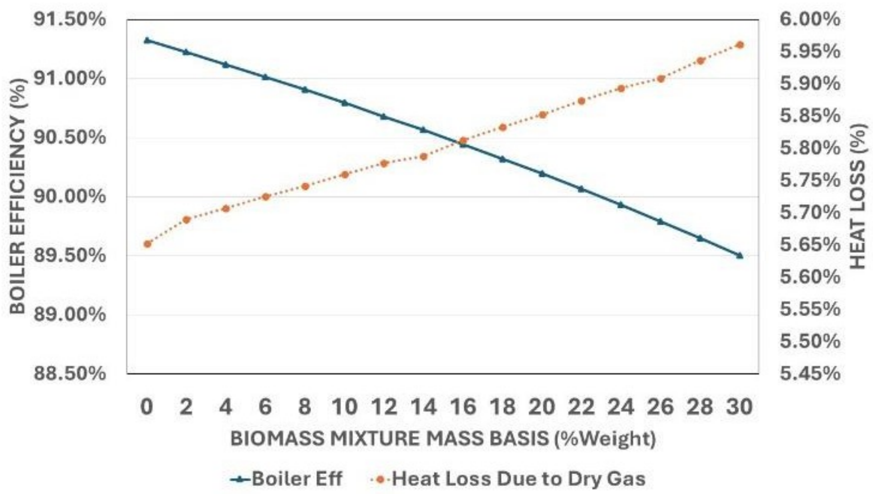

Figure 5. Biomass Mixture Effect on Boiler Efficiency and Heat Loss

From Figure 5, by increasing biomass mixture can reduce boiler efficiency from 91.33% with 0% mixture to 89.51% with 30% mixture at the same generator load. Boiler efficiency calculation assumed same fly ash and bottom ash production. Decreased boiler efficiency was caused by the increase of Heat Loss due to dry flue gas from 5.65% to 5.96%. Increasing biomass mixture will reduce Air and Fuel Ratio, but since the total fuel flow increased significantly, it will require more combustion air flow which can be seen in Figure 6.

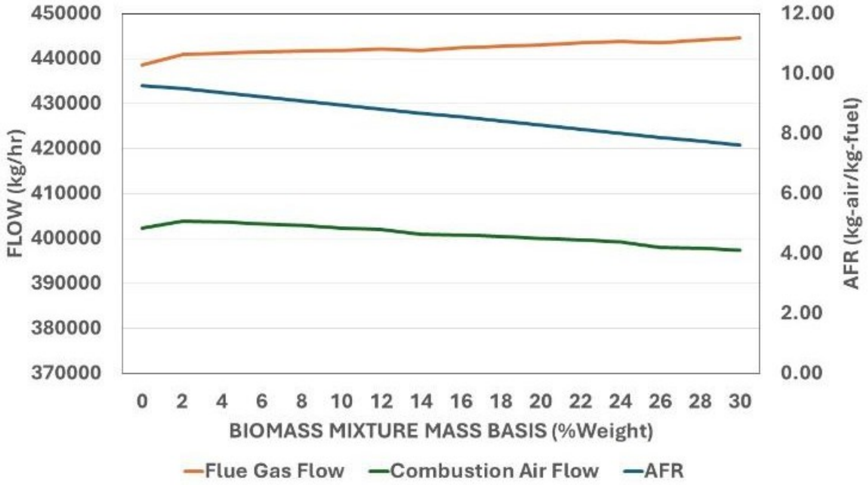

Figure 6. Flue Gas and Combustion Air Flow

Increasing biomass mixture will decrease total %Carbon fuel mixture, using stoichiometric formula shown in Eqs. (14)-(16), lower %Carbon will need lower O_2 for combustion:

$$C + O_2 \rightarrow CO_2 \quad (14)$$
$$H_2 + O_2 \rightarrow 2H_2O \quad (15)$$
$$S + O_2 \rightarrow SO_2 \quad (16)$$

Carbon Content will have more effects to determine the amount of oxygen flow for combustion than the other coal elements. Theoretically, with lower %Carbon, will require less Oxygen ratio, but since Oxygen flow is determined by total fuel flow, total oxygen required for combustion will fluctuate. For 30% mixture, total %Carbon is 47.58%.

Different biomass mixtures will also affect total performance since the boiler efficiency decreased as the increasing biomass mixture. Energy Performance Indicator (EnPI) for plant performance can be determined in NPHR, GTHR and SFC. Simulation result of NPHR, GTHR and SFC can be seen in Figures 7 and 8.

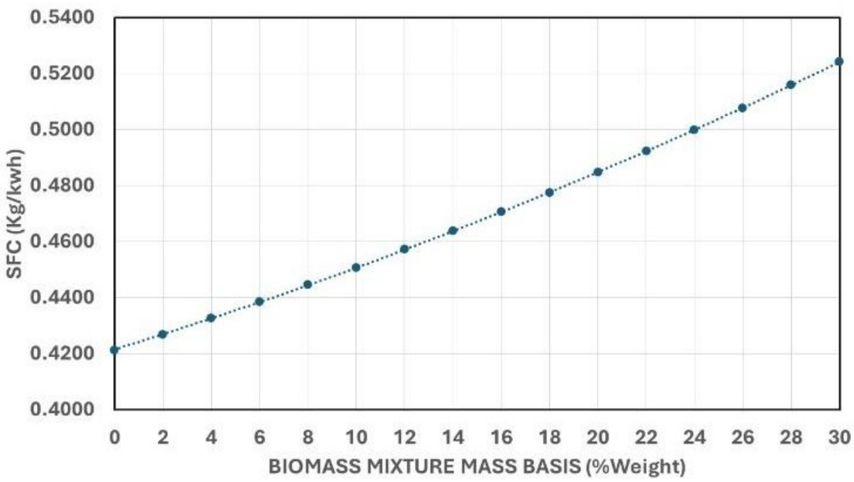

Figure 7. SFC Rise on Increasing Biomass Mixture Mass Basis

Since increasing biomass mixture will decrease final calorific value, in order to generate same load will need more energy which leads to higher total fuel flow. SFC is the amount of fuel flow to generate 1 kwh electricity. Higher total fuel flow will also increase plant SFC as seen in figure 7. When using 0% mixture, plant SFC is 0.4213 kg/kwh, and it keeps increasing as more biomass is added into furnace. From empirical polynomial formula, increasing 1% biomass mixture tends to increase SFC by 0.0028 kg/kwh to generate same load.

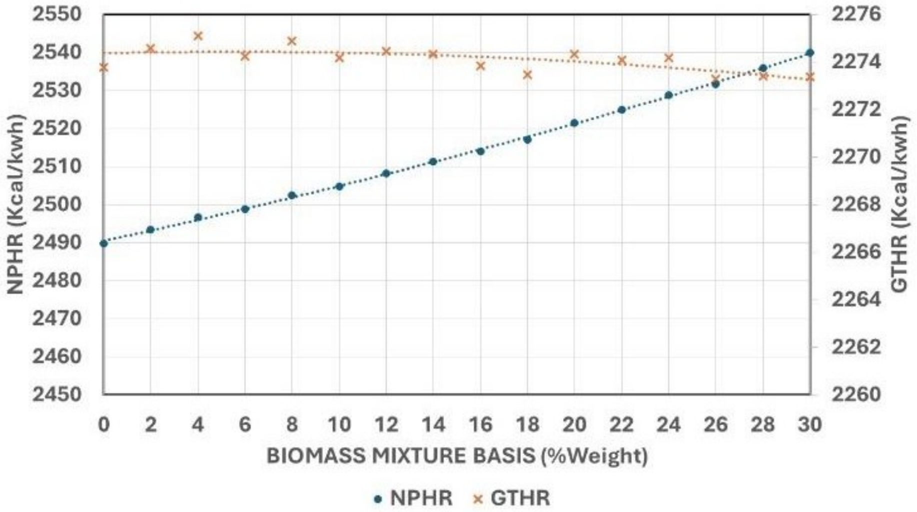

Figure 8. NPHR and GTHR Rise on Increasing Biomass Mixture Mass Basis

Same thing also works in GTHR and NPHR, since SFC, NPHR and GTHR are comparison of input energy to output energy. Figure 8 shows the NPHR and GTHR movement versus biomass mixture. By increasing biomass mixture also tends to rise NPHR, when using 0% mixture, plant NPHR is 2,489.72 kcal/kwh and it keeps increasing until 30% mixture with plant NPHR is 2,539.93 kcal/kwh. Increased NPHR occurred due to decreased Boiler Efficiency as the biomass mixture is increased. GTHR tends to stay steady as biomass mixture is increased because it will only affect combustion progress which affects only boiler performance. Using empirical polynomial equation, increasing 1% biomass mixture tends to increase NPHR by 1.3602 Kcal/kwh.

From Analysis of boiler characteristics and performance characteristics, in order to set a maximum mixture of biomass percentage, maximum mill capacity will be the constraint. From figure 3 it is shown maximum mixture is 8% biomass percentage in order to produce 100 MW. Increasing biomass mixture can be achieved but the total fuel flow must be limited corresponding to maximum mill capacity, thus will result in reduced power generated as shown in figure 9.

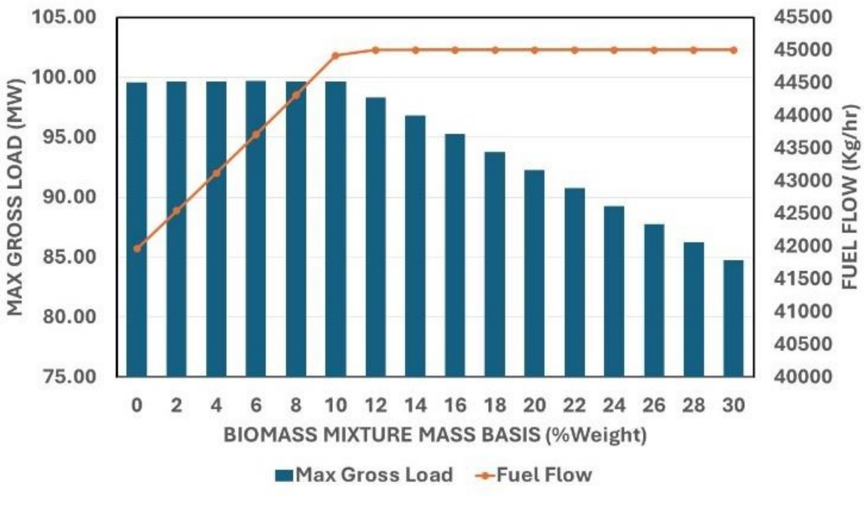

Figure 9. Maximum Load with Maximum Mill Capacity Fuel Flow

From Figure 9, three mixture is simulated by setting maximum mill capacity as its total fuel flow. From the simulation, it is shown that by using 10% mixture, maximum gross load is 98 MW, 20% mixture's maximum load is 92.27 MW and 30% mixture's maximum load is 84.75 MW. The effect of biomass mixture after exceeding 8% mixture on maximum Generator load can be seen in Figure 10.

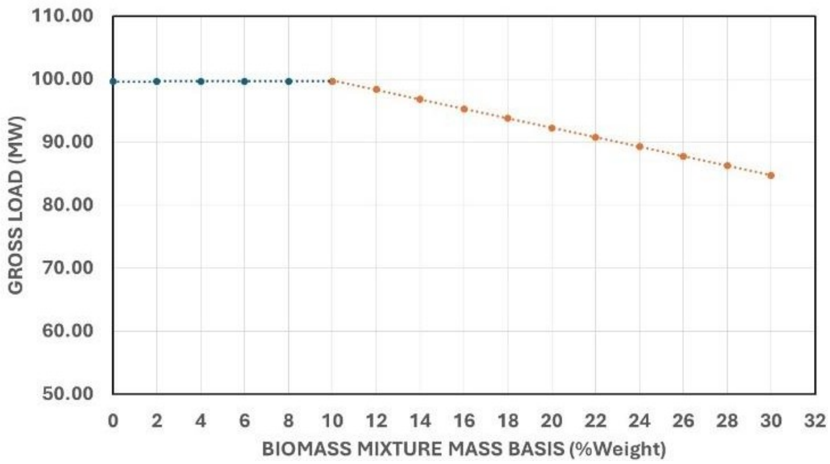

Figure 10. Effect of Biomass Mixture to Generator Gross Load

From figure 10 is shown that after exceeding 8% mixture and total fuel flow reach maximum mill capacity, maximum gross power will be decreased. By increasing 1% biomass mixture after 8% mixture, maximum generator power will decrease by 0.7505 MW. Even though it is still possible to increase biomass mixture above 8% by reducing gross load, it is still not recommended due to higher furnace temperature than biomass ash fusion temperatures, increasing biomass flow into furnace will tend to increase slagging rate, inefficient performance and severe damage on boiler tube.

4. CONCLUSION

The increased of biomass mixture will tend to increase total fuel flow required to produce same Generator Load, and will potentially damage mill for exceeding its capacity. Increasing biomass mixture also tend to increase Specific Fuel Consumption by 0.0028 kg/kwh for every 1% rise of biomass mixture. Maximum biomass mixture allowed for generating 100 MW without exceeding maximum mill capacity is 8%. Operation with biomass mixture higher than 8% will result in reduced Maximum generator Load by 0.7505 MW for every 1% mixture addition and Increasing of slagging rate in boiler tube due to higher furnace temperature than biomass ash fusion temperature. This maximum biomass mixture should be able to be applied to other PC Boiler with larger scale, as long as using sawdust biomass, however the amount of performance degradation will be quite different and require another simulation. When using lower density and Calorific Value biomass, a further simulation is required in order to calculate maximum biomass mixture.

5. ACKNOWLEDGMENT

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