Comprehensive Review of Biomass Co-firing Methods and Pulverizer Performance in Large-scale Applications

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Abstract. The increasing need for sustainable energy production has led to extensive exploration of alternative fuel sources and innovative combustion techniques. Co-firing, the simultaneous combustion of biomass with traditional fossil fuels, has emerged as a viable strategy to reduce greenhouse gas emissions (GHG) and diversify the energy mix. This review paper focuses on the specific application of large-scale sawdust utilization as a co-firing material in pulverized coal (PC) combustion systems and its influence on pulverizer performance. The utilization of biomass as fuel in power plants still creates several problems. Challenges and considerations related to integrating large amounts of sawdust into pulverized coal combustion from the perspective of the pulverizer are discussed. From several studies, it was found that the use of biomass tend to increase mill amperes as biomass use increases. 15% biomass use on a mass basis need modification. This limitation prevents increasing the amount of biomass use. Furthermore, optimization strategies and best practices for efficient sawdust co-firing are presented, emphasizing the need to balance environmental benefits with maintaining pulverizer performance. The paper concludes by summarizing key findings and providing insights into future research directions to facilitate informed decision-making in sustainable energy production.

Keywords: *biomass, co-firing, greenhouse gas emissions, pc boiler, pulverizer performance.*

1 Introduction

Co-firing biomass involves burning biomass and coal together, which can potentially reduce greenhouse gas emissions (GHG) and increase the use of renewable fuels [1]. From an economic and environmental perspective, cofiring biomass is a desirable energy-generating alternative [2]. Biomass, which includes wood-based fuels, agricultural waste, and energy crops, is considered a renewable energy source [3]. Its combustion does not contribute to net greenhouse gas emissions, making it an attractive choice for coal cofiring [1], [4]. The co-firing process not only displaces coal but also utilizes materials that would otherwise be sent to landfill, thereby preventing the formation of methane, a potent greenhouse gas [4].

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Co-firing biomass and coal has several benefits, including reducing sulphur and mercury emissions, improving combustion efficiencies, and enabling fuel diversity and local supply of fuel markets for agricultural waste [5]. Utilizing biomass in the combustor can reduce NOx and SOx emissions as well as total greenhouse gas emissions from existing gas and coal-fired power plants [6]. Additionally, biomass co-firing is an economical technology that enables the clean and efficient conversion of biomass to electricity. [5].

The successful implementation of co-firing, however, is not without its challenges. Despite these challenges, the prospects for biomass co-firing are favorable, particularly in areas abundant in biomass sources with potential to a sustainable supply. To fully utilize the benefits of co-firing, logistical and technical concerns must be addressed quickly. This requires a coordinated system among all pertinent stakeholders to guarantee the long-term viability of high-quality biomass fuels, advantageous policies such as tax exemptions, subsidies, and a regulatory framework enforcing greenhouse gas reduction, and ongoing research and development initiatives [7], [8].

Prior research has demonstrated that biomass co-firing can lead to changes in mill performance, such as increased mill amps and decreased mill fineness [1]. The pulverizer type used, whetherall-and-race, bowl, or Atritta mill, can also influence the performance when co-firing biomass [1]. Furthermore, the percentage of biomass in the fuel mix can also be a limiting factor, with some studies suggesting that 5% composition by weight may serve as an approximate threshold for the transportation of wood into bowl or ball mills [1]. Untreated biomass samples were found to be difficult to pulverize [9].

The milling characteristics of different fuels were a critical factor influencing net plant efficiency [10]. A study by Tamura and Van de Kamp showed that unblended pulverized wood with a particle size less than 1 mm demonstrates devolatilization and char burnout characteristics similar to high volatile sub-bituminous coal, suggesting that the performance of pulverizers can also be influenced by the size of the particles being pulverized [11]. The grinding performance is an important parameter that should not be ignored. With several things that can affect the pulverizer's performance, further research is needed to overcome these problems.

This review paper discusses the effects of large-scale biomass utilization on pulverizer performance, drawing from various studies and tests conducted on biomass co-firing in pulverized coal power plants. The goal of this review is to provide a comprehensive understanding of the effects of biomass co-firing on pulverizer performance and to identify potential solutions to mitigate these impacts.

2 Methods of Co-Firing

Co-firing is a method that involves the simultaneous burning of two distinct materials: coal as the primary fuel the boiler was originally designed to use and biomass as supplementary fuel in the boiler [7]. Co-firing is very important to reduce the use of fossil fuels and greenhouse gas emissions. There are several co-firing strategies, including direct, indirect, and parallel co-firing as shown in Figure 1 [8], [10], [12].

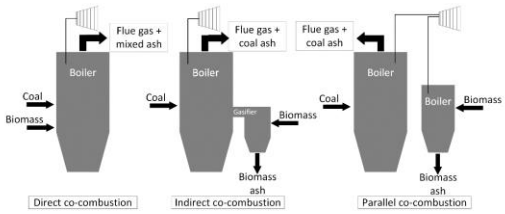

Figure 1 Co-Firing Methods [8]

2.1 Direct Co-Firing Method

Direct co-firing is the simplest, cheapest, and most prevalent method [12]. In this method, biomass and coal are mixed and fed into the boiler for combustion [1], [4]. The combustion can be combined or separated, this allows more flexibility in terms of the type and quantity of biomass [12]. While direct co-firing enables fuel diversity, it is dependent on the availability of suitable biomass fuels, which may be limited in some regions [5]. The co-firing rate typically ranges from 3% to 5%, but can go to 20% when utilizing cyclone boilers, with optimal results obtained from pulverized coal (PC) boilers [12]. Direct co-firing method does not require significant investment in specialized equipment, making it a cost-effective option [4]. Unfortunately, direct co-firing risks disrupting the boiler unit's combustion capability due to high levels of corrosion from alkali accumulation or agglomeration on the surface of boiler, which can reduce heat output and operational time [4]. Biomass naturally contains alkali metal that is released when burned in boiler and compound with other elements that may deposit the surface of the boiler [8].

Direct co-firing can be further divided into four methods as shown in Figure 2. The first (method a) employs a specialized pulverizer for biomass and a distinct burner for the milled biomass, making it the most costly process among direct co-firing methods. The second and third procedures entail the injection of milled biomass into a pre-existing coal boiler, either directly into the coal burner (method b) or blended with milled coal in the pipeline (method c). The fourth method is the simplest and potentially most economical where biomass is mixed with coal and milled together (method d) [10].

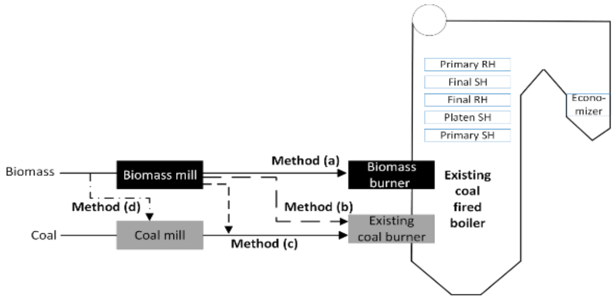

Figure 2 Types of Direct Co-Firing [10]

2.2 Indirect Co-Firing Method

Indirect co-firing is a method where the producer gas (combustible gas including hydrogen and carbon monoxide) is produced from biomass in a separate gasifier and then mixed with the coal in the boiler [10]. Indirect co-firing is a process in which biomass is gasified, and the resulting gas is burned in a separate unit, such as a coal-fired furnace or lime kiln. An indirect co-firing method is considered as a form of biomass pre-processing and is less common than direct co-firing [13]. Additionally, indirect co-firing can lead to technical issues arising during the co-gasification of coal and biomass [14].

Indirect co-firing method needs a significant investment than direct co-firing, because it requires a separate biomass infrastructure, such as storage, conveying, feeding, and milling, integrated into the existing coal system [7], [13]. Indirect co-firing is is appropriate when the quality of the ash is crucial or for biomass including problematic elements. Additionally, indirect co-firing can help reduce net CO2 emissions and diversify the power plant's fuel portfolio [13]. Indirect co-firing method reduces the risk of boiler corrosion and agglomeration but requires additional investment in gasification equipment [4]. Both direct and indirect co-firing methods can contribute to reducing greenhouse gas emissions and improving the sustainability of coal-fired power plants. However, the choice between these methods depends on factors such as installation costs, technical concerns, and the quality of the ash [13].

2.3 Parallel Co-Firing Method

A system for burning biomass in an external boiler is parallel co-firing. In this situation, the coal boiler will enhance the low-quality steam generated from the separate biomass boiler for more effective generation of electricity [10]. The parallel co-firing method involves the installation of an independent, separate 100% biomass-fired boiler to produce low-grade (pressure and temperature) steam while the conventional boiler tops up the superheat [6]. This method is less common compared to direct co-firing and is typically used in industries with specific biomass waste streams available for energy generation [15].

There are some potential disadvantages of parallel co-firing. This method may involve higher installation costs than direct co-firing [16]. Furthermore, parallel method is primarily suitable for industries with specific biomass waste streams available for energy generation, which may not be the case for all power plants. Lastly, parallel co-firing may present operational challenges related to handling and managing biomass, which can be more complex than indirect co-firing [5].

3 Biomass Characteristics

Fossil fuels like coal and natural gas are not included as biomass even though their origin also comes from the remains of dead plants and animals [6]. Biomass is a renewable, carbon-neutral energy source derived from plants and animals, and it can be used in various forms, such as solid, liquid, or gas [17]. Characteristics of biomass include heat value, or amount of heat available in a fuel (kJ/kg), varies depending on the biomass type . For example, wood has a higher heat value than straw [18]. Biomass fuels typically have a higher moisture content compared to fossil fuels like coal [19]. The chemical composition of biomass varies among species, but plants generally are made of approximately 25% lignin and 75% carbohydrates [20]. Biomass fuels come in various forms and sizes, with different densities. For example, sawdust has a bulk density of 300 kg/m³, while wood pellets 600 kg/m³ [18]. Biomass energy is considered sustainable because plants and algae can regrow relatively quickly, and the carbon dioxide they absorb during growth is the same amount they emit when burned [6]. However, it is crucial to sustainably farm and manage biomass feedstocks to maintain a healthy environment [17].

Biomass can be categorized into woody herbaceous biomass, biomass, straw-derived biomass, aquatic biomass, and wastes such as manure, sewage, and refuse containing biological material. The most suitable biomass for co-firing activities is woody biomass because its naturally low ash, sulphur, nitrogen content, and highly reactive also has more volatile matter [6], [8]. Many sites in North America and Europe have co-fired forest waste and mill waste such as sawdust with coal, finding them to be the most appropriate biomass fuels. Agricultural items include straw, switchgrass, corn stover, rice hulls, and olive pits have been co-fired as biomass feedstocks [6].

Characteristics of fuel used in co-firing can be analysed by looking at physical properties and chemical content of mixtures fuel (a mixture of coal and biomass) which can be known through laboratory tests. The laboratory test includes proximate analysis, ultimate analysis, ash analysis, ash fusion temperature (AFT) and chlorine analysis [4]. The importance of doing the laboratory tests of the fuel blend used is to determine the the calorific value, substances contained in fuels, and the results of combustion. From the test, the potential formation of slagging, fouling and agglomeration and the potential for corrosion in boiler can be predicted [4], [12].

There are several characteristics differences between coal and biomass listed in Table 1, which is the sulphur content of biomass less than coal, so the combustion emission can be lower. Sawdust has higher volatile matter than coal, so it will easily burn. The hardgrove grindability index (HGI) sawdust less than coal, so it’s not easy to grind. Sawdust has lower ash content, so it will decrease the ash product from combustion [12]. In general, biomass has a lower bulk density [21], a lower heating value [16], more volatile matter, more oxygen and hydrogen, less nitrogen and sulfur, and less carbon. These characteristics influence the design, operation, and performance of co-firing systems [8].

Table 1 Coal and Biomass Characteristics [12].

Analysis	Parameter	Bituminous Coal	Subbituminous Coal	Biomass - Sawdust
Proximate Analysis (% wt)	Moisture	26,41	35,82	8,56
	Volatile Matter	33,29	32,59	73,16
	Fixed Carbon	33,31	28,64	15,87
	Ash	6,98	2,95	1,1
Ultimate Analysis (% wt)	Carbon	49,88	44,03	44,7
	Hydrogen	3,9	3,17	5,43
	Oxygen	11,65	13,27	10,75
	Sulphur	0,38	0,12	0,09
	Nitrogen	0,79	0,65	0
Hardgrove Grindability Index		47	55	<32
Gross Caloric Value (kcal/kg)		4750	4157	2295
Bulk Density (kg/m3)		900	800	-

The test of biomass characteristics using pinus residue was conducted with as received method. It is shown that its calorific value is comparable to CE 4,500 coal, even so, it shows a higher moisture content than mineral coal. The analysis indicates that the nitrogen and sulfur content are significantly higher than that of coal, and biomass have high oxygen content so the air needs to combustion is smaller [22].

The physical characteristics of biomass particles, such as their morphology and dimensions, significantly affect their trajectory and conversion within a combustor [7]. Larger particles of a specific mass demonstrate accelerated burnout due to their non-spherical shape. The co-milling of biomass with coal typically produces larger biomass particles due to their low particle density, which diminishes the efficiency of the pulverization process. Moreover, substantial particle sizes, elevated moisture content, uneven geometries, and diminished bulk density typically contribute to inconsistencies in feed rates [7].

Biomass can combust more vigorously and may produce higher local peak temperatures due to its greater reactivity compared to coal [8]. The prior generation of volatiles from biomass lowers the ignition temperature relative to coal and enhances flame stability [8]. However, biomass handling still needs solutions for milling, pre-treatment, and transportation. The utilization of raw biomass for co-firing has numerous challenges, including its substantial bulk volume, elevated moisture content, and comparatively low calorific value, rendering raw biomass a costly fuel for transportation [23]. The combustion behaviour of biomass is strongly dependent upon its chemical and physical characteristics, presenting significant challenges due to its nature [8].

4 Effects of Biomass Co-Firing

Generally, the main operational parameters affected by co-firing biomass sawdust in a PC boiler include furnace exit gas temperature (FEGT), mill outlet temperature (MOT), emissions, and economy. Most PC boiler use vertical roller mill or roller mill because of their small energy consumption [11]. The ash produced from the biomass and coal mixture can cause problems such fouling, slagging, corrosion, bed agglomeration, sintering, and clinkering [24]. A different study examined how ammonia co-firing affected the operation of a utility boiler that burned pulverized coal. It is suggested that modifications to the heat exchangers might be necessary to enable a higher co-firing ratio in the current boiler, which could affect the boiler's efficiency [25]. Compared to coal, biomass fuels frequently have different qualities related to grindability, which can affect how well the pulverizer works. For biomass fuels to achieve high blend ratios and good combustion efficiency, separate pulverizers might be needed [26].

4.1 Overall Effect

The co-firing of biomass with coal in PC boilers has been extensively tested and studied in recent years. The Southern Company performed comprehensive co-firing experiments at Plant Hammond, with wood constituting between 9.7% and 13.5% of the overall fuel composition. The test highlighted many aspects, including slight boiler efficiency reductions and increased unburned combustibles during co-firing compared to coal burning. [1]. According to preliminary test results, woody biomass co-firing has the potential to reduce nitrogen oxides, which are responsible for ozone and smog, by up to 30% [27].

The PT. PLN test indicated that emissions of NOx and SO2 gases during co-fire were 2% to 3% lower compared to coal firing. The specific fuel consumption during co-firing was 1.21% lower at 0.629 kg/kWh, compared to coal firing at 0.637 kg/kWh. The primary energy cost for 5% co-firing is around 8.41 Rp/kWh, which is 2.22% cheaper than that of coal firing [4]. Compared to burning simply coal, the test found that adding biomass waste from palm oil could enhance the tendency to slag foul. Reduced AFT, deposition material, and sticky material in the probe, as assessed by SEM morphology and EDX, are indicators that co-firing 25% biomass with bituminous coal increases the likelihood of slagging [24].

4.2 Pulverizer Performance

Co-firing with high ratios of biomass usually limited by the ability of coal mills to co-mills biomass, because the grinder's ability is better to grind brittle material (coal) than the fibrous materials (biomass). The fuel blend is more challenging to grind when wood is present. A mere 3% of wood can lower the HGI by about six points [25]. There is a tendency for the pulverizer's differential pressure and ampere rises as the biomass usage ratio increase. Biomass also has high volatile matter, the hot air entering the pulverizer to dry coal can trigger biomass to burn inside the pulverizer and influence MOT [16]. The test results by PT. PLN using 5% biomass showed that the FEGT value by 4.2°C or 0.4% lower than during coal combustion. The mill outlet temperature showed little variations under both co-firing and coal firing circumstances [4].

Co-firing a high biomass ratio with coal in pulverized coal-fired boilers can negatively impact the grinding performance [7], [16]. Biomass has a higher moisture content than coal, which can limit the capacity of grinders when biomass is co-milled [7]. Additionally, biomass is more difficult to pulverize than coal using a roller mill, and a high ratio of biomass in the feedstock remains unpulverized [21]. The test at Plant Hammond resulting a modest increase in mill amps when co-firing [1].

The grinding of biomass in a pulverized coal boiler often produces larger biomass particles due to the low particle density, which diminishes the efficiency of the grinding process [7]. PC boilers can only grind biomass materials less than 10-20 mm, whereas they can reduce coal to particles of 75-300 µm [6]. There are several types of boilers that performance is limited by the biomass usage ratio as shown in Table 2.

Table 2 Common coal combustion technology in biomass co-firing system [6].

Co-combustion system	Operating requirements	Co-firing percentage (%	Technical features
Pulverized combustion	Fuel type: coal, sawdust, and fine shavings; Particle size: < 10-20 mm; Moisture content: < 20 wt%	1-40%	Can decrease Nox significantly; Limited by biomass particle size and moisture content.
Fluidized-bed combustion	Fuel type: various fuels, better suited for woody biomass than for herbaceous biomaterial; Particle size: < 80 mm(BFB), < 40 mm (CFB); Temperature: < 900 C	CFB: 60-95,3% BFB: 80%	The fluidized bed combustion system is the most suitable boiler for biomass co-firing. The soot formation is problematic, expecially in CFB.
Packed-bed combustion	Fuel type: wide range of fuels, including coal, peat, straw and woody residues; Particle size: fairly large pieces < 30 mm	3-70%	Not suitable for direct co-firing, although can be used for parallel or in-direct co-firing.
Cyclone combustion	Ash content: > 6% volatiles: > 15% except in a dried form, moisture content: > 20%	10-15% by heat input or 20-30% by mass	Suitable for co-firing since minimal modifications are needed for feeding and mixing the biomass and the coal

Numerous co-firing approaches include co-firing wood at 2-5% heat input, co-firing at 10-15% heat input, and co-firing at higher rates of wood or biofuel use. Co-firing at 10-15% heat input to the boiler involves an individual wood preparation system; for pulverized coal (PC) boilers, this involves a separate wood fuel burner [1]. In conventional power facilities, co-firing usually involves the modification of existing equipment, which is exclusively designed to handle the coal. Due to the variations between coal and biomass, co-firing biomass is normally limited to 5-15% of the total heat input to the boiler [16]. In certain circumstances, a large percentage of wood co-firing in pulverized coal boilers may be effective if wood is combusted independently from fossil fuels. A study at Plant Kraft of Savannah Electric showed that wood and coal may be co-fired, with coal combusted in one row of burners and wood combusted in another row of burners [1].

A study has been done regarding biomass grinding behaviour with different type of mills [11]. Ball, vibration, and roller mill were used in this study with variable condition. The biomass used in this study are waste wood, pinus bark, and wood pellet. Figure 3 show the result of required grinding energy by various type of mills with function of mass fraction Studies indicate that roller mills provide rapid grinding and need less energy across all biomasses. Condition b of the vibration mill for grinding pinus bark demonstrates the maximum yield with increased grinding energy. Pieces of pinus bark are stuck to the roller, resulting in diminished grinding ability[11].

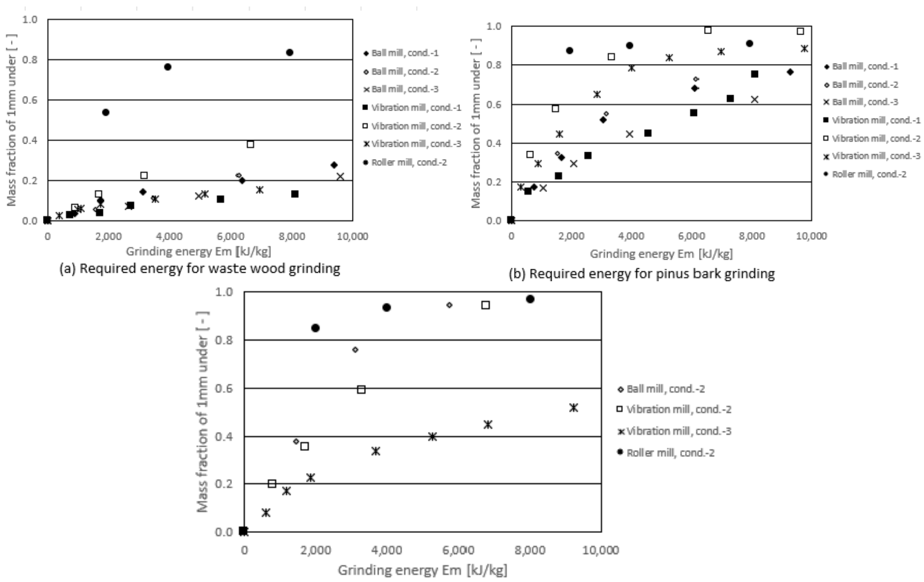

Figure 3 Energy demand for various mills with different biomass [11].

After conducting experiments using wood pellet and checking the inside of the mill, it was found that large amount of wood powder was left in the mill. The upflow velocity is possibly not enough to rise the wood powder. To handle this situation, an interior device inside mill was added. The results show that the addition of this device is quite effective in increasing fuel feeding rate [11].

The grinding test was conducted using hammer mill with different mill opening screen. Wheat straw, barley straw, corn stover, and switchgrass are used as biomass samples. The test represents the specific energy requirement for grinding biomass samples. The experimental results show that the larger mill screen opening, the smaller energy consumption for each biomass. The higher moisture content of biomass, the higher the specific energy consumption. Corn stover consumed the lowest specific grinding energy, while switchgrass was the highest because of the fibrous of nature [28].

An experiment has been done regarding mill differential pressure with fuel feeding rate. The test compares fuel feeding rate with three objects: wood chip, bituminous coal, and wood pellet. From the result in Figure 4, this shows that bituminous coal can be ground up to 2.2 t/h. However, the differential pressure of the grinder is unstable and continues rising for wood pellet at 400 kg/h and wood chip at 250 kg/h fuel feeding rate [11].

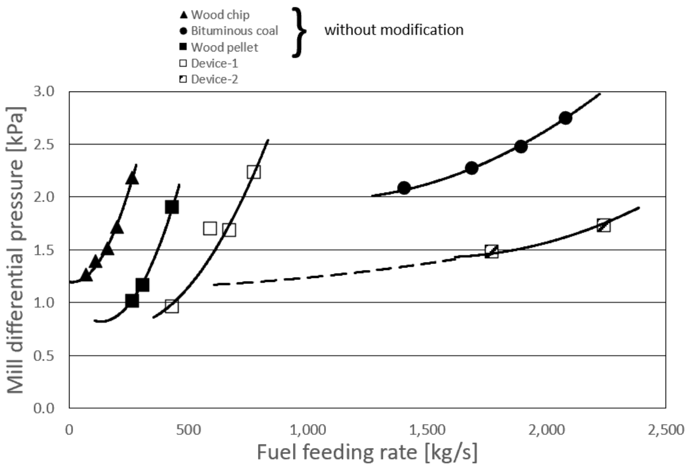

Figure 4 Grinding capacity for several biomass [11].

5 Challenges

In all co-firing systems, the stability and heat transfer properties of the flame can be influenced by variations in combustion characteristics between coal and biomass [4]. While co-firing presents a promising method for reducing greenhouse gas emissions, it also presents several challenges that need to be addressed. These include problems with fuel sourcing, fuel quality, ash quality connected to fly ash sales, and restrictions on the quantity of biofuel burnt configurations [1], [7].

The challenges in grinder performance when co-firing biomass with coal are primarily related to the difficulty of grinding the biomass particles into the required fineness. This can affect the performance of the pulverizing system up to a certain limit [29]. The experiment utilizing eucalyptus as biomass faced challenges in minimizing the size of the raw biomass, with just 29% of the untreated biomass passing through the 425 μm screen [23].

In direct co-firing, co-firing biomass tends to produce ash deposit, resulting slagging and fouling [2]. Biomass has different characteristics, especially biomass's alkali content, which greatly influences the formation of slagging and fouling [16]. The limitation of biomass flow is also a challenge for further research due to the equipment's capabilities [2]. The supply of biomass fuel also one of those things that must be considered [27]. Lack of flexibility to use various types of biomasses, so this requires a lot of further research [2].

The potential issues that need to be further researched when co-firing biomass sawdust with coal in power plants include the long-term impact on the durability of the power plant, the risk of slagging, fouling, and corrosion during continuous co-firing operations [4]. The feasibility of co-firing is dependent upon transportation, handling, and biomass storage [2]. Another challenge to increase the cofiring ratio is biomass pre-treatment. A simulation was conducted with several conditions, where the cost required for plant redesign was $112/kWh with the plant already had pre-processing infrastructure. Meanwhile, for plants that do not have pre-processing infrastructure, the cost required is $301/kWh [30].

6 Future Implementations

According to PLN's co-firing roadmap, 114 of its current coal-fired power plants would switch to co-firing by 2024. 'Feedstock increases' are part of the plan for 2021–2023. The Ministry of Energy and Mineral Resources (MEMR) has proposed a co-firing plan that calls for the establishment of a large-scale biomass industry to guarantee a steady supply of co-firing fuel, estimated to be between 4 and 9 million tonnes per year [31]. By 2025, the Indonesian government and state utility intend to have 52 coal plants in the nation using co-firing, which will require a substantial supply of biomass [32]. For biomass co-firing to succeed, a reliable, affordable biomass supply and an ideal delivery system are essential. There is also a lack of standardization in the characterization and handling of biomass [8].

The study found that treating biomass with torrefaction improves its grindability by increasing the percentage of particles passing to smaller fractions. From the grindability results, a mild torrefaction treatment at 240 ºC for 30 min could improve the grinding characteristics of the biomass with little loss of the heating value yield [23].

There are several methods to improve the grinding performance of coal/biomass mixtures when co-firing high ratios of biomass with coal. These methods include: Carbonization of biomass can improve its grindability, leading to a higher yield of smaller-sized particles suitable for combustion [21]; Formulating and pre-treating the fuel mixture can improve the combustion properties and limit the challenges related to biomass grinding and co-milling [7], [25]; Indirect co-firing configurations, where separate lines are available for biomass milling or grinding, can avoid the challenges related to biomass grinding and co-milling [7]; and optimizing the grinding equipment, such as roller mills and tub grinders, can improve the grinding performance of coal/biomass mixtures [16], [21].

7 Conlusion

Co-firing can be done using direct, indirect, and parallel methods where all the methods have different advantages and disadvantages. Various tests and research related to co-firing shows that co-firing method is very useful in reducing greenhouse gas emissions (GHG). This paper review provides a comprehensive review of co-firing methods, biomass characteristics, and the effect of pulverizer performance when using large amount of biomass. Especially when co-firing with large amount of biomass in PC boiler.

Several studies have been conducted regarding co-firing using biomass ratio on PC boiler. It was found that percentage of biomass be the limiting factor for co-firing. On average, only around 10-15% of biomass can be used for co-firing with direct method in PC boiler without modification. The limitation occurs because of the bulk density and heating value is different from coal, it is requiring a larger amount of biomass. The grinder's ability is better to grind brittle material (coal) than the fibrous materials (biomass). There is a tendency for the pulverizer's differential pressure and ampere rising as the biomass usage ratio increase. The use of biomass ratio above 15% require modification or additional equipment.

Equipment modification and pre-treatment of biomass are considered capable of increasing the biomass co-firing ratio. Equipment modification usually require a very large investment, financial feasibility needs to be carried out. Therefore, it is very important to carry out further research regarding pulverizer performance effect of high utilization of biomass.

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