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Research Article

Techno-Economic Analysis of Co-firing for Pulverized Coal Boilers Power Plant in Indonesia

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Abstract. The utilization of co-firing (coal-biomass) in existing coal-fired power plants (CFPPs) is the fastest and most effective way to increase the renewable energy mix, which has been dominated by pulverized coal (PC) boilers, particularly in the Indonesian context. This study aims to investigate the technical and economic aspects of co-firing by conducting a pilot project of three PC boiler plants and capturing several preliminary figures before being implemented for the entire plants in Indonesia. Various measured variables, such as plant efficiency, furnace exit gas temperature (FEGT), fuel characteristic, generating cost (GC), and flue gas emissions, were identified and compared between coal-firing and 5%-biomass co-firing. The result from three different capacities of CFPP shows that co-firing impacts the efficiency of the plant corresponding to biomass heating value linearly and has an insignificant impact on FEGT. Regarding environmental impact, co-firing has a high potential to reduce SO_2 and NO_x emissions depending on the sulfur and nitrogen content of biomass. SO_2 emission decreases by a maximum of 34% and a minimum of 1.88%. While according to economic evaluation, the average electricity GC increases by about 0.25 USD cent/kWh due to biomass price per unit of energy is higher than coal by 0.64×10^{-3} USD cent/kcal. The accumulation in the one-year operation of 5%-biomass co-firing with a 70% capacity factor produced 285,676 MWh of green energy, equal to 323,749 tCO2e and 143,474 USD of carbon credit. The biomass prices sensitivity analysis found that the fuel price per unit of energy between biomass and coal was the significant parameter to the GC changes.

Keywords: co-firing, biomass, coal-fired power plant, PC boiler

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1. Introduction

Fossil fuel, especially coal, is still the primary energy source on the earth and significantly contributes to atmospheric greenhouse gas (GHG) emissions. For example, even though coal power generation has already decreased to 50% of the Indonesian energy capacity, the contribution to the electricity fuel mix is still relatively high at 66.6%, making the power sector as the most significant contributor to CO_2 emissions in Indonesia. Indeed, it is directly correlated with global warming and climate change issues (Gil & Rubiera, 2019; Xu *et al.*, 2020). It causes the present environmental regulation to become even more stringent. On the other hand, the worldwide electricity demand has increased and continues to increase as a result of economic growth activity, which aligns with the electrification of all sectors due to electricity being a crucial need in modern life. Scientists, engineers, and technologists are facing the tough challenge to meet this demand, not only in the way of high-efficiency technology and affordable price but also in the sustainability of energy sources, such as biodiesel and biomass (Ibham Veza *et al.*, 2021; Verma *et al.*, 2021; Wahyudi & Garniwa M.K., 2021).

Renewable energy has been an unavoidable portion of achieving sustainable development worldwide. The recent primary worldwide agenda to reduce GHG emissions and achieve carbon neutral or net-zero emissions has encouraged every country to participate in this crucial global agenda actively. Moreover, the utilization of coal-fired power plants (CFPPs) in the world is still significantly contributing to global GHG emissions (Gil & Rubiera, 2019; Xu *et al.*, 2020). Instead of implementing low-carbon technologies (such as PV solar, wind energy, geothermal, hydropower, and ocean energy), biomass, one renewable energy with enormous availability, is potentially converted to produce electricity. Biomass can be directly used to produce electricity by two main processes: combustion and gasification. In the combustion process, biomass is used for single and mixed with other fuels such as fuel oil, natural gas, or coal. For the existing CFPP, co-firing (coal-biomass) becomes one of the solutions to reduce GHG emissions and decrease fossil fuel consumption (Devaraja *et al.*, 2020; Dzikuć & Łasiński, 2014).

As a major developing country, Indonesia shall vigorously participate in efforts to reduce GHG emissions in the world. Renewable energy usage in the electricity generation sector can significantly reduce GHG emissions in Indonesia (Dani & Wibawa, 2018). Furthermore, the Indonesian energy policy has an ambitious target to increase the renewable energy mix in the

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electricity generation sector by 23% in 2025 and 31% by 2050 (The Decree of Ministry of Energy and Mineral Resouces No188.K/HK.02/MEM.L/2021, 2021). It can be higher if some developed countries and international agencies externally support it.

Nowadays, the Indonesian energy mix in the electricity generation sector is still dominated by coal firing. The capacity of CFPP is about 32.8 GW, with 126 units located around the Indonesia region. 16 GW of CFPP is connected to the Jawa Bali Madura through a high-voltage grid system. Therefore, co-firing is utilized as a potential option to increase the renewable energy mix. Co-firing combustion can be simply done on the existing CFPP by mixing the fuel using coal and biomass before feeding the fuel to the boiler (A. Taleb *et al*., 2020; Primadita *et al*., 2020; Sugiyono *et al*., 2022). Co-firing can increase the renewable energy portion without building a new power plant, which is the fastest and cheapest way to increase the renewable energy mix (Battista *et al*., 2000; Dong *et al*., 2002; Ekmann *et al*., 1998). On the emissions impact, using biomass as a fuel substitute or mixed with coal can reduce SO_2, NO_x, and particulate matter emissions on CFPP (Devaraja *et al*., 2020).

Until 2025, the Indonesian government, through PLN as a state-owned company, has planned to implement co-firing for CFPP with a total capacity of around 18.000 MWe with an average percentage of co-firing is 10% or equal to ~9 million/year of biomass consumption (The Decree of Ministry of Energy and Mineral Resouces No188.K/HK.02/MEM.L/2021, 2021). The aforementioned total capacity is dominated by pulverized coal (PC) boiler with a percentage of 86%, followed by circulating fluidized boiler (CFB) and Stoker with a percentage of 13% and 1%, respectively.

To implement co-firing successfully, the existing plant should conduct the pilot project to ensure that specific parameters are within the acceptable value. A feasibility study of co-firing implementation at CFPP is needed. Therefore, this study aims to investigate the technical and economic aspects of co-firing by conducting a pilot project of three PC boiler plants and capturing some preliminary figures before being implemented for the entire plants in Indonesia.

2. Literature Review

2.1 Co-firing (Coal-Biomass)

Co-firing is the method of supplementary a base fuel with a different fuel. The schematic of technology is depicted in Figure 1. The variation of biomass percentage allows the use of up to 5% of biomass to avoid significant modification of the plant, which means no additional significant capital cost is needed. The portion of biomass can be increased to a higher percentage, but it needs improvement for the existing related equipment. At a certain percentage of the mix ratio, the benefits of increasing biomass ratio require the capital investment cost by modifying the plant.

The direct method is commonly used for co-firing, as shown in Figure 1a. The parallel method is implemented by installing an additional separated boiler for biomass. Figure 1b displays the schematic installations for the production of steam from two boilers; for coal and biomass. Figure 1c shows a schematic of the indirect method which can be performed in coal boilers by an additional gasifier. This method allows a high degree of the percentage of the gasification gas and provides high flexibility. Indeed, the fastest way to do co-firing is the direct method (Figure 1a) which only adds a biomass fuel “nozzle” to the existing boiler burner. It is no need for significant modification of the power system. However, the indirect method provides a positive environmental impact and can minimize emissions during combustion.

Regarding the operational experience, Indonesia is one of the late countries to implement co-firing in CFPP, especially in the utility sector. Tillman reported that co-firing was initiated in the US for several CFPPs with a range capacity of 32-469 Mwe (Tillman, 2000). The highest percentage of biomass is up to 20%. The types of biomass were wood, hybrid poplar, and switchgrass. On another continent, Monsour and Zulawa reported co-firing implementation in Europe, which consists of Austria, Denmark, Germany, Netherlands, the UK, and Poland (Tillman, 2000). The CFPP capacity varies between 124 MW to 1800 MW, with the highest biomass percentage up to 20%. The types of biomass were wood chips, straws, wood, sewage sludge, kernels, paper sludge, shells, fiber, pellets, pulverized wood, sawdust, and coffee shells. While Xu *et al.* summarized the application of co-firing in several regions, such as China, Finland, and the UK (Xu *et al*., 2020). The CFPP varies from 167 MW up to 660 MW and the lowest and the highest percentage of biomass are 1.8% and ~100%, respectively. Co-firing has been successfully operated in over 150 installations worldwide (Li *et al*., 2012).

The types of biomass were wheat straw, corn stalk, molding biomass, straw, rice husk, wood, waste, forest tree wood pallet, and olive core. Theoretically, the negative impact on plant efficiency is affected by the lower heating value of biomass (<4500 kal/kg). The study measured and summarized the efficiency reduction of the boiler by a curve-fitting approximation. The biomass percentage was measured on a mass basis in the fuel blend. The goodness of fit value was 0.7, which indicates that biomass was a significant parameter in the performance of boiler efficiency (Tillman, 2000). Another study showed that efficiency was generally lower than 30% for pure biomass and higher than 40% for co-firing (Xu *et al*., 2020).

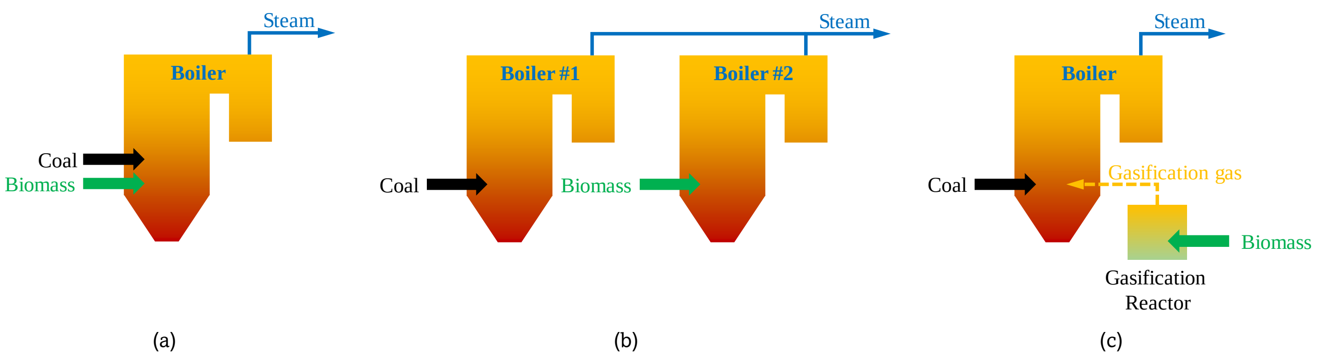

Fig. 1. The technology of co-firing: (a) direct co-firing; (b) parallel co-firing; (c) indirect co-firing. Adapted from (Al-Mansour & Zuwala, 2010).

Mehmood *et al.* have conducted a numerical simulation of PC co-firing regarding the energy losses on the boiler (Mehmood *et al., 2012).* Based on fixed heat input energy analysis, it was found that boiler energy losses from moisture become higher if the moisture content on the co-firing fuel is higher than the coal. Whereas FEGT mainly depends on ash content, total moisture, and the heating value of the fuel. The higher the ash and moisture content on the fuel, the FEGT decreases. On the other hand, the higher the heating value, the FEGT becomes higher (Mehmood *et al*., 2014).

2.2 Environmental Impact

One of the most significant sectors which produce CO_2 emissions is the energy sector (Lamb *et al*., 2021). CFPPs are one of the most emissions producers and need some measurement to reduce the emitted emissions (Anugia *et al*., 2022). Co-firing can contribute to reducing the negative impact on the environment and also provide a carbon-neutrality target.

The first step to achieve the carbon neutrality target can be obtained by substituting coal consumption (Jia & Lin, 2021). Biomass is the fuel energy source containing the fewest number of carbon chains, which contribute to the amount of CO_2 emission. Hence, it can be considered as a carbon-neutral resource. Carbon-neutral resources provide net zero emissions, which can achieve net-zero CO_2 emissions by balancing CO_2 emissions with their removal or eliminating carbon dioxide emissions (Srivastava *et al*., 2021).

Dzikuć and Łasiński investigated the contribution of co-firing to the environment by life cycle assessment (LCA) in three impact categories, such as human health, ecosystem quality, and resources. The study has analyzed some CFPPs with different percentages of biomass (5% and 7% of biomass percentage). They showed that the increased biomass in electricity production significantly reduces the environmental impact. The 7% biomass obtained a lower impact point than 5%, which means a better environmental impact (Dzikuć & Łasiński, 2014).

Co-firing with a low percentage of biomass effectively reduces emissions by a small margin, while using a high percentage of biomass gives more advantages to reduce emissions if the biomass availability is abundant (Miedema *et al*., 2017). Substituting coal with biomass on existing CFPPs decreases emissions such as SO_2, CO_2 and NO_x (Roni *et al*., 2017).

Adding biomass to coal reduces the emissions of NO_x and SO_2, but it also depends on the nitrogen concentration of the biomass (Moroń & Rybak, 2015). Co-firing of biomass using rice straw and wood reduces SO_2 emissions due to the sulfur content of rice straw and wood is lower than coal (Chang *et al*., 2019). The SO_2 emission insignificantly decreases as the proportion of woody biomass in the mixture increases and does not depend on how the combustion air was supplied (Hodžić *et al*., 2018).

Reducing GHG emissions, especially CO_2, by co-firing in fossil power plants (Kazulis *et al*., 2018), could give a robust contribution to electric power sector companies, not only to achieve Paris Agreement but also to Environmental, Social and Governance (ESG) issues, especially on environmental aspect. Commitment to ESG is becoming a powerful indicator of corporate profits and future financial performance (Atz *et al*., 2022; Koundouri *et al*., 2022; Whelan *et al*., 2021).

2.3 Existing Coal-Fired Power Plant in Indonesia

Perusahaan Listrik Negara (PLN), an Indonesian electricity state-owned company, has already developed a co-firing roadmap to implement co-firing technology on its 52 CFPPs around the nation. These power plants' capacity varies between 3.5 – 625 MW and the boiler types used consist of PC, CFB (Circulating Fluidized Bed), and Stoker. The CFPP operated and owned by PLN in detail can be seen in Table 1. The number of CFPPs with a co-firing method based on boiler type and power plant capacity. The mixing percentage of coal and biomass during the co-firing depends on the boiler type. During full-scale co-firing implementation, PC, CFB, and Stoker boilers use up to 6%, 40%, and 70% biomass mixing. Introducing co-firing method on PLN's CFPP can approximately contribute ~5% renewable energy mix in 2025 toward the national energy policy in Indonesia (The Decree of Ministry of Energy and Mineral Resouces No188.K/HK.02/MEM.L/2021, 2021).

Table 1
List of co-firing CFPP implementation

Regions	Boiler Type	No	Capacity (MW)	Green Energy & emissions reduction
Sumatera	Stocker	0	713	21 GWh & 24 thousand tCO_2
	CFB	3		
	PC	1		
Jawa-Bali	Stocker	0	11,690	231 GWh & 221 thousand tCO_2
	CFB	0		
	PC	13		
Kalimantan	Stocker	3	452	7 GWh & 11 thousand tCO_2
	CFB	2		
	PC	1		
Sulawesi	Stocker	1	471	3 GWh & 4 thousand tCO_2
	CFB	4		
	PC	0		
Nusa Tenggara	Stocker	2	151	2 GWh & 2 thousand tCO_2
	CFB	2		
	PC	0		

Table 2
Coal and biomass properties

Parameter	Plant A		Plant B		Plant C	
	Coal	Biomass	Coal	Biomass	Coal	Biomass
Proximate Analysis (As Received Basis)						
Total Moisture (%wt)	5.66	43.87	27.42	11.87	34.73	8.60
Ash (%wt)	18.48	0.92	4.10	19.76	3.08	1.17
Volatile Matter (%wt)	33.46	47.61	36.38	57.25	31.85	75.16
Fixed Carbon (%wt)	42.40	7.60	32.10	11.12	30.33	15.07
Ultimate Analysis (As Received Basis)						
Carbon (%wt)	64.17	19.71	50.08	34.10	43.24	45.70
Hydrogen (%wt)	4.30	4.19	3.84	5.68	3.05	5.45
Nitrogen (%wt)	1.28	0.33	0.90	0.54	0.63	0
Oxygen (%wt)	5.16	30.95	13.32	28.01	13.81	38.99
Sulfur (%wt)	0.95	0.03	0.34	0.04	0.16	0.09
HHV (kcal/kg)	6037	2508	4459	3241.3	4237	4294

As of February 2022, 28 CFPPs have been operated intermittently using co-firing technology. The mixing percentage of fuel and the biomass used during co-firing combustion depends on the biomass availability in each location. Mostly wood chips, wood pellets, sawdust, rice husk, and solid recovered fuel (SRF) were used for co-firing at PLN CFPPs.

Then the three selected CFPPs were investigated firstly to identify their fuel properties. The ultimate analysis of biomass is slightly different from the ultimate analysis of coal. A comparison of the ultimate analysis of coal and biomass on each plant is shown in Table 2.

2.4 Biomass Utilization in Indonesia

Biomass is an alternative fuel that can be used for co-firing. Biomass, if appropriately managed, offers many advantages, most notably as a renewable and sustainable energy feedstock because it can be produced quickly (Wulandari *et al.*, 2020). It is easily planted in various environments everywhere. Biomass from energy plantation forests or waste from palm oil or wood industry is used as coal substitution. The waste product, such as sawdust, is around 6% to 10% weight on average. Wood waste products or waste from processing agriculture products are the cheapest sources of biomass energy.

Regardless of the biomass potential is abundance around Indonesia, biomass availability is still limited to supply fuel needs. Hence, it is necessary to plant biomass for energy feedstock at a thermal power plant. The shape and size of the biomass fuel must be uniform to avoid problems in feeding the biomass fuel (Higman & van der Burgt, 2008). To obtain a uniform shape and size, biomass fuel shall be mainly processed into sawdust, woodchip, or wood pellet.

There is a potential production of about 11 million hectares (Ha) which can be converted to produce woodchips of about 95 million tonnes/year for 20.000 MW of co-firing. In addition, the availability of potential 'idle' land is about 3 million Ha. It can be converted to produce woodchips of about 25 million tonnes/year for 5.000 GW of co-firing of CFPP.

3. Method

The evaluation of technical and economic aspects were performed in this paper. Technical evaluation performed the process of assessing the technical parameter in CFPP, especially in boiler combustion performance. Then, an economic evaluation was conducted to determine the cost impact and outcomes as a result of technical changes.

3.1 Technical Evaluation

The main parameter of the technical aspect is plant performance, such as plant efficiency (η) and furnace exit gas temperature (FEGT). In addition, GHG emissions calculation was added to analyze the GHGs impact after co-firing was conducted. The following Eq. (1)-(6) were applied. The basic evaluation of coal (C) and biomass (B) co-firing were conducted by examining the difference (Δ) value between co-firing and coal firing results with parameters η, high heating value (HHV), FEGT, NOx, and SO_2.

$$\%\Delta\eta = \frac{\eta_{\text{co-firing}} - \eta_{\text{coal-firing}}}{\eta_{\text{coal-firing}}}100\% \tag{1}$$

$$\%\Delta\,\text{HHV} = \frac{\text{HHV}_{\text{co-firing}} - \text{HHV}_{\text{coal-firing}}}{\text{HHV}_{\text{coal-firing}}}100\% \tag{2}$$

$$\%\Delta\,\text{FEGT} = \frac{\text{FEGT}_{\text{co-firing}} - \text{FEGT}_{\text{coal-firing}}}{\text{FEGT}_{\text{coal-firing}}}100\% \tag{3}$$

$$\%\Delta\,\text{NO}_x = \frac{\text{NO}_{x\,\text{co-firing}} - \text{NO}_{x\,\text{coal-firing}}}{\text{NO}_{x\,\text{coal-firing}}}100\% \tag{4}$$

$$\%\Delta\,\text{SO}_2 = \frac{\text{SO}_{2\,\text{co-firing}} - \text{SO}_{2\,\text{coal-firing}}}{\text{SO}_{2\,\text{coal-firing}}}100\% \tag{5}$$

$$\%\Delta\,\text{S} = \frac{\text{S}_{\text{co-firing}} - \text{S}_{\text{coal-firing}}}{\text{S}_{\text{coal-firing}}}100\% \tag{6}$$

3.2 Economic Evaluation

The details of the economic aspect evaluated generating cost (GC) and potential benefit of CO_2 reduction. The following eq. (7)-(11) were applied. The basic evaluation of coal and biomass co-firing was conducted by examining the difference (Δ) value between co-firing and coal firing results with parameters of GC, specific fuel consumption (SFC), and fuel price.

Table 3
Plant specification

Parameter	Unit	Plant A	Plant B	Plant C
Power Output	MW	95 (100 MW Class)	322 (300 MW Class)	637 (600 MW Class)
Testing commencement	year	2021	2020	2020
Type of Boiler		PC	PC	PC
HHV Coal, ar	kcal/kg	6037	4459	4237
Coal Price	USD/tonne	0.062	0.041	0.042
Type of biomass		Sawdust	Rice Husk	Sawdust
HHV Biomass, ar	kcal/kg	2508	3241	4294
Biomass Price	USD/tonne	0.074	0.037	0.033
Co-firing	%	5	5	5
Coal	kg/hr	42,683	186,147	361,000
Biomass	kg/hr	2,246	9,797	19,000

$$\%\Delta GC = \frac{GC_{co-firing} - GC_{coal-firing}}{GC_{coal-firing}} 100\% \quad (7)$$

$$GC_{co-firing} = [(CPrice \times \%C) + (BPrice \times \%B)]SFC_{co-firing} \quad (8)$$

$$GC_{co-firing} = CPrice \times SFC_{coal-firing} \quad (9)$$

$$SFC = \frac{\text{Total Fuel Consumption}}{\text{Generated Energy}} = \frac{1}{\eta \times HHV} \quad (10)$$

$$\%\Delta \text{Fuel Price} = \frac{BPrice - CPrice}{CPrice} 100\% \quad (11)$$

3.3 Parameter Data

Experimental investigation data were taken from three CFPPs, one plant in Sumatera and two in Java island. All three power plants have excellent performance in operation and their data were collected between 2020-2021 by direct measurement. The investigated CFPPs are represented by three different sizes of power plants, e.g., ~100 MW, ~300 MW, and ~600 MW. All investigated plants were PC boiler type, which is the largest population of CFPP in Indonesia. The basic specification of the plant is shown in Table 3.

Thus, some assumptions were also taken for evaluation purposes for the three plants. The percentage of biomass was based on mass (tonne) and the 100% mixture consists of 5%-biomass and 95%-coal. The testing method was conducted by following energy demand from the grid. It may show the different result tendencies for each plant due to different fixed and variable parameters. Based on previous research, to evaluate potential CO_2 reduction, this study assumed that 1 kWh equals 0.9 - 1 kg-CO_2 (Yokoyama & Matsumura, 2008). The GHG emissions of CFPP are represented by CO_2 emissions to evaluate the potential benefit of CO_2 emissions reduction. Based on Indonesian Law No. 7 Harmonisation of Tax Regulation, this study assumed that 1 tonne CO_2 equivalent (tCO_2e) equals 2.1 USD.

4. Result and Discussion

The analysis of 5%-biomass co-firing in three plants was investigated by comparing several parameters on the coal firing and co-firing condition.

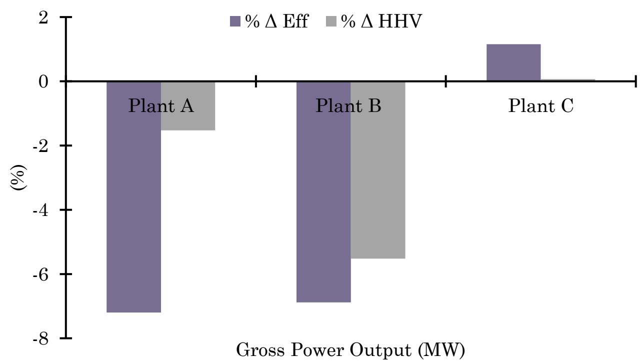

Fig 2. Co-firing effect on efficiency due to heating value

The tests were performed to evaluate the effect of co-firing on the plant performance, emissions, and power generating cost (GC), which were the significant parameters of the plant. The 5% was chosen as the baseline for the project to increase the renewable energy fuel mix without additional capital investment.

Figure 2 shows the effect of co-firing on the efficiency point of view. The Figure 2 explains the difference (Δ) result between coal firing and co-firing in terms of efficiency and heating value. The negative result shows that the efficiency and heating value in the coal firing condition is greater than the co-firing condition and vice versa.

The experimental test results show that the power plant efficiency is directly proportional to the heating value of the fuel. Power plant efficiency depends on boiler efficiency. The ratio of heat absorbed in the working fluid and total heat input to the boiler. The total heat input is directly proportional to the fuel heating value. Lower heating value contributes to the lower heat input to the boiler. The lower heating value on Plant A and B are mainly affected by the lower carbon content and higher total moisture on co-firing fuel. Higher moisture content reduces the heat absorbed due to higher heat loss. Hence, the higher moisture content has lower boiler efficiency and decreases the plant efficiency and vice versa. It is relevant to the study from Mun *et al.*, which mentioned that higher moisture content would decrease the boiler efficiency and power plant efficiency is directly proportional to the boiler efficiency (Mun *et al.*, 2016).

In line with the previous explanation, Plant C has higher plant efficiency since the co-firing fuel has a higher heating value than coal fuel. The moisture content of co-firing fuel is also lower than coal, so it increases the boiler and plant efficiency.

Figure 3 shows the impact of co-firing on FEGT. The negative FEGT indicates that co-firing combustion has lower FEGT than coal firing and vice versa. The FEGT is one of the foremost parameters to describe heat transfer performance in the boiler. FEGT value depends on the heating value, total moisture, and ash content of the fuel used for co-firing applications (Mehmood *et al*., 2012).

Plant B with co-firing has lower FEGT than coal firing since the co-firing fuel has higher moisture, although ash content is lower than coal fuel. Higher moisture on the co-firing fuel absorbs more heat from combustion. Hence, it decreases the FEGT. Plant C has an insignificant result on FEGT during the co-firing process since the co-firing fuel properties are almost similar to coal. Even though co-firing fuel has lower moisture and ash content than coal, it only slightly increases the heating value of co-firing fuel and does not impact much FEGT inside the furnace.

However, further investigation is required on Plant A, which has an abnormal result. FEGT during co-firing is higher than coal firing, even though the co-firing fuel has a lower heating value and a higher moisture content than the coal. The only parameter affecting the increase of FEGT on Plant A is the lower ash content on the co-firing fuel. It needs an empirical deeper and longer investigation to know the determinant factors for the FEGT during co-firing and which one has a more significant effect than other factors.

Using a baseline of 5% biomass mixing for boiler fuel, the emissions impacts for three power plants as indicated in Figure 4 and Figure 5. NO_x emissions correspond linearly with nitrogen content, but the contrary result is shown in Plant B. The cause is probably the inaccuracy of fuel during the sampling process.

SO_2 emissions during the co-firing process on all power plants decrease compared to the coal firing process due to the sulfur content of co-firing fuel is lower than the sulfur content of coal. Table 2 shows that all biomass used in this experimental study has much lower sulfur content than the sulfur content of the coal. The higher the sulfur content reduction on the fuel, the lower SO_2 emissions. In this case, it can be concluded that co-firing reduces SO_2 emissions of CFPPs.

GC is defined as co-firing fuel price multiplied by SFC, while SFC itself is inversely proportional to the power plant efficiency and fuel heating value. Referring to Figure 2, co-firing fuel on Plant A has higher SFC due to lower heating value than coal firing and decreases the power plant efficiency.

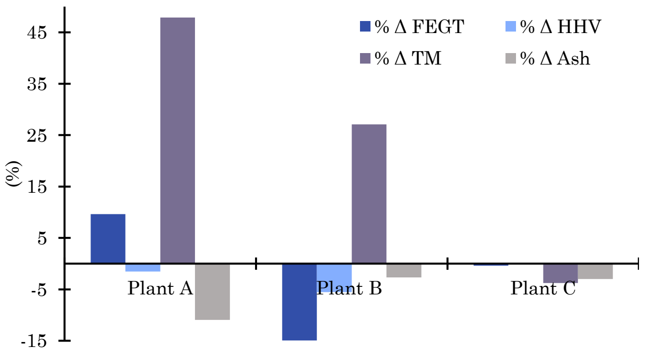

Fig 3. Co-firing effect on FEGT due to heating value, moisture content, and ash content

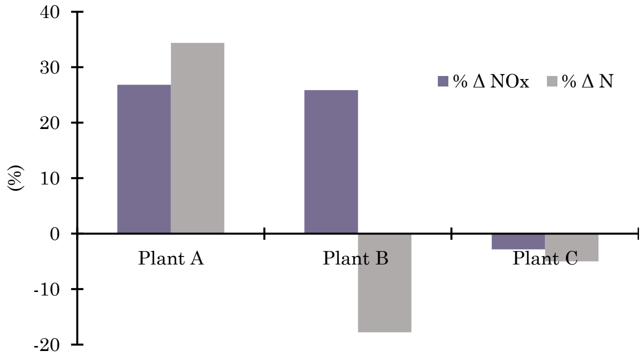

Fig 4. Co-firing effect on NO_x emissions due to nitrogen content

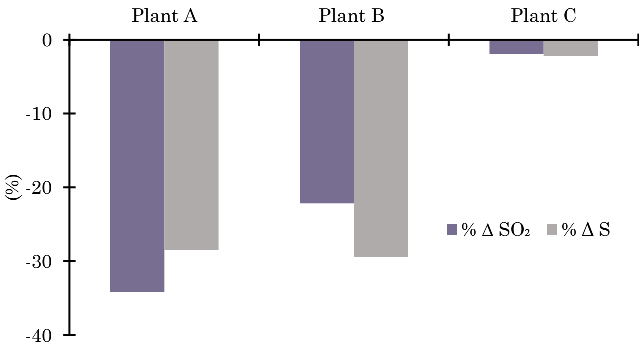

Fig 5. Co-firing effect on SO_2 emissions due to sulfur content

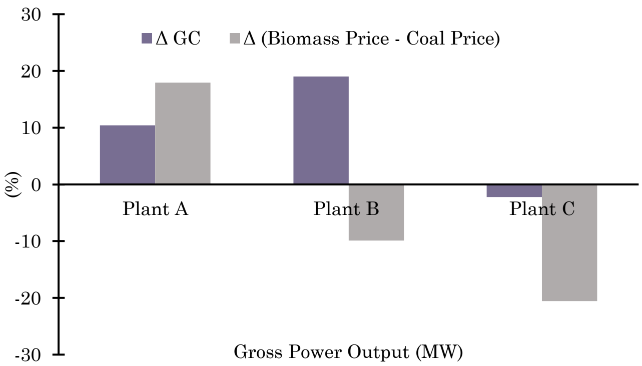

Fig. 6. Co-firing effect on plant GC

Additionally, as the cost of co-firing fuel is higher than coal, the GC of Plant A during co-firing is higher than the coal firing. On the contrary, Plant C has lower SFC due to higher plant efficiency and heating value during the co-firing condition. The lower SFC and co-firing fuel price decrease the GC of Plant C. The GC is not only affected by fuel price but also the plant efficiency, or SFC could be a dominant factor. As shown in Plant B, which results in a higher GC in co-firing condition compared with the coal-firing condition, even though the co-firing fuel price is lower.

The CO_2 emissions during co-firing on the three power plants for an hour of operation are shown in Figure 7. The data were measured on the equal load demand and similar operation modes for all plants. Higher power plant capacity not only reduces CO_2 emissions but also produces higher green energy due to the higher co-firing energy production on the larger plant capacity using the same co-firing ratio. Reducing CO_2 emissions provides benefits by obtaining potential gains from the carbon credit scheme (Plant A and Plant C) and reducing potential carbon tax (Plant B). The potential gain of carbon credit and reduced carbon tax depends on the cap baseline corresponding to the GHG emissions produced during the coal firing operation. The accumulation in the one-year operation of co-firing for three power plants with a 70% capacity factor potentially produces 285,676 MWh of green energy. It is estimated to equal 323,749 tCO_2e and 143,474 USD of carbon credit.

Regarding economic analysis, the pilot projects show different results concerning biomass price sensitivity. Generally, biomass prices were affected by several factors, such as biomass type, transportation, storage, production costs, and the supply-demand market.

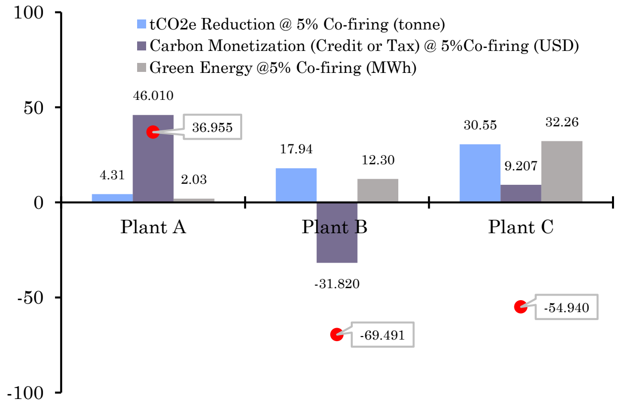

Fig. 7. Co-firing potential benefit on the CO_2 emissions reduction

For this study, the biomass for co-firing was sawdust and rice husk. For financial evaluation, the sensitivity analysis was conducted by decreasing and increasing the biomass price by 100% with an interval of 20% increase for each plant.

The GC sensitivity analysis result of co-firing is depicted in Figure 8. Applying co-firing on Plant A increases the GC even though the biomass price is reduced by 100%. While GC of plant B during co-firing can be lower than coal if the current biomass price is cheaper by more than 36%. Introducing co-firing on Plant C has a beneficial impact on the GC. The GC of Plant C co-firing is lower than the coal firing even though the biomass price increases by 57%.

The above results can be explained by comparing each plant's fuel price per unit of energy (USD cent/kcal), as seen in Figure 8. The biomass price per unit of energy on Plant A and B is higher by ~184% and ~24% than coal, respectively. On the other hand, the current biomass price per unit of energy for Plant C is lower by ~22%. Since there is a significant discrepancy between the biomass and coal price of plant A, the GC of plant A during co-firing still be higher than coal firing even though the biomass price decreased by 100%. Based on the recent market sounding, the study result demonstrated that the significant discrepancies in fuel price per unit of energy between biomass and coal are the main reason the GC in Plant A is still higher even though the biomass prices decreased up to 100%.
Besides some interesting findings of this study, it is essential to investigate further research regarding biomass sustainability and required technical improvement on each plant which can provide a different perspective for each investigated plant. Then, the specific solution of each plant can be obtained and provide valuable insight, especially for implementing coal-biomass co-firing with a higher percentage.

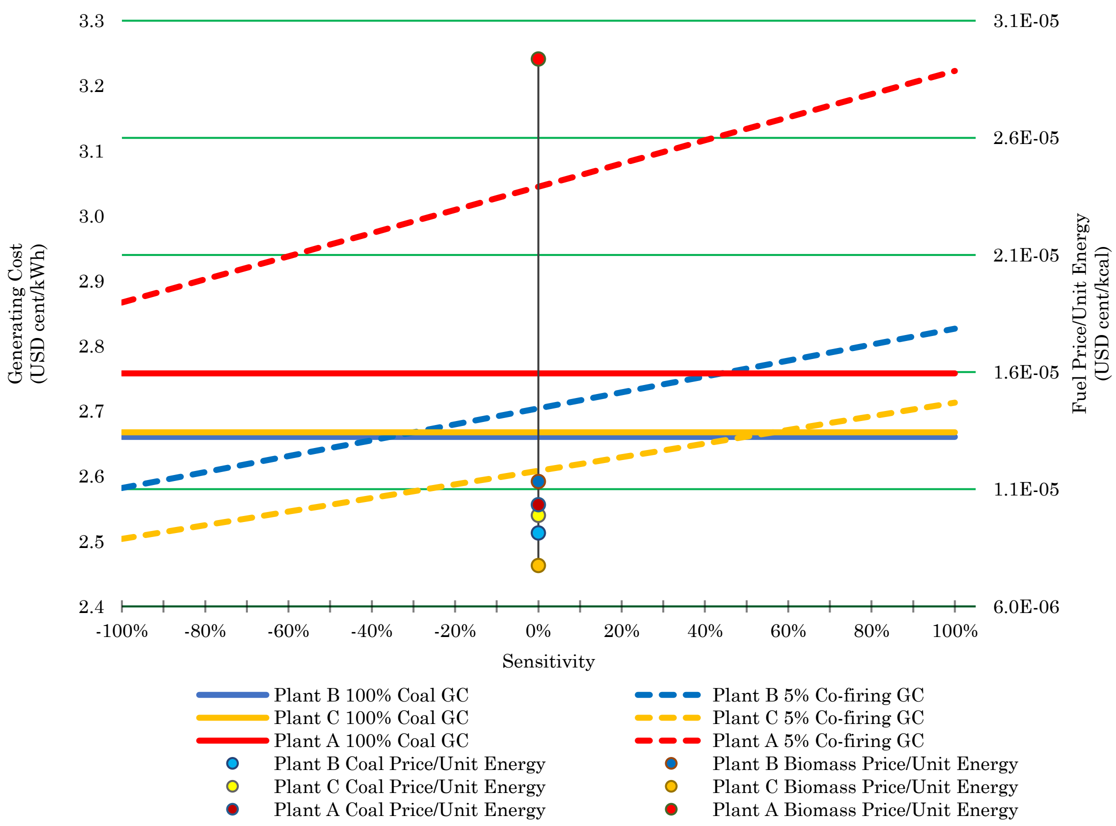

Fig. 8. Sensitivity analysis

5. Conclusion

Implementation of co-firing has proven to increase renewable energy penetration to the fuel mix of electricity without additional capital investment. Based on the empirical data and a technical evaluation, it can be concluded that co-firing impacts the efficiency of the plant, which corresponds to biomass heating value linearly. Co-firing implementation has no empirically significant impact on FEGT due to the low biomass ratio (maximum 5%). Regarding environmental impact, co-firing has a high potential to reduce emissions, such as CO_2, NO_x, and SO_2. However, the value of NO_x and SO_2 depends on the biomass's nitrogen and sulfur.

While according to economic evaluation, this study found that the average electricity generating cost of the three plants increases by about 0.25 USD cent/kWh due to biomass price per unit of energy is higher than coal by 0.64×10^{-3} USD cent/kcal. The accumulation in the one-year operation of co-firing for three power plants with a 70% capacity factor produce 285,676 MWh of green energy, equal to 323,749 tCO2e and 143,474 USD of carbon credit. The findings on biomass prices sensitivity analysis obtained that fuel price per unit energy between biomass and coal was the significant parameter to the GC changes.

The study has some limitations due to several boundaries. First, the empirical data was gathered only from 3 of 52 PLN's CFPP in Indonesia. Second, this study was conducted on the PC boiler technology, which differs from CFB and Stoker CFPP. Third, this study has not yet provided long time series data and was only based on short measurements. Then further research is recommended for another boiler type of CFPP in Indonesia. A more extended observation is required to examine the tendency of co-firing performance through a life cycle assessment approach.

Lastly, a further study can be designed so that the relationship among some determinant factors can be well defined to achieve technically and financially successful implementation. Due to the positive impacts of biomass utilization on decreasing emissions, all stakeholders should encourage the increasing biomass ecosystem, such as supportive regulation, technology advancement, and biomass roadmap implementation. The policy shall set out the framework of biomass utilization in the short, medium, and long term to meet the ultimate goal.

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