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Toward Carbon-Neutral Power Generation in Indonesia: A Techno-Economic Assessment of Renewable Ammonia Co-Firing in Combined Cycle Power Plants

Saddam Hussein[1,2], *S. Syafi'i*[2], *Rahma Muthia*[1,2*]

[1]Universitas Indonesia, Jakarta, Indonesia
[2]National Electricity Company, PT PLN (Persero), Indonesia
*Correspondence: E-mail: rahmamuthia@ui.ac.id

ABSTRACT

The urgency of climate change mitigation demands transformative shifts in energy systems, especially in fossil fuel-dependent regions like Southeast Asia. This study evaluates the techno-economic feasibility and environmental impact of green ammonia co-firing in existing combined cycle power plants. Using advanced simulations, including alkaline electrolysis, cryogenic air separation, and the Haber-Bosch process followed by GateCycle modelling, the integration of green ammonia was assessed. The results show that a 50:50 blend of natural gas and green ammonia delivers an 80 MW output, 11.3 MJ/kWh heat rate, and 31.8% thermal efficiency. While this reduces carbon emissions significantly, economic analysis reveals a negative net present value and a high levelized cost of electricity of 0.63 USD/kWh, indicating financial infeasibility under current market conditions. These findings highlight the need for policy support and strategic incentives. Green ammonia presents a scalable pathway for decarbonized power generation, contributing to sustainable energy transitions in Southeast Asia.

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1. INTRODUCTION

Climate change is an unprecedented global crisis with profound implications for humanity. In recent decades, the escalating emissions of greenhouse gases, particularly carbon dioxide, have increasingly threatened human welfare, biodiversity, and environmental sustainability worldwide. The continued dominance of fossil fuels across various sectors, especially the energy generation and transportation sectors, significantly elevates greenhouse gas concentrations. Recognizing the severe risks posed by climate change, nations worldwide committed under the Paris Agreement to limit global warming to well below 2°C and preferably 1.5°C. Recent Assessments indicate that the global average temperatures have already risen by approximately 1.2°C relative to pre-industrial levels, raising critical concern that temperature increases could soon surpass the 1.5°C threshold if emission trajectories are not drastically reduced. These developments necessitate the implementation of targeted mitigation strategies, particularly emphasizing the transition toward sustainable and low-carbon energy systems.

Globally, renewable energy options such as solar, wind, hydro, and biomass energy are increasingly recognized as effective means of reducing fossil fuel consumption. In recent years, green ammonia has emerged as a promising and transformative energy solution. Green ammonia, produced via the Haber-Bosch process using hydrogen from water electrolysis powered by renewable electricity, offers notable advantages over other alternative fuels. The stability and safety of ammonia are attributed to its non-flammable nature under ambient conditions and its ability to remain in liquid form at moderate pressures, which simplifies storage and transport [1]. Importantly, the combustion of green ammonia does not emit CO_2, but instead releases only nitrogen and water vapor, making it a truly clean energy alternative with significant environmental and public health benefits [2]. The potential of green ammonia is gaining worldwide recognition, primarily due to its higher volumetric energy density (12.7 MJ/L compared to 8.5 MJ/L for liquid hydrogen) and its relative ease of storage and transportation under ambient conditions [3]. These attributes make ammonia suitable for large-scale energy applications, including power generation and long-distance maritime transportation, and it has significant sustainability and climate resilience goals.

Countries such as Japan, Australia, and the European Union are actively investing in green ammonia infrastructure to meet domestic and international energy needs. Japan, in particular, has incorporated ambitious goals for green ammonia within its national strategy to achieve net-zero emissions by 2050, and allocated substantial funding toward electrolyser capacity and supply chain development [4]. Green ammonia has emerged as a viable and socially responsible solution for Southeast Asia. Specifically, Indonesia, geographically positioned along the equator, is exceptionally rich in solar resources with an annual average Global Horizontal Irradiation (GHI) ranging between 4.5 and 6 kWh/m^2/day, making it a highly prospective nation for solar-driven hydrogen production via water electrolysis [5]. The energy sector alone accounts for a major portion of Indonesia's total emissions, underscoring the urgency of developing and implementing viable alternative energy sources. Additionally, Indonesia's renewable energy target of 23% by 2025 indicates significant potential for scaling green ammonia production, positioning the country as a promising case study for evaluating the feasibility of green ammonia as part of a sustainable energy transition [6].

In recent years, extensive research into ammonia utilization as an alternative fuel has significantly advanced, primarily due to its longstanding role as a fertilizer and increasingly as a sustainable shipping fuel, thus highlighting its versatility [7]. Previous studies [1,2] have extensively analysed ammonia combustion and its viability under controlled laboratory conditions, yet lacked comprehensive integration between onsite ammonia production and real-world utilization in existing power plant infrastructures. Some researchers [3] emphasized the macroeconomic potential of ammonia as an energy storage medium but did not provide detailed insights into practical, operational-level integration strategies within power generation frameworks.

While green ammonia is increasingly recognized as a promising clean fuel, especially for power generation, much of the existing research has focused on individual segments of its application-such as combustion characteristics in gas turbines or feasibility studies at the point of energy conversion. These studies have been invaluable in proving that ammonia can be safely co-fired with natural gas under specific conditions [1,2], and that such an approach could support near-term emission reductions without requiring radical changes to existing infrastructure. However, most of this literature treats green ammonia as a readily available input, without examining how it is produced, processed, and delivered as if the upstream systems of hydrogen generation, nitrogen separation, and ammonia synthesis operate in isolation from the end-use context.

This creates a critical gap in our understanding. The viability of ammonia as a co-firing fuel is not just a matter of turbine compatibility. It depends just as much on how sustainably and efficiently we can produce it, especially when relying on renewable energy sources. The lack of integrated studies connecting production, synthesis, and utilization means we are missing the full picture, particularly for developing countries like Indonesia that seek practical, stepwise solutions to decarbonize their power sector.

The novelties of this study are threefold. First, it presents a fully integrated assessment of the green ammonia value chain, covering upstream hydrogen production via alkaline electrolysis, nitrogen separation using a cryogenic air separation unit (ASU), and ammonia synthesis through the Haber-Bosch process linked directly to its downstream application in a co-firing configuration within a combined cycle power plant. Second, the study utilizes a comprehensive simulation approach, including GateCycle modelling, to evaluate the thermodynamic performance impacts of ammonia integration under realistic plant-scale operating conditions. Third, the economic and environmental feasibility is analysed in detail, combining techno-economic indicators such as net present value (NPV), levelized cost of electricity (LCOE), and system efficiency, thus offering insights into the practicality of implementation in the Southeast Asian context. This holistic perspective contributes to filling a crucial research gap by demonstrating how green ammonia can transition from a theoretical clean fuel to a viable operational solution within existing energy infrastructure.

By taking this end-to-end perspective, the research not only offers a more grounded and realistic view of green ammonia's role in energy transition but also provides technical and economic insights that can inform future deployment strategies. This study focuses on the integrative techno-economic approach explicitly combining the green ammonia production process via Aspen Hysys simulations and its application within CCPPs using GateCycle simulations. This study establishes green ammonia not as an isolated technological innovation, but as a pivotal catalyst for advancing cleaner, more equitable, and more resilient power systems. By reframing its role within the broader energy ecosystem, this research aims to unlock green ammonia’s full potential as a transformative driver of sustainable and inclusive energy transitions. Through a holistic techno-economic assessment combined with a comprehensive analysis of its environmental and societal implications, this study offers critical scientific insights and actionable recommendations tailored for policymakers, energy providers, and local communities. It aims to accelerate the adoption of green ammonia as a cornerstone of decarbonization strategies, supporting Indonesia's national energy goals while contributing to global efforts for a more sustainable and just energy future.

2. METHODS

2.1 Research Approach

This research employed a comprehensive techno-economic analysis approach, simultaneously integrating technical evaluation and economic assessment. This approach was deliberately selected to provide a holistic view of the technical feasibility and economic viability of implementing green ammonia as an alternative fuel in CCPPs under a co-firing scheme. The techno-economic methodology has been widely validated in prior studies evaluating new energy technologies and their commercial implementation potential [3].

2.2 Research Scope and Assumptions

This study was developed based on well-defined assumptions and system parameters to ensure consistency and relevance. The referenced power plant was assumed to be located in Southeast Asia. The Green ammonia production capacity was set at 30 tons per hour, and the capacity of the CCPP was defined as 80 MW. Economic assumptions included a project lifespan of 25 years, an equipment depreciation rate of 5% per annum, and a discount rate of 10%, in alignment with parameters commonly used in techno-economic assessment of hydrogen and ammonia systems [8]. Renewable electricity pricing was assumed to be 0.04 USD/kWh, consistent with the global solar electricity cost average reported in recent literature [9].

2.3 Research Flow Diagram

This research approach explicitly combined the green ammonia production process via Aspen Hysys simulations and its application to CCPPs using GateCycle simulations **Figure 1**. The integrated ammonia production process consisted of three main subsystems: (i) hydrogen production via water electrolysis, (ii) nitrogen generation through an air separation unit (ASU), and (iii) ammonia synthesis using the Haber-Bosch process.

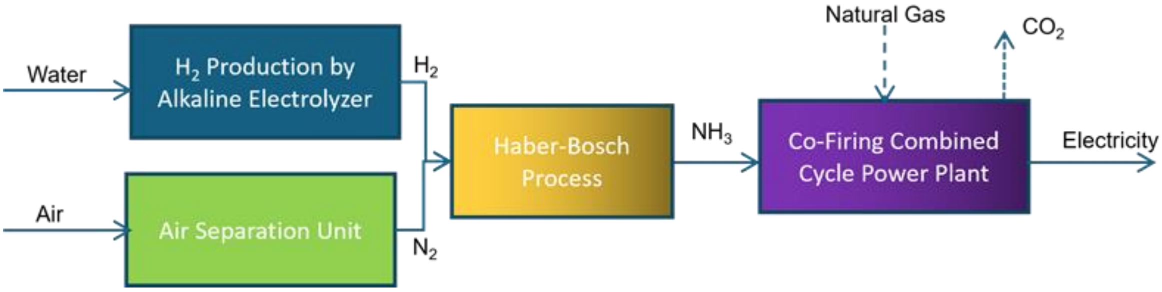

Figure 1. Block Flow Diagram of Integrated Renewable Ammonia-to-Power System for Co-Firing Applications in Combined Cycle Power Plant.

The entire system of ammonia production was simulated using Aspen HYSYS v12.1 **Figure 2**, which incorporated thermodynamic models appropriate for high-pressure gas systems. In the final step, CCPPs were elaborated using GateCycle Simulation to express the power and efficiency of power plants.

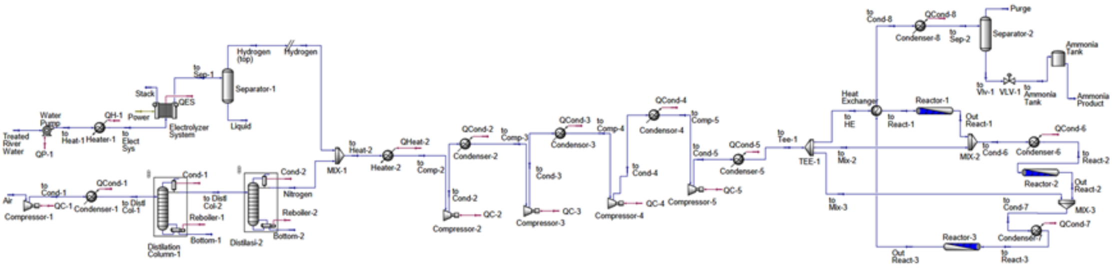

Figure 2. Ammonia Production Simulation.

2.3.1 Hydrogen Production via Water Electrolysis

The production of hydrogen in this process flowsheet was achieved through water electrolysis, a sustainable and carbon-free method that decomposes purified water into hydrogen and oxygen gases using electrical energy **Figure 3**. This section outlines in detail the thermodynamic considerations, operational constraints, and system configurations used to optimize hydrogen yield and energy efficiency.

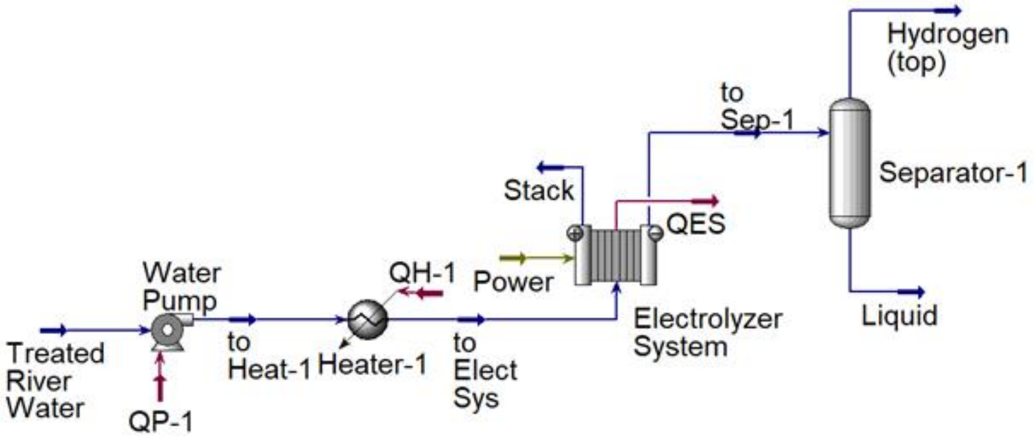

Figure 3. Water Electrolysis Simulation.

This study was developed based on well-defined assumptions and system parameters to ensure consistency and relevance. The green ammonia production capacity was set at 30 tons per hour, and the capacity of the CCPP at 80 MW. Economic assumptions included a project lifespan of 25 years, equipment depreciation rate of 5% per annum, and a discount rate of 10%, aligning with parameters commonly used in techno-economic assessment of hydrogen and ammonia systems [8]. Renewable electricity pricing was assumed to be 0.04 USD/kWh, consistent with the global solar electricity cost average reported in recent literature [9].

Following thermal conditioning, the pre-heated water was directed into an electrolyser unit composed of multiple electrolytic cells operating in parallel. These cells performed the decomposition of water under an externally applied DC electrical potential, according to the electrochemical half-reactions shown in Equations (1) and (2):

At Cathode:

$$2H_2O + 2e^- \rightarrow H_2 + 2OH^- \quad (1)$$

At Anode:

$$2OH^- \rightarrow 1/2O_2 + H_2O + 2e^- \quad (2)$$

The system operated at atmospheric pressure during the reaction but delivered hydrogen product at an elevated pressure of 30 bar and a temperature of 126.9°C, post-compression and thermal carryover. These values were consistent with the previous findings [10], who reported that hydrogen generated in pressurized alkaline systems typically ranges between 10–40 bar, depending on downstream requirements.

The electrical input to the system, as reported by the simulation, is 1,281 kW, with a current load of 8,368,000 A. This corresponded to the power demands of a mid-scale electrolyser facility and aligns with real-world implementations. Alkaline electrolysers at the megawatt scale have been widely studied and deployed, with single-stack configuration commonly operating at similar input levels [11].

The simulation reported an overall voltage efficiency of 97%, which was considered high but achievable with modern electrode materials and cell design, typically ranging between 85–98% under optimal conditions [12].

The hydrogen production rate from the simulation was 15,610 kgmol/h, equivalent to approximately 31,376 kg/h. This production rate placed the system in the category of industrial-scale green hydrogen production. To ensure product purity, the gas stream was directed to a phase separator (Separator-1) to remove entrained water droplets. This practice has been well-established in industrial electrolyser systems for protecting downstream compression or synthesis units [13].

The oxygen by-product, formed at the anode, was vented or optionally stored for auxiliary applications. The valorisation of this oxygen could enhance the overall process economics [14], particularly when integrated with industries requiring high-purity O_2.

One critical indicator of system performance was the specific energy consumption, which was calculated in the simulation as 40.31 kWh/kg H_2. This value aligned well with reported values for alkaline electrolysis systems, typically ranging between 39-52 kWh/kg H_2 depending on system pressure, thermal management, and current density. **Table 1** provides comparative specified operating values between simulated parameters and literature values.

Table 1. Specified Operating Values for Alkaline Electrolyser.

Parameter	Simulation Output	Literature Range	References
Operating Temperature	90°C	60-90°C	[10]
Electrolyser Pressure Output	30 bar	10-40 bar	[10]
Voltage Efficiency	97%	85-98%	[12,15]
Electrical Power Input	1281 kW	1000-4000 kW	[11]

This high-fidelity simulation of alkaline electrolysis demonstrated consistency with internationally validated performance metrics and confirmed the viability of the modeled system for integration into green ammonia production. Moreover, the precision of hydrogen output and its purity provided a reliable feedstock for subsequent nitrogen-hydrogen synthesis processes in the ammonia loop.

2.3.2 Nitrogen Generation via Air Separation Unit

The second phase involved the air separation process, utilizing cryogenic distillation techniques in the ASU **Figure 4**. The design implemented here followed the dual-column distillation method, which is the industrial standard for achieving high-purity nitrogen.

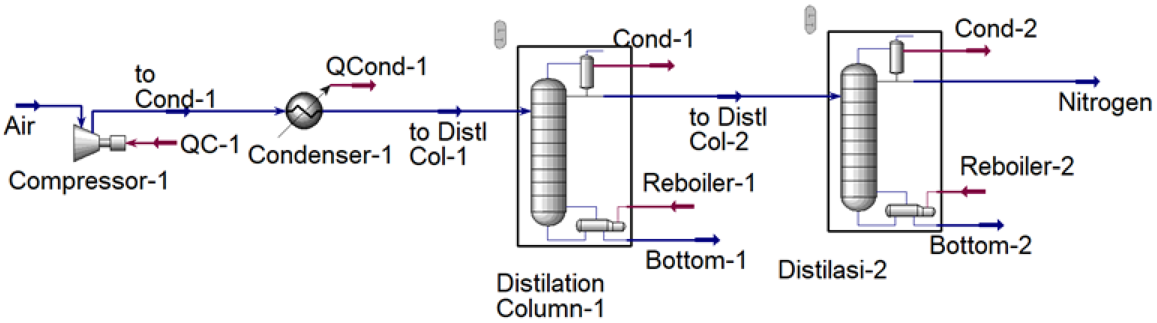

Figure 4. Nitrogen Generation Simulation.

Ambient air, containing approximately 78% nitrogen, 21% oxygen, and minor constituents such as argon and carbon dioxide, was introduced into the system at 25°C and 1.013 bar, then compressed to approximately 5.5 bar using a low-pressure centrifugal compressor (Compressor-1). This compression stage was essential to facilitate the subsequent cooling and liquefaction of air, which is a prerequisite for efficient cryogenic separation. This pressure level was consistent with industrial benchmarks for low-pressure ASU cycles, typically ranging from 5 to 6 bars in nitrogen-focused systems [16].

Following compression, the air stream underwent multi-stage cooling and partial condensation, achieving cryogenic temperatures in the vicinity of -180°C, using a combination of Condenser-1 and internal heat exchangers. This cooling range aligned with the boiling points of nitrogen (-195.8°C) and oxygen (-183°C) under atmospheric pressure, allowing for the effective initiation of fractional distillation [17].

The cooled, partially liquefied air was fed into the first rectification column (Distillation Column-1), where it was separated based on volatility differences between nitrogen and oxygen. Nitrogen, having a lower boiling point, preferentially rose through the column and was withdrawn from the top, while the oxygen-rich liquid settled at the base. To enhance purity beyond 99.9 mol%, the gaseous nitrogen product was directed to a second rectification column (Distillation Column-2) for final purification. This step was critical for downstream Haber-Bosch synthesis, where catalyst poisoning by trace oxygen or argon must be strictly avoided [18].

Both distillation columns were equipped with thermally integrated reboilers (Reboiler-1 and Reboiler-2) that supplied controlled heat to sustain the upward vapor flow and ensure effective mass transfer. The column pressure was maintained in a near-isobaric condition to stabilize the vapor-liquid equilibrium. The model adopted the Peng–Robinson equation of state, which is suitable for modeling non-ideal gas mixtures under cryogenic and pressurized conditions.

The simulation also incorporated quasi-steady-state assumptions to reflect realistic operational conditions during continuous production. Heat duties for both the condensers and reboilers were evaluated, providing valuable insights into the potential energy integration with the ammonia synthesis loop, particularly via waste heat recovery or cross-utilization of refrigeration streams.

The resulting nitrogen product stream exited the second column at approximately -173°C and was subsequently warmed via internal heat exchange prior to mixing with hydrogen in MIX-1, forming a synthesis gas with an H_2:N_2 molar ratio of 3:1, the stoichiometric standard for ammonia synthesis reactions [19]. **Table 2** provides comparatively specified operating values between simulated parameters and literature values.

Table 2. Specified Operating Values for Nitrogen Production.

Parameter	Simulation Output	Literature Range	References
Compressor Outlet Pressure	5.5 bar	5-6 bar	[16]
Cryogenic Temperature Range	-180°C	-170 to -190°C	[17]
H_2:N_2 mixing ratio	3:1	3:1	[19]

This simulation demonstrated strong agreement with industrially validated ASU design principles. Moreover, the process's thermodynamic efficiency and product purity were suitable for immediate integration into ammonia synthesis processes, ensuring high reactivity and minimizing catalytic deactivation risks.

2.3.3 Ammonia Synthesis via The Haber-Bosch Process

The final stage of the ammonia production process was the catalytic synthesis reaction, in which hydrogen and nitrogen obtained from previous stages were mixed in precisely controlled ratios **Figure 5**. The core chemical transformation in this plant was the exothermic reaction between nitrogen and hydrogen to form ammonia, as shown in Reaction (R3):

$$N_2 + 3H_2 \rightleftharpoons 2NH_3 \quad \text{(R3)}$$

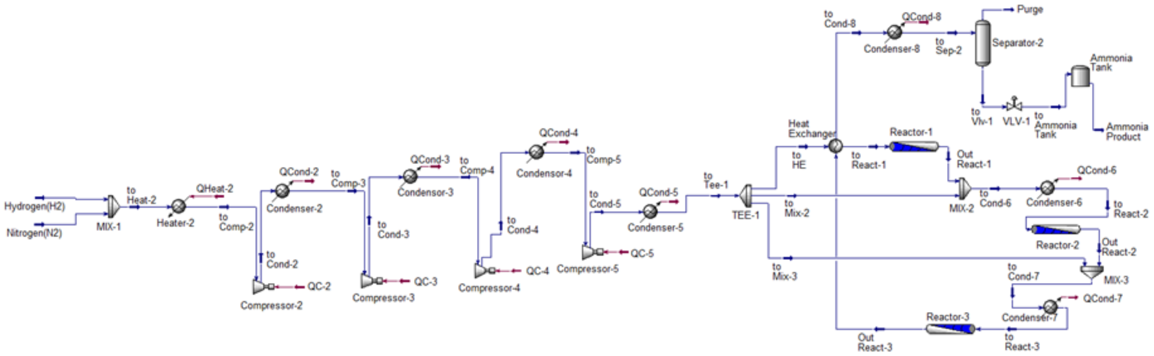

Figure 5. Synthesis Ammonia Simulation.

The synthesis began by introducing a hydrogen-nitrogen gas mixture, prepared at a stoichiometric molar ratio of 3:1, into a multistage compression system consisting of five sequential compressors (Compressor-2 through Compressor-5). These units elevated the process stream to a synthesis pressure of approximately 200 bar, consistent with the operational range for contemporary Haber–Bosch reactors (150–250 bar) [20].

To mitigate the temperature, rise due to adiabatic compression, each compressor stage was followed by an intercooler unit (Condensers-2 to Condensers-5), which reduced the thermal load on downstream equipment and enhanced compression efficiency. Intercooling between stages was critical to maintain safe mechanical performance and maximize isentropic efficiency, particularly in large-scale operations.

Once the gas mixture reached the desired synthesis pressure, it was passed through a heat exchanger (HE). This exchanger utilized the hot reactor effluent to preheat the feed, enhancing energy integration and reducing the need for external heat input. Such heat recuperation systems have been widely adopted in ammonia synthesis loops to conserve energy and stabilize reactor temperatures.

The reaction zone consisted of three catalytic fixed-bed reactors (Reactor-1 to Reactor-3), arranged in series with intermediate cooling. These reactors operated within an optimized temperature window of 450–500°C, which balanced thermodynamic equilibrium constraints and reaction kinetics. The use of multiple reactors in series, with interstage cooling (e.g., Condenser-6, Condenser-7), served to shift the equilibrium toward ammonia formation in each stage by continuously removing the reaction heat and enabling a more favorable conversion profile [21].

The final reactor effluent, enriched in ammonia, was cooled in Condenser-8 and directed to Separator-2, where liquid ammonia was condensed and collected. The simulation output indicated that ammonia existed at a manageable temperature of 32.8°C and atmospheric pressure (1.013 bar), suitable for downstream storage or utilization. The system achieved a mass flow rate of 30.21 tones/h, equivalent to 1,774 kgmol/h, which was consistent with industrial-scale ammonia plant capacities [1].

To enhance reactant utilization, unconverted hydrogen and nitrogen gases were recycled back to the inlet stream. However, a purge stream was maintained to prevent the accumulation of inert gases (e.g., argon, methane), which could otherwise dilute the reactive mixture and reduce reactor performance. This purge-recycle strategy was essential for maintaining long-term operational stability and maximizing overall process efficiency. **Table 3** provides comparative specified operating values between simulated parameters and literature values.

Table 3. Specified Operating Values for Synthesis Ammonia.

Parameter	Simulation Output	Literature Range	References
Reactor Operating Pressure	200 bars	150-250 bar	[20]
Reactor Temperature Range	450-500°C	400-550°C	[21]

2.3.4 Generation Power Plant via GateCycle Simulation

The GTCC system integrated Brayton and Rankine cycles to achieve high thermal efficiency in power generation. This study presented an analysis of a GTCC process simulated using GateCycle software (**Figure 6**), focusing on the operational dynamics of key components, including the compressor, combustor, gas turbine, heat recovery steam generator (HRSG), and steam turbine.

GTCC systems were widely regarded as one of the most efficient fossil or alternative fuel-based power generation technologies. By coupling the Brayton cycle (gas turbine) with the Rankine cycle (steam turbine), thermal efficiencies of 55–62% were achievable under optimal design conditions [22]. The integration of ammonia as a carbon-free combustion fuel in this configuration introduced both opportunities for decarbonization and new thermodynamic considerations due to its unique flame characteristics and heat content [1].

The process began with the intake of ambient air (25°C, 1.013 bar) into the axial compressor (COMP), where it was compressed to a typical pressure ratio of 10:1 to 20:1, consistent with modern high-efficiency GT systems. In the simulation, compressed air exited the compressor at approximately 16 bar and 400°C, values that aligned with industry baselines for heavy-duty gas turbines. The combustion products, primarily steam and nitrogen, exited the chamber at temperatures of 1250–1350°C, which was comparable to methane combustion and suitable for turbine expansion [2]. These hot gases were expanded in the gas turbine (GT), producing mechanical energy that was converted into electricity via a coupled generator. The standalone Brayton cycle efficiency in the simulation was calculated to be approximately 38.7%, which reflected the typical range for simple-cycle operation.

The turbine exhaust gases, which retained substantial thermal energy (typically 500–600°C), were directed to the Heat Recovery Steam Generator (HRSG). The HRSG configuration simulated included economizers (ELPC-1 and ELPC-2), an evaporator drum (DRUM), and a superheater (EHP-1), a configuration commonly found in triple-pressure HRSG systems. Feed water was supplied via a centrifugal feed pump (FP-1) and underwent preheating in the economizer section, where it reached temperatures near saturation. The water was then evaporated in the drum and converted into saturated steam, which subsequently flew into the superheater. There, it was heated to superheated conditions of 500-550°C and pressures around 80 bar, consistent with optimized Rankine cycle performance standards.

After exiting the superheater, the superheated steam expanded through the steam turbine (ST), delivering additional mechanical power. The exhaust steam was directed to the condenser (COND), where it was condensed using circulating cooling water. The resulting condensate was recycled back to the HRSG, closing the Rankine loop. The integration of the Rankine cycle raised the overall plant thermal efficiency in the simulation to approximately 58.2%, a value consistent with combined-cycle ammonia combustion plants proposed in recent feasibility studies [23].

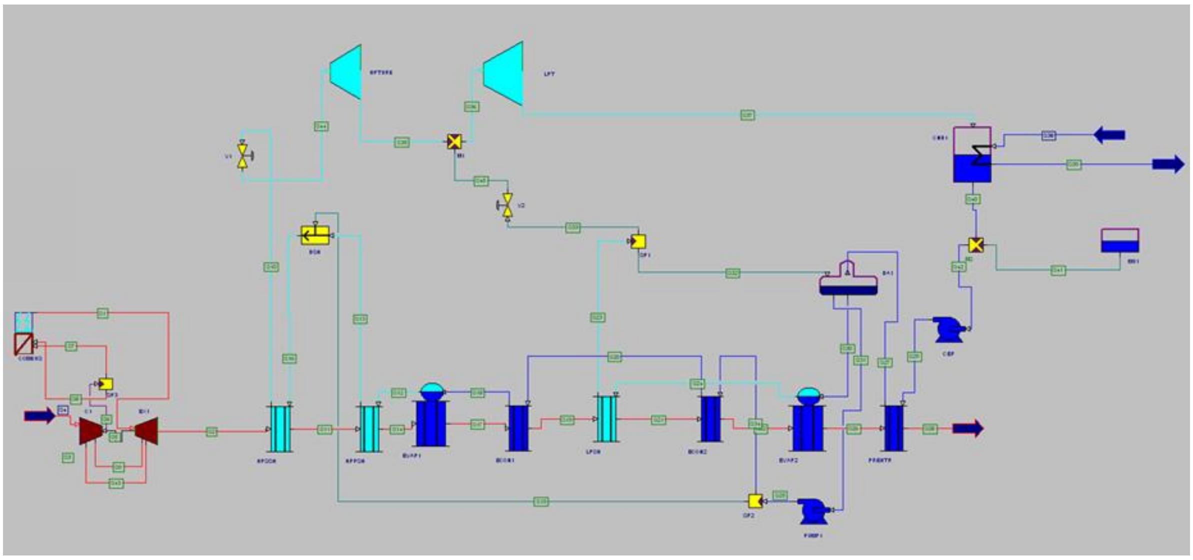

Figure 6. Gas Turbine Combined Cycle Simulation.

In **Table 4**, in assessing the feasibility and effectiveness of ammonia-natural gas co-firing in a GTCC configuration, this study emphasized a set of interrelated performance metrics that collectively capture the thermodynamic and environmental behavior of the system. The three central indicators employed are the heat rate, the net thermal efficiency, and the CO_2 emissions. These metrics served not only as technical benchmarks but also as a critical foundation for evaluating the broader sustainability of the co-firing strategy.

The heat rate was a fundamental indicator that quantified the total amount of fuel energy required to generate one kilowatt-hour of net electricity. It provided a direct measure of the plant's thermal efficiency from a fuel utilization perspective. In this study, the heat rate was calculated by dividing the aggregate thermal energy input based on the lower heating value (LHV) of both natural gas and green ammonia by the net electrical output. Each simulation scenario incorporated the specific mass flow rates and combustion profiles of the two fuels, accounting for ammonia's lower calorific value and distinct combustion dynamics. This approach ensured that variations in the heat rate reflect the true energetic trade-offs associated with fuel blending. A lower heat rate implied better energy conversion and thus signifies a more efficient process [24].

To complement the heat rate, net thermal efficiency was introduced as an intuitive expression of how effectively the fuel energy was transformed into usable electricity. Instead of being measured independently, net efficiency was derived from the heat rate using the standard thermodynamic relation. This formulation allowed direct benchmarking against international efficiency standards for modern GTCC units. While ammonia offered substantial environmental advantages, its introduction into the fuel stream might marginally reduce net efficiency due to its higher latent heat and lower flame temperature, which could slightly diminish the thermal performance of the gas turbine [1]. However, these thermodynamic penalties have often been considered acceptable in the context of larger decarbonization objectives.

A vital dimension of this evaluation was the quantification of CO_2 emissions, especially in the context of Indonesia's national commitment to energy decarbonization. Emission estimates in this study were carried out using the official methodology issued by the Directorate General of Electricity under the Ministry of Energy and Mineral Resources, which aligned with IPCC Tier 1 protocols. Emissions were calculated using Equation (3), which followed the Tier 1 emission estimation methodology:

$$CO_2 \text{ Emission} = \text{Activity Data} \times \text{Emission Factor} \tag{3}$$

where Activity Data refers to the total fuel consumption, and the Emission Factor represents the emission factor specific to each fuel. This inherent advantage enables a linear reduction in total CO_2 emissions as ammonia replaces natural gas in the blend, offering a compelling environmental benefit.

By integrating these three-performance metrics, heat rate, efficiency, and emissions, this study provided a balanced and rigorous framework for evaluating the viability of co-firing as a transitional energy strategy. The results offered not only insight into the thermodynamic behavior of blended fuel combustion but also a pathway for quantifying its contribution to national and global emission reduction goals.

Table 4. Specified Operating Values for CCPPs.

Component	Simulated Value	Reference Benchmark	References
GT Inlet Temperature	~1300°C	1200-1400°C	[2]
GT Exhaust Temperature	~560°C	500-650°C	[23]
HRSG Stream Condition	550°C, 80 bar	500-565°C, 60-100 bar	[23]

2.3.5 Research Economic

Economic analysis evaluated the investment feasibility of incorporating green ammonia into existing CCPP infrastructure. Economic parameters included Capital Expenditure (CAPEX), encompassing construction costs for ammonia production facilities, electrolyzers, and modifications to existing infrastructure, and Operating Expenditure (OPEX), covering routine operational and maintenance expenses and renewable electricity costs. Investment feasibility was assessed using financial indicators such as Net Present Value (NPV), Internal Rate of Return (IRR), Payback Period, and Levelized Cost of Electricity (LCOE). The net present value was calculated using Equation (4):

$$NPV = \sum_{t=0}^{n} \frac{R_t}{(1+i)^t} \tag{4}$$

where Rt is the net cash inflow or outflow for period t; n is the sum of periods; t is the period; and i is the discount rate.

Meanwhile, the levelized cost of electricity was calculated using Equation (5):

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$$LCOE = \frac{\sum_{t-0}^{n} \frac{C_t + O\&M_t}{(1+r)^t}}{\sum_{t-0}^{n} \frac{E_t}{(1+r)^t}} \quad (5)$$

where C_t is the investment cost; n is the lifetime of plants; t is the period; $O\&M_t$ is the operation and maintenance cost at time; E_t is the electricity produced at time; and r is the weighted average cost of capital.

To quantify the investment and operational requirements of the green ammonia production system, a detailed breakdown of CAPEX and OPEX was conducted for each core technological unit, including water electrolysis, air separation, and the ammonia synthesis section. The CAPEX was derived based on unit-specific cost intensities scaled to design capacity, incorporating both equipment and system-level considerations. For the electrolyser unit, which employed Alkaline Electrolyser technology due to its responsiveness and compact design, the specific capital cost was set at 600 USD per kilowatt of installed capacity, while annual OPEX was estimated at 18.1 USD/kW, based on current market data and scale-up scenarios provided by IRENA, and further detailed information is explained in elsewhere [25]. The stack replacement cost, which represented 25% of the total electrolyser CAPEX, was included, considering a typical operational lifetime of 10 years, whereas auxiliary components were assumed to last for 25 years.

The nitrogen supply system, implemented via cryogenic ASU technology, was evaluated using an empirical cost function derived from process plant design benchmarks. The capital cost of the ASU was estimated using the regression-based model as shown in Equation (6) [25]:

$$CAPEX_{ASU} = 2.096x10^6 x\dot{m}_{N_2}^{-0.6249} + 12163 \quad (6)$$

where $\dot{m}N_2$ represents nitrogen output in tons per day.

For the ammonia synthesis loop, which integrated high-pressure hydrogen feed (up to 160 bar) and iron-based catalyst beds operating in a loop configuration, the capital intensity was assumed to be 4,983 USD per kg NH_3/h, a figure drawn from techno-economic analyses of Haber–Bosch configurations [1]. The total capital cost of the synthesis loop was estimated by scaling this reference value using Equation (7):

$$CAPEX_{Synt} = C_{spesific} x F_{NH_3} \quad (7)$$

where FNH_3 denotes the hourly ammonia design capacity and the pressure-dependent capital factor. The OPEX for the synthesis unit was likewise estimated as 1.5% of the CAPEX, consistent with empirical ratios for mature chemical manufacturing units [1].

3. RESULTS AND DISCUSSION

3.1. Ammonia Production

The following results present the detailed output of the ammonia synthesis process simulated using Aspen HYSYS under a 100% production scheme. The simulation encompasses critical operational stages, including multiple reactor passes, condensation, and separation units, to ensure optimal ammonia recovery and system efficiency. The tabulated data in Table 5 summarizes the mole fraction compositions of key components across various process streams as well as the corresponding material balances, including vapor fraction, temperature, pressure, molar flow rate, and mass flow rate. These results form the foundation for evaluating the performance and mass balance integrity of the integrated ammonia synthesis system.

Initially, the feed entering the first reactor (React-1) primarily consists of hydrogen (22.49%) and nitrogen (77.51%), aligning closely with the stoichiometric ratio necessary for ammonia synthesis, approximately a 3:1 molar ratio (Haber-Bosch process) [20]. After passing through Reactor-1, the ammonia mole fraction significantly increases to 7.77%, indicating a substantial initial conversion of reactants into ammonia. Subsequent stages progressively increase ammonia concentration, with the final stream to the ammonia tank achieving a mole fraction of 99.42%, demonstrating efficient separation and purification.

Operating temperatures and pressures align well with the industrial standards for ammonia synthesis. The reactor inlet temperature is maintained at around 350°C, a commonly recommended condition for optimal catalytic activity [21]. The pressure conditions remain consistently high (150 bar) throughout most stages, consistent with standard industrial practices, except where downstream purification and condensation processes necessitate pressure reduction to near atmospheric conditions (approximately 1 bar). **Tables 5 and 6** provide is results of the simulation.

Table 5. Component mole fractions.

Component Mole Fraction	to React-1	Out Rect-1	to Cond-6	to React-2	Out React-2	to Cond-7	to React-3	Out React-3	to Cond-8	to Sep-2	Purge	to Vlv-1	to Ammonia Tank	Ammonia Product
Hydrogen	0.2249	0.2035	0.2075	0.2075	0.1965	0.2011	0.2011	0.1944	0.1944	0.1944	0.199	0.005	0.005	0
Nitrogen	0.7751	0.7187	0.7293	0.7293	0.7001	0.7123	0.7123	0.6946	0.6946	0.6946	0.774	0.0008	0.0008	0
Ammonia	0	0.0777	0.0631	0.0631	0.1035	0.0866	0.0866	0.111	0.111	0.111	0.027	0.9942	0.9942	1

Table 6. Material Balance Stream.

Parameters	to React-1	Out Rect-1	to Cond-6	to React-2	Out React-2	to Cond-7	to React-3	Out React-3	to Cond-8	to Sep-2	Purge	to Vlv-1	to Ammonia Tank	Ammonia Product
Vapor Fraction	1	1	1	1	1	1	1	1	1	0.8996	1	0	0.0257	0
Temperature (°C)	350	479.3	456.2	350	412.7	403	350	386.8	386.8	-36	-36	-36	-38	-38
Pressure (Bar)	150	135	135	150	135	135	150	150	150	150	150	150	1.013	1.013
Molar Flow (tonmole/h)	14.1	13.1	16.1	16.1	15.5	18.5	18.5	181	18.1	18.1	16.3	1.82	1.82	1.773
Mass Flow (tones/h)	110.9	110.9	134.6	134.6	134.6	158.4	158.4	158.4	158.4	158.4	127.5	30.87	30.87	30.2

A sensitivity analysis was conducted to evaluate the dynamic response of the green ammonia production system under varying co-firing ratios in a GTCC power plant, specifically at 25, 50, 75, and 100% ammonia substitution levels. As the co-firing ratio increases, the demand for ammonia production escalates proportionally, thereby influencing the required input of hydrogen from electrolysis and nitrogen from ASU.

To accurately estimate the ammonia output under each co-firing scenario, a mass balance-based approach was adopted by referencing the simulated conversion efficiencies derived from the ammonia synthesis reactor. **Table 7** presents the basis of conversion obtained from the steady-state reactor simulation, with a hydrogen mass conversion of 25.1% and nitrogen mass conversion of 25.2%. These conversion ratios were applied to calculate the effective yield of ammonia as a function of feedstock input.

Table 7. Mass balances and conversion of the 100% ammonia scenario.

Items	Mass In (tonnes/h)	Mass Out (tonnes/h)	% Conversion
Hydrogen	23,639.46	17,705.05	25.10%
Nitrogen	109,005.36	81,518.05	25.22%

To quantify the impact of increasing co-firing ratios on the upstream green ammonia supply chain, a scenario-based mass balance analysis was performed, focusing on the key input requirements and corresponding ammonia output. The reference point was established at a full 100% co-firing substitution scenario, where ammonia demand reaches 30.2 tonnes per hour, as validated by reactor conversion efficiency simulations. Based on this benchmark, proportional reductions were calculated to model partial substitution scenarios at 25, 50, and 75%. **Table 7** presents the calculated feed input requirements and corresponding ammonia production outputs for each scenario. As the ammonia substitution level increases, a significant escalation in hydrogen and nitrogen input demand is observed, driven by the stoichiometric requirements and inherent conversion limitations within the synthesis reactor.

The staged analysis of green ammonia production under varying co-firing scenarios reveals a compelling linear relationship between substitution levels and ammonia output **Figure 7**. Starting from 25% substitution (7.56 tonnes/h) and progressing to 100% (30.2 tonnes/h), the system demonstrates a predictable and scalable yield pattern. However, this apparent simplicity in output growth masks the underlying complexity at the feedstock level. Both hydrogen and nitrogen feed requirements exhibit a nonlinear increase, with hydrogen rising from 7,310.7 tonnes/h at 25% to a striking 23,639.4 tonnes/h at 100%, and nitrogen climbing from 33,471.6 to 109,005.3 tonnes/h in parallel. These figures underscore the low conversion efficiencies within the synthesis reactor-approximately 24-25% for hydrogen and 25% for nitrogen, which necessitate disproportionately high input flows relative to the ammonia yield. Similar findings have been noted in studies on green ammonia synthesis, where conversion bottlenecks due to thermodynamic equilibrium and kinetic limitations require large recycle flows and energy-intensive separation [1]. As such, while the system output scales linearly, it becomes exponentially more demanding in upstream resources, presenting significant design and operational challenges.

This intensification of resource needs raises strategic considerations for the configuration and deployment of hydrogen and nitrogen supply systems. Electrolyser capacity must be expanded significantly to deliver tens of thousands of tonnes of hydrogen per hour, demanding high renewable electricity input, advanced water management, and thermal integration strategies to achieve optimal performance [14]. Likewise, air separation units must be sized to meet nitrogen flow requirements exceeding 100,000 tones/h under full substitution, highlighting the need for efficient cryogenic ASU configurations and energy recovery mechanisms. These constraints point toward the critical importance of modular and flexible infrastructure, allowing gradual scaling that aligns with policy, finance, and grid-readiness. Moreover, this analysis reinforces the need for a just and managed transition; beginning with low-to-moderate substitution ratios allows for validation of process performance, mitigation of techno-economic risks, and accommodation of social and industrial learning curves. In this context, ammonia co-firing is not merely a matter of fuel substitution but a broader transformation tool-bridging the technical, economic, and human dimensions of the energy transition [26].

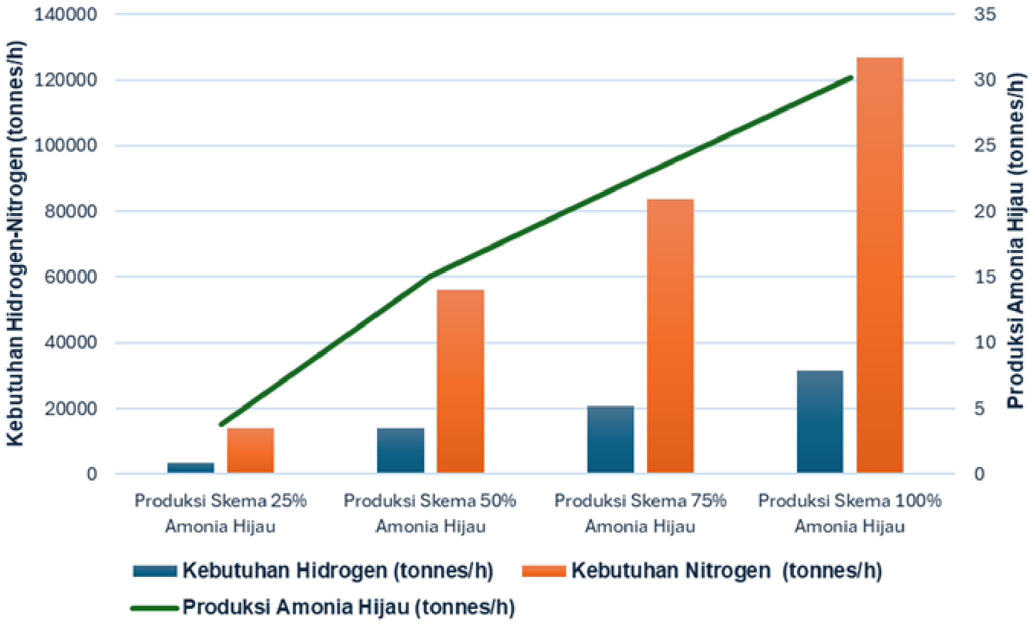

Figure 7. Parameter Input-Output Ammonia Production.

3.2. Ammonia to Power

The simulation results presented in **Figure 8** provide an overview of the technical implications of progressive green ammonia substitution in a natural gas-fired combined cycle power plant. Five co-firing scenarios were analysed, ranging from 100% natural gas to 100% green ammonia, with intermediate mixtures of 25, 50, and 75% green ammonia. The analysis focuses on three key performance indicators: net thermal efficiency (%), heat rate (MJ/kWh), and annual CO_2 emissions (kiloton/year), each of which plays a critical role in evaluating the feasibility and sustainability of fuel substitution strategies.

The data reveal a strong inverse relationship between the green ammonia share and carbon dioxide emissions. A baseline operation using 100% natural gas yields CO_2 emissions of 318.23 kiloton/year. This value progressively decreases with higher green ammonia shares, dropping to 238.67 kiloton/year (25% GA), 159.11 kiloton/year (50% GA), and 79.56 ton/year (75% GA), until complete decarbonization is achieved at 100% GA (0 kiloton/year). This consistent downward trend demonstrates green ammonia's potential to significantly reduce greenhouse gas emissions, consistent with findings in the literature [1,2]. This decarbonization trajectory aligns with international climate targets and reinforces ammonia's value as a carbon-free alternative fuel.

However, this environmental gain comes at the cost of declining energy performance. The heat rate, a measure of fuel energy input per unit of electricity output, increases as the green ammonia ratio grows. From an efficient 8.1 MJ/kWh under 100% natural gas, the heat rate rises to 9.4 MJ/kWh (25% GA), 11.3 MJ/kWh (50% GA), 14.7 MJ/kWh (75% GA), and reaches a high of 21.7 MJ/kWh at 100% green ammonia. The primary cause for this increase is the lower combustion temperature and slower flame propagation characteristics of ammonia compared to natural gas [2]. Consequently, thermal efficiency shows a parallel degradation trend, falling from 44.4% (100% NG) to 16.6% (100% GA). This drop-in performance raises critical operational and economic considerations, particularly for utilities that rely on high efficiency benchmarks for dispatch priority and cost recovery.

The most balanced configuration emerges in the mid-range green ammonia share, particularly at the 50% co-firing scenario. In this configuration, the plant achieves a notable 50% reduction in CO_2 emissions, equivalent to approximately 159.11 kilotons per year. Despite the partial fuel substitution, the heat rate remains within an acceptable range at 11.3 MJ/kWh, reflecting a moderate compromise in performance. The corresponding thermal efficiency is recorded at 31.8%, which, while lower than the typical design standard for combined-cycle power plants, still indicates reasonable operational viability. The thermal efficiency for combined-cycle power plants in the power range near 400 MW typically approaches 54.45%, emphasizing that the co-firing of green ammonia introduces expected thermodynamic penalties due to its different combustion characteristics [27]. Nevertheless, the 50% co-firing case offers a pragmatic balance between environmental impact and performance, making it a potentially optimal pathway for phased decarbonization in existing power infrastructure. This trade-off suggests that partial substitution of natural gas with green ammonia offers a compelling transitional pathway, delivering meaningful environmental benefits while maintaining acceptable technical performance.

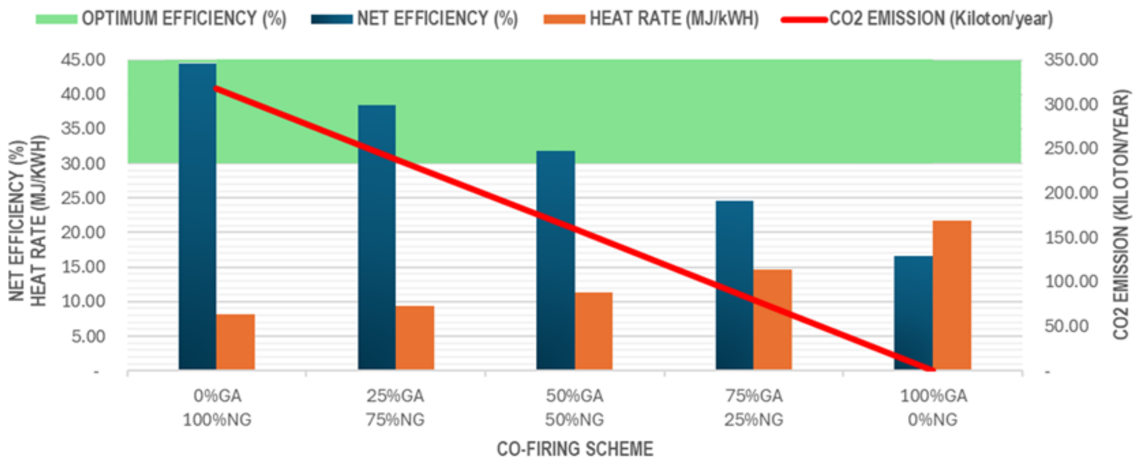

Figure 8. Comparison of Net Thermal Efficiency, Heat Rate, and CO_2 Emissions Across Green Ammonia and Natural Gas Co-Firing Scheme.

3.3. Economic Assessment

The techno-economic feasibility of deploying a fully integrated green ammonia system for power generation has been rigorously evaluated in this study. The system is designed to encompass green hydrogen production via alkaline electrolysis, nitrogen separation from air using cryogenic distillation, ammonia synthesis through the Haber-Bosch process, and ultimately the utilization of ammonia as a co-firing fuel in a CCPP. A comprehensive breakdown of capital and operational expenditures has been developed, supported by relevant literature and benchmarked industrial data, to assess the overall financial performance of the project (see **Figures 9** and **10**).

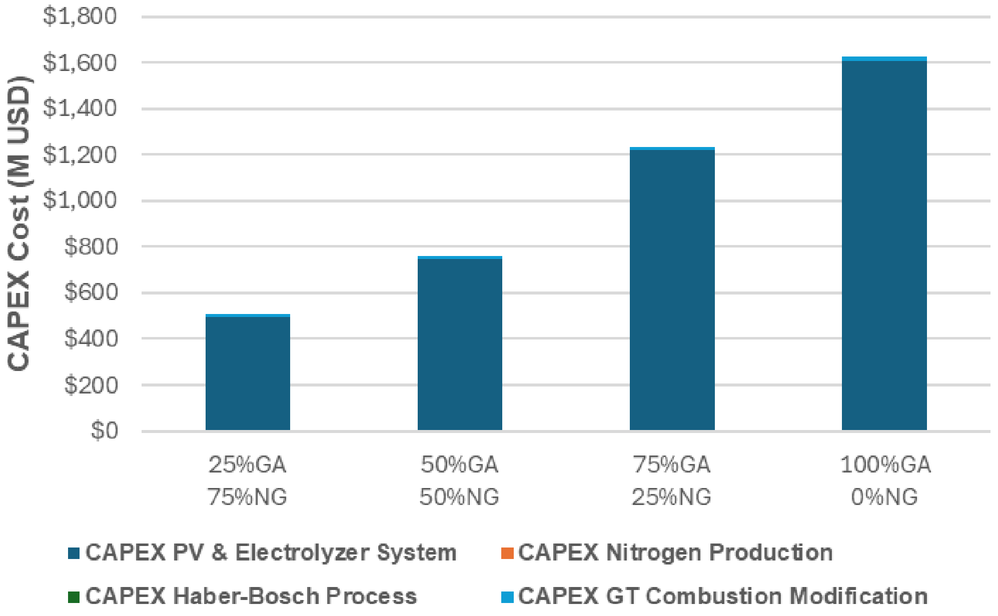

Figure 9. CAPEX Composition of Systems.

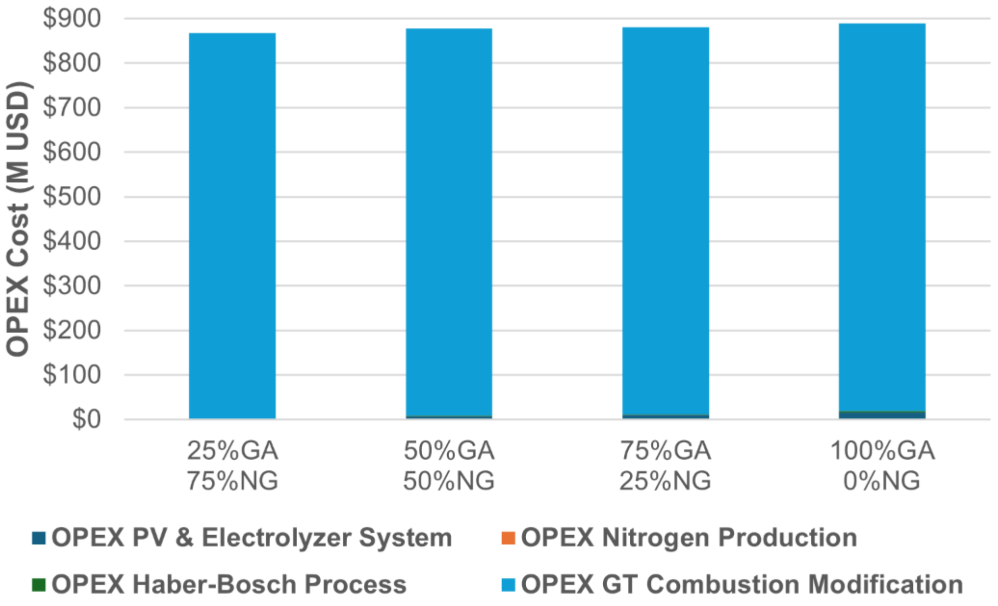

Figure 10. OPEX Composition of Systems.

In the context of transitioning toward cleaner power generation, the strategic use of green ammonia as a co-firing fuel within combined cycle gas turbine (CCGT) systems represents a compelling pathway. This section presents a detailed evaluation of four implementation scenarios at 25, 50, 75, and 100% of green ammonia substitution by analyzing capital and operational expenditures, NPV, and LCOE. The aim is to quantify the economic implications of increasing ammonia usage and determine the most balanced and sustainable integration level.

From a cost composition, a strong correlation exists between the ammonia substitution rate and the overall investment required. As reflected in **Figure 9**, the CAPEX increases significantly from USD 506.80 million (Scheme 25%) to USD 1,622.83 million (Scheme 100%). This cost escalation is primarily driven by the scaling of key process units such as the electrolyser system. These units, while central to the production of green ammonia, are energy and capital-intensive. The electrolyser system and PV alone contribute up to 96% of the hydrogen production cost, in line with findings from peer-reviewed studies that highlight electrolysers' CAPEX as a dominant contributor to green hydrogen cost profiles [10]. Unlike CAPEX, OPEX is predominantly influenced by the day-to-day operational requirements of the existing gas turbine combined cycle power plant. Beyond the recurring fuel costs associated with the co-firing scheme, OPEX also encompasses additional expenses arising from necessary modifications to the plant’s fuel delivery and handling systems to accommodate ammonia integration. The elevated OPEX is primarily driven by the conversion costs of natural gas fuel, aligned with the operational demands of the co-firing configuration. Furthermore, significant electricity consumption both for nitrogen production and the Haber-Bosch synthesis process contributes substantially to the OPEX. While solar PV is employed as a renewable energy source, a considerable portion of the electricity demand is met through the grid, under Renewable Energy Certificate (REC) arrangements, further amplifying operational costs.

Figure 11 presents the economic performance indicators under four co-firing scenarios that progressively increase the share of green ammonia from 25% to 100% while reducing the natural gas proportion correspondingly. The results reveal a clear trend: as the fraction of green ammonia increases, both the LCOE and NPV exhibit notable changes, reflecting the economic dynamics of substituting conventional fossil fuels with renewable alternatives. The LCOE escalates from 0.64 USD/kWh at 25% GA to 0.62 USD/kWh at 100% GA, indicating a significant rise in production costs due to the higher price and operational complexity of ammonia-based combustion. Interestingly, while a moderate increase is observed from 25% to 50% to 75% GA, this may reflect transitional system efficiencies or temporary cost optimizations at mid-to-high co-firing ratios. However, this benefit appears unsustainable at full ammonia utilization, where costs sharply rise again.

In contrast, the NPV demonstrates a pronounced decline as the ammonia proportion increases. With all various co-firing processes, the NPV turns decisively negative. This decline underscores the growing financial risk and diminishing investment appeal when transitioning fully to green ammonia without significant cost offsets or supportive policy mechanisms.

The transfer price remains unchanged across all scenarios, implying that the electricity sale price is either regulated or fixed independently of production costs. This static pricing structure, combined with the rising LCOE, widens the gap between cost and revenue, exacerbating the project's financial viability, particularly at higher ammonia shares.

Although the study confirms the technical feasibility of green ammonia co-firing, the escalating costs and declining NPV at higher ammonia ratios expose a significant gap in current renewable energy deployment strategies. Specifically, there is an urgent need to address this economic gap through substantial reductions in green ammonia production costs, enhanced combustion efficiency at high ammonia shares, and policy mechanisms that align transfer prices with the true cost of sustainable energy production. Furthermore, from a systems-level viewpoint, partial co-firing enables gradual adaptation of existing infrastructure, which significantly mitigates both technological and policy-related risks. This gradual approach is particularly critical for emerging economies such as Indonesia, where power grid resilience, investment capacity, and societal readiness are pivotal factors influencing the success of energy transition initiatives. To bridge the existing gaps, future research should prioritize process intensification, innovative combustion technologies, and market reforms that facilitate the cost-effective, full-scale integration of green ammonia as a viable decarbonization solution.

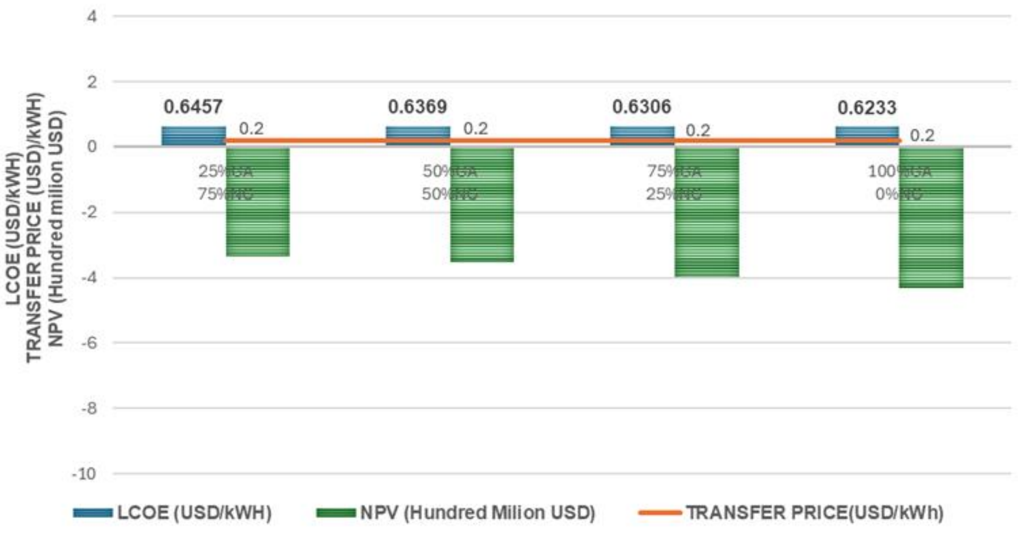

Figure 11. Comparison of LCOE, NPV, and Transfer Price.

4. CONCLUSION

This research presents a comprehensive techno-economic assessment of green ammonia utilization as a co-firing fuel in combined cycle power plants, examining technical feasibility, economic viability, and environmental benefits. Simulation results and subsequent evaluations indicate that, from a technological standpoint, integrating green ammonia and natural gas through co-firing in existing gas and steam power plants is feasible. Specifically, operational simulations conducted using GateCycle confirmed that the renewable ammonia co-firing in combined cycle power plants can maintain stable and reliable electricity supply systems while substantially reducing carbon emissions. Nonetheless, from an economic perspective, project implementation under current conditions appears financially unviable, particularly indicated by negative NPV outcomes. This economic infeasibility is notably pronounced in countries with regulatory, geographic, and geopolitical similarities to Indonesia, highlighting the necessity for supportive policy frameworks and further technological advancements to improve economic attractiveness.

From a technological standpoint, simulation analyses indicate that among the co-firing scenarios involving green ammonia and natural gas in existing gas turbine combined cycle power plants, the scenario with a 50% blend of GA and NG stands out as particularly optimal. This scenario effectively balances electricity supply, operational dependability, and plant efficiency. Specifically, at this 50-50 blend, the plant maintains an efficiency of 31.78%, comfortably within the optimal operational efficiency range of 30-46% typically expected for conventional power generation units. Furthermore, this configuration significantly supports the transition towards lower-carbon energy by notably reducing CO_2 emissions, aligning effectively with gradual, sustainable energy transition policies.

Moreover, the analysis indicates that the co-firing scenario employing a 50% blend of green ammonia and 50% natural gas, despite being classified as technically optimal, is currently economically unfeasible under existing regulatory and market conditions. Specifically, this configuration results in an NPV below zero when applying a selling price of 0.2 USD/kWh, yielding an LCOE of approximately 0.63 USD/kWh. This significant gap between the selling price and LCOE means the scenario would lead to financial losses. Consequently, implementing this strategy would require either a subsidy support of approximately 0.43

USD/kWh to offset potential financial losses or regulatory adjustments designed to incentivize renewable energy adoption, thus positively impacting operational economics. Therefore, the successful deployment of ammonia co-firing technologies will heavily depend on comprehensive stakeholder cooperation, significant reductions in green ammonia production costs, enhanced combustion efficiencies at elevated ammonia blend ratios, and effective regulatory frameworks that align transfer prices with the true costs associated with sustainable energy generation. This economic disparity highlights the urgent need for well-designed policy support and strategic market interventions, especially in countries with geographic and geopolitical contexts similar to Indonesia.

Successful implementation of such co-firing strategies will require comprehensive support from all stakeholders, including substantial reductions in the production cost of green ammonia, improvements in combustion efficiency at higher ammonia ratios, and the introduction of regulatory mechanisms that align transfer prices with the actual cost of sustainable energy production. Despite these challenges, it is important to emphasize that the adoption of green ammonia co-firing offers broader benefits beyond direct emission reductions. It strengthens energy security through diversification of fuel sources, fosters technological innovation, and positions participating countries as proactive contributors to global decarbonization efforts. With the right policy frameworks and strategic investments, this approach holds significant potential to accelerate progress toward net zero emissions while delivering long-term socio-economic advantages.

5. AUTHORS' NOTE

The authors declare that there is no conflict of interest regarding the publication of this article. The authors confirmed that the paper was free of plagiarism.

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