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Review Article

The Potential Implementation of Biomass Co-firing with Coal in Power Plant on Emission and Economic Aspects: A Review

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Abstract: Applying coal-biomass co-firing power generation is the strategy to accelerate the renewable energy share in the energy mix to reach 23% by 2025. Although biomass co-firing trials have been carried out at several Coal-Fired Power Plants (CFPP), the potential for implementing biomass co-firing on a larger scale and for the long-term propose still needs to be identified. This article evaluates emission characteristics and economic aspects of implementing biomass and coal in power plants. The traditional review method is used by identifying journal articles as data sources and further elaborating according to the context of the study. The primary emissions from co-firing biomass with coal contain CO, SO_2, NO_x, and particulate matter. The coal-biomass co-firing power generation has been widely adopted due to its various positive effects. However, it is still necessary to consider the cost of retrofitting, OM, biomass prices, and incentives in its application.

Keywords: Biomass, Co-firing, Emissions, Power plants.

Introduction

The necessity of lowering Greenhouse Gas (GHG) emissions globally, along with limited fossil energy reserves, has prompted a global shift away from fossil energy usage and toward New and Renewable Energy (NRE). Biomass use is a technique for reducing GHG emissions in Europe [1], while also increasing the proportion NRE mix [2]. Because biomass absorbs CO_2 during growth and emits it during combustion, it is becoming an increasingly important contributor to the global energy mix [3].

Co-firing of biomass is a method that uses a specific ratio of coal to biomass fuel. Biomass co-firing technology in Coal-Fired Power Plants (CFPP) has been widely implemented in various countries and is recognized as an important technology to help limit the use of fossil fuels, particularly because it is relatively easy to implement [4], responds quickly, and requires little investment capital [5], [6].

Biomass co-firing with coal in the power production sector is an economically and environmentally appealing alternative. Co-firing is deemed cost-effective because it does not necessitate major investments and uses of existing CFPP infrastructure [7]. According to Life Cycle Assessment (LCA) modeling, co-firing with a 10% combination of wood pellets and coal can result in a 9% reduction in GHG emissions [8].

The technology and efficiency of co-firing are constantly being developed to reduce coal consumption. The type of biomass and the composition of the mixture utilized can impact on the boiler's efficiency. The pre-mixing conditions of biomass and coal are critical determinants in the performance of co-firing applications [9]. Biomass with a high moisture content, a low calorific value, and poor grind ability must be considered [10]. As a result, optimizing biomass quality is critical for achieving constant combustion performance.

Utilization of biomass, particularly from agricultural waste, is another option because it can be an environmental solution, especially given the abundance of materials. Sawdust, bark, wood chips, urban wood waste, rice straw, rice husks, and herbaceous plants are all examples of biomass that can be used in co-firing [11]. Even co-firing with waste pellets at a 5% mixing ratio in a Circulating Fluidized Bed (CFB) CFPP is viable [12].

Malaysia's co-firing uses palm oil by products, wood chips, sawdust, and municipal solid waste [13]. Rice straw waste is used in co-firing in Vietnam because open burning creates major air pollution during the harvest season [14], [15]. Co-firing wood biomass mixtures with coal is effective in Europe and North America at mixing ratios of up to 10% [15].

The most common biomass fuels in Indonesia are palm oil processing waste, wood pellets, sawdust, and domestic solid waste. Although Oil Palm Empty Fruit Bunches (OPEFB) have been widely used for various products, their abundance has resulted in OPEFB not being fully exploited, resulting in OPEFB being waste [16]. Because of its high potential, OPEFB can be used as a fuel in power plants. It is recommended to improve fuel quality using Hydrothermal Treatment (HT) or Torre faction to lessen the impact of ash from biomass combustion on attributes such as alkaline content, high water content, and low calorific value. According to Praevia and Widayat's research, the HT process may improve the calorific value of empty bunches from 7.86 MJ/kg to 22.22 MJ/kg, which is comparable to the calorific value of coal (22.34 MJ/kg) [17].

Furthermore, palm shells have significant potential as an energy source for direct combustion heat and power generation [18], [19]. Fuel production prices, OPEFB supply capacity from palm oil mills nearby, electricity, and transportation costs are all factors to consider when developing biomass co-firing on a wide scale [20].

Co-firing has been established as one of the strategic initiatives in the green booster program by PLN, the Indonesian Electricity Company to accelerate the achievement of the NRE mix target of 23 percent by 2025 by utilizing existing power plant infrastructure as well as a waste management solution. The total capacity of PLN Group's steam power plants with co-firing capability is 18.9 GW. If the CFPP operates co-firing with a ratio of 6% for Pulverized Coal (PC) boilers, 40% for CFB boilers, and 70% for stoker boilers, it is comparable to acquiring an NRE production capacity of 2.7 GW per year (assuming a capacity factor of 70%) [21].

The activities in co-firing have been carried out at several PLN Group CFPP locations since 2020 on various types of boilers, namely PC, CFB, and stoker. Types of biomass used include sawdust, palm shells, wood chips, wood pellets, rice husks, coconut shells, OPEFB, Solid Recovered Fuel (SRF) pellets, water hyacinth, and corn cobs, as shown in Figure 1.

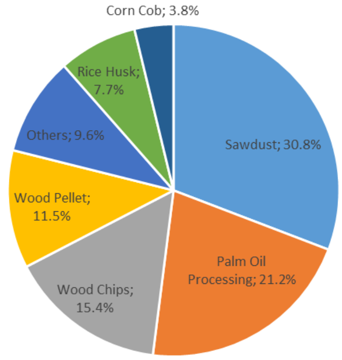

Figure 1. Types of biomass used in PLN.

Considering the plan for the sustainability of the co-firing program in the future at PLN, this study will focus on identifying the impact of implementing biomass co-firing with coal in CFPP on emission characteristics and economic aspects based on various available publications.

Methods

As a guideline for performing a literature evaluation, an objective traditional review approach was used. The initial stage in this study was to identify the problem. The following phase was to gather information, data, and literature from renowned worldwide journals and related national publications based on eligibility requirements, and then screen them based on the issues they discussed.

Information and literature relevant to the themes addressed, notably the features of biomass co-firing emissions and their economic implications, are analyzed for information and used to write review articles.

The review is divided into two stages: the first stage is the stage related to the data collected and consists of: the identification of problems, determination of library sources based on eligibility criteria and inclusion or exclusion criteria, data collection, and sorting (screening) based on the suitability of the literature with the topic. The second stage is processing the data that has passed the sorting, consisting of data analysis, interpretation, and confirmation. Confirmed data will be included in the review, while unconfirmed data will be re-sorted.

The references used are at least 35 from trusted and valid scientific journals, articles, and books relevant to the topic. The eligibility criteria for the library sources used are as follows:

1. International journals indexed by reputable institutions, including (SCOPUS, SCIMAGOJR, and Google Scholar)
2. Accredited national journal indexed in SINTA
3. Proceedings published in national and international seminars
4. Academic textbooks are written with the primary purpose of providing information and providing relevant data or theory

The libraries obtained are then sorted (screened) based on several criteria that must be met to be involved in the review, namely in the form of inclusion criteria (Table 1) [22].

Table 1. Inclusion criteria overview [22]

Type	Inclusion Criteria
Language	Bahasa Indonesia or English
Source	All journals, articles, and books that meet the eligibility criteria
Research design	Experimental research or/and literature review
Contents	Biomass co-firing emissions and their economic implications

Co-firing Technology

Direct co-firing, parallel co-firing, and indirect co-firing are the three basic ways for co-firing [3], [23].

Direct Co-firing

In this technique, biomass is used as a secondary fuel alongside coal as a primary fuel in the same boiler as shown in Figure 2. There are four options that can be used in direct co-firing. The first option involves combining biomass with coal and feeding it into the existing coal combustion chamber. The first alternative is the most straightforward, with cheap investment costs, but it poses a considerable risk to boiler operation. Alkali or other corrosive compounds in biomass might build up on the boiler surface, limiting output and operational duration [24]. Furthermore, the differences between coal and biomass may impact coal's combustion qualities. The use of biomass kinds is limited in this first choice, and the biomass-to-coal co-firing ratio is low [5].

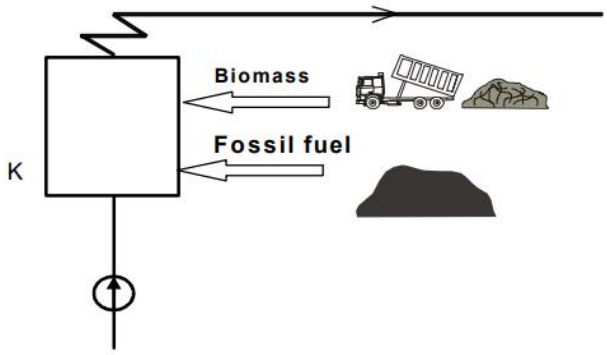

Figure 2. Simplified process of the direct co-firing system [25].

In the second option, initial treatment such as biomass and coal handling and pulverization are carried out separately before being fed into the existing coal combustion chamber. This alternative necessitates modification, including installing new equipment around the combustion chamber.

The third alternative is to build a separate coal-fired biomass treatment plant, complete with combustion equipment. This option expands the biomass material that can be fed into the boiler but comes at a greater cost [5].

The fourth alternative is to use burned biomass to control NO_x concentrations. This method also necessitates separate handling and pulverization systems, necessitating a greater investment cost than other solutions, but the operational risk to the boiler is low.

Parallel Co-firing

Biomass is burned in a different boiler from coal in this method (Figure 3). There is no technical way to provide fossil fuels to biomass combustion boilers.

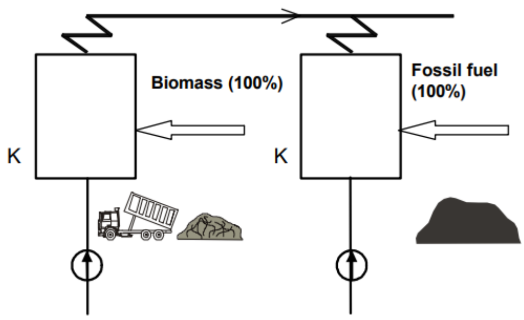

Figure 3. Simplified process of the parallel co-firing system [25].

Biomass and coal are kept separately in a parallel co-firing setup. Because coal and biomass are transformed into separate units, the best boiler for each fuel can be chosen (e.g., the CFB type for biomass and the PC type for coal). The investment required for parallel co-firing installations is more than that required for direct co-firing, but the ability to optimize the combustion process, use of fuels with high alkali and chlorine content, and ash separation are all potential benefits of parallel co-firing.

Indirect Co-firing

The biomass is gasified or burned separately in this configuration, and the gas produced is injected and burned in a coal boiler as shown in Figure 4.

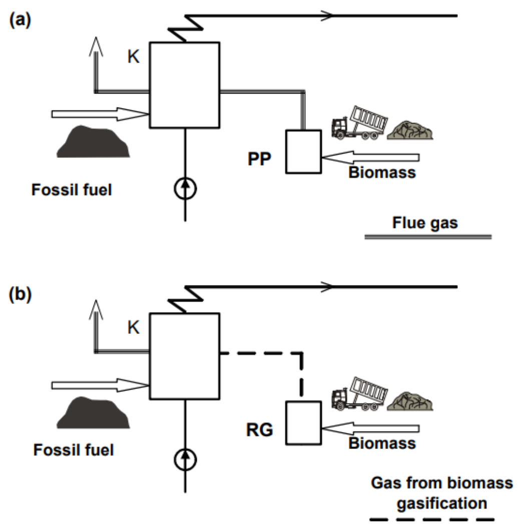

Figure 4. Simplified process of indirect co-firing with (a) PP pre-funace, and (b) GE gasifier [25].

The indirect co-firing design is more expensive since it requires an additional unit, particularly a gasifier, but it allows for a wider range of biomass types to be employed and a higher biomass-to-energy ratio. Because the biomass does not enter the coal combustion chamber directly, indirect co-firing technology can reduce slagging and allows for separate residue collection [5]. Indirect co-firing with pre-gasification is presently being used in several pilot plants, including in Austria (Zeltweg), Finland (Lahti), and the Netherlands (Geertruidenberg) [26].

Direct co-firing is currently the most popular method for co-burning biomass and coal in Europe, owing to the comparatively low investment costs of turning existing CFPP into CFPP [13]. For this reason, the direct co-firing option was chosen as the primary alternative for the deployment of biomass co-firing at PLN.

Emission Aspect of Co-firing

Given the increase in total energy consumption, the increasing proportion of electricity generation in energy consumption, as well as the issue of climate change, the transformation of CFPP and the expansion of NRE capacity are critical. Thus, the primary motive for the adoption of co-firing in many countries, including Indonesia, is the goal to reduce world GHG emissions by replacing coal with biomass [17], [27].

The properties of the generated emissions will be influenced by the composition of the biomass utilized. CO, SO_2, NO_x, and fine particles are the primary emissions produced by co-firing biomass and coal. CO production is linked to combustion efficiency. Because of its high volatile content, biomass burns and decomposes quickly, resulting in a decrease in combustion retention time and a loss in combustion efficiency. NO_x emissions can be influenced by fuel nitrogen concentration and combustion temperature. The NO_x emissions from biomass co-firing vary depending on the situation. The SO_2 emissions and biomass mixing ratio in co-firing are depicted as a linear relationship. As a result, the more biomass added during co-firing, the less SO_2 emitted. Furthermore, biomass co-firing produces fine particles (PM10, PM2.5, and PM1) with far greater unpredictability than coal combustion [28].

Carbon Monoxide (CO) Emissions

CO production is proportional to the efficiency of fuel burning in the combustion chamber. The lesser the CO produced, the more efficient the carbon oxidation reaction produces CO_2. In the coal-biomass pellet co-firing process at a CFB type, an increase in excess air supply and an increase in bed temperature increases the char reaction rate and supports the oxidation reaction of CO to CO_2, making combustion more efficient [29]–[31]. The following equations (1), (2), and (3) demonstrate how combustion efficiency is affected by the lower heating value (LHV) of biomass [31].

$$q_{ic} = 10^{-4}(126{,}4CO + 358{,}2CH_4)V_{dg}\frac{(100 - q_{uc})}{LHV} \tag{1}$$

$$q_{uc} = \left(\frac{32{,}866}{LHV}\right)\left(\frac{C_{fa}}{100 - C_{fa}}\right) \times A \tag{2}$$

$$n_c = 100 - (q_{uc} - q_{ic}) \tag{3}$$

η_c is the combustion efficiency, q_{uc} and qic are heat loss values due to unburned carbon and heat loss values due to incomplete combustion, respectively. V_{dg} is the volume of "dry exhaust gases" (Nm^3/kg) during the actual combustion of 1 kg of fuel in air. C_{fa} is the unburned carbon in fly ash (wt.%). A is the ash content of the fuel (wt.%, as-received basis).

Based on Equations (1) and (2), the values of q_{uc} and q_{ic} are inversely proportional to the LHV value of the biomass. If the LHV value is lower, then the q_{uc} value has the potential to be greater so that the combustion efficiency is low, and consequently the concentration of CO exhaust gas is high. Therefore, it can be said that the characteristics of the biomass used affect the concentration of CO exhaust emissions. LHV values, C, N and S contents of various biomass can be seen in Table 2.

Table 2. LHV value, C, N and S content of various biomass and bituminous

Fuel Type	LHV (MJ/kg)	Ultimate Analysis (%)		
		C	N	S
Rice Husk Pellets [(a)]	10.97	36.29	0.50	0.10
Wood pellets [(b)]	12.04	45.07	0.00	0.00
Palm kernel shells [(b)]	16.77	47.67	0.39	0.00
Palm fruit bunches [(b)]	11.99	44.66	0.38	0.00
Eucalyptus Pellets [(a)]	13.57	42.30	3.10	0.00
Pine wood chips [(b)]	28.19	49.73	0.14	0.00
Pine bark [(b)]	19.25	54.33	0.23	0.00
Marula seeds [(b)]	18.17	47.38	1.46	0.37
Coconut Belt [(b)]	12.44	47.60	0.20	0.00
Manga wood [(b)]	16.94	46.20	0.30	0.00
Tea waste [(b)]	17.64	45.04	3.48	0.50
Food waste [(b)]	15.85	45.33	1.29	0.20
Empty fruit bunch [(a)]	14.40	4.67	0.60	0.00
Bituminous coal [(a)]	18.67	66.20	0.50	0.10

[(a)][31] , [(b)][32]

According to [31], as shown in Figure 5 the lowest CO emission concentration was obtained for coal burning at an Excess Air ratio (EA) of 1.41. EA = 1.84 when co-firing coal blends with EFB at 50% wt. EA = 1.54 and 1.6 when co-firing rice husk pellets (SP), and EA = 1.39 and 1.62 when co-firing with eucalyptus (Euca) at 25% and 50% wt. This demonstrates that the bigger the amount of biomass added, the greater the extra air ratio necessary for a minimum CO concentration emission. More air is required for full combustion when a higher proportion of biomass is in the fuel mixture.

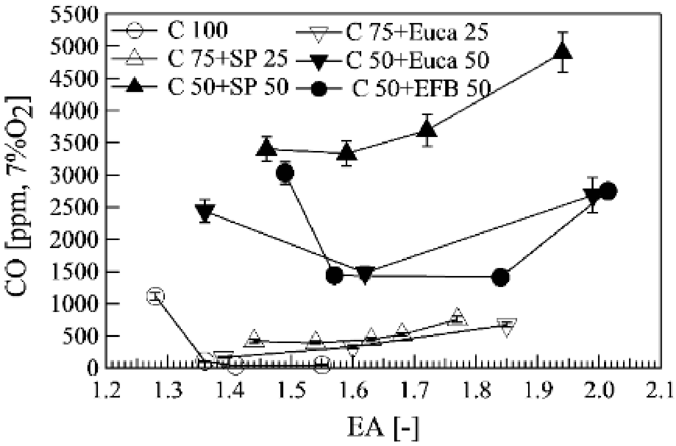

Figure 5. Effect of fuel mixture and excess air ratio on CO emissions [31].

Emissions of Nitrogen Oxides (NO_x)

In the combustion chamber, NO_x are formed by burning nitrogen included in fuel and obtained from nitrogen contained in atmospheric air (thermal). The rate of NO_x generation from combustion in the environment (thermal) grows exponentially with the combustion temperature of excess air. However, because thermal NO_x is relatively low and can be ignored, the main source of NO_x emitted in co-firing is the type and amount of biomass used. Unchaisri et al. [31] investigated what happened when the proportion of excess air to NO_x (NO and NO_2) in the mixture changed. Figure 6 depicts the results.

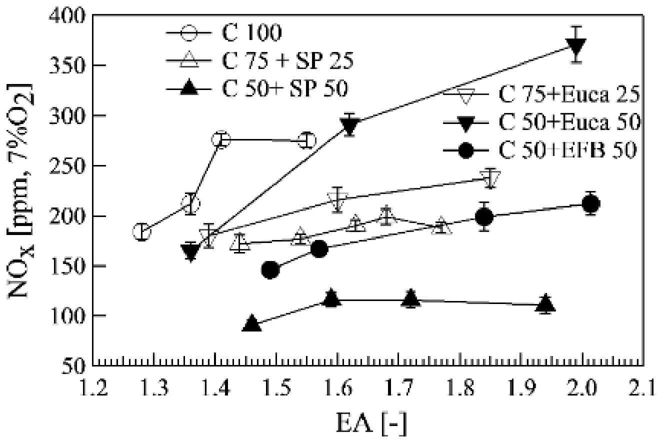

Figure 6. Effect of fuel mixture and excess air ratio on NO_x emissions [31].

According to Figure 6, co-firing pellets of varied biomass with coal at varying levels of excess air yields a lower concentration of NO_x than burning coal altogether. The concentration of NO_x increases as excess air increases, according to Equations (4) and (5) [33], [34].

$$\mathrm{HCN} + \frac{1}{2}\mathrm{O_2} \rightarrow \mathrm{CNO} \tag{4}$$

$$\mathrm{CNO} + \frac{1}{2}\mathrm{O_2} \rightarrow \mathrm{NO} + \mathrm{CO} \tag{5}$$

The NO_x concentration produced by co-firing eucalyptus biomass with coal was higher than the other mixtures (see Figure 6) because it contained CaO. CaO triggers the formation of NO_x from ammonia and hydrogen cyanide (Equations (6) and (7)), then releases volatile nitrogen from eucalyptus [31].

$$NH_3 + O_2 \xrightarrow{CaO} NO + CO \tag{6}$$

$$HCN + O_2 \xrightarrow{CaO} NO + N_2 \tag{7}$$

NO_x emissions from co-firing activities in a PC type using 5% sawdust show a lower concentration (2-3%) when compared to burning coal alone [35]. The concentration of NO_x emitted in the co-firing test utilizing wood pellets at a 5 percent ratio in a PC-type with a capacity of 330 Mwe is lower than that from burning coal [36]. Co-firing testing with a 5% wood pellet ratio in a 315 MWe PC-type resulted in a very small change in NO_x concentration, which increased by 3.62 percent but remained low at 310 mg/Nm^3 due to a decrease in combustion quality [37]. Another study found a reduction in NO_x concentration of 132.3 mg/Nm^3 when palm shells were co-fired in a CFB-type with a capacity of 10 Mwe [38].

Emissions of Sulfur Dioxide (SO_2)

Because biomass has a lower sulfur content than coal, coal combined with biomass produces less SO_2 than coal burned entirely [39]. This phenomenon is illustrated in Figure 7 by research findings [31]. The sulfur dilution effect of the fuel mixture accounts for the low SO_2 emissions from the co-firing system. The SO_2 concentration produced by co-firing rice husk and coal pellets was somewhat more significant than eucalyptus pellets. This is due to the increased sulfur content (0.1 wt. percent) of rice husk compared to eucalyptus (0.0 wt. percent) at a co-firing ratio of 25 wt. percent. The concentration of SO_2 emissions is caused not only by the sulfur content of the biomass but also by the high bed temperature, which can raise the concentration of SO_2 generated [40].

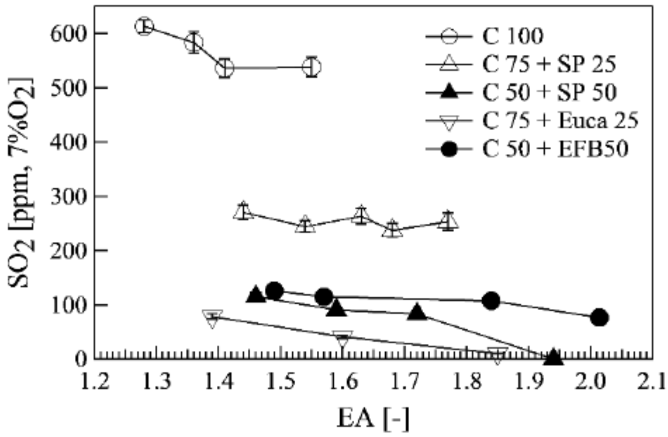

Figure 7. Effect of fuel mixture and excess air ratio on SO_2 emissions [31].

Figure 7 shows that the concentration of SO_2 produced by co-firing with eucalyptus is lower than that produced by other fuel mixes. According to Equation, the presence of CaO in eucalyptus reduces SO_2 emissions, and the higher the CaO content, the greater the reduced SO_2 concentration [8].

$$CaO + SO_2 + \frac{1}{2}O_2 \rightarrow CaSO_4 \tag{8}$$

From another study, co-firing using wood pellets [36] and palm shells [38] showed typical results, namely lowering SO_2 concentrations because both biomasses have lower sulfur content compared to coal. Co-firing sawdust with a ratio of 5% in a PC type boiler contributed to reducing the concentration of SO_2

(265.99 mg/Nm^3) by 2.4% when compared to the concentration of SO_2 emissions produced from burning coal alone (272.52 mg/Nm^3) [35].

Emissions of Particulate Matter (PM)

According to the findings of Ibrahim et al. [39], co-firing 50 percent (weight percent) wheat bran in a CFB type dramatically reduced PM emissions by 90 percent, whereas co-firing 3.8 percent wood chips did not effect on PM emissions [39].

The amount of potassium, chlorine, and sulfur in the fuel significantly impacts the composition of the inorganic submicron particles produced. The major components produced in the discharged submicron particles are potassium chloride and potassium sulfate. The major potassium component discovered was K_2SO_4 gas, which evaporated and condensed to produce PM1 with an average size of 0.5 m. At high combustion temperatures, the principal vaporized potassium component is gaseous KOH, the majority of which can react with alumino silicate to generate coarse particles, and the remaining evaporated K_2SO_4, and other sulfate or oxides are condensed to form PM1, with an average size of 0.2-0.3 m. The more volatile potassium that is transported to the coarse particles, the greater the combustion temperature. The high potassium content of the biomass results in the development of relatively big fine particles [28], [41].

Economic Aspects of Co-firing

The economic viability of implementing co-firing is often assessed using several cost components, including assumption biomass prices, investment expenses, Operating and Maintenance costs (OM), and the applicable carbon tax rate. OM costs encompass both fixed and variable costs. Fixed expenses include maintenance, staff expenditures, and insurance premiums. Variable costs include increased maintenance and fuel costs and less money gained by selling ash and gypsum [42].

Ideally, the benefits (avoidance of coal costs and Renewable Energy Certificate (REC) payments) should outweigh the higher construction and operating costs (biomass and OM costs) [43]. According to [44], incentives such as carbon prices and REC could make co-firing a viable option for reducing CO_2 emissions in Australia.

According to Sugiyono et al., the most challenging in implementing co-firing is the price of biomass, which is considerably higher than the price established by the company because it can disrupt the continuity of biomass supply, particularly for wood biomass raw materials. The cost of collecting, transporting, and handling biomass and the price of biomass are economic issues to consider. If CO_2 emission reductions can be monitored and monetized on the carbon market, the economy of co-firing can be improved. Creating a robust raw material supply chain is also a challenging because it is a new initiative [45].

The economics of co-firing biomass in CFPP must also consider Specific Fuel Consumption (SFC). For example, when using palm kernel shells, which costs 109 IDR/kg, co-firing 5% of palm kernel shells corresponds to a 5 IDR/kWh reduction in the price of products supplied (BPP) component C [38].

To expedite co-firing investments, tariff incentives for biomass co-firing, such as Feed-in Tariffs (FiT), should be considered. If FiT is used, the tariff for each NRE source must be optimized based on the NRE target and energy mix. McEvilly et al. recommend US13-16/kWh as a FiT for the wider development of biomass use in the ASEAN region [43].

Conclusion

The technique of using biomass as a partly replacement fuel or coal mixture in power plants is known as co-firing technology. The use of biomass co-firing has grown in popularity as the greatest short-term alternative for reducing GHG emissions and encouraging the use of NRE in the energy industry. Direct co-firing has been widely implemented since it requires a cheaper initial investment than other co-firing methods, although it has a few drawbacks.

This research examined at the emissions and economics of co-firing mixed biomass and coal in power plants. Biomass co-firing generally emit CO, SO_2, NO_x, and particulate matter. The properties of biomass and plant operations can influence the properties of the generated emissions. The low sulfur content of biomass compared to coal helps reduce the concentration of SO_2 emissions. Meanwhile, the nitrogen content of the biomass and the oxygen supply during burning have a considerable influence on the NO_x emissions produced. On the other hand, the usage of biomass might affect the rise in fine particulate matter and the concentration of CO_2 emissions emitted. CO production is proportional to the boiler's combustion efficiency [28]. Several studies have found that torrefaction is a promising future method of using biomass.

In addition to the investment, OM costs, the price of biomass, coal, and carbon tax rates impact the economic sustainability of co-firing [42]. According to McEvilly et al. [43], incentives are also an important way to encourage the development of future biomass co-firing. Further research using the Life Cycle Assessment (LCA) approach is required to examine the impact of implementing a more comprehensive biomass co-firing project. Meanwhile, the Levelized Cost of Electricity (LCOE) model can be used to assess its economic feasibility. LCOE is a well-known method for determining whether a technology is economically viable.

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