Journal of Technology and Policy in Energy and Electric Power
Volume 1, Number 1, December 2024
https://doi.org/10.33322/jtpeep.v1i1/95

Research Article

Study on the Application of Ammonia Co-firing in Existing 600 MW Subcritical Coal-Fired Power Plants in Indonesia: Investigation of Combustion Equipment

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CITATION

Author Name. (2024). Article title. *Journal of Technology and Policy in Energy and Electric Power.* 1:1. https://doi.org/10.33322/jtpeep.v1i1

ARTICLE INFO

Received May 20, 2024
Accepted December 22, 2024
Available online December 30, 2024

Abstract: *PLN, Indonesia's only electricity provider company, still relies on coal-fired power plants (CFPP) for most of its electricity needs. The energy transition agenda forces PLN to review existing options so that coal-fired power plants can continue to operate until the end of their useful life. One of the hottest and newest programs in Indonesia is co-firing ammonia. Ammonia, a non-carbon fuel, replaces some coal burned in the boiler. Its application to existing boilers will shift operating patterns, especially on the combustion side. The investigation results said that co-firing ammonia would affect boiler performance, combustion profile, and several operating equipment. Boiler efficiency becomes lower in the presence of ammonia. Based on the combustion simulation results, the combustion temperature can be higher due to the additional heat of the injected fuel to maintain the power plant output. Some equipment, such as fan draft capability, should be re-examined because this application can increase its performance level.*

Keywords: *CFPP, Ammonia, Indonesia, CO_2, Combustion, Boiler*

1. Introduction

With the increasing demand for decarbonization in the electricity sector, PLN (Perusahaan Listrik Negara) is making substantial efforts to accelerate the development of renewable energy power plants and reduce carbon emissions. According to the 2021-2023 version of the RUPTL (Electricity Supply Business Plan), PLN has planned to develop various renewable energy power plants. Simultaneously, for existing fossil fuel power plants, PLN is working on a fuel substitution program. Fossil fuel power plants represent a significant portion of total electricity production [1], with coal being the largest contributor. As we know, Indonesia is rich in coal resources. Data from the Indonesia Energy Outlook 2022 indicates that Indonesia had coal reserves of 36 billion tons by the end of 2021 [2]. This substantial amount positions Indonesia as one of the world's largest coal suppliers. It also drives the country to build many coal-fired power plants (PLTU) due to the availability of raw materials and competitive prices.

Indonesia is committed to implementing a decarbonization program targeting net zero emissions by 2060. PLN has created various programs to enable a smooth energy transition to achieve this goal. By the end of 2030, coal-fired PLTUs are

projected to remain the primary electricity source, accounting for approximately 60% of total power generation according to the RUPTL.

Existing PLTUs cannot be retired immediately, as doing so could disrupt the stability of PLN's power grid. Nevertheless, PLN is exploring alternative ways to decarbonize existing PLTUs without retiring them [1].

Referring to the G20 held in Indonesia in November last year, several action guidelines were outlined for existing coal-fired PLTUs before reaching the final stage of decommissioning [3]. These options include efforts to reduce carbon emissions, such as 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 PLTUs. However, this program has faced challenges due to biomass supply constraints. Biomass cultivation requires vast land areas, which are limited, particularly in densely populated regions [4].

The next promising option is the implementation of ammonia co-firing in existing PLTUs. As is well known, ammonia and hydrogen are carbon-free fuels capable of generating heat without producing carbon emissions. This approach is relatively new, particularly in Indonesia. Various studies have highlighted it as one of the most innovative programs, requiring less space compared to the previous option [5].

The carbon capture option requires further investigation as it is not easy to implement, considering the need to determine where the captured carbon emissions will be stored [6]. Therefore, this study focuses on ammonia co-firing as the next actionable step that can be applied to existing coal-fired PLTUs in Indonesia.

This research aims to investigate the effects of ammonia co-firing on existing PLTUs in Indonesia, particularly on combustion equipment. Several parameters will change with the addition of ammonia, with the combustion side being the most affected. Ammonia has different characteristics under ambient conditions, such as combustion stoichiometric air ratios, exhaust gas density, and more. Its application could negatively impact the boiler's performance, necessitating further investigation to mitigate potential risks.

Several manufacturers and academics have initiated ammonia co-firing implementation programs for existing PLTUs. IHI Corporation has implemented a 20% ammonia co-firing program with JERA Co., Inc. at the Hekinan PLTU, which is planned to operate commercially by 2025 [7]. Mitsubishi Corporation has conducted a pre-feasibility study for a 20% ammonia co-firing application in Indonesia, including its supply chain. The reference plant used is PLTU Suralaya Units 5-7 [8]. Lee reported the latest developments in ammonia co-firing applications for thermal power plants, particularly concerning the burner side. The presence of ammonia alters the flame profile, which must be considered for burner modifications [9]. These references provide valuable insights for this research on ammonia co-firing.

2. Materials and methods

2.1. Research Methodology

This study is based on power plant simulations using heat balance software and process simulation tools. First, the specifications of the power plant used in this study will be established and modeled in the heat balance software. The basis is derived from PLTU in Indonesia, which will be described in the subsequent sections.

After the model is created, the work will continue with off-design simulations. In this simulation, the design parameters of the existing model will be maintained while introducing different variables to simulate a co-firing implementation as close to reality as possible. The ammonia ratio will be the variable in this study, ranging from 0–30% energy.

The purpose of this simulation is to investigate the impact of co-firing on combustion equipment operating parameters: fans (combustion air fans and induced draft fans), exhaust gas temperature, boiler efficiency, and greenhouse gas emissions reduction. Thus, these parameters will be observed for each variable.

The simulation results will then be analyzed to provide recommendations regarding the application of ammonia co-firing in existing PLTU.

2.2. PLTU Basis

As mentioned earlier, this study will use PLTU Coal in Indonesia as its basis. Larger PLTU classes are prioritized because of their vital role in the electrical system. Additionally, larger capacities tend to be more efficient, making them less likely to be retired under the PLTU decommissioning program.

Currently, the largest PLTU capacity owned by PLN is in the 600 MW class, 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 capacities range from 600–660 MW. Most utilize subcritical cycles with single reheating. Therefore, this class of PLTU is the most suitable basis for the study.

The power plant simulation will be based on the typical design of the aforementioned PLTU. The general input parameters for the power plant simulation are shown in Table 1.

The net power output is 660 MW, with auxiliary power accounting for approximately 5% of the gross output. This value is relatively low because the design model does not include flue gas desulfurization, which could increase auxiliary power consumption. The main steam pressure is 170 bar, and the reheated steam pressure is 59 bar. On the combustion side, the power plant has a boiler efficiency of 85.7% on a higher heating value (HHV) basis. The plant uses 15% excess air and ideally produces exhaust gas at a temperature of 135 °C at the air pre-heater outlet. The coal consumed is low-calorie coal with an HHV of 4601 Kcal/kg. Its composition follows the data outlined in Table 2.

Table 1. General Modeling Parameters of PLTU

Parameter	Value	Unit
Daya Netto	660.69	MW
Daya *Gross*	694.36	MW
Net Heat Rate (HHV)	2359.70	Kcal/Kg
Gross Heat Rate (HHV)	2479.96	Kcal/Kg
Tekanan *Main Steam*	170.00	Bar
Temperatur *Main Steam*	540.00	Celsius
Tekanan *Reheated Steam*	59.00	Bar
Tekanan *Condenser*	0.08	Bar
Rasio Udara Ekses	15.00	%
Efisiensi Boiler (HHV)	85.70	%
Temperatur *Flue Gas Heater Exit*	135.00	Celsius

The power plant was modeled using heat balance simulation with Steam Pro 30.0 software. The model is shown in Figure 1. There are three stages of steam turbines: high pressure (HP), intermediate pressure (IP), and low pressure (LP). These turbines consume approximately 338.6 tons/hour of coal to generate the maximum net power output, as indicated in Table 1.

On the emissions side, the PLTU adheres to Indonesia's latest regulation, the Ministry of Environment and Forestry Regulation No. P.15 of 2019. This regulation specifies four emission parameters: particulates, SO_2, NO_x, and mercury. For particulate control, the plant uses an electrostatic precipitator (ESP) to capture ash. For SO_2, no flue gas desulfurization equipment is required because the coal used contains low sulfur (sulfur-compliant coal) [10]. Both NOx and mercury emissions are generally below regulatory limits.

The boiler used is a pulverized coal type with opposed firing burners. Combustion air is supplied by a forced draft fan and a primary air fan through a regenerative air preheater on the cold side. Part of the air from the primary air fan is directed to the pulverizer to transport the coal. On the exhaust gas side, to balance the boiler pressure, an induced draft (ID) fan is used to draw the exhaust gases and channel them to the chimney.

Table 2. Coal Specifications

Component	Value	Unit
C – Karbon	47.46%	*As Received*
H - Hidrogen	3.63%	*As Received*
O - Oksigen	13.25%	*As Received*
S - Sulfur	0.17%	*As Received*
N - Nitrogen	0.49%	*As Received*
Total Moisture	29.00%	*As Received*
Ash	6.00%	*As Received*
Total	100.00%	*As Received*

Inside the boiler, the highest combustion temperature is located at the upper point of the radiation area, reaching 1560.3°C. Heat is absorbed in several sections, transitioning from the radiation area (absorbed by the wall tube evaporator) to the convective area (superheater, reheater, and economizer). The combustion diagram can be seen in Figure 2.

2.3. Ammonia Co-firing Concept

Ammonia (NH_3) is essentially a chemical compound with various applications as raw material or utility in industrial processes. Recently, ammonia has found another use as a fuel. Ammonia co-firing in PLTU has been developed by several manufacturers, including *IHI* Corporation, Mitsubishi Corporation, and others.

The concept of ammonia co-firing differs from biomass. Ammonia naturally exists in a gaseous phase at relatively low temperatures, which gives it higher reactivity for combustion. However, its flame propagation is slower than coal [11]. Therefore, ammonia injection is a critical parameter that must be carefully managed to achieve effective co-firing combustion.

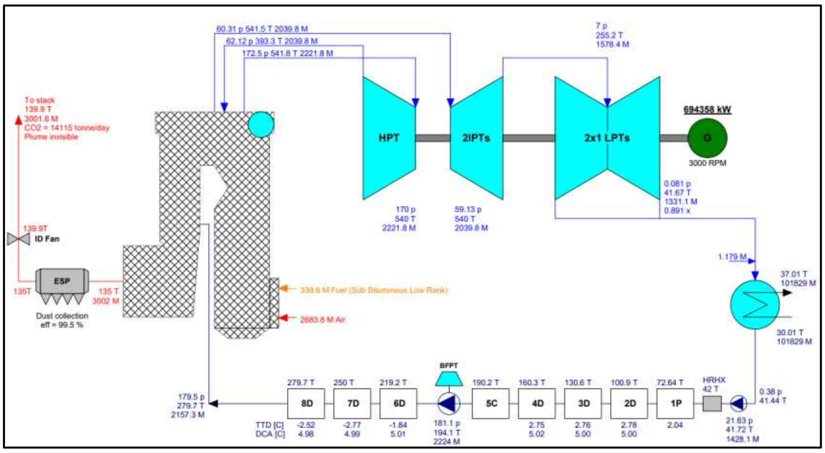

Figure 1. General Steam Cycle Model of PLTU

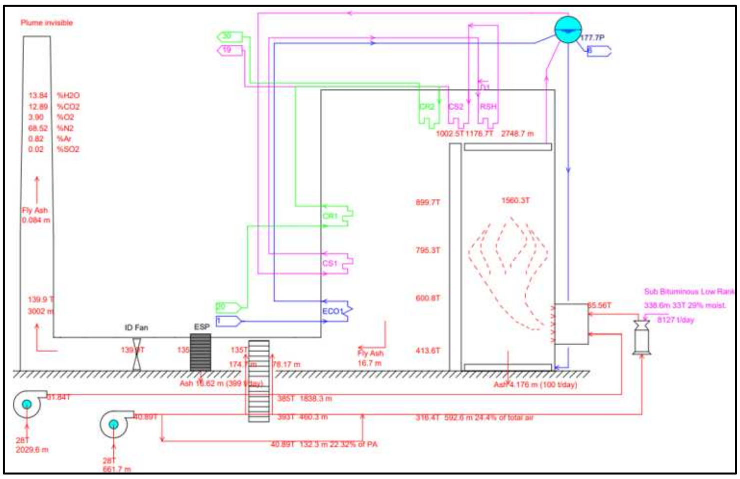

Figure 2. Combustion Model in PLTU

In this study, ammonia will primarily be injected into the lower combustion area. This approach aims to prevent incomplete combustion of ammonia due to its slower reaction kinetics. The burner for ammonia may require modification to regulate the injection profile. However, burner modification will not be the main focus of this study.

Ammonia will be injected in a gaseous phase, free of impurities. In its gaseous phase, ammonia will not absorb significant heat for vaporization within the boiler, a common practice based on manufacturer reports [8][12]. The design considerations for the ammonia processing system are not included in this study; therefore, it is assumed that ammonia is ready for injection into the boiler.

Co-firing ammonia may impact the performance of the existing boiler. Meanwhile, the steam turbine side is assumed to maintain the same performance since it only receives heat from combustion in the boiler. Changes in boiler efficiency due to ammonia co-firing may affect the quantity of energy transferred to the steam turbine and power output. As a result, additional heat input from the fuel may be needed to maintain gross power output. In this study, generator power output is a parameter to be maintained. As mentioned in Table 1, the generator's gross power output is represented as 694.36 MW.

The injection of combustion air into the boiler will be controlled. Based on literature studies from IHI Corporation, which has observed ammonia co-firing combustion in existing PLTUs, it is recommended to maintain the excess air ratio. However, combustion air flow may differ even with the same ratio due to stoichiometric reaction differences.

3. Results and discussion

The ammonia co-firing simulation uses the Steam Master 30.0 software as an off-design simulator. The presence of ammonia is expected to alter the operational parameters of the existing coal-fired power plant (PLTU). These parameters are explained in the subsections below.

3.1. Boiler Efficiency

The combustion of ammonia will affect the exhaust gas conditions and also impact heat absorption in the boiler. As a result, this can change the boiler efficiency as shown by the curve in Figure 3. The curve indicates that as the co-firing ratio increases, the boiler efficiency will decrease. This happens because the exhaust gases from ammonia combustion have a lower density, which increases the volume of exhaust gas, subsequently reducing the heat absorption efficiency due to faster retention time. The quantification of exhaust gas losses mentioned in Table 3 also explains this relationship.

Referring to the energy loss list according to ASME PTC 4, exhaust gas losses represent the largest amount of losses in ammonia co-firing applications. These losses are divided into two categories: sensible and latent losses. The increase in sensible losses is directly affected by the rise in exhaust gas temperature. The less efficient the heat absorption in the boiler, the higher the exhaust gas temperature, which occurs in ammonia co-firing applications. The second category is latent losses, which refers to the latent heat of the steam in the exhaust gas. In ammonia co-firing, the exhaust gas becomes more humid, resulting in an increase in latent losses.

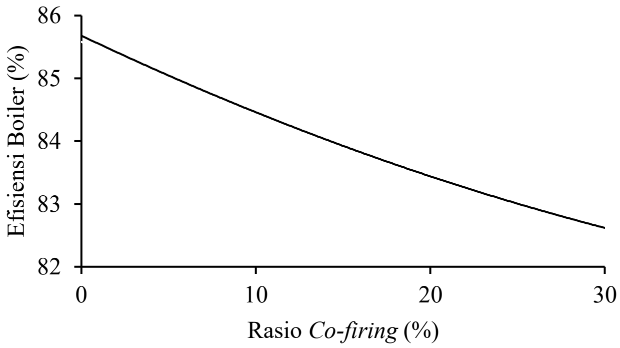

Figure 3. Boiler Efficiency (HHV) vs Co-firing Ratio

Table 3. Simulation Results on Exhaust Gas Losses

Rasio *Co-firing* (%)	Temperatur Gas Buang (°C)	*Losses* Gas Buang Sensibel (%)	*Moisture Content* Gas Buang (%)	*Losses* Laten (%)
0	135.00	6.41	13.84	9.53
10	142.70	6.75	15.23	10.45
20	148.00	6.86	16.62	11.19
30	153.80	6.99	18.02	11.91

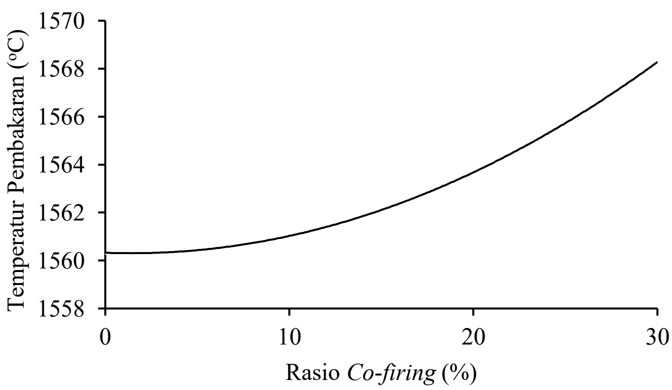

Figure 4. Combustion Temperature vs Co-firing Ratio

https://doi.org/10.33322/jtpeep.v1i1/95

3.2. Combustion Temperature of the Boiler

Each boiler is designed to maintain combustion within a specific temperature range. In the case of ammonia co-firing, there is a concern that the combustion temperature in the boiler may increase. Figure 4 shows the trend of the relationship between ammonia co-firing and the combustion temperature in the boiler. The combustion temperature point refers to the upper side of the radiation zone. Theoretically, the combustion temperature will increase due to the increased heat input from the fuel in the co-firing application, in order to maintain the output power at 694.36 MW. Additionally, ammonia has a slower combustion propagation, so ammonia combustion occurs at the top of the boiler, influencing the increase in temperature. The heat input from the fuel, as seen in the simulation results, is shown in Table 4. An increase in combustion temperature raises the risk of material overheating. Therefore, further consideration is needed to ensure the combustion temperature remains safe. If the material design is already at the upper limit, one solution is to operate with higher excess air. Combustion temperature can be reduced, although it may decrease boiler efficiency.

3.3. Draft Fan

Fans play a crucial role in the boiler system by balancing boiler pressure and maintaining the combustion process. On the upstream side, there are generally two types of fans that blow combustion air into the boiler: forced draft (FD) fan and primary air (PA) fan [13]. The FD fan provides secondary air to optimize the combustion process, while the PA fan supplies primary air and transports coal from the pulverizer into the boiler [14]. On the downstream side, the induced draft (ID) fan is responsible for drawing exhaust gases from the combustion process [15].

The operation can change in ammonia co-firing applications, even if the excess air ratio is maintained. This is due to the stoichiometric difference in oxygen requirements for burning coal and ammonia, with ammonia requiring less oxygen than coal. An investigation must be conducted to analyze the operation of the existing fans. This becomes one of the parameters observed in the simulation.

According to the simulation results, the airflow of combustion air and exhaust gases can be seen in Table 5. On the upstream side, the operation of the positive draft fans (FD and PA fans) tends to decrease. This is because, as the co-firing ratio increases, less combustion air is required while maintaining the excess air ratio. According to Table 1, the excess air ratio in the power plant is 15%. However, ammonia combustion produces more water due to its large hydrogen content. Thus, the exhaust gas density will be lower, meaning the volumetric flow increases. The operational level of the induced draft fan will increase by 3.82% compared to the maximum design operation at 0% co-firing. This could cause issues for the ID fan if the design margin is insufficient to handle the increased workload. Therefore, one solution is to reduce the excess air combustion ratio, which contradicts the combustion temperature aspect that recommends improving it. The simulation data is shown in Table 5.

Table 4. Heat Input From Fuel

Rasio Co-firing (%)	Input Bahan Bakar (KJ/s)	Peningkatan (%)
0	1,820,043.00	-
10	1,848,664.00	2%
20	1,869,290.00	3%
30	1,889,996.00	4%

Table 5. Simulation Results on Combustion Draft

Rasio *Co-firing*(%)	**0**	**10**	**20**	**30**
Laju Alir Udara Pembakaran (Ton/h)	2691.30	2682.20	2624.20	2566.70
Densitas Udara (kg/m^3)	1.194			
Laju Alir Volumetrik Udara Pembakaran (m^3/h)*10^3	2254.02	2246.40	2197.82	2149.66
Tingkat Kerja *Positive Draft Fan*	100.00%	99.66%	97.51%	95.37%
Laju Alir Gas Buang (Ton/h)	3002.00	3003.00	2940.50	2878.70
Densitas Gas Buang (kg/m^3)	0.83	0.80	0.78	0.76
Laju Volumetrik Gas Buang (m^3/h)*10^3	3625.17	3732.29	3752.55	3763.50
Level Kerja *Induced Draft Fan*	100.00%	102.95%	103.51%	103.82%

3.4. Greenhouse Gas Emissions

As mentioned in the introduction, the application of ammonia co-firing aims to reduce greenhouse gas emissions. Therefore, this study concludes with an estimate of greenhouse gas emissions.

In the case of 30% co-firing, CO2 emissions can be reduced by up to 29.26% while maintaining the same generator output power. However, this assumes the use of green ammonia, where no CO2 is emitted during the ammonia production process, as the energy used comes from renewable sources. If CO2 is generated during the production process, the CO2 reduction ratio may be lower than the simulation results presented in this study.

4. Conclusion

Based on the simulation results, it is concluded that several operational parameters of the coal-fired power plant (PLTU) must be reconsidered when implementing ammonia co-firing.

First, there is boiler efficiency. With the introduction of ammonia co-firing, the boiler efficiency will decrease, especially on a higher heating value (HHV) basis. Higher exhaust gas temperatures and more steam generation are key factors in reducing boiler efficiency. Therefore, to maintain the generator output, it is necessary to consider higher fuel heat input to sustain the amount of heat absorption into the feedwater/steam.

Second, due to the increase in fuel heat input, there are concerns that combustion temperatures may rise. Based on the simulation results, the implementation of 30% co-firing will increase combustion temperature by approximately 8°C. The boiler material specifications must be reviewed, unless the combustion temperature remains within the material's capability range, in which case overheating can be avoided.

Third, the operating levels of the positive draft fan (FD fan and PA fan) and the induced draft fan will shift. At the same excess air ratio, the combustion air rate will decrease with ammonia co-firing. As a result, the operation of the positive draft fan decreases and can be considered safe. However, on the exhaust gas side, the exhaust gas density becomes lower due to the increase in temperature and the higher steam composition, causing the volumetric flow of exhaust gas to increase. From the simulation results, the application of 30% co-firing can increase the induced draft fan (ID fan) operating level by approximately 3.8%. The design capacity of the ID fan must be reviewed to determine whether it was designed with margin considerations. Generally, the ID fan is designed to handle the worst coal conditions with additional margin. This can still be feasible if the maximum capacity (worst coal condition plus margin) is greater than the co-firing application.

Finally, the co-firing program aims to reduce greenhouse gas emissions. Therefore, the CO_2 emission reduction calculation is investigated in the final part of this study. At a 30% co-firing ratio, CO_2 generation can be reduced by approximately 29.26% for the same gross power output. This does not result in a linear reduction due to performance decline, especially in the boiler.

This study presents good results for initiating an ammonia co-firing program in existing power plants. However, further investigation is necessary to provide a more comprehensive analysis. Several parameters should be further investigated, as listed below.

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