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Techno-Economic and Life Cycle Evaluation of Low Carbon Ammonia Co-Firing Implementation in Coal-Fired Power Plants

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Abstract. This study assesses the techno-economic feasibility and environmental impact of ammonia co-firing in coal-fired power plants (CFPPs) in Indonesia. Using Aspen Plus simulation on a 660 MWe subcritical boiler, various blending ratios of low carbon ammonia (0–50%) were evaluated. The results show that increasing the ammonia co-firing ratio reduces direct CO_2 emission intensity from 0.90 to approximately 0.45 ton CO_2/MWh. Emissions of SOx and NOx also decrease due to reduced coal consumption and the reaction of unburned ammonia with NO through a selective non-catalytic reduction (SNCR) mechanism. The Levelized Cost of Electricity (LCoE) increases with higher ammonia content. At a 50% ratio, LCoE reaches 146 USD/MWh (grey), 156 USD/MWh (blue), and 252 USD/MWh (green), compared to a baseline of 49 USD/MWh. Life Cycle Assessment (LCA) shows that grey ammonia increases Global Warming Potential (GWP) by 4.83%. while green ammonia reduces GWP by 49.9% compared to 100% coal combustion. Emissions also vary by delivery distance; supply from Gresik results in 0.17% lower emissions than from Bontang. Ammonia co-firing offers a viable low-carbon transition strategy for Indonesia's coal-dominated power sector, particularly with blue or green ammonia. Its success depends on fuel selection, supply chain efficiency, and comprehensive life cycle-based policy support.

Keywords: ammonia, carbon footprint, coal-fired power plant, co-firing, economic analysis, greenhouse gas emissions.

1 Introduction

Global and national energy demands are rising. Coal-fired power plants supply 51% of Indonesia's electricity, including PLN and private assets [1]. Installed capacity grew from 72,032.9 MW in 2023 to 74,555.8 MW in 2024, while coal consumption dropped from 68.67 to 59.1 million tons [1]. Coal combustion at 800–1200°C emits CO_2, SO_2, NO_x, and other pollutants [2][3], producing greenhouse gases such as carbon dioxide (CO_2), sulfur dioxide (SO_2), nitrogen oxides (NO_x), and other pollutants [4]. These gases contribute to climate change by trapping solar heat, which is absorbed by the oceans, leading to rising sea temperatures and sea levels [5]. To address this, various efforts have been made to reduce greenhouse gas emissions, particularly CO_2. These include Ministerial Decree of Energy and Mineral Resources No. 14.K/TL.04/MEM.L/2023 on Emission Upper Limits (PTBAE), Presidential Regulation No. 14 of 2024 on the implementation of Carbon Capture and Storage (CCS), and Presidential Regulation No. 98 of 2021 concerning Carbon Economic Value (NEK) [6][7][8]. These policies are complemented by strategic energy planning documents, including the Rencana Umum Ketenagalistrikan Nasional (RUKN) and Roadmap Hidrogen dan Amonia Nasional (RHAN), which position ammonia co-firing as a key transition strategy culminating in a 100% ammonia-based PLTU target of 8.4 GW by 2060 [9][10].

Besides CCS, co-firing coal with lower-carbon fuels like ammonia offers a near-term solution. Ammonia is easier to handle than hydrogen and emits no CO_2, though it poses NO_x challenges requiring combustion optimization [11]. Studies on 550–1000 MWe units show CO_2 reductions of 16.3–36.4% at 30–40% ammonia ratios [3][5]. Recent studies also demonstrate the viability of larger-scale applications, such as in Sun et al. (2023) and Deng et al. (2024), who report LCOE values ranging from 74–142 USD/MWh depending on ammonia type and carbon capture configuration. Despite the increase in LCOE, the reduction in lifecycle emissions and alignment with national decarbonization policies make co-firing a strategically favorable option[12][13]. Existing research has also highlighted necessary modifications in combustion air ratios and NO_x control due to ammonia's combustion characteristics [14]. For instance, Nagatani et al. demonstrated lower NO_x emissions in a two-stage combustion system with a 30% air ratio compared to pure coal firing [15]. Sousa Cardoso et al. (2022) reported that at 40–80% ammonia co-firing, unburned ammonia reacts with NO_x gases, reducing net emissions[16]. Ahmad et al. further observed that increasing the steam rate by 0.5% for every 10% ammonia addition helped maintain stack temperature and contributed to lower NO_x and SO_x emissions, attributable to ammonia's lower adiabatic flame temperature [14].

Ammonia can be categorized based on production method: grey ammonia (produced from fossil fuels with high CO_2 emissions), blue ammonia (produced with CCS at the final stage), and green ammonia (produced using renewable energy, near-zero emissions) [12]. While co-firing ammonia with coal can reduce power plant emissions, upstream emissions especially for grey ammonia must also be considered. Studies such as Sun et al. [12] highlight that grey ammonia's life cycle GWP per kWh can exceed that of pure coal combustion, whereas green ammonia has lower GWP. Kong et al. [17] recommend minimizing green ammonia's production emissions using solar-powered photovoltaic (PV) systems in high solar potential regions. Despite its lower GWP, green ammonia faces barriers in cost and availability for large-scale use. A 30% co-firing ratio could be more cost-effective than CCS-equipped coal plants by 2030 under favorable carbon pricing or coal price conditions [12]. Conversely, using grey ammonia at increasing ratios may reduce gross revenue by up to USD 22 million per 10% ammonia increment [18]. In Indonesia's coal-dependent power sector, ammonia co-firing provides a strategic opportunity to balance energy security with environmental responsibility. This is increasingly relevant as the nation pursues carbon reduction goals aligned with its 2060 carbon neutrality roadmap. Ammonia co-firing allows significant GHG emission reductions without requiring full replacement of existing power infrastructure. This study evaluates ammonia co-firing comprehensively analyzing its effects on combustion emissions, techno-economic performance, and life cycle carbon footprint, including comparisons across grey, blue, and green ammonia.

2 Methods

This research employs a quantitative approach through modeling and simulation using ASPEN Plus software to evaluate the combustion process of coal and ammonia mixtures in power plant boilers. The methods used are as follows:

2.1 Modeling and Simulation

The ammonia–coal co-firing simulation was conducted at heat input ratios ranging from 0–50%, based on Chen et al. [11], co-firing 50% ammonia does not cause overheating of the pipeline, decreases gas abrasion due to solid particles, and increases the dew point of acid, so as to reduce the need for retrofitting. In this study, the O_2 content in the flue gas was maintained at 1.64% by volume. Analysis of simulation results is carried out by reviewing the effect of variations in ammonia - coal ratio on CO_2 composition, NO_x emissions, SO_x emissions, CO content in flue gas, and changes in fuel-air ratio to maintain %vol O_2 in flue gas. The simulation results will be compared with the initial condition of the baseline power plant at 0% co-firing. Reaction parameters such as temperature and pressure are adjusted to approximate operating conditions at a 660 MWe subcritical coal-fired power plant. In this simulation, ammonia is treated as an additional fuel injected at a certain fraction to achieve a balance between emission reduction and energy efficiency.

In this model Figure 1, coal is decomposed in the RYield block using yield distributions based on ultimate and proximate analyses, as well as the dry-basis heating value. The decomposition products H_2O, N_2, O_2, S, H_2, Cl_2, C, and ash—are determined from Excel-based calculations [19]. Combustion occurs in the RGibbs block, where the resulting heat is transferred to the boiler to generate steam under validated conditions, producing electricity. After model verification, co-firing simulations with 0–50% ammonia mass ratios are performed to assess system performance and flue gas composition. The base case uses coal with a higher heating value (HHV) of 6678.9 kcal/kg (Table 1), and the 100% coal model is validated using key parameters listed in Table 2.

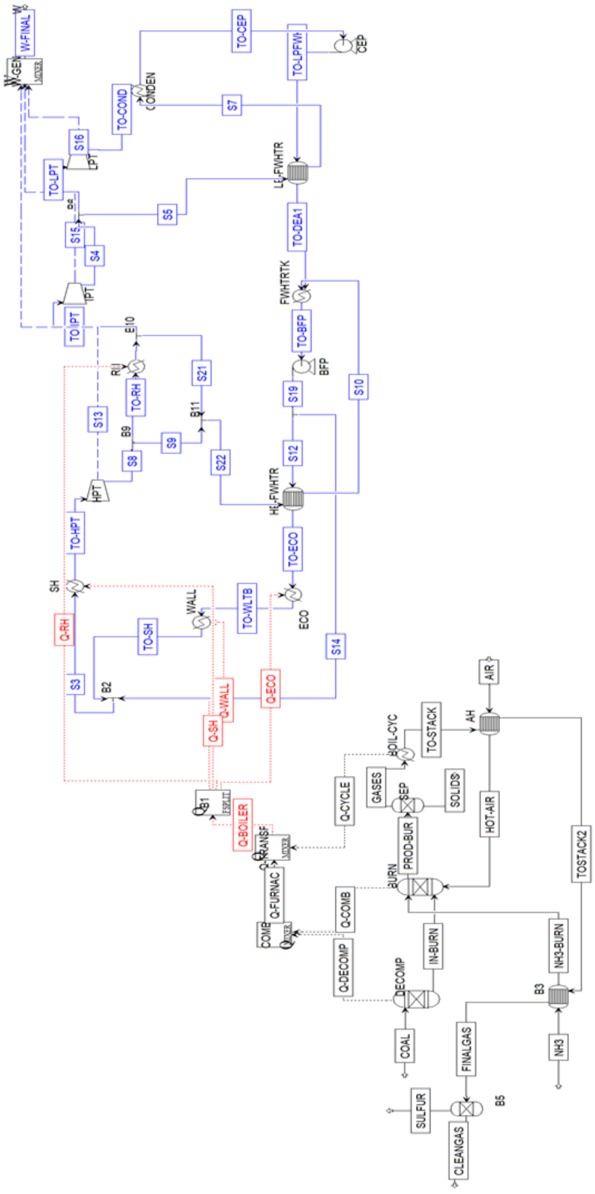


Figure 1 Simulation Model

Table 1 Coal Analysis

Type	Proximate Analysis			Ultimate Analysis (%)					Total Sulphur (%)			HHV (kcal/kg)
	ASH	VM	FC	C	H	N	S	O	Sp	Ss	So	
AR	4.99	36.29	40.68	57.88	3.92	1.20	1.14	12.8	0	0	1.14	5,638
DB	5.89	45.55	48.56	5.89	5.84	1.79	1.1	10.3	0	0	1.1	6,678.9

2.2 Economic Analysis

The economic analysis in this study includes estimating capital (CAPEX) and operational (OPEX) costs using the Aspen Process Economic Analyzer (APEA). Retrofit costs for accommodating ammonia co-firing are calculated based on a modular cost adjustment scheme aligned with the Chemical Engineering Plant Cost Index (CEPCI). Variables analyzed include ammonia raw material costs and boiler retrofit costs. The calculation of Levelized Cost of Energy (LCoE) will follow the equation below [12][19]:

$$LCoE_{Incremental} = \frac{CAPEX_i + OPEX_i}{Electricity} \tag{1}$$

$LCoE_{Incremental}$ = The levelized cost for the next unit of electricity produced after a modification (USD/MWh)
$CAPEX_i$ = Investment value of additional project (USD)
$OPEX_i$ = Changes in operating and maintenance costs (including fuel) per year as a result of the project (USD)
$Electricity$ = Annual electricity generated (MWh/year)

The incremental method adds the base LCoE value to the incremental LCoE. Where LCoE is valued at 49.25 USD/MWh, while incremental LCoE is divided into incremental annual CAPEX and incremental OPEX. Incremental CAPEX refers to additional costs arising from the procurement of equipment, storage tanks, and boiler retrofits, which are allocated over the production lifespan. Incremental OPEX includes the costs of substituting coal with ammonia and the maintenance costs of additional equipment [20]. Therefore, the final LCoE after the retrofit is as follows:

$$LCoE_{Final} = LCoE_{Baseline} + LCoE_{Incremental} \tag{2}$$

$LCoE_{Final}$ = The levelized cost of electricity produced final after a modification (USD/MWh)
$LCoE_{Baseline}$ = The levelized cost of electricity (USD/MWh)
$LCoE_{Incremental}$ = The levelized cost for the next unit of electricity produced after a modification (USD/MWh)

2.3 Life Cycle Assessment (LCA)

To assess the environmental impact of coal and ammonia co-firing, this study adopts a Life Cycle Assessment (LCA) approach to measure the carbon footprint from the production and use of several types of ammonia (grey, blue, and green). The LCA method is applied following the IPCC 2006 guidelines [21], utilizing Tier 1 emission factors, encompassing stages such as fuel combustion, fugitive emissions from coal production and supply activities like open-pit mining and uncontrolled burning, CO_2 transportation and injection, and ammonia production and transportation. Greenhouse gas (GHG) impacts are converted over a 100-year period to CO_2 equivalents [22].

3 Result and Discussion

The validation of simulation shown in Table 2, outlines the validation process by comparing actual operational data from the power plant with output generated by simulation. Most of the values show a close match, with the largest deviation observed in the CO_2 flue gas concentration at 4.44%. Even so, this remains within the generally accepted threshold for combustion system simulation, where variations of up to 5% are often tolerated [23]. Several key indicators such as the net power output 0.05%, oxygen content in flue gas 0.07%, and coal flow rate 1.06% demonstrate exceptionally small differences. These findings suggest that models successfully mirror the real-world performance of the system, both in terms of energy balance and gas emission characteristics. These results confirm that the model has a high degree of accuracy and can be trusted as a dependable platform conducting further simulation. Therefore, this validated model is suitable for analyzing ammonia co-firing scenarios, with reasonable confidence that it will remain within operationally realistic bounds.

Table 2 Validation Baseline

Parameter	**Units**	**Data**	**Simulation**	**Deviation**
W-Nett	MW	656.78	656.46	0.05%
Temperature steam	°C	516.44	517.66	0.24%
Pressure steam	atm	165.04	168.58	2.15%
O_2 flue gas	%vol	1.64	1.64	0.07%
CO_2 flue gas	%vol	16.87	16.12	4.44%
Emission Intensity	kg CO_2/kWh	0.88	0.90	2.32%
Coal Flow	tonne/hr	276.757	273.829	1.06%

Next, a simulation of the co-firing of ammonia was carried out with a variation of the ratio from 10 to 50% by maintaining the boiler heat, steam temperature, steam pressure, excess oxygen, power produced, and the results can be seen in Table 3.

Table 3 Fuel Requirements for Co-firing Ratio

Co-Firing Ratio	Coal Mass (tonne/hr)	Ammonia Mass (tonne/hr)	Air Mass (tonne/hr)	Air-Fuel Ratio
0%	273.829	0.000	2377.55	8.68
10%	246.380	30.720	2342.15	8.45
20%	218.975	61.411	2306.94	8.23
30%	191.638	92.034	2271.88	8.01
40%	164.210	122.770	2236.76	7.79
50%	136.820	153.470	2201.74	7.58

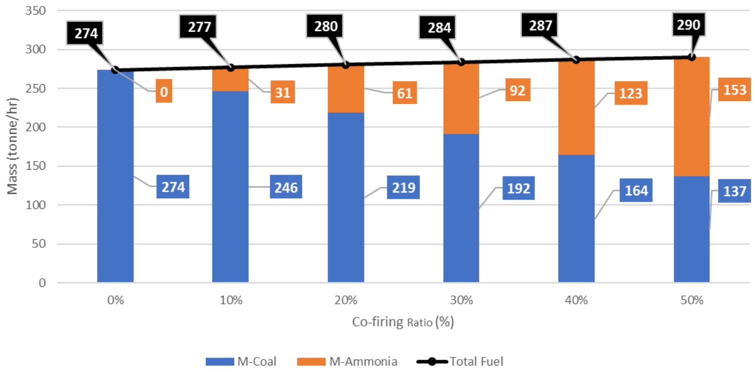


Figure 2 Fuel Requirement

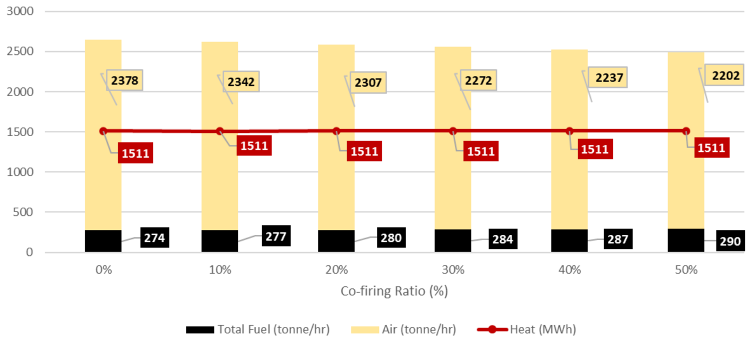
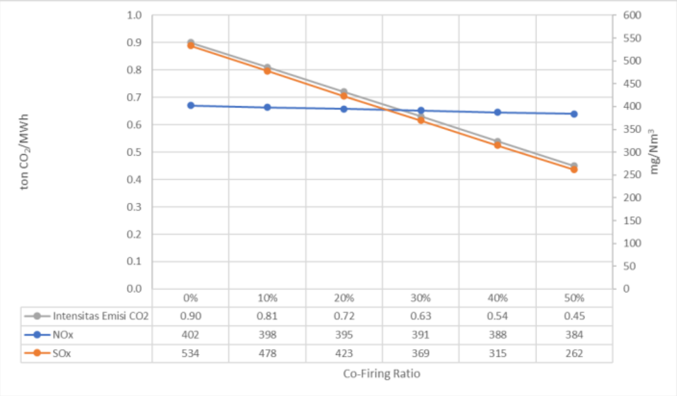


Figure 3 Air and Heat Requirements

Figure 2 shows that as the ammonia co-firing ratio increases the total fuel requirement also increases 6% from 274 tonne/hr to 290 tonne/hr, similar to findings reported in Chen et al. (2023) increases until 15% [11]. Meanwhile, Figure 3 of air requirement versus co-firing ratio shows that the amount of air used in combustion decreases from 2378 tonne/hr to 2202 tonne/hr, similar to the findings of Chen et al. (2023) [11], which also reported a 7% decrease in air from the initial condition.

3.1 Impact of Co-Firing on Flue Gas

The substitution of ammonia for coal significantly reduces direct CO_2 emissions, as illustrated in Figure 4. At a 50% co-firing ratio, CO_2 intensity decreased from 0.90 to 0.45 tCO_2/MWh, equivalent to a 50% reduction. This is because CO_2 originates from coal combustion, while ammonia contains no carbon. In parallel, SOx emissions decreased from 533.54 to 261.72 mg/Nm^3, or approximately 51%, due to the reduced sulfur input from lower coal consumption. NOx emissions also declined from 402.11 to 383.91 mg/Nm^3 (−4.5%), attributed to the SNCR mechanism, where unburned NH_3 reacts with NOx to form N_2 and H_2O.



	0%	10%	20%	30%	40%	50%
Intensitas Emisi CO2	0.90	0.81	0.72	0.63	0.54	0.45
NOx	402	398	395	391	388	384
SOx	534	478	423	369	315	262

Figure 4 CO_2 Emission Intensity, NO_x, and SO_x Emission

These results are consistent with findings by Sousa Cardoso et al. (2022) and Ahmad et al. (2023), which confirm that ammonia co-firing can effectively suppress thermal NO_x formation through SNCR reactions [16][14]. The application of co-firing also has no impact on meeting the maximum levels of NOx and SOx as limited by the regulation of the minister of environment Number P.15 / MENLHK / SETJEN / KUM.1/4 / 2019 [24].

3.2 Impact Co-Firing on LCoE

The implementation of co-firing in power plants affects the CAPEX and OPEX in power plant.

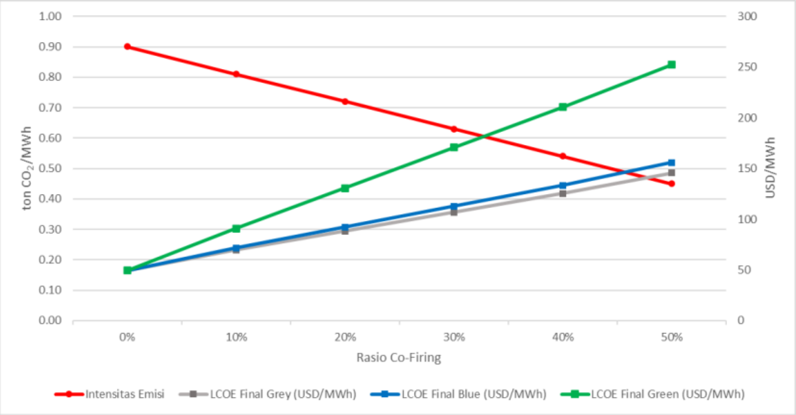
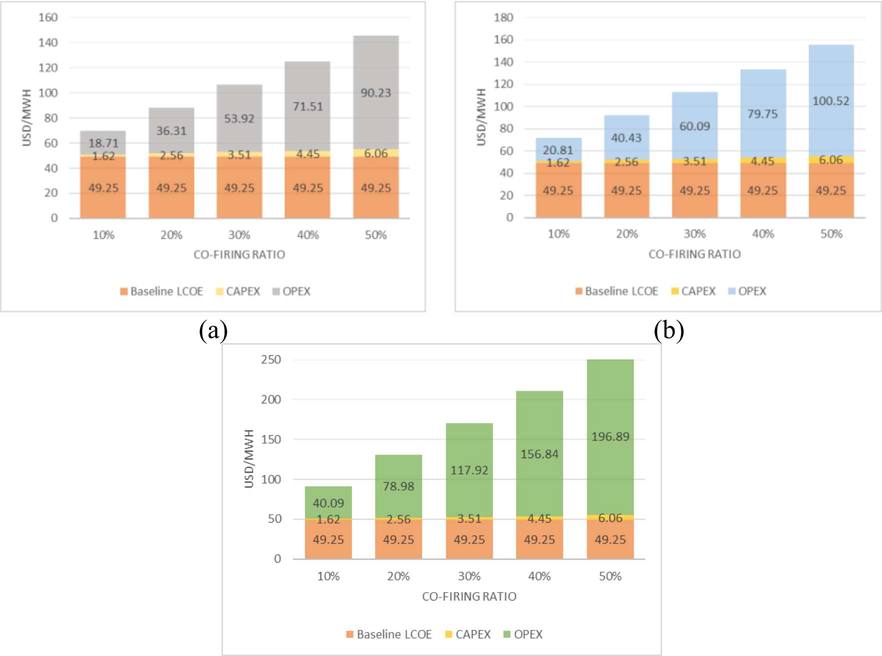


Figure 5 Co-Firing Effect to LCoE



(a) (b)

(c)

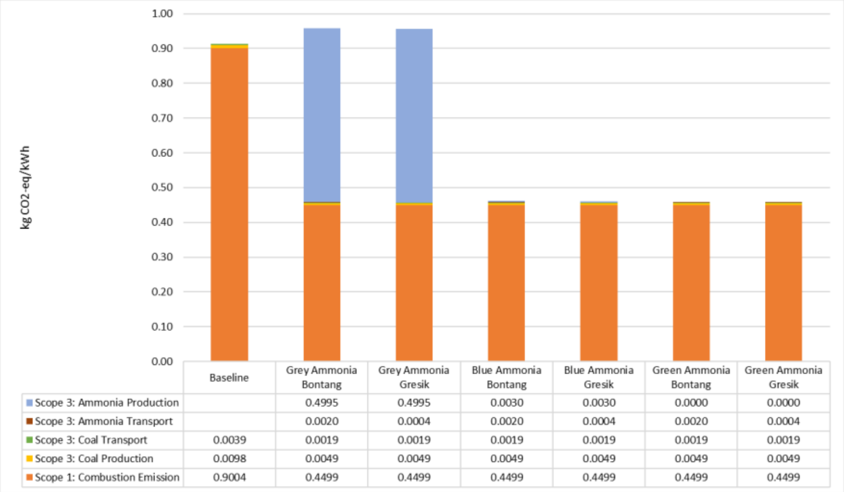
Figure 6 (a) LCoE Grey Ammonia, (b) LCoE Blue Ammonia, (c) LCoE Green Ammonia

As shown in Figure 5, increasing the co-firing ratio linearly reduces direct emission intensity but raises total LCoE. Green ammonia contributes to the highest LCoE due to its high fuel cost—priced at 885.36 USD/MT, compared to blue 473.50 USD/MT, grey 429.50 USD/MT,[25] and coal price 70 USD/MT. At a 50% co-firing ratio, LCoE reaches 145.54 USD/MWh for grey, 155.84 USD/MWh for blue, and 252.20 USD/MWh for green ammonia.

Figure 6 details LCoE components: baseline, incremental CAPEX, and OPEX. The baseline LCoE is 49.25 USD/MWh, reflecting the existing coal-only condition. As co-firing ratio increases, both CAPEX and OPEX rise, but OPEX dominates due to ammonia's much higher cost up to 6–12 times that of coal. At 50% co-firing, LCoE increases 2–5 times above baseline, with green ammonia showing the sharpest jump. Co-firing with grey and blue ammonia remains relatively more economical. These findings are consistent with Sun et al., who reported LCoE of 110 USD/MWh (30% grey) and 142 USD/MWh (30% green) [12].

3.3 Impact Co-Firing on Global Warming Potential (GWP)

This section assesses the GWP of ammonia co-firing across the entire supply chain, including emissions from mining, production, transport, and combustion. Coal is assumed to be delivered from Kalimantan 2626.84 km, while ammonia is sourced from Gresik 501.4 km and Bontang 2401.56 km to capture delivery-related emission variations.



	Baseline	Grey Ammonia Bontang	Grey Ammonia Gresik	Blue Ammonia Bontang	Blue Ammonia Gresik	Green Ammonia Bontang	Green Ammonia Gresik
Scope 3: Ammonia Production		0.4995	0.4995	0.0030	0.0030	0.0000	0.0000
Scope 3: Ammonia Transport		0.0020	0.0004	0.0020	0.0004	0.0020	0.0004
Scope 3: Coal Transport	0.0039	0.0019	0.0019	0.0019	0.0019	0.0019	0.0019
Scope 3: Coal Production	0.0098	0.0049	0.0049	0.0049	0.0049	0.0049	0.0049
Scope 1: Combustion Emission	0.9004	0.4499	0.4499	0.4499	0.4499	0.4499	0.4499

Figure 7 GWP Co-Firing 50% Ammonia

Figure 7 shows that grey ammonia increases total GWP, while blue and green ammonia reduce it. Gresik-sourced ammonia yields slightly lower emissions than Bontang due to shorter transport. At a 50% co-firing ratio, grey ammonia increases GWP by 4.66% (Gresik) and 4.83% (Bontang) compared to baseline. While Scope 1 emissions decline, Scope 3 particularly from grey ammonia production—offsets these gains, resulting in a net increase. Emission contributions consist of 47% from Scope 1 (combustion) and 53% from Scope 3, comprising 0.5% from coal mining, 52.25% from ammonia production, and 0.25% from transport.

3.4 Sensitivity Analysis of Ammonia Price to LCoE

Ammonia is gaining traction as a low-carbon fuel for co-firing in coal-fired power plants (CFPPs). However, its economic viability remains highly sensitive to price fluctuations, particularly for blue and green ammonia produced via low-emission pathways. To evaluate this, a sensitivity analysis was conducted under a 50% co-firing scenario to assess the impact of ammonia price variations on the Levelized Cost of Electricity (LCoE).

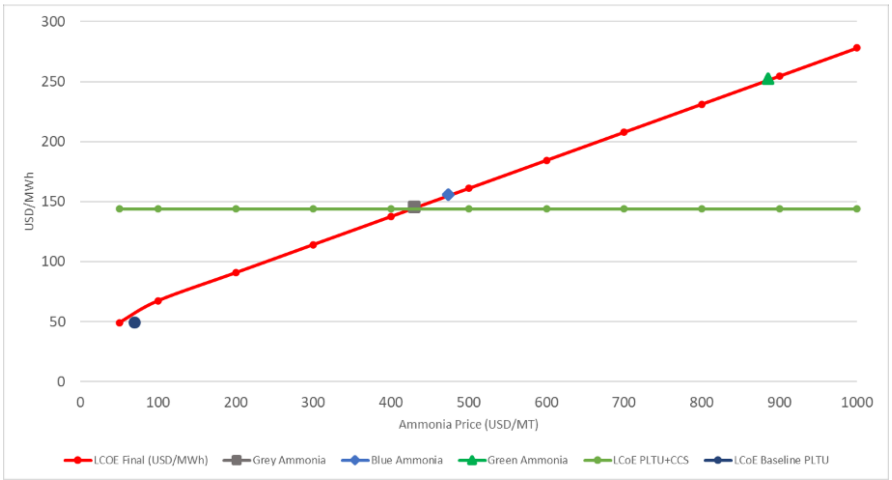


Figure 10 Sensitivity Analysis of Ammonia Price to LCoE

Figure 10 illustrates a linear relationship between ammonia price (USD/MT) and LCoE (USD/MWh). As prices rise, LCoE increases proportionally, reflecting the direct influence of fuel cost on generation economics. The red line shows LCoE trends, while the horizontal green line serves as a benchmark—comparing the baseline LCoE of a conventional coal plant and one using CCS. Three key data points mark current market conditions: grey ammonia at 429.50 USD/MT results in 145.54 USD/MWh, blue at 473.50 USD/MT yields 155.84 USD/MWh, and green at 885.36 USD/MT leads to the highest LCoE at 252.20 USD/MWh. Notably, the analysis suggests that if ammonia prices fall below 430 USD/MT, the LCoE from co-firing could be lower than that of a coal plant with CCS strengthening the economic case for ammonia as a transitional decarbonization strategy.

3.5 Sensitivity Analysis of Ammonia Price to Avoidance Cost

As decarbonization pressure mounts, evaluating the cost-effectiveness of low-carbon technologies becomes critical. One key metric is carbon avoidance cost (USD/ton CO_2), reflecting how economically emissions are reduced compared to fossil-based systems. In ammonia co-firing, this cost is highly sensitive to fuel prices and emission reduction levels. A sensitivity analysis was conducted under a 50% co-firing scenario to assess the impact of ammonia price variations for grey, blue, and green ammonia.

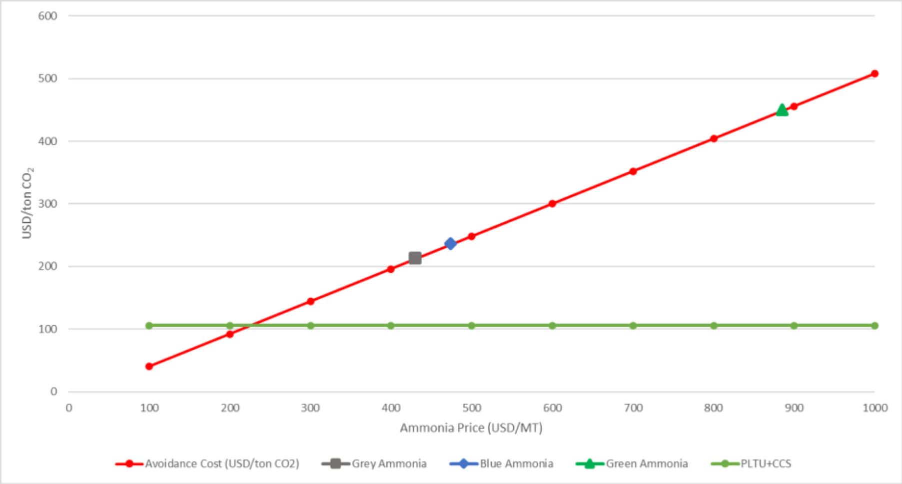


Figure 11 Sensitivity Analysis of Ammonia Price to Avoidance Cost

Figure 11 shows a linear relationship between ammonia price (USD/MT) and avoidance cost (USD/ton CO_2). At current prices, grey ammonia yields 213.7 USD/ton CO_2, blue 236.6, and green 450.5—significantly higher than CCS-based mitigation, which averages 105.6 USD/ton CO_2. Economic parity with CCS is only achieved if ammonia prices fall below 230 USD/MT, underscoring the importance of reducing fuel costs to enhance co-firing viability.

For comparison, studies on CCS and CCUS in Indonesia reveal substantial technical and economic barriers. Reza et al. (2023) reported efficiency losses of up to 26% in 600 MW units like Suralaya 5–7, with avoidance costs reaching 105 USD/ton CO_2, requiring strong policy support [26]. Ramadhan et al. (2024) highlighted that although CO_2 storage capacity is abundant (276,017 $MtCO_2$), over 73% of CCUS costs come from the capture phase, limiting its short-term feasibility in CFPPs [27]. In contrast, ammonia co-firing requires minimal retrofit, offers immediate deployment potential, and achieves a 50% GWP reduction at 50% blending. If green ammonia prices drop to 200 USD/MT, the avoidance cost could fall to 92 USD/ton CO_2—below that of CCS. These results reinforce ammonia's role as a promising decarbonization strategy, particularly if supported by policies such as subsidies, supply chain optimization, and investment in renewable-based production. Ultimately, developing an integrated green ammonia ecosystem is vital to achieving Net Zero Emissions (NZE) targets and supporting broader Sustainable Development Goals (SDGs).

4 Conclusion

This study demonstrates that ammonia co-firing in a 660 MWe subcritical coal-fired power plant is technically feasible and environmentally compliant using existing infrastructure. At a 50% ratio, CO_2 intensity drops from 0.90 to 0.45 kg CO_2/kWh, SO_x from 534 to 262 mg/Nm^3, and NO_x from 402 to 384 mg/Nm^3 well below the 550 mg/Nm^3 threshold. Combustion air demand also decreases by 7.4% without impairing boiler performance, indicating minimal retrofit needs.

Economically, LCoE rises sharply due to ammonia higher cost 6–12 times that of coal. At 50% co-firing, LCoE reaches USD 145.54/MWh (grey), 155.84 (blue), and 252.20 (green), compared to 49.25 for coal-only. However, green ammonia may become competitive if carbon prices exceed USD 83.76/ton CO_2 or coal prices rise above USD 165.25/ton [12], underscoring the importance of fiscal support. Life cycle analysis shows green ammonia can reduce GWP by 50%, while grey ammonia from Bontang may increase it by 4.83%. Shorter supply chains, such as from Gresik, yield slightly lower emissions. Avoidance costs reach 214 (grey), 237 (blue), and 451 USD/ton CO_2 (green), potentially decreasing to 100, 111, and 218 with lower ammonia prices, though still above CCS 106 USD/ton CO_2 highlighting the need for targeted policy instruments. Aligned with RHAN and RUKN 2025 goals of 8.4 GW ammonia-based capacity by 2060, co-firing offers a scalable transition solution. Its success hinges on integrated policies: subsidies, investment in green ammonia, and lifecycle-based carbon pricing.

Nonetheless, technical challenges arise above 50% co-firing. Oh et al. (2024) report increased ammonia slip, causing unburned emissions and secondary pollution. High nitrogen content also raises NO_x risks under high temperatures if not controlled with SCR. Higher ratios require major retrofits and stricter safety measures due to ammonia's toxicity and corrosiveness [3].

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