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Performance Evaluation of Boiler Efficiency and Net Plant Heat Rate (NPHR) under 1–3% Ammonia Co-Firing in a 300 MW Coal-Fired Power Plant

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Abstract - **Ammonia co-firing is increasingly considered a transitional decarbonization strategy for existing coal-fired power plants because ammonia contains no carbon and can theoretically reduce direct CO_2 emissions from fuel combustion. However, its combustion characteristics differ from coal and may affect boiler efficiency, heat-loss distribution, and Net Plant Heat Rate (NPHR). This study evaluates the available-data-based performance implications of low-ratio ammonia co-firing (1%, 2%, and 3%) in a 300 MW subcritical tangentially fired coal boiler located in Pandeglang, Banten, Indonesia. A quantitative performance-test framework was used, with boiler efficiency evaluated using the indirect method based on ASME PTC 4 and plant heat-rate assessment based on net electrical output. The available spreadsheet data provided coal laboratory properties, including an as-received higher heating value of 4,276.59 kcal/kg, total moisture of 33.23 wt%, carbon content of 44.87 wt%, and a baseline coal flow of 162.78 t/h. Based on a 280 MW net-load assumption, the baseline heat input was 696.15 × 10^6 kcal/h and the reference NPHR was 2,486.26 kcal/kWh. Replacing 1–3% of fuel energy with ammonia requires approximately 1.30–3.89 t/h of NH_3, reduces coal use to 161.15–157.90 t/h, and provides an estimated CO_2 displacement of 2.68–8.03 t/h. The data also indicate additional water-vapor formation of 2.06–6.18 t/h from ammonia combustion and an estimated unburned-carbon heat loss of 1.044% under baseline coal operation. APH evaluation shows a valid gas-side effectiveness of 60.63% for APH B, while the APH A gas-side effectiveness of 106.29% requires verification. Final boiler-efficiency and complete heat-loss values still require flue-gas composition, oxygen, CO, CO_2, humidity, and complete performance-test data.**

Keywords: ammonia co-firing; boiler efficiency; heat loss; NPHR; coal-fired power plant; air preheater.

I. INTRODUCTION

Coal-fired power plants remain important in Indonesia's electricity supply, even as national energy policy increasingly emphasizes emission reduction and the long-term transition toward lower-carbon generation. Because many coal-fired units are still expected to operate during the transition period, practical decarbonization options that can be implemented in existing infrastructure are highly relevant (Wahyuni & Ardiansyah, 2022, p. 296; Yudiartono *et al.*, 2023, p. 425). Co-firing is one such option because it allows a portion of coal energy input to be replaced by an alternative fuel without immediately retiring the unit (Karampinis *et al.*, 2015; Lou *et al.*, 2023, p. 2).

Ammonia (NH_3) has received growing attention as a carbon-free fuel candidate (Huang *et al.*, 2024; Sun *et al.*, 2025). Unlike hydrocarbon fuels, ammonia does not contain carbon; therefore, its ideal combustion does not directly produce CO_2 (Erdemir & Dinçer, 2020; Li *et al.*, 2021, p. 1). This characteristic makes ammonia attractive for reducing carbon intensity in thermal power generation (Rekhraj & Hasini, 2024; Zhang *et al.*, 2025). Nevertheless, ammonia is not a drop-in equivalent to coal. It has lower reactivity, lower laminar flame speed, different ignition behavior (Erdemir & Dinçer, 2020; Sun *et al.*, 2025; Wang *et al.*, 2021, p. 31880), and produces more water vapor during combustion due to its hydrogen content (Hayashi *et al.*, 2022; Kim *et al.*, 2021). These characteristics can influence flame stability, heat transfer, and flue-gas composition (Kim *et al.*, 2021; Wang & Sheng, 2023).

From an operational perspective, the main concern is not only whether ammonia can reduce carbon emissions, but also whether it can be introduced without causing unacceptable performance deterioration. Boiler efficiency and Net Plant Heat Rate (NPHR) are key indicators for this assessment (Darmadi *et al.*, 2024, p. 43; Liang *et al.*, 2023, p. 9150017). Boiler efficiency reflects the ability of the boiler to convert fuel energy into useful steam energy (Goel & Rosenberg, 2016, p. 221; Kumar, 2017, p. 713), whereas NPHR represents the fuel energy required to produce one unit of net electricity (Aderibigbe & Osunbor, 2019, p. 22; Sitanggang *et al.*, 2023, p. 2372). A higher NPHR indicates lower overall plant efficiency and may lead to higher fuel consumption for the same net output (Aderibigbe & Osunbor, 2019, p. 22; Darmadi *et al.*, 2024, p. 43).

Previous studies have shown that ammonia co-firing may affect heat loss, NO_x formation, unburned fuel, and furnace temperature. However, studies on low-ratio ammonia co-firing in large subcritical coal boilers under practical performance-test conditions remain limited. This study therefore focuses on an available-data-based evaluation of 1%, 2%, and 3% ammonia co-firing in a 300 MW coal-fired power plant, with emphasis on boiler efficiency, heat-loss contributors, APH performance, and NPHR.

II. METHODOLOGY

2.1 Research Design

This study uses a quantitative engineering approach based on power-plant performance-test data. The analysis compares a baseline condition using 100% coal with ammonia co-firing cases of 1%, 2%, and 3% by fuel-energy share. The evaluation focuses on thermal performance parameters commonly used in coal-fired power plant assessment: boiler efficiency, heat-loss distribution, APH performance, and NPHR.

2.2 Plant Description and Test Object

The test subject is a 300 MW coal-fired power plant located in Pandeglang, Banten, Indonesia. The unit is equipped with a subcritical tangentially fired pulverized-coal boiler. The boiler and associated turbine-generator system are treated as an integrated plant-performance system because changes in combustion behavior can affect both boiler efficiency and net plant heat rate.

2.3 Scenarios and Variables

The independent variable is the ammonia co-firing ratio, with four scenarios: 0% NH_3 as the baseline, followed by 1%, 2%, and 3% NH_3 by fuel-energy share. The dependent variables are boiler efficiency, heat-loss components, APH performance indicators, and NPHR. Controlled variables include plant load, coal quality, and excess-air setting, which should be maintained as consistently as possible across all test scenarios.

Table 1: Ammonia co-firing scenarios

Scenario	NH_3 share	Coal share	Purpose
Baseline	0%	100%	Reference case
CF-1	1%	99%	Low-ratio co-firing
CF-2	2%	98%	Intermediate low-ratio co-firing
CF-3	3%	97%	Highest ratio in this study

2.4 Fuel-Property and APH Data

The uploaded spreadsheet was reviewed to identify usable input data. The workbook contains coal laboratory properties, weighted fuel-quality calculations, and an APH performance sheet. The coal-property data are used as the basis for fuel-energy, theoretical-air, carbon-displacement, and preliminary unburned-carbon calculations. The APH sheet is used to evaluate gas-side effectiveness and air-side efficiency. Complete final boiler-efficiency calculations still require verified operational data from the performance-test workbook.

Table 2: Coal properties extracted from the available spreadsheet

Parameter	Basis	Unit	Value
Higher heating value	As received	kcal/kg	4,276.59
Higher heating value	As received	kJ/kg	17,905.23
Total moisture	As received	wt%	33.23
Fixed carbon	As received	wt%	30.28
Volatile matter	As received	wt%	29.91
Ash	As received	wt%	6.58
Carbon	As received	wt%	44.87
Hydrogen	As received	wt%	3.25
Oxygen	As received	wt%	10.92
Sulfur	As received	wt%	0.41
Nitrogen	As received	wt%	0.73

2.5 Calculation Method

Boiler efficiency was evaluated using the indirect method, which calculates efficiency by subtracting the total percentage of heat losses from the fuel-energy input. The main heat-loss components include dry flue-gas loss, moisture-related losses, unburned-carbon loss, and radiation/convection loss. The total relationship is expressed as: $\eta b, indirect(\%)=100-\Sigma Lini=1$, where Li represents each heat-loss component as a percentage of fuel input. NPHR is calculated as the ratio of total fuel heat input to net electrical output: NPHR=$\dot{Q}inPnet$. For the available-data calculation, the baseline coal heat input is calculated from coal flow and HHV. The ammonia flow required for each co-firing case is calculated by replacing the selected percentage of baseline fuel-energy input with ammonia, using an ammonia heating value of 5,369.4 kcal/kg. The theoretical-air requirement is calculated from ultimate analysis using TA = [(11.6C) + 34.8(H − O/8) + 4.35S]/100.

III. RESULTS

3.1 Baseline Fuel-Energy and Theoretical-Air Calculation

Using the available coal-flow and coal-quality data, the baseline coal flow was 162.782 t/h and the as-received HHV was 4,276.59 kcal/kg. The calculated baseline fuel heat input was 696.15 × 10^6 kcal/h. With a net-load assumption of 280 MW, the reference NPHR was 2,486.26 kcal/kWh. The theoretical air requirement based on the coal ultimate analysis was 5.878 kg air/kg fuel.

Table 3: Baseline fuel-energy indicators

Indicator	Value	Unit	Remark
Coal flow	162.782	t/h	From available spreadsheet
Coal HHV	4,276.59	kcal/kg	As received
Baseline heat input	696.15	10^6 kcal/h	Coal flow × HHV
Assumed net load	280,000	kW	Based on DMN test assumption
Reference NPHR	2,486.26	kcal/kWh	Heat input / net load
Theoretical air	5.878	kg air/kg fuel	Based on ultimate analysis

3.2 Fuel-Substitution Requirement and Reference NPHR

Table 4 presents the estimated fuel substitution for 1–3% ammonia co-firing. The calculation assumes that total fuel heat input is kept equal to the baseline heat input. Under this assumption, the reference NPHR remains constant because both total heat input and net electrical output are kept constant. Therefore, the values in this table should be interpreted as an input-basis scenario calculation, not as final performance-test results.

Table 4: Estimated fuel substitution and reference NPHR

Scenario	Coal flow (t/h)	NH_3 flow (t/h)	Total heat input (10^6 kcal/h)	Reference NPHR (kcal/kWh)
0% NH_3	162.782	0.000	696.15	2486.26
1% NH_3	161.155	1.297	696.15	2486.26
2% NH_3	159.527	2.593	696.15	2486.26
3% NH_3	157.899	3.890	696.15	2486.26

3.3 Preliminary Unburned-Carbon Heat-Loss Estimate

The available spreadsheet includes fly-ash and bottom-ash carbon data. Based on the available ash content, ash split, and carbon-in-ash values, the estimated baseline unburned-carbon heat loss was 1.044% of fuel heat input. Because ammonia replacement reduces coal flow in the energy-share scenarios, the unburned-carbon heat loss associated with coal ash decreases slightly when the same ash and unburned-carbon characteristics are assumed.

Table 5: Preliminary unburned-carbon heat-loss estimate

Scenario	Fly-ash UBC loss (%)	Bottom-ash UBC loss (%)	Total UBC loss (%)
0% NH_3	0.895	0.149	1.044
1% NH_3	0.886	0.148	1.034
2% NH_3	0.877	0.146	1.024
3% NH_3	0.868	0.145	1.013

3.4 Air Preheater Performance

The APH sheet provides commissioning and actual APH performance values. The actual gas-side effectiveness for APH B was 60.63%, while APH A showed 106.29%. Because heat-exchanger effectiveness above 100% is not physically reasonable, the APH A gas-side effectiveness should be verified before it is used as a final result. The primary-air and secondary-air efficiency values remain usable as temperature-based indicators.

Table 6: Commissioning APH performance

Parameter	Unit	APH A	APH B
Gas-side effectiveness	%	65.71	62.93
Primary-air efficiency	%	94.60	92.21
Secondary-air efficiency	%	93.27	91.87

Table 7: Actual APH performance from available sheet

Parameter	Unit	APH A	APH B	Remark
Gas-side effectiveness	%	106.29*	60.63	APH A value >100%; requires verification
Primary-air efficiency	%	91.75	95.24	Valid as temperature-based indicator
Secondary-air efficiency	%	88.68	82.50	Valid as temperature-based indicator

3.5 Estimated CO_2 Displacement and Additional Water-Vapor Formation

Carbon displacement was estimated from the reduction in coal input, using the coal carbon content from ultimate analysis. The calculation indicates that replacing 1–3% of fuel energy with ammonia can reduce carbon-derived CO_2 input by approximately 2.68–8.03 t CO_2/h. However, ammonia combustion also produces additional water vapor. Based on the stoichiometric reaction $4NH_3 + 3O_2 \rightarrow 2N_2 + 6H_2O$, 1 kg of NH_3 produces approximately 1.588 kg of H_2O. This leads to an estimated additional water-vapor formation of 2.06–6.18 t/h for the 1–3% ammonia cases.

Table 8: Estimated CO_2 displacement and additional H_2O from NH_3 combustion

Scenario	Estimated CO_2 displacement (t/h)	Additional H_2O from NH_3 combustion (t/h)
0% NH_3	0.000	0.000
1% NH_3	2.678	2.059
2% NH_3	5.356	4.118
3% NH_3	8.035	6.178

3.6 Data Required for Final Boiler-Efficiency and NPHR Results

Although the available data are sufficient to calculate fuel-energy substitution, theoretical air, unburned-carbon loss estimates, APH indicators, carbon displacement, and water-vapor formation, they are not sufficient to finalize the full indirect boiler-efficiency calculation. Complete results require verified operational data for each scenario, especially flue-gas temperature, O_2, CO_2, CO, humidity, actual air supply, and net electrical output.

Table 9: Additional data required to finalize the calculation

Analysis item	Additional data required
Indirect boiler efficiency	Flue-gas temperature, ambient temperature, O_2/CO_2, CO, humidity, actual air supply, radiation/convection assumptions
Heat-loss distribution	Complete L1–L8 inputs for each scenario, including gas composition and ash flow
Actual NPHR	Coal flow, NH_3 flow, gross power, auxiliary power, and net power for each scenario
Air leakage	O_2 concentration at APH inlet and outlet for APH A and APH B
Emissions	Measured CO_2, NO_x, CO, and NH_3 slip for each scenario

FEGT	Measured Furnace Exit Gas Temperature for baseline and co-firing cases
Production cost	Coal price, ammonia price, handling cost, and net energy output

IV. DISCUSSION

The available-data-based calculation provides several useful preliminary insights even though the complete performance-test dataset has not yet been verified. First, the baseline fuel-energy calculation shows that the unit required approximately 696.15×10^6 kcal/h of heat input under the selected 280 MW net-load assumption. This corresponds to a reference NPHR of 2,486.26 kcal/kWh. This value should be treated as a reference calculation because the final NPHR must be based on actual measured net output and fuel flow for each test scenario.

Second, the fuel-substitution calculation shows that low-ratio ammonia co-firing requires a relatively small ammonia mass flow compared with coal flow. At 3% fuel-energy replacement, the estimated ammonia flow is 3.89 t/h and the coal flow decreases from 162.78 t/h to 157.90 t/h. This confirms that the proposed co-firing ratios are operationally low and represent an early-stage implementation rather than a high-ammonia substitution case.

Third, the estimated CO_2 displacement increases almost linearly with the ammonia energy share because ammonia contains no carbon. At 3% ammonia co-firing, the estimated carbon-derived CO_2 displacement reaches approximately 8.03 t/h. However, this reduction is based on carbon input displacement and should not be interpreted as measured stack emission reduction. Actual stack emissions require direct CO_2, CO, NO_x, and NH_3 slip measurements.

Fourth, ammonia addition produces additional water vapor during combustion. The estimated additional H_2O formation reaches 6.18 t/h at 3% ammonia co-firing. This mechanism is important because increased water vapor in flue gas can contribute to moisture-related heat loss. Therefore, although ammonia can reduce direct carbon input, it may also increase moisture-related losses if combustion and heat-transfer conditions are not optimized.

The preliminary unburned-carbon loss estimate shows a slight decrease as ammonia replaces part of coal energy input. This occurs because the calculation assumes the same ash and unburned-carbon characteristics while reducing coal flow. However, this should not be interpreted as proof that ammonia improves combustion completeness. Actual unburned-carbon behavior depends on furnace temperature, residence time, air distribution, mixing quality, and ammonia injection strategy. Therefore, fly-ash and bottom-ash carbon should be measured for each co-firing scenario before a final conclusion is drawn.

The APH results show that APH B has an actual gas-side effectiveness of 60.63%, which is close to the commissioning value of 62.93%. In contrast, APH A shows a calculated gas-side effectiveness of 106.29%, which is not physically reasonable and indicates a likely data-entry or data-linking issue, especially in the outlet gas temperature. Therefore, APH A gas-side effectiveness should be verified before being included in final performance interpretation. The primary-air and secondary-air efficiency values suggest that the APH still provides significant heat recovery, although the lower secondary-air efficiency on APH B may influence combustion-air temperature.

Overall, the available data support the expected trade-off in ammonia co-firing. Ammonia replacement reduces carbon input but may increase moisture-related heat loss and introduce combustion-stability concerns. The final direction of boiler efficiency and NPHR can only be confirmed after completing the indirect heat-loss calculation using verified flue-gas composition and operating data. The most important next step is therefore to complete the performance-test workbook for all scenarios so that boiler efficiency, total heat loss, and actual NPHR can be calculated consistently.

V. CONCLUSIONS

This study provides an available-data-based preliminary performance assessment of low-ratio ammonia co-firing in a 300 MW subcritical coal-fired power plant. The available coal-quality data show an as-received HHV of 4,276.59 kcal/kg, total moisture of 33.23 wt%, carbon content of 44.87 wt%, and baseline coal flow of 162.782 t/h.

Using a 280 MW net-load assumption, the calculated baseline heat input is 696.15×10^6 kcal/h and the reference NPHR is 2,486.26 kcal/kWh. For 1–3% ammonia co-firing by fuel-energy share, the estimated ammonia requirement is 1.30–3.89 t/h, while coal flow decreases to 161.15–157.90 t/h.

The estimated CO_2 displacement increases from 2.68 t/h at 1% ammonia co-firing to 8.03 t/h at 3% ammonia co-firing. However, ammonia combustion also produces additional water vapor of 2.06–6.18 t/h, which may increase moisture-related heat loss. The preliminary unburned-carbon heat-loss estimate decreases slightly from 1.044% under baseline coal operation to 1.013% at 3% ammonia co-firing under constant ash and UBC assumptions.

APH evaluation indicates that APH B has a valid actual gas-side effectiveness of 60.63%, while APH A requires verification because the calculated gas-side effectiveness exceeds 100%. Final boiler-efficiency, complete heat-loss distribution, actual NPHR, air leakage, emissions, FEGT, and production-cost analysis still require additional verified performance-test data.

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