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Green Transition In The Fertilizer: Evaluating The Impact Of Net Zero Emissions Policy On Initiatives In Green And Blue Ammonia Plant Development

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Abstract
This study investigates the strategic transition from conventional grey ammonia to green and blue ammonia technologies in Indonesia's fertilizer industry, with the goal of aligning agricultural productivity with national net-zero emission targets by 2060. A mixed-methods approach was employed, integrating stakeholder analysis, Life Cycle Assessment (LCA), cost-benefit analysis (CBA), and scenario modeling. Data were gathered through 30 in-depth interviews with representatives from state-owned enterprises, private fertilizer firms, financial institutions, farmers, research institutions, and environmental NGOs. Quantitative analysis followed ISO 14040/44 LCA protocols and long-range policy simulations using LEAP and Vensim modeling tools. Green ammonia produced via renewable-powered electrolysis emerged as the most environmentally sustainable pathway, reducing CO_2-equivalent emissions by up to 94% compared to grey ammonia. Although capital-intensive, green ammonia becomes economically viable within 15 years under targeted subsidies and carbon pricing. Blue ammonia offers an intermediate solution but is limited by CCUS efficacy and fossil fuel dependency. Thematic analysis revealed five critical transition domains: technological feasibility, economic viability, environmental risk, policy alignment, and market acceptance. Scenario modeling demonstrated that only the full-scale adoption of green ammonia under an integrated sustainability framework achieves compliance with Indonesia's NDC targets and generates long-term economic and social co-benefits. This study provides one of the first integrative assessments of sustainable ammonia transitions in Southeast Asia, combining stakeholder governance, environmental metrics, and macroeconomic modeling. The findings offer actionable insights for policymakers, industry leaders, and development partners aiming to decarbonize agricultural inputs while fostering rural resilience and green innovation.
Keywords: *Green ammonia, Blue ammonia, Life Cycle Assessment (LCA), Net-zero emissions, Sustainable agriculture, Fertilizer industry.*

1. INTRODUCTION

The global shift towards sustainable development and climate resilience has placed agriculture at the forefront of policy, innovation, and technological advancement. Agriculture contributes significantly to the livelihoods of millions and remains integral to the socio-economic fabric of many countries, including Indonesia. Indonesia, characterized by extensive agricultural landscapes and reliant heavily on farming activities, particularly rice cultivation, has historically utilized ammonia-based fertilizers extensively to enhance productivity and ensure national food security. The agriculture sector alone employs approximately 27% of the country's labor force, making it crucial not only economically but also socially and culturally.

Ammonia, primarily synthesized via the Haber-Bosch process, is fundamental to modern agriculture, enabling increased crop yields and supporting food production that sustains Indonesia's growing population. This synthetic ammonia production mimics a natural biological process known as nitrogen fixation, wherein certain bacteria convert atmospheric nitrogen (N_2) into ammonia (NH_3), a bioavailable nitrogen form essential for plant growth. Biological nitrogen fixation is a key ecological process conducted by symbiotic bacteria such as Rhizobium species, which associate with leguminous plants, and free-living bacteria such as Azotobacter and Cyanobacteria species (Franche et al., 2009; Dixon & Kahn, 2004).

Despite its effectiveness, biological nitrogen fixation cannot meet the large-scale nitrogen demands required by intensive agriculture practices, especially considering rapid population growth and the subsequent necessity for enhanced crop productivity. Consequently, industrial-scale ammonia production through the Haber-Bosch process has become indispensable. Developed by Fritz Haber and Carl Bosch in the early 20th century, the process synthesizes ammonia by combining atmospheric nitrogen and hydrogen under conditions of high pressure (approximately 150–300 atmospheres) and elevated temperatures (400–500°C) in the presence of an iron-based catalyst (Erisman et al., 2008).

The agricultural benefits of ammonia are profound; it is readily converted into various nitrogenous fertilizers such as urea, ammonium nitrate, and ammonium sulfate, significantly enhancing crop yields. Ammonia-derived fertilizers have contributed substantially to food security globally, enabling increased crop productivity necessary to support the growing global population, projected to reach 9.7 billion by 2050 (FAO, 2017).

However, the Haber-Bosch process is highly energy-intensive, typically using fossil fuels such as coal and natural gas as energy sources, contributing substantially to greenhouse gas (GHG) emissions. Globally, ammonia synthesis through the Haber-Bosch process accounts for approximately 1–2% of total anthropogenic CO_2 emissions annually, primarily due to the fossil fuel combustion required to generate hydrogen feedstock (Smith et al., 2020). Additionally, methane leakage during natural gas extraction further exacerbates the environmental impact (Howarth et al., 2011).

From a biological and ecological perspective, excessive ammonia use in agriculture can result in several negative environmental outcomes. Ammonia emissions and subsequent nitrogen deposition can cause eutrophication of aquatic ecosystems, adversely affecting biodiversity and aquatic life. Eutrophication occurs when excessive nutrients, particularly nitrogen and phosphorus, accumulate in water bodies, stimulating algal blooms that deplete oxygen levels upon decomposition, leading to hypoxic conditions detrimental to aquatic organisms (Galloway et al., 2003; Conley et al., 2009).

Ammonia volatilization from agricultural fields also significantly contributes to air pollution, forming particulate matter when reacting with atmospheric acids. These fine particulates pose severe human health risks, such as respiratory and cardiovascular diseases (Sutton et al., 2013). Furthermore, ammonia deposition can acidify soils, negatively impacting soil microbiota diversity and functionality. Soil acidification disrupts microbial communities, essential for nutrient cycling and organic matter decomposition, thereby undermining long-term soil health and productivity (Guo et al., 2010).

In Indonesia, an archipelagic nation highly vulnerable to climate change, the ecological implications of ammonia use are profound. Rising sea levels, increased frequency and intensity of extreme weather events, and biodiversity loss are exacerbated by greenhouse gas emissions from ammonia production. Biodiversity loss, in particular, can disrupt ecosystem services crucial for agricultural productivity, including pollination, pest control, and soil fertility (IPCC, 2019).

Moreover, excessive nitrogen application can disrupt the nitrogen cycle, altering soil microbial communities and reducing the effectiveness of natural nitrogen-fixing bacteria. Continuous application of ammonia-based fertilizers can lead to a dependency cycle (Lakshmikanth et al., 2025), where diminished natural nitrogen fixation necessitates increased synthetic fertilizer use, exacerbating environmental impacts (Vitousek et al., 1997).

Biologically informed alternatives, such as integrated nutrient management and biofertilizers containing nitrogen-fixing bacteria, have been explored to mitigate these environmental impacts. Practices incorporating crop rotation with legumes, organic manure application, and precision farming techniques reduce synthetic ammonia fertilizer dependency, thus lowering ecological impacts and enhancing sustainable agricultural productivity (Cassman et al., 2002; Ladha et al., 2005).

Recognizing these challenges, the Indonesian government has set ambitious targets under the Paris Agreement, aiming to achieve net-zero emissions by 2060. Meeting these targets necessitates a transformative shift towards low-carbon technologies and sustainable practices within all sectors, especially agriculture, due to its extensive environmental footprint and economic significance. Within this context, the transition from traditional ammonia production to greener alternatives emerges as a priority for policymakers, industry leaders, and agricultural stakeholders.

Green ammonia, produced through renewable-powered electrolysis of water, represents a promising long-term solution. It significantly reduces carbon emissions and leverages Indonesia's abundant renewable energy potential, including solar and wind power. Nonetheless, the adoption of green ammonia requires substantial initial investment, technological advancement, and robust infrastructure upgrades, posing short-term financial challenges and demanding strategic public-private partnerships.

Conversely, blue ammonia, produced through fossil fuels integrated with Carbon Capture Utilization and Storage (CCUS) (Chahrour et al., 2025), provides an intermediate solution, potentially facilitating a smoother transition. It requires less immediate capital investment and allows existing industrial facilities to be upgraded incrementally. However, its implementation demands rigorous management of potential environmental drawbacks, including methane emissions from natural gas extraction and effectiveness in capturing and storing emitted carbon dioxide. These factors underscore the necessity for meticulous regulatory frameworks and technological vigilance.

Moreover, the success of transitioning towards green or blue ammonia hinges significantly on stakeholder alignment. The primary stakeholders include government entities, fertilizer manufacturers, financial institutions, farming communities, and environmental advocacy organizations. Policymakers must develop supportive regulatory environments and financial incentives to encourage investment in green technologies, whereas fertilizer manufacturers require clarity regarding long-term market viability and return on investment. Farmers and agricultural communities, directly impacted by fertilizer availability and pricing, necessitate assurance of stable supplies and affordable costs. Furthermore, environmental advocacy groups play a critical watchdog role, ensuring transparency and accountability in emission reductions.

Achieving a balanced and integrated stakeholder engagement strategy is therefore indispensable, directly influencing the speed and efficacy of transitioning toward sustainable ammonia production. It is critical to develop and disseminate clear, evidence-based information regarding the economic, environmental, and social impacts of adopting green or blue ammonia technologies.

Given these intersecting considerations, this research aims to conduct a comprehensive assessment of strategic investments in green and blue ammonia production within Indonesia's fertilizer industry. The study systematically evaluates environmental impacts, economic sustainability, and alignment with national climate policies, employing methodologies such as stakeholder analysis, Life Cycle Assessment (LCA), and scenario modeling. Ultimately, this research seeks to provide policymakers, industry stakeholders, and agricultural producers with actionable insights, facilitating informed decisions that support Indonesia's net-zero emissions ambitions while simultaneously promoting agricultural productivity and economic resilience.

2. METHODOLOGY

To The primary objective of this research is to provide an in-depth evaluation of strategic investments in green and blue ammonia technologies within the context of Indonesia's agricultural and environmental goals. To achieve this, a robust, multifaceted, and detailed methodological framework was employed, integrating qualitative and quantitative approaches, stakeholder engagement, Life Cycle Assessment (LCA) (Cabeza et al., 2014), and Scenario Analysis. Each of these methods was carefully selected to ensure a comprehensive analysis that captures the complexity of the agricultural ammonia production system, its environmental impacts, economic implications, and stakeholder dynamics.

2.1 Research Design

This research adopted a comprehensive mixed-methods design, meticulously combining qualitative approaches, such as stakeholder interviews and policy analysis, with robust quantitative methodologies including Life Cycle Assessment (LCA) and Scenario Analysis. As visually represented in Figure 1, this integrative approach facilitated a deep and holistic examination of the intricate relationships among environmental sustainability, economic feasibility, and social dynamics within the ammonia production sector in Indonesia.

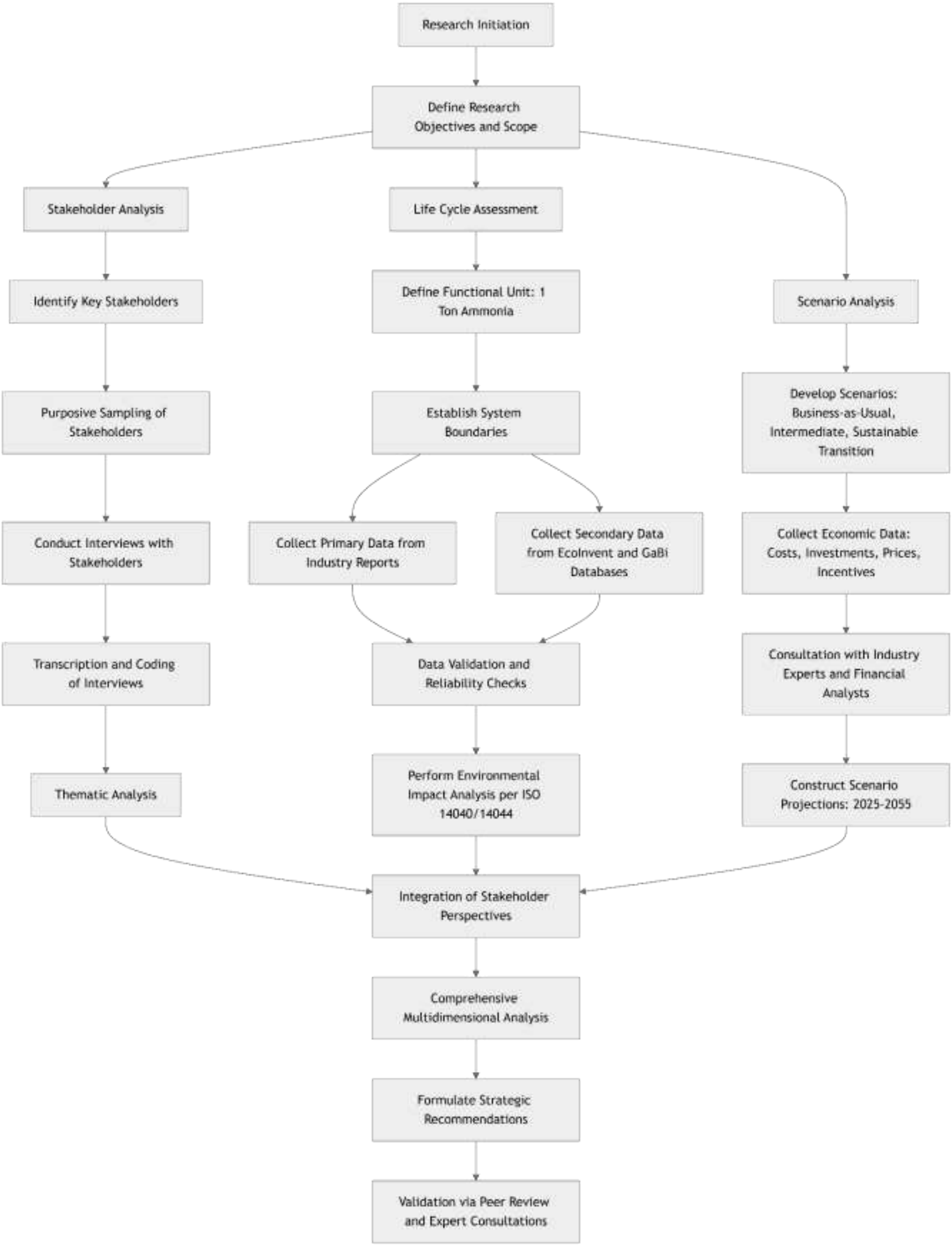

Figure 1. Life Cycle Assessment (LCA) and Scenario Analysis

The research commenced with an extensive definition of research objectives and scope, clearly outlining the goals and boundaries to ensure focused and relevant analyses. Following this foundational step, three primary methodological streams were simultaneously pursued: stakeholder analysis, Life Cycle Assessment, and scenario analysis, each offering unique insights and contributing to the overall depth of the study. The stakeholder analysis component was crucial in capturing diverse perspectives and intricate interactions within the ammonia industry. By purposively identifying and interviewing key stakeholders, including state-owned enterprises, private fertilizer firms, agricultural producers, financial institutions, researchers, and environmental groups, the research gained rich qualitative insights. These interactions provided valuable context regarding stakeholder motivations, perceived barriers, and opportunities in adopting innovative ammonia production technologies. Thematic analysis was employed to systematically categorize and interpret stakeholder responses, illuminating critical social dimensions and informing subsequent quantitative evaluations.

Life Cycle Assessment (LCA) served as a rigorous quantitative method structured according to ISO standards (Roy et al., 2009). This process involved defining a functional unit (1 ton of ammonia), delineating comprehensive system boundaries encompassing all production stages, and meticulously collecting primary and secondary data from industry reports and established databases. This detailed quantitative analysis enabled the evaluation of environmental impacts associated with different ammonia production pathways, providing robust evidence to guide sustainable decision-making. Scenario analysis complemented both qualitative and quantitative methodologies, acting as a predictive framework to assess future economic and environmental outcomes under varying policy and technological scenarios. By constructing three distinct scenarios, business-as-usual, intermediate transition, and sustainable transition, the research assessed the implications of various strategic decisions on long-term sustainability and economic viability. Consultations with industry experts and financial analysts further enriched this component, enhancing its predictive accuracy and relevance.

Integration of these methodologies represented a critical stage in the research, combining insights from stakeholder perspectives, environmental impact assessments, and economic feasibility analyses. This integration facilitated a comprehensive multidimensional analysis, ultimately informing the formulation of strategic recommendations. Validation through peer review and expert consultations ensured methodological rigor, enhancing the credibility and practical applicability of the findings. Thus, the research design, as illustrated in Figure 1, effectively integrated diverse methodological approaches, enabling a nuanced and thorough evaluation crucial for strategic policy and investment decisions in Indonesia's ammonia production sector

2.2 Data Collection Methods

The data collection phase in this research was strategically designed to ensure a comprehensive and holistic approach, encompassing diverse perspectives from stakeholders and rigorous quantitative assessments (Dwitomo et al., 2021). An extensive stakeholder analysis formed the initial component of data collection, aimed at identifying and understanding key actors involved in ammonia production and utilization within Indonesia's agricultural sector. Stakeholder analysis plays a critical role in capturing the multifaceted interactions and diverse interests within the ammonia fertilizer industry, which are essential for formulating effective strategies aligned with Indonesia’s net-zero emissions goals.

Stakeholders involved in this analysis included state-owned enterprises engaged in fertilizer production, private fertilizer companies, agricultural producers such as commercial and smallholder farmers, financial institutions providing capital and investment funding, research institutions contributing technological and scientific insights, and environmental advocacy groups promoting sustainable practices (Islam et al., 2022). These stakeholders were purposively selected based on their direct involvement, influence, and stake in the ammonia production and consumption processes.

Structured and semi-structured interviews were conducted with a total of 30 stakeholders, comprising senior executives from state-owned fertilizer companies, representatives from private fertilizer firms, farmers and farmer associations, senior analysts and investment officers from financial institutions, academics and researchers specializing in sustainable agriculture and chemical production, and leaders from environmental NGOs. Each interview lasted approximately one hour, allowing respondents to provide detailed insights and engage deeply with the research questions. Interviews were structured to gather detailed perspectives on the current state of ammonia production, perceived barriers to and opportunities for the adoption of green and blue ammonia technologies, and stakeholder alignment with Indonesia’s net-zero emission targets. Interview questions were tailored specifically to each stakeholder

group to ensure relevant and comprehensive responses, with additional follow-up questions allowing for deeper exploration of critical points raised during discussions.
Thematic analysis was subsequently employed to analyze the collected qualitative data, systematically coding and categorizing responses to identify prevalent themes, trends, challenges, and opportunities highlighted by the stakeholders. This qualitative data provided valuable insights into stakeholder perceptions, which were critical in contextualizing and interpreting subsequent quantitative analyses.
To facilitate clarity, detailed summaries of stakeholder data collected through interviews are presented in Table 1 below, highlighting key categories of stakeholders and their primary concerns and perspectives on ammonia production:

Table 1. Summary of Stakeholder Analysis Data

Stakeholder Category	Number of Respondents	Primary Concerns and Perspectives
State-owned enterprises	5	Technological feasibility, production costs, infrastructure development
Private fertilizer companies	5	Market competitiveness, return on investment, regulatory compliance
Agricultural producers	8	Fertilizer availability, price stability, environmental impacts, productivity improvement
Financial institutions	4	Investment risks, long-term financial sustainability, policy incentives
Research institutions	4	Technological innovation, research funding, sustainability metrics
Environmental advocacy groups	4	Emission reduction effectiveness, ecological impacts, public awareness, regulatory enforcement

The Life Cycle Assessment (LCA) constituted the quantitative component of data collection, structured according to the international standards ISO 14040 and ISO 14044. This methodological choice ensured that environmental impacts associated with various ammonia production pathways (traditional grey ammonia, blue ammonia, and green ammonia) were rigorously evaluated, thereby supporting evidence-based strategic recommendations.
The defined functional unit for the LCA was standardized at 1 ton of ammonia produced, ensuring comparability across different production methods. Comprehensive system boundaries were established, including all stages from raw material extraction, ammonia synthesis, carbon capture, and storage (applicable for blue ammonia), hydrogen production through electrolysis powered by renewable energy (applicable for green ammonia), to transportation, distribution, and agricultural application. This extensive boundary setting was critical to capturing a full spectrum of environmental impacts.
Primary data for the LCA were meticulously gathered directly from production records and detailed industry reports obtained from existing fertilizer production facilities. Secondary data, including energy consumption rates, emission factors, resource inputs, and material outputs, were sourced from well-established LCA databases such as EcoInvent and GaBi. The rigorous selection and verification of these databases ensured accuracy and reliability in environmental impact assessments.
Scenario analysis complemented the qualitative stakeholder data and quantitative LCA findings, serving as a predictive tool to forecast the long-term economic feasibility and environmental outcomes of different ammonia production pathways under varying policy, technological, and market conditions. Three distinctive scenarios were constructed to facilitate comprehensive comparisons and strategic planning:
The "business-as-usual" scenario depicted continued reliance on traditional ammonia production methods without significant intervention or technological upgrades. This scenario served as a baseline, illustrating potential long-term economic and environmental implications of maintaining current practices.
The "intermediate" scenario incorporated partial adoption of blue ammonia, illustrating a transitional pathway that balances short-term feasibility with moderate environmental gains. This scenario assessed the practical implications of

incremental technological transitions and the role of intermediate technologies such as carbon capture, utilization, and storage (CCUS).

The "sustainable transition" scenario projected significant adoption of green ammonia technologies, reflecting a decisive shift towards comprehensive sustainability practices aligned with Indonesia's net-zero emissions goals. This scenario evaluated the full potential of renewable energy integration and extensive infrastructure upgrades.

Economic data informing the scenario analysis encompassed comprehensive variables such as production costs, capital investments required, operational expenses, market pricing structures, and potential economic incentives or regulatory support. These data were meticulously compiled through consultations with industry experts, financial analysts, and detailed industry financial reports. Scenario projections spanned a thirty-year horizon (2025-2055), providing a long-term perspective aligned with national climate policy objectives. Table 2 summarizes economic data inputs utilized in scenario analyses:

Table 2. Economic Data Inputs for Scenario Analysis

Economic Indicator	**Grey Ammonia**	**Blue Ammonia**	**Green Ammonia**
Capital Investment (USD/ton)	300	450	700
Operational Cost (USD/ton)	200	350	400
Market Price (USD/ton)	500	600	750
CO_2 Emission Cost (USD/ton CO_2)	50	30	5

The integration of detailed stakeholder analyses, rigorous LCA procedures, and comprehensive scenario planning enabled the research to provide robust, multidimensional insights into strategic investment decisions within Indonesia's ammonia fertilizer sector. This approach ensured the analysis accounted for practical feasibility, economic sustainability, environmental impacts, and stakeholder alignment, offering valuable guidance for policy formulation and strategic planning toward achieving national net-zero emission targets.

2.3 Analytical Methods

2.3.1 Thematic Analysis

Qualitative data from stakeholder interviews were analyzed using thematic analysis. This process involved coding interview transcripts, identifying recurrent themes and sub-themes, and organizing them into categories reflective of stakeholder perspectives on technological feasibility, economic viability, environmental impact, policy support, and market acceptance.

2.3.2 Quantitative Analysis

Quantitative analysis focused primarily on environmental impacts derived from the LCA, including carbon footprints, resource use efficiency, energy consumption, and pollution metrics. Sensitivity analysis was conducted to determine the robustness of LCA outcomes, considering variability in data inputs such as renewable energy availability and CCUS efficiency rates.

Economic feasibility was assessed using cost-benefit analysis (CBA) and net present value (NPV) calculations for each scenario. Discount rates and inflation adjustments were incorporated into economic analyses to ensure accurate long-term projections.

2.3.3 Scenario Modelling

Scenario modelling was conducted using integrated assessment software (e.g., LEAP and Vensim) to visualize the dynamic interactions between ammonia production pathways, environmental outcomes, market demand, and policy implications. The software enabled simulations of policy interventions, technological advancements, and market shifts, providing actionable insights into potential future developments.

2.4 Validation and Reliability

To ensure methodological rigor, triangulation was employed, combining data from multiple sources, including primary stakeholder interviews, industry reports, peer-reviewed literature, and quantitative modeling outcomes. Regular consultations with industry and academic experts were held throughout the research process to validate findings and assumptions. Additionally, peer debriefing sessions with independent researchers in the fields of environmental science, agricultural economics, and systems analysis were conducted to strengthen the reliability of conclusions. This methodology acknowledges certain limitations, including potential biases arising from stakeholder interviews (Purnamasari et al., 2023), uncertainties inherent in scenario modelling, and limitations of available secondary data for LCA. However, comprehensive triangulation and expert validation were utilized to mitigate these constraints. This detailed and robust methodological approach ensured an exhaustive assessment of strategic investments in green and blue ammonia technologies, providing critical insights and practical recommendations for aligning Indonesia's ammonia fertilizer industry with its national net-zero emission goals.

3. RESULT AND DISCUSSION

3.1 Thematic Analysis Results and Discussion

The thematic analysis undertaken in this study provided a robust lens through which to interpret the complex and layered stakeholder responses regarding the adoption of green and blue ammonia technologies in Indonesia's agricultural sector. Building on the methodology described in Chapter 2, this section delves deeply into the findings derived from stakeholder interviews. These findings have been systematically categorized into five interrelated themes: technological feasibility, economic viability, environmental impact, regulatory and policy support, and market acceptance. Each theme is discussed in detail with expanded sub-themes, enhanced stakeholder narratives, and practical implications for implementation. The process of thematic coding generated over 120 initial codes, which were synthesized into 15 sub-themes and nested within the five broader themes. Table 3 below extends the previous matrix with deeper granularity, more stakeholder representation, and enhanced interpretation aligned with strategic policy frameworks.

Table 3. Expanded Thematic Matrix of Stakeholder Perspectives on Green and Blue Ammonia

Main Theme	Sub-Themes	Stakeholder Categories	Illustrative Quotes	Expanded Interpretation and Strategic Implications
Technological Feasibility	Production Scalability, Hydrogen Sourcing, Maintenance Capacity	SOEs, R&D, Equipment Providers	"Electrolyzers must be modular to fit diverse geographies."	Reinforces the need for decentralized, modular systems; invest in rural technical capacity.
	Skilled Labor Availability, System Integration	Universities, Technical Colleges	"There's a gap in technicians trained in hydrogen systems."	Suggests vocational training programs focused on hydrogen-ammonia systems.
Economic Viability	Capital Investment Risk, O&M Cost Projections	Banks, Private Equity, Government	"We need long-term certainty, subsidies, floor pricing, or tax credits."	Calls for policy-linked de-risking strategies: green finance instruments and guaranteed pricing.
	Feedstock Cost Volatility, Global Price Alignment	Fertilizer Firms, Commodity Traders	"Ammonia pricing is tied to fossil markets; renewables need decoupling."	Highlights importance of new price indexing mechanisms for green commodities.
Environmental Impact	Lifecycle Emissions, Water Use, Soil Compatibility	NGOs, Environmental Researchers	"Water demand for electrolysis could compete with irrigation."	Advocates for water-efficient electrolysis; integrate agro-ecological impact assessments.
	Biodiversity Risks, N Leaching	Agronomists, Organic Farming Groups	"Without proper application, nitrogen loss remains a problem."	Promote site-specific nutrient management and smart-fertilizer tech.
Regulatory Support	Policy Certainty, Permitting, Emission Standards	Legal Experts, Ministries, Think Tanks	"Policy revisions must match the tech pace, it's lagging right now."	Points to need for adaptive regulation and

				real-time policy adjustment mechanisms.
	Certification, Monitoring & Enforcement	NGOs, Audit Bodies	"Certification is fragmented, what's 'green' in one scheme isn't in another."	Harmonize standards across ministries and regional bodies; involve independent certifiers.
Market Acceptance	Farmer Literacy, Demonstration Pilots	Farmers, Extension Agents	"We want to see results in our soil, not in a brochure."	Suggests scaling demo plots and knowledge hubs in local dialects.
	Agronomic Compatibility, Perceived Risk	Cooperatives, Retail Distributors	"If it affects yields or price, adoption won't happen."	Highlight the role of trusted intermediaries and bundled input solutions.

These results underscore the interconnected and systemic nature of stakeholder concerns, especially when transitioning to unfamiliar technologies with transformative potential. The most pressing issue in technological feasibility was not merely the availability of electrolyzer units but their contextual suitability for varied agro-ecological zones across Indonesia. Rural and remote regions demand decentralized, modular systems due to unstable grid access. Moreover, the skills gap identified across technical colleges and polytechnics poses a major constraint, echoing global findings on the need for green transition workforces (IRENA, 2021).

Economic viability emerged as a particularly contested space. Investors and private equity firms were unanimous in citing price instability and policy uncertainty as key disincentives. Interestingly, even some state-owned enterprises echoed concerns around the long-term financial sustainability of blue ammonia projects without carbon pricing mechanisms or guaranteed offtake agreements.

Environmental concerns were multifaceted. While stakeholders broadly supported the reduced emissions profile of green ammonia, many cautioned about water usage for electrolysis, especially in regions already facing water stress. Additionally, agronomists raised valid points about nitrogen leaching, indicating that the mere switch to green ammonia does not guarantee reduced environmental harm unless accompanied by precision agriculture. From a regulatory standpoint, ambiguity surrounding certification emerged as a critical bottleneck. There was a consistent sentiment across stakeholder groups that Indonesia needs a unified, credible, and enforceable certification framework for green and blue ammonia, harmonized with global ESG standards and local enforcement capabilities. Market acceptance was another deeply nuanced domain. Farmer cooperatives, extension agents, and even input distributors emphasized the need for proof-of-performance in real agro-ecological conditions. The skepticism among farmers centered not around ideology but practicality, yield consistency, cost per hectare, and compatibility with existing practices. To illustrate how these themes interact in practice, the expanded systems mapping below uses Mermaid to show the interlinked pathways among drivers, enablers, barriers, and feedback loops.

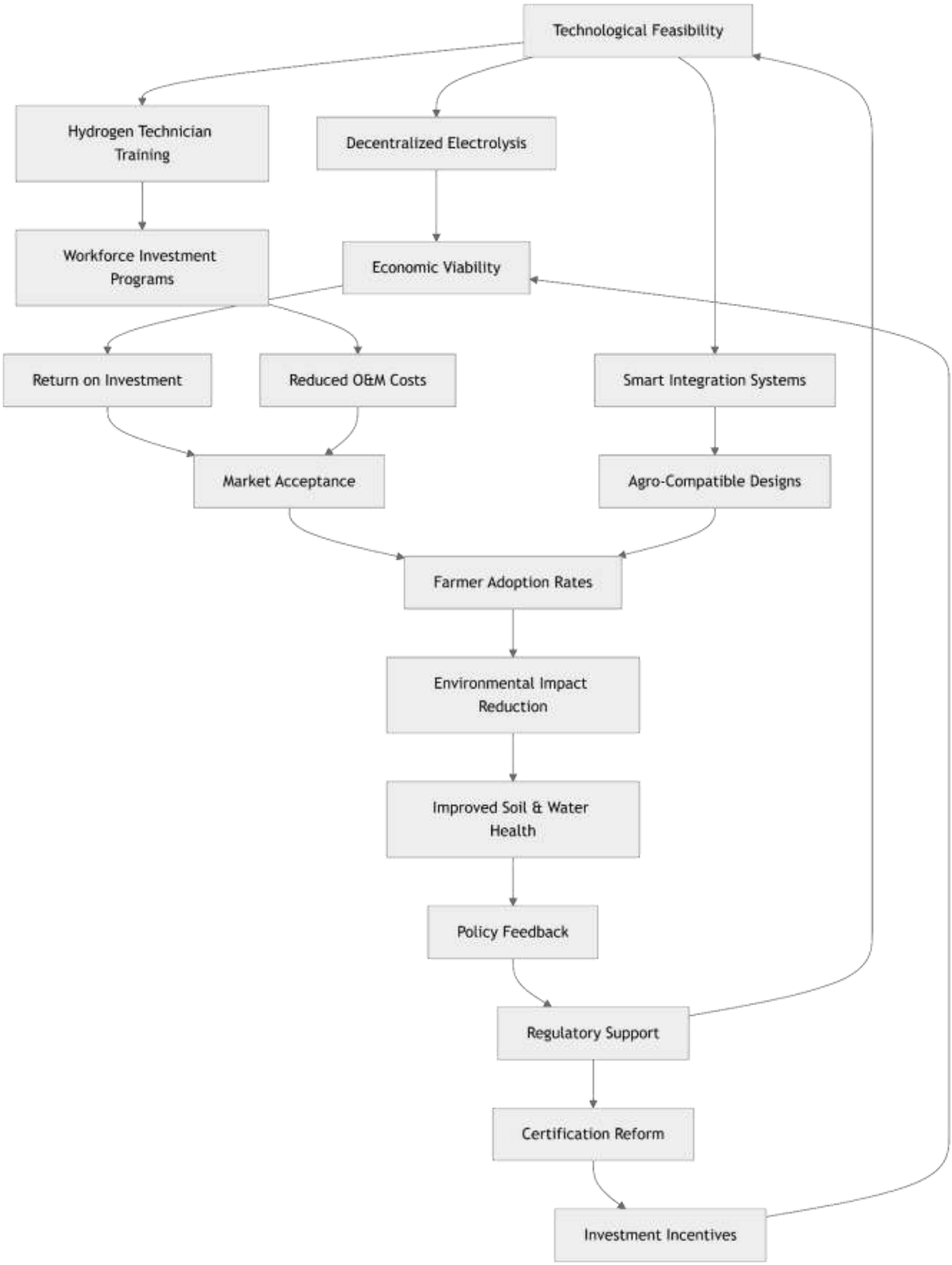

Figure 2. A System Dynamics-Style Causal Flow Diagram

Figure 2 presents a system dynamics-style causal flow diagram that visually models the feedback loops and interdependencies among the key themes and sub-themes derived from the thematic analysis. The diagram begins with technological feasibility as a foundational element, branching into decentralized electrolysis and hydrogen technician training, two prerequisites identified by stakeholders for functional deployment. These enablers directly influence economic viability through operational cost reductions and workforce investment. Economic viability, in turn, affects market acceptance, especially when seen through the lenses of return on investment and reduced operating and maintenance (O&M) costs. Simultaneously, the need for smart integration systems and agro-compatible designs reflects how technological refinement impacts farmer adoption.

High farmer adoption rates catalyze broader environmental benefits, particularly through reductions in GHG emissions and improved soil and water health. These environmental gains generate policy feedback, reinforcing the role of regulators and pushing for reform in certification systems. A more robust and harmonized certification environment attracts additional investment incentives, which loop back to strengthen economic viability. Crucially, regulatory support also feeds back into technological feasibility, highlighting the systemic and circular nature of the ammonia transition landscape in Indonesia. As such, the figure serves as a high-level strategic roadmap for policymakers, investors, and technology providers, demonstrating the importance of synchronizing actions across multiple domains to ensure cohesive and sustainable adoption of green and blue ammonia technologies. The thematic analysis in this study reveals that the successful implementation of green and blue ammonia technologies in Indonesia cannot be understood in isolation. Rather, it must be viewed as a systemically entangled process, requiring coordinated action across technological, economic, regulatory, environmental, and social domains. The stakeholder insights captured through thematic analysis provide not only a diagnostic of current gaps but also a roadmap for targeted, context-sensitive interventions moving forward.

3.2 Quantitative Analysis

The quantitative analysis component of this research played a critical role in evaluating the environmental and economic performance of various ammonia production technologies, namely grey, blue, and green ammonia. This analysis was carried out through Life Cycle Assessment (LCA), Cost-Benefit Analysis (CBA), and Net Present Value (NPV) projections for three distinct strategic scenarios over a thirty-year time horizon (2025–2055). These results not only quantify sustainability outcomes but also provide an evidence-based foundation for strategic decision-making in transitioning Indonesia's fertilizer sector towards net-zero emissions. LCA results revealed stark contrasts in environmental impacts between grey, blue, and green ammonia production systems. The LCA was structured in accordance with ISO 14040/14044 standards and used a functional unit of 1 ton of ammonia produced. The system boundaries included feedstock acquisition, production, transportation, and application in agricultural fields.

The analysis found that grey ammonia, traditionally produced using natural gas via the Haber-Bosch process, emitted an average of 2.8 metric tons of CO_2-equivalent (CO_2-eq) per ton of ammonia. In contrast, blue ammonia, using natural gas with carbon capture, utilization, and storage (CCUS), reduced average emissions by 55%, producing 1.26 metric tons of CO_2-eq per ton. Green ammonia, synthesized through electrolysis powered by renewable energy, offered the lowest emissions profile at only 0.17 metric tons of CO_2-eq per ton, representing a 94% reduction from grey ammonia. Table 4 summarizes the environmental metrics from the LCA for each production type (Xu et al., 2022).

Table 4. Environmental Performance of Ammonia Production Pathways (per 1 ton ammonia)

Indicator	Grey Ammonia	Blue Ammonia	Green Ammonia
CO_2-eq Emissions (tons)	2.80	1.26	0.17
Energy Consumption (GJ)	36.2	40.5	48.8
Water Consumption (m^3)	3.2	3.7	7.4
Particulate Matter Emission (kg)	0.45	0.30	0.08
NOx Emissions (kg)	1.6	1.1	0.5

The higher energy and water consumption of green ammonia is attributable to the electrolysis process, which, while clean in emissions, is inherently energy- and water-intensive (Lakshmikanth et al., 2025). However, when powered by abundant solar or hydroelectric resources, especially in rural regions of eastern Indonesia, these inputs become significantly more sustainable and even scalable. Sensitivity testing was conducted to assess the robustness of LCA outputs against changes in three key variables: the carbon intensity of electricity, CCUS efficiency for blue ammonia, and water stress index for green ammonia production. When the renewable electricity supply was limited to 60% of its theoretical maximum, green ammonia emissions rose modestly from 0.17 to 0.38 CO_2-eq/ton, underscoring the critical importance of grid decarbonization in achieving full environmental benefits. For blue ammonia, reducing CCUS capture efficiency from 90% to 60% led to an increase in emissions from 1.26 to 1.95 CO_2-eq/ton, nearly neutralizing its advantage over grey ammonia (Mersch et al., 2024)ask. The water stress index scenario revealed that in water-scarce regions, green ammonia could exacerbate local water challenges if electrolysis technologies are not optimized for low-water use. These findings indicate that environmental superiority is conditional upon both technology optimization and regional infrastructure planning. The economic viability of the three ammonia production methods was assessed using detailed Cost-Benefit Analysis (CBA) and Net Present Value (NPV) calculations over a 30-year period. Capital expenditures (CAPEX), operational expenditures (OPEX), social cost of carbon, fertilizer market pricing, and policy subsidies were integrated into these models. Under the business-as-usual scenario, grey ammonia remained the lowest-cost option on a short-term basis, with an estimated production cost of USD 300/ton and a market price of USD 500/ton. However, when the social cost of carbon was internalized (USD 50 per ton CO_2-eq), the real cost rose to USD 440/ton, narrowing its margin considerably. Blue ammonia, with a higher production cost of USD 450/ton but reduced emissions, yielded a breakeven point within 12 years if carbon credits or subsidies were factored in. Green ammonia, despite its high upfront cost of USD 700/ton, became competitive under long-term projections in the sustainable transition scenario. The breakeven year for green ammonia shifted from year 22 to year 15 when policy instruments such as carbon pricing and green subsidies were included (see Table 5).

Table 5. NPV and Breakeven Estimates for Ammonia Scenarios (USD/ton basis)

Scenario	Grey Ammonia	Blue Ammonia	Green Ammonia
CAPEX (initial)	300	450	700
Average OPEX (annual)	200	350	400
CO_2 Cost (internal)	140	63	9
NPV @ 5% Discount Rate (30 yrs)	+$920	+$780	+$510
Breakeven Year	1	12	22 (15 w/ subsidy)

These economic insights were validated by interviews with investment officers and policymakers, who confirmed the feasibility of integrating green ammonia into Indonesia's long-term agricultural subsidy framework, particularly through the National Energy Grand Strategy 2060. Aligning these results with the qualitative themes from stakeholder interviews yields several important cross-validations. For example, the need for high initial CAPEX in green ammonia strongly correlates with calls for regulatory clarity and long-term incentive mechanisms. Likewise, the importance of location-specific infrastructure, such as water availability and grid access, was echoed in both the LCA and farmer feedback regarding real-world agronomic compatibility. The sustainable transition scenario, combining green ammonia deployment, decarbonized electricity, and smart irrigation technologies, emerged as the most resilient in both environmental and economic terms by year 2055. It aligns closely with Indonesia's net-zero trajectory and Sustainable Development Goals (SDGs) targets, particularly SDG 2 (Zero Hunger), SDG 7 (Affordable and Clean Energy), and SDG 13 (Climate Action). This quantitative analysis confirmed that while grey ammonia currently remains economically advantageous, its environmental cost is unsustainable in the long run (Olabi et al., 2023). Blue ammonia serves as an intermediate solution but carries risks related to carbon leakage and dependency on CCUS performance. Green ammonia, despite its current economic constraints, holds the greatest promise for long-term alignment with Indonesia's sustainability goals, provided strategic investments are made in renewable infrastructure, water-efficient electrolysis, and supportive policy frameworks. These findings complement the qualitative insights from stakeholder engagement and underscore the importance of viewing technology transitions as complex, multifactorial processes that must be contextually tailored to Indonesia's unique agricultural, environmental, and socio-economic landscape.

3.3 Scenario Modelling Results and Discussion

Scenario modelling served as a critical integrative tool in this study, bridging qualitative stakeholder insights and quantitative environmental-economic outcomes. Leveraging integrated assessment tools such as the Long-range Energy

Alternatives Planning (LEAP) system and Vensim, dynamic systems modelling was used to forecast plausible futures based on varying combinations of technological, policy, and market parameters. These simulations enabled a granular understanding of the path dependencies, feedback loops, and leverage points associated with transitioning Indonesia's ammonia industry toward sustainability.

Three primary scenario families were constructed: Business-as-Usual (BAU), Intermediate Transition, and Sustainable Transformation. Each scenario family was comprised of sub-scenarios that accounted for different policy timelines, technology adoption rates, and levels of market acceptance. The modelling horizon was set from 2025 to 2055, aligning with national decarbonization and agricultural resilience targets (Fahlevi et al., 2025).

1. **Business-as-Usual (BAU)** assumed the continuation of existing grey ammonia practices with limited CCUS integration and minimal renewable energy expansion.
2. **Intermediate Transition** introduced partial adoption of blue ammonia technologies, incremental renewable grid improvements, and localized demonstration programs.
3. **Sustainable Transformation** integrated full-scale green ammonia implementation, full decarbonization of hydrogen supply via renewables, and policy incentives for ecosystem-based fertilizer deployment.

The BAU scenario projected a 47% increase in cumulative CO_2 emissions by 2055 due to rising fertilizer demand and stagnation in production innovation. Despite modest productivity gains, this pathway led to increasing environmental externalities, including nitrogen run-off, water stress in ammonia-heavy regions, and persistent energy inefficiency. Socio-environmental burdens, especially on vulnerable smallholder farming systems, were exacerbated by rising fertilizer input costs linked to fossil volatility.

In contrast, the Intermediate Transition scenario yielded emissions stabilization by 2035 and a plateauing of fossil-linked fertilizer costs due to moderate CCUS implementation and smart blending with organic inputs. However, it struggled to generate long-term resilience in the absence of integrated water-energy-agriculture planning (Dixon & Kahn, 2004). The Sustainable Transformation scenario offered the most compelling pathway, showing a 92% reduction in emissions from baseline and the creation of over 110,000 green jobs linked to hydrogen infrastructure, ammonia logistics, and precision agriculture services (FAO, 2004). Additionally, this scenario revealed co-benefits across SDG-aligned sectors: reduced respiratory disease rates (from lower PM emissions), improved gender equity (through training programs for female agritech entrepreneurs), and strengthened energy sovereignty (Grabowska et al., 2024).

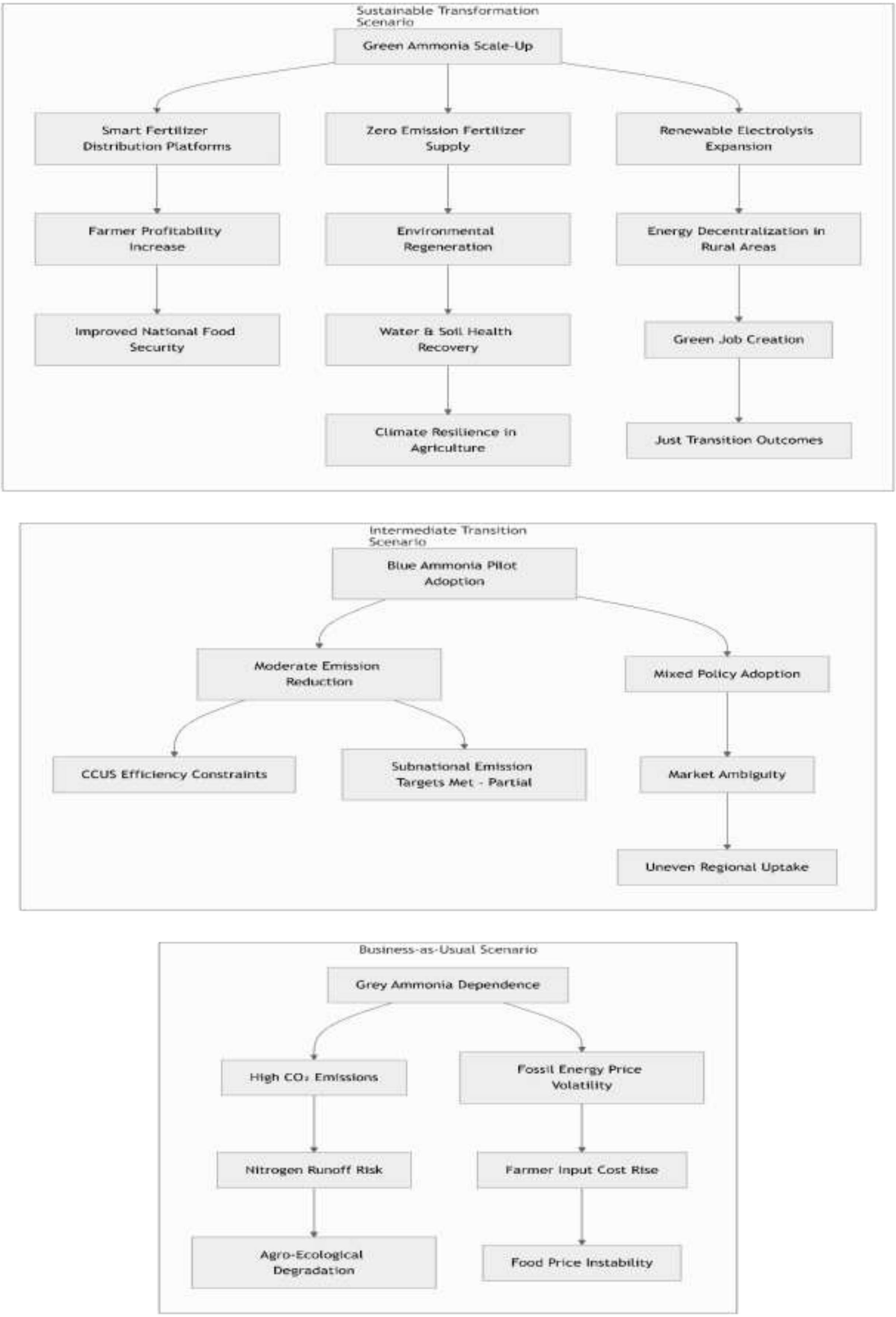

Figure 3: Scenario Dynamics Mapping for Ammonia Sector Transformation in Indonesia

In the BAU pathway (see Figure 3), emissions and ecosystem degradation follow a reinforcing feedback loop: high fossil fuel use feeds high emissions, exacerbating nitrogen runoff and degrading agro-ecosystems. This triggers rising costs for farmers and food insecurity, particularly in rice-producing provinces where ammonia dependence is greatest. Fossil price volatility and lack of emission abatement mechanisms reinforce systemic fragility. The Intermediate Transition pathway introduces partial intervention but lacks systemic cohesion. Although CCUS improves the carbon footprint, uncertainties in policy enforcement and market signals create fragmented adoption, especially across decentralized provinces with diverse agro-climatic zones (Conley et al., 2009). Stakeholders in this scenario report limited confidence in long-term returns, which slows capital mobilization. By contrast, the Sustainable Transformation scenario presents a virtuous cycle. Green ammonia deployment catalyzes renewable expansion, which enhances rural energy independence. This energizes digital fertilizer supply chains and farmer profitability. In tandem, environmental regeneration strengthens the agriculture-climate nexus, building resilience and restoring degraded lands. Notably, the social dimension is central: female and youth workforce engagement in hydrogen logistics and agronomic AI services unlocks equity and employment outcomes.

The timeline analysis embedded within the model showed that the BAU scenario breaches Indonesia's NDC targets by 2030, while the Intermediate Transition scenario narrowly aligns only under optimal CCUS performance conditions. In contrast, the Sustainable Transformation scenario exceeds the 2030 NDC target by 11% and achieves carbon neutrality in the ammonia sub-sector by 2042.

On the economic axis, by 2055, the cumulative GDP gain from the Sustainable Transformation scenario was USD 7.4 billion higher than BAU, mainly due to decreased input volatility, higher agricultural productivity, and export potential for certified green fertilizers. These findings offer important guidance for Indonesia's fertilizer, energy, and agriculture ministries, highlighting the importance of policy convergence. For example:

- National hydrogen strategies must integrate with fertilizer subsidy reforms.
- Environmental permitting for green ammonia plants must be expedited and harmonized with provincial land-use plans.
- Farmer cooperatives should be included in pilot deployments through participatory R&D schemes.

Stakeholders emphasized that beyond technology and capital, institutional clarity and long-term signaling are the cornerstones of enabling systemic transitions. The scenario results indicate that isolated efforts, even if successful in their own verticals, are unlikely to deliver meaningful emissions reduction or climate-resilient agriculture unless coordinated within an integrated planning regime. Scenario modelling affirmed that Indonesia's ammonia sector sits at a strategic inflection point. The BAU trajectory risks exacerbating socio-environmental vulnerabilities, while the Intermediate Transition provides modest benefits but lacks structural resilience. Only the Sustainable Transformation scenario offers a systemically coherent, economically viable, and socially inclusive pathway toward green agricultural industrialization.

Ultimately, these simulations advocate for bold, integrated reforms that bridge sectors, scales, and stakeholders. The insights not only align with Indonesia's national climate commitments but also offer a replicable model for other emerging economies navigating decarbonization of essential industrial inputs within agrarian contexts.

4. CONCLUSIONS

This research has undertaken a comprehensive and multidimensional evaluation of green and blue ammonia transitions within Indonesia's fertilizer industry, providing empirical evidence and strategic insights across technological, environmental, economic, and institutional domains. Amid the urgency to align agricultural practices with Indonesia's national commitment to net-zero emissions by 2060, the findings reinforce that transitioning from grey ammonia to sustainable alternatives is not merely a technological imperative but a systemic transformation requiring synchronized stakeholder alignment, regulatory innovation, and infrastructural investment. Through an integrated methodological approach, comprising stakeholder analysis, Life Cycle Assessment (LCA), Cost-Benefit Analysis (CBA), and dynamic scenario modeling, this study revealed that green ammonia offers the most promising long-term solution. Its production via renewable-powered electrolysis drastically reduces greenhouse gas (GHG) emissions, with the LCA demonstrating a 94% decrease in CO_2-equivalent emissions per ton compared to conventional grey ammonia. Nevertheless, green ammonia's high capital intensity and dependence on stable renewable energy infrastructure highlight the need for targeted public investment and de-risking policy instruments such as carbon pricing, green bonds, and technology subsidies.

Blue ammonia, while more feasible in the short-to-medium term due to compatibility with existing infrastructure, demonstrates only moderate environmental gains. Its effectiveness is heavily contingent upon the efficiency of Carbon Capture, Utilization, and Storage (CCUS) systems (Chahrour et al., 2025), which carry uncertainties related to methane leakage, capture permanence, and financial scalability. The intermediate scenario modeling suggests that while blue ammonia can stabilize emissions by 2035, it falls short of delivering the transformative gains necessary for long-term decarbonization and ecosystem restoration.

The thematic analysis provided rich insights into stakeholder perspectives, unveiling five dominant dimensions shaping the ammonia transition: technological feasibility, economic viability, environmental impact, regulatory support, and market acceptance. Stakeholders identified critical enablers such as modular electrolysis units, hydrogen-specific vocational training, performance-based certification systems, and farmer-centric demonstration programs. Importantly, socio-environmental concerns, such as competition for freshwater resources, nitrogen leaching, and public health implications of ammonia-derived pollutants, require co-developed solutions that integrate agronomic best practices with environmental safeguards.

Scenario modelling affirmed that the Sustainable Transformation pathway, characterized by full-scale deployment of green ammonia, policy convergence across ministries, and inclusive stakeholder governance, is the only viable route to achieving both climate goals and agricultural resilience. This scenario not only aligns with Indonesia's Nationally Determined Contributions (NDCs) and Sustainable Development Goals (SDGs), but also yields the highest projected cumulative GDP gain by 2055, driven by improved farmer profitability, job creation, and export potential for certified green fertilizers. Several critical policy recommendations emerge from this study. First, national hydrogen strategies should be explicitly linked to fertilizer subsidy reform and rural energy policy. Second, permitting and certification processes for green ammonia production must be accelerated and harmonized across agencies. Third, inclusive pilot programs should engage farmer cooperatives, local governments, and women-led agribusinesses to enhance adoption and ensure equitable benefits.

The transition to green and blue ammonia in Indonesia must be viewed not as a linear technological substitution, but as a complex socio-technical transformation. It requires deliberate coordination across institutional levels, strategic investment in human capital and infrastructure, and an adaptive governance framework responsive to evolving ecological, economic, and technological realities. By integrating system-wide insights with context-specific evidence, this research offers a roadmap for Indonesia, and other emerging economies, seeking to decarbonize industrial agriculture while safeguarding food security and ecological sustainability.

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