Investigation of Ammonia Co-firing Effects on Combustion Equipment Performance in an Existing PLN 660 MW Coal-fired Power Plant

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In Indonesia's electricity system, coal-fired power plants (CFPP) have a vital role in meeting the primary needs of the community. On the other hand, the energy transition agenda forces PLN (State Electricity Company) to observe the options to decarbonize while maintaining the operation of the CFPP to continue operating at least until near the end of its lifetime. One of the hottest and newest programs in Indonesia is ammonia co-firing. Ammonia, a non-carbon fuel, can partially replace coal for combustion in boilers. Applying to existing boilers will certainly shift the existing operating profile, especially on the combustion side. The investigation shows that co-firing ammonia will affect the boiler performance, fuel consumption, draft system, and emission reduction. The boiler efficiency becomes slightly lower with the presence of ammonia. Based on the study result on the existing 660 PLN CFPP, the boiler efficiency will slightly degrade by about 3.6% from 85.7% to 82.6% on an HHV basis. For that reason, the fuel consumption in the boiler should be increased to maintain the amount of heat transfer to the steam cycle. Hence, it can keep the power plant output. On the draft system, it shows that there is a concern about the ID fan. The combustion flue gas has a lower density, which increases the flue gas volumetric. When the volumetric flow increases, the work of the ID fan will also increase. On GHG emission, ammonia co-firing possibly reduces CO2 emission production by about 29.26% at a 30% co-firing ratio. Then, for non-GHG emissions, SO2 and particulate emissions of the CFPP will be decreased by approximately 25.34% and 25.81%, respectively. Nevertheless, initiating ammonia co-firing is a good and exciting option for conducting decarbonization in the existing power plant.

Keywords: Ammonia co-firing, Decarbonization, Energy transition, Coal-fired power plant.

INTRODUCTION

Indonesia is a country with rich coal resources distributed in various locations. Coal is an abundant and cheap resource for energy and as a raw material for various industrial commodities. This caused the development of Indonesia's electricity to be predominantly from coal, which was converted to coal-fired power plants (CFPP). However, coal combustion must emit a massive carbon emission of about 850 – 1500 Ton CO_2/MWh. Compared with other fossil fuels such as gas and diesel, it has the highest carbon emission intensity per electricity energy generated. According to the Paris Agreement and Kyoto Protocol, most countries worldwide are committed to reducing their carbon emission generation from various sectors. Indonesia's carbon generation is dominantly coming from electricity generation. In late 2023, the coal power plant composed the energy mix for about 50%. Because of several factors, coal power plants play a critical role in Electricity Supply in Indonesia. First, it provides a stable electricity supply. Second, it generates a lower electricity price. Third, it has high provision availability.

At the same time, PT Perusahaan Listrik Negara (PLN), as a state-owned electricity company in Indonesia, is committed to avoiding massive carbon emission generation held by its power generation sector. PLN released the greenest electricity planning strategy, RUPTL 2021-2030 [1]. In this RUPTL, PLN planned to develop a massive renewable power plant to increase the renewable energy mix. For existing fossil power plants, especially with coal, PLN tries to develop any low-carbon technology.

Referring to the G20 held in Indonesia in November 2022, there are several guidelines for actions that must be taken on existing coal-fired power plants before they reach the final stage, namely retiring them [2]. These options include efforts to reduce carbon emission production, namely biomass co-firing, ammonia co-firing, and carbon capture applications. In Indonesia, biomass co-firing is the only option from this list that has been implemented. It was introduced in 2019 into PLN's coal-fired power plants. However, the program could not be implemented smoothly due to the biomass supply factor. Planting biomass requires a large amount of land, while not much land is available, especially in densely populated areas [3].

The next promising option is the application of ammonia co-firing in existing power plants. As we know, ammonia and hydrogen are non-carbon fuels that can produce heat without producing carbon emissions. This is something new, especially for Indonesia. Various studies mention this is one of the most innovative programs, and the space required is less than the previous options [4].

The carbon capture option should be further investigated as it is not easy to implement and must consider where the carbon emissions will be transmitted [5]. Therefore, this study is focused on the ammonia co-firing option as the following action that can be applied to existing coal-fired power plants in Indonesia.

This study aims to investigate the effects of ammonia co-firing on existing power plants in Indonesia, especially on combustion equipment. Several parameters will change with the addition of ammonia. The most affected is the combustion side. Ammonia has a different form under ambient conditions, combustion stoichiometric air ratio, flue gas density, etc. The application can affect the boiler to a worse condition. Therefore, it is necessary to investigate further to prevent the risk.

Several manufacturers and academicians have conducted ammonia co-firing implementation programs at existing CFPPs. IHI Corporation has implemented a 20% ammonia co-firing program with JERA Co, Inc. in Hekinan, which is planned to be commercially operational in 2025 [6]. Mitsubishi Corporation conducted a pre-feasibility study for a 20% ammonia co-firing application in Indonesia, including its supply chain. The reference plant used was PLTU Suralaya units 5-7 [7]. In the academic field, Wang (2023) analyzed the effect of ammonia co-firing on the performance of a utility coal boiler [8]. It showed that the ammonia co-firing application of up to 20% in the existing boiler would not significantly affect the performance, with a note that the ammonia injection is technically optimized. Kobayashi (2024) studied the ammonia for fuel in ASEAN Countries [9]. Recently, the co-firing technology at a rate of up to 60% is reportedly feasible.

This study investigates the impact of ammonia co-firing on power generation performance, particularly on the combustion side.

Methods

This study will use heat balance software-assisted power plant and process simulations. First, the power plant specifications used in this study will be developed and modeled in the heat balance software. The basis refers to the existing power plants in Indonesia, which will be explained in the next section. Once the model is established, work will proceed to the off-design simulation. In this simulation, the design parameters of the existing model will be maintained by including different variables so that the simulation can describe a co-firing implementation that is close to reality. The ammonia ratio will be the variable of this study, with a range of 0 - 30% energy.

After that, the investigation will analyze the effect of the combustion parameters, such as combustion air dosage, combustion temperature, and flue gas specification. Hence, the loss due to combustion can be estimated. The simulation results will then be analyzed to provide recommendations regarding ammonia co-firing applications in existing power plants.

Power Plant Basis for Simulation

As mentioned earlier, this study will use CFPP in Indonesia as a base. Larger classes of power plants are prioritized because they are more vital to the electricity system. In addition, larger capacities tend to be more efficient, thus avoiding CFPP retirement programs.

Currently, the largest CFPP capacity per unit owned by PLN is 600 MW class and centralized on Java Island. There are four power plants: Suralaya Units 5-7, Adipala, Paiton Unit 9, and Tanjung Jati B Units 1-4. Their net capacity ranges from 600 - 660 MW. Most of them use a subcritical cycle with a single reheat. Therefore, they are the most appropriate class of CFPP on which to base the study.

As mentioned earlier, the power plant simulation will be based on the typical power plant design. The general power plant input parameters of the simulation can be seen in Table I.

TABLE I. GENERAL PARAMETER OF POWER PLANT

Parameter	Value	Unit
Power Plant Net Output	660.69	MW
Plant Heat Rate (HHV)	2359.70	Kcal/Kg
The pressure of the Main Steam	170.00	Bar
Temperature of Main Steam	540.00	Celsius

Ratio of Combustion Excess Air	15.00	%
Base Boiler Efficiency	85.70	%
Flue Gas Air Heater Exit	135.00	Celsus

TABLE II. EXISTING COAL SPECIFICATION

Composition	Value	Unit
Carbon (As Received)	47.46%	Weight (AR)
Hydrogen (As Received)	3.63%	Weight (AR)
Oxygen (As Received)	13.25%	Weight (AR)
Sulfur (As Received)	0.17%	Weight (AR)
Nitrogen (As Received)	0.49%	Weight (AR)
Total Moisture (As Received)	29.00%	Weight (AR)
Ash (As Received)	6.00%	Weight (AR)
Total	100.00%	Weight (AR)

The power plant operates with subcritical main steam pressure and temperature to generate 660.69 MW net power. The plant heat rate shows the net efficiency, which is composed of boiler efficiency, steam cycle performance, and auxiliary power consumption. The boiler efficiency at normal operation was estimated at 85.7% (HHV). At normal operation, the typical existing coal specification is mentioned in Table II. That coal is determined as sub-bituminous C, which has a calorific value of 4601 kCal/kg based on the Dulong-Petit equation [10]. The power plant is modeled by heat balance simulation using Steam Pro 30.0 software. The model can be seen in fig. 1. There are three stages of the steam turbine: high pressure (HP), intermediate pressure (IP), and low pressure (LP).

Fig. 1 shows the CFPP modeling result by heat balance simulation. The heat from coal combustion in the boiler is utilized to heat the feedwater to generate steam. The steam will rotate the turbine to produce power. On the flue gas side, the flue gas will enter the particulate emission handling after the exit air preheater. The treated flue gas is then sucked by an induced draft (ID) fan to flow the flue gas into the atmosphere via the chimney. The coal consumption is 338.6 Ton/h to generate the maximum power plant rating.

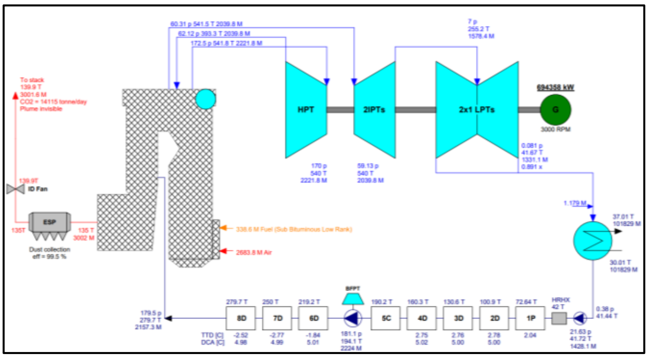

Fig. 1. CFPP modeling by simulation.

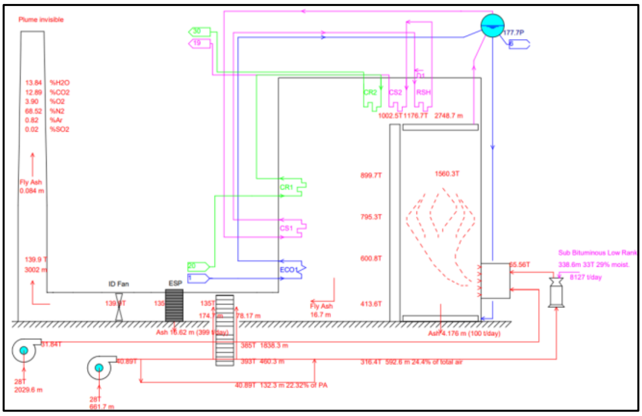

Fig. 2. CFPP modeling on the combustion side

The simulation can also show a more detailed illustration of the combustion side, which is illustrated in Fig. 2. The fuel enters the boiler via the burner along with primary combustion air. In this case, the burner configuration is front-rear firing with four burner elevation levels. In ammonia co-firing applications, the ammonia injection is prioritized at a lower burner elevation because ammonia has a longer combustion time than coal. Hence, modification of the lower burner is required.

After that, it goes to off-design simulation. From the simulation, the impact on the performance can be estimated. In normal conditions, the heat from coal combustion will be absorbed by the water tube inside the boiler. In an ammonia co-firing application, the heat absorption profile into the water tube might be different since there are several distinct aspects of ammonia and coal properties.

Ammonia Co-firing Concept

Ammonia (NH_3) is a chemical compound with various functions as a raw material or utility in industrial processes. Currently, ammonia has another use as a fuel. Ammonia has a molecular weight of 17.03 g/mol with a boiling point temperature of -33°C in normal pressure [11]. Thus, at ambient temperature, ammonia is in the gaseous form. Ammonia has an autoignition temperature of 651°C, which is much above coal. Therefore, the boiler start-up strategy shall be reconsidered in a co-firing application to prevent premature combustion.

In Indonesia, ammonia co-firing was initiated by Jawa 9 & 10 CFPP, which planned to conduct until 60% ammonia co-firing. On the engineering side, it was supported by PLN Engineering as the only engineering entity in the PLN group to conduct a pre-feasibility study on that project. Besides that, pilot testing was done in several existing gas turbine power plants with a small-scale ammonia ratio. However, the ammonia co-firing on existing gas turbines still yields a problem regarding combustion profile and vibration.

Ammonia is basically in the gaseous phase on ambient pressure and temperature. However, ammonia transport and liquid phase storage will be preferred since it can reduce the space requirement. Thus, the ammonia storage is usually at a low temperature or pressurized to keep it liquid.

The gaseous phase is a better choice as a feed for the combustion process. This is because when liquid ammonia is directly injected into the boiler, there is a massive energy penalty from the combustion heat to satisfy the ammonia vaporization process that absorbs a significant amount of heat before it is ready to combust. Based on process calculation, it consumes about 0.41 MW per ton of ammonia [12]. Hence, to condition the ammonia, a vaporizer is required.

The combustion air adjustment into the boiler is conducted with similar excess air. It refers to ammonia co-firing implementation by IHI corporation [13]. In this CFPP study, the excess air ratio will be maintained at 15%, as in Table I.

Result

Effect on Boiler Performance

Technically, the combustible composition of coal and ammonia is different. In coal, the combustible chemical is generally composed of carbon, sulfur, and hydrogen. Meanwhile, in ammonia, the combustible chemical is only hydrogen. Hydrogen combustion results in moisture; thus, ammonia combustion will produce a wetter flue gas than coal. This is one factor that could change the boiler efficiency.

The simulation result on boiler performance is shown in Table III. The performance was calculated using ASME Performance Test Code (PTC) 4 with a high heating value (HHV) basis [14]. It can be seen that in ammonia co-firing applications, the boiler energy conversion efficiency would get lower. The increase in losses factor impacts it. As mentioned in the previous paragraph, ammonia combustion produces a wetter flue gas, lowering the flue gas density. This phenomenon makes the flue gas flow as if it would be much higher, whereas the heat content is almost the same. Thus, the faster flue gas movement could interfere with the heat absorption process from the hot gas side into the tube.

The decline of boiler energy conversion efficiency is represented by two flue gas loss factors, which are Sensible and latent heat. Sensible losses are caused by the degradation of heat absorption described in the previous paragraph. Meanwhile, latent losses are influenced by the escalation of flue gas moisture content. Based on the simulation, the ammonia co-firing application would increase the flue gas moisture content from 13.84% to 18.02% in a 30% co-firing ratio. The performance degradation values may result in a less significant value when using a lower heating value (LHV) calculation basis because it neglects the heat latent value [15].

TABLE III. RESULT ON BOILER EFFICIENCY AND LOSSES FACTORS

Cofiring Ratio (%)	Boiler Efficiency (%)	Flue gas Sensible Losses (%)	Flue Gas Latent Losses (%)
0	85.70	6.41	9.53
10	84.40	6.75	10.45
20	83.50	6.86	11.19
30	82.60	6.99	11.91

TABLE IV. HEAT INPUT TO MAINTAIN POWER OUTPUT

Cofiring Ratio (%)	Fuel Input (KJ/h)	Increase (%)

0	6,552,154.80	-
10	6,655,190.40	1.57%
20	6,729,444.00	2.71%
30	6,803,985.60	3.84%

Fuel Heat Input

The degradation of boiler efficiency causes the possibility of reducing power output. Therefore, it should consider adding more fuel to maintain the power output rating in ammonia co-firing applications. Table IV shows the fuel heat input value in ammonia co-firing application to keep the power plant power output.

The fuel heat input should be higher by about 3.84% in a 30% co-firing ratio. There is a potential risk that should be mitigated, which is material overheating. More fuel consumption in the same boiler might increase combustion temperature.

Combustion Air and Flue Gas

Combustion air and flue gas are variables that correspond to each other. The more air is injected, the more flue gas flow tends to increase. Another factor is the value of combustion air required by the specific fuel. One kilogram of coal consumes about 6-8 kg of air to hold stoichiometric combustion [16], [17]. Meanwhile, ammonia consumes 6 (six) kg of air [18]. It means that ammonia requires less air to combust, which probably impacts the boiler operation when applying ammonia co-firing.

Based on the simulation result related to sections A and B, it can be seen that the higher the ammonia co-firing ratio, the lower the combustion air flow might be, even with the maintained excess air ratio. It will probably impact positive draft equipment works, namely primary air (PA) and forced draft (FD) fan. In a 30% ammonia co-firing ratio, the working level can be lowered to about 5.6%. However, reducing combustion air does not mean that the combustion downstream equipment work can also follow the trend. As mentioned in section A, the volumetric flow of the flue gas is increased, which will mount up the negative draft equipment work, namely the induced draft (ID) fan. In the 30% ammonia co-firing ratio, the working level of the ID fans could increase by about 3.8%. The simulation results on draft equipment work are shown in Table V.

Investigation of combustion air and flue gas has a function to mitigate the implementation risk due to the changes in draft equipment work. The increased flue gas volumetric flow caused the ID fan to have a higher working level. Hence, there is a manipulating option that probably can mitigate the equipment stress or overwork. It should consider resetting the combustion excess air ratio to become lower. The residual risk of combustion temperature overheating caused by that can probably be mitigated by adjusting the burner tilt angle.

TABLE V. IMPACT ON COMBUSTION AIR AND FLUE GAS

Cofiring Ratio (%)	Combustion Air	Combustion flue gas
0	100.00%	100.00%
10	99.66%	102.95%
20	97.51%	103.51%
30	95.37%	103.82%

TABLE VI. IMPACT ON SO_2 CONCENTRATION

Cofiring Ratio (%)	SO_2 Concentration at 7% dry O_2 (mg/Nm^3)	SO_2 Reduction (%)
0	487.81	-
10	461.22	5.45%
20	405.62	16.85%
30	349.55	28.34%

TABLE VII. IMPACT ON PARTICULATE CONCENTRATION ENTER ESP

Cofiring Ratio (%)	Particulate Concentration at 7% dry O_2 (mg/Nm^3)	Particulate Reduction (%)
0	7,083.40	-
10	6,497.55	8.27%
20	5,884.64	16.92%
30	5,254.95	25.81%

SO_2 and Particulate Emission

Sulfur dioxide (SO_2) and particulate matter (PM) are emission types that have to be limited by local regulations, namely the Ministry of Environment and Forestry number 15 in the year 2019 [19]. Both emission concentrations shall be corrected to milligrams per normal cubic meter (mg/Nm3) at 7% oxygen (O_2) in dry conditions by using generic calculation [20].

Ammonia is a free sulfur and free particulate chemical. Hence, there will be no SO_2 and particulate emission generation in ammonia combustion in the flue gas. Therefore, the emission concentration can be lowered in ammonia co-firing applications, particularly for SO_2 and particulate. For SO_2 emission, ammonia co-firing will drop the emission by about 28.34% from 487.81 to 349.55 mg/Nm^3 at the regulation condition.

Boiler particulate emission will reduce the concentration by about 25.81%, from 7,083.40 to 5,254.95 mg/Nm^3. This condition will probably ease the electrostatic precipitator (ESP) work capturing particulate emission. The impact of SO_2 and particulate emission is shown in VI and VII.

Impact on Greenhouse Gas Reduction

Ammonia co-firing is a considerable solution to reduce carbon emission generation in existing CFPP. Therefore, this study will be closed with the estimation of greenhouse emissions. Based on the simulation results, the declining trend of carbon emissions is depicted in the curve in Fig. 3.

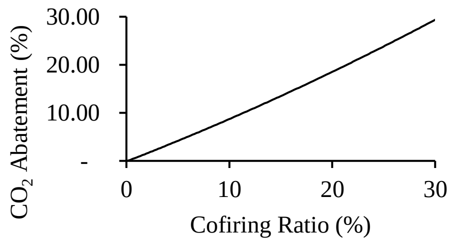

Fig. 3. CO_2 abatement vs Co-firing ratio

At 30% co-firing application, the CO_2 emission reduction reaches 29.26% with the same generator power output. However, this assumes that the ammonia class used is green ammonia, where there is no CO_2 emission in the ammonia manufacturing process because the energy comes from renewable energy. The CO_2 emission previously was 0.854 kg/kWh and possibly reduced to 0.604 kg/kWh when applying 30% ammonia co-firing. It shows that ammonia co-firing might be an excellent option for CFPP to decrease its carbon emission intensity.

Conclusion

The study shows that ammonia co-firing will cause differences in operational aspects, particularly on the combustion side. Combustion equipment consists of fuel feeding, combustion air, boiler, and flue gas equipment, which generate heat and transfer it to the steam cycle. In ammonia co-firing application, coal will be substituted partially. Thus, the main concern of ammonia co-firing implementation is the investigation of the combustion side.

Based on the study result, the boiler efficiency will slightly degrade by about 3.6% from 85.7% to 82.6% on an HHV basis. For that reason, the fuel consumption in the boiler should be increased to maintain the amount of heat transfer to the steam cycle. Hence, it can keep the power plant output. However, the increase in fuel consumption will probably result in a higher combustion temperature. So, the material design temperature should be rechecked to prevent overheating. On the draft system, it shows that there is a concern about the ID fan. The combustion flue gas has a lower density, which increases the flue gas volumetric. When the volumetric flow increases, the work of the ID fan will also increase to keep the pressure balance of the boiler. From the simulation, a 30% co-firing ratio will increase the ID fan works by about 3.8%.

CFPP combustion produces two emission types: GHG (greenhouse gas) and non-GHG. On GHG emission, ammonia co-firing possibly reduces CO_2 emission production by about 29.26% at a 30% co-firing ratio. For non-GHG emissions, there are various emission types. However, not all emissions are investigated because of data and simulation restrictions. Nevertheless, the study tried to estimate the concentration of two important emission types, SO_2 and particulate. At a 30% co-firing ratio, SO_2 and particulate emission of the CFPP will be decreased by about 25.34% and 25.81%.

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