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Strategic Investment Decision Analysis for Hydrogen Supply Alternatives at PT Energi Nasional X

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Hydrogen Supply Strategy, Strategic Investment Decision, Fuzzy Delphi Method, Analytic Hierarchy Process.

Abstract

This study aimed to identify feasible hydrogen supply alternatives and determine the most suitable strategic option for PT Energi Nasional X. To achieve this objective, the research employed an integrated analytical framework consisting of SWOT–TOWS analysis, the Fuzzy Delphi Method (FDM), and the Analytic Hierarchy Process (AHP). SWOT–TOWS analysis was used to identify internal strengths and weaknesses as well as external opportunities and threats, which were then translated into feasible strategic alternatives. The FDM was applied to validate the relevance of evaluation criteria and obtain expert consensus from subject matter experts (SMEs). Finally, AHP was used as the primary multi-criteria decision-making method to determine criteria weights, evaluate alternatives through pairwise comparisons, and generate a final ranking of alternatives in a structured and consistent manner. The FDM analysis validated eight main evaluation criteria, namely capital expenditure (CAPEX), operating expenditure (OPEX), net present value (NPV), equipment reliability, supply continuity, H_2 quality/purity assurance, implementation risk, and operability and maintainability. The AHP results indicated that equipment reliability, net present value (NPV), and supply continuity were the most influential criteria in determining the preferred hydrogen supply strategy. The final AHP ranking showed that the New Plant alternative achieved the highest global priority score compared with the Revitalization and External Procurement alternatives. Although the New Plant option required the highest initial investment cost, it provided superior long-term operational reliability, stronger supply continuity, better process control, and improved operational independence from external suppliers. A sensitivity analysis was also conducted to evaluate the robustness of the decision model under various weighting scenarios. The results showed that the ranking of alternatives remained stable despite changes in criteria weights, indicating that the decision model is robust and reliable for supporting strategic investment decisions. Based on the overall analysis, this study concluded that the development of a new hydrogen plant is the most appropriate and sustainable hydrogen supply strategy for PT Energi Nasional X. The selected alternative offers the best balance between financial value, operational reliability, risk management, and long-term business sustainability, while supporting continuous polypropylene production and strengthening the competitiveness of PT ONE ENERGY.

INTRODUCTION

Operational efficiency and reliability have become strategic imperatives in the modern oil and gas refining and petrochemical industry. Increasing competition, fluctuating crude oil and gas prices, tightening environmental regulations, and growing pressure to ensure uninterrupted supply require refinery operators to maintain high asset availability and minimize unplanned shutdowns. For integrated refinery and petrochemical facilities, utility reliability is particularly critical because disruptions in supporting utilities may directly affect process continuity, production stability, and financial performance (Al-Douri, 2021; Ekechi, 2024; Khalili et al., 2026; Shil, 2023). In this context, securing the availability of critical utilities is not only an operational concern but also a strategic business requirement (George et al., 2024).

Hydrogen is one of the most important utilities in refinery and petrochemical operations. At PT Energi Nasional X, hydrogen plays a vital role in supporting the Polypropylene Unit (PPU), which produces homopolymer polypropylene pellets under the PolyX brand. The PPU is strategically important because polypropylene is a high-margin petrochemical product with strong demand from packaging, automotive, and consumer goods industries (Ahunbaev et al., 2024; Weber & Wasner, 2023). Compared with conventional fuel products, polypropylene provides a more attractive margin contribution and has shown relatively strong price resilience even during periods of crude oil price volatility. Therefore, any disruption in hydrogen supply may directly reduce the ability of PT Energi Nasional X to capture value from one of its most profitable product lines (Kaheel, 2024; Permana et al., 2025; Sambodo et al., 2026).

PT Energi Nasional is a downstream subholding of PT ONE ENERGY (Persero), responsible for managing refinery and petrochemical operations in Indonesia. PT Energi Nasional X is one of its strategic refinery assets, with a refining capacity of approximately 118,000 barrels per day. The refinery produces petroleum products such as gasoline, diesel, and LPG, as well as petrochemical products such as polypropylene. The integration of refinery and petrochemical operations strengthens the company’s role in supporting national energy security, reducing import dependency, and improving domestic industrial competitiveness (Al-Sadoun et al., 2026; Habrylevych, 2025; Zhdaneev & Ovsyannikov, 2025). Within this operational structure, the reliability of supporting facilities, including the hydrogen plant, is essential to ensure sustainable production (Dagdougui et al., 2018; Rodríguez Castillo et al., 2024).

The Polypropylene Unit at PT Energi Nasional X has an installed capacity of 45,200 tons per year and is supported by several auxiliary plants, including the nitrogen plant, hydrogen plant, and bagging plant. Hydrogen is required in the polymerization process to support stable operating conditions and product quality. However, since 2017, the existing hydrogen plant has been inoperable due to significant damage to its modules and several critical components, including valves, sensors, catalysts, and pumps. As a result, the PPU has become fully dependent on externally supplied hydrogen to maintain operations.

This dependence on external hydrogen supply creates several strategic challenges. First, external procurement exposes the refinery to price volatility, logistics delays, contract uncertainty, and potential supply disruptions. Second, high dependency on external suppliers reduces the company’s flexibility in managing operational risks and responding to unexpected market or supply chain disturbances. Third, although purchasing hydrogen from third-party suppliers may appear more economical in the short term, the long-term implications related to supply continuity, quality assurance, operational reliability, and cost escalation must be carefully evaluated. Previous studies on supply chain dependency also suggest that higher reliance on external suppliers may reduce organizational flexibility in responding to disruptions (Koberg & Longoni, 2019).

Based on internal data, PT Energi Nasional X requires approximately 3–10 Nm^3/hr of hydrogen for PPU operations, with an estimated annual demand of around 50,000 Nm^3. The current external hydrogen procurement cost is approximately IDR 1.4 billion per year. Meanwhile, preliminary assessments for a new hydrogen plant indicate that construction of a new unit may require an investment of approximately IDR 15 billion. This creates a strategic decision dilemma. Continuing external hydrogen procurement may require lower immediate capital expenditure, but it may increase long-term supply risk and dependency. Conversely, constructing or restoring internal hydrogen production capacity may strengthen supply reliability and operational control but requires significant capital investment and implementation planning.

The decision regarding hydrogen supply is therefore complex because it involves multiple considerations, including financial feasibility, operational reliability, supply continuity, implementation risk, technical readiness, and strategic alignment with refinery objectives. The decision cannot be based solely on the lowest short-term cost because hydrogen availability directly affects the production continuity of a high-margin petrochemical unit (Hoang, 2025; Kandil, 2024). A failure to secure reliable hydrogen supply could reduce polypropylene production, weaken business performance, and increase the risk of operational disruption. Therefore, a structured decision-making framework is needed to evaluate the available hydrogen supply alternatives comprehensively (Ghanbari et al., 2025; Hai et al., 2026; Ransikarbum et al., 2023).

This issue also involves several key stakeholders with different roles and priorities. Top management and the General Manager of PT Energi Nasional X are responsible for strategic investment approval, capital allocation, and alignment with long-term refinery objectives. Engineering teams provide technical evaluation regarding the condition of the existing hydrogen plant and potential restoration or new construction requirements. The Investment Board focuses on economic performance, including capital expenditure, operating expenditure, and lifecycle cost. The Reliability Manager, as the problem owner, emphasizes operational risk, asset reliability, safety, and prevention of unplanned shutdowns. Procurement teams are responsible for supplier selection, contracting, and compliance, while planning teams support execution planning, scheduling, cost estimation, and implementation feasibility. The involvement of these stakeholders indicates that hydrogen supply decision-making is not merely a technical issue but a multidimensional strategic problem.

Despite the importance of hydrogen supply reliability, the decision between continuing external procurement, restoring the existing hydrogen plant, or constructing a new internal hydrogen production facility requires a more systematic evaluation. Conventional decision-making that focuses only on cost comparison may overlook important factors such as reliability improvement, supply risk reduction, execution complexity, and operational impact. Therefore, this study applies a multi-criteria decision-making approach to determine the most appropriate hydrogen supply alternative for the Polypropylene Unit at PT Energi Nasional X.

This study aims to identify available hydrogen supply alternatives, evaluate the best option by considering financial aspects, reliability, and operational risk, and formulate an implementation timeline for the selected alternative. By integrating technical, economic, operational, and stakeholder perspectives, this research is expected to provide a practical decision-support framework for PT Energi Nasional X. The findings are intended to support more transparent, accountable, and strategic decision-making in securing hydrogen supply for high-value petrochemical production, while also contributing to broader asset reliability and supply chain resilience practices in refinery operations.

METHOD

This study employed a mixed-method research design integrating quantitative, qualitative, and semi-quantitative approaches to determine the most appropriate hydrogen supply alternative for the Polypropylene Unit at PT Energi Nasional X. The design was selected because the decision problem involved multiple dimensions, including financial feasibility, operational reliability, supply continuity, technical readiness, implementation risk, and long-term business sustainability. Therefore, the evaluation required a structured multi-criteria decision-making framework rather than reliance on financial indicators alone.

The research was conducted in three main stages. The first stage focused on identifying feasible hydrogen supply alternatives using qualitative methods, including semi-structured interviews, focus group discussions, and SWOT–TOWS analysis. Subject matter experts (SMEs) from process engineering, mechanical engineering, reliability, procurement, planning, finance, and external vendors were involved to identify internal strengths and weaknesses as well as external opportunities and threats related to hydrogen supply. The SWOT factors were then translated into strategic alternatives using the TOWS matrix, resulting in options such as constructing a new hydrogen plant, revamping the existing facility, or continuing external hydrogen procurement.

The second stage focused on validating decision criteria and evaluating the alternatives. Primary data were collected through semi-structured interviews, Fuzzy Delphi questionnaires, and Analytic Hierarchy Process (AHP) pairwise comparison questionnaires. The interviews were used to explore expert perspectives on hydrogen supply reliability, cost implications, technical constraints, risk exposure, and implementation feasibility. The Fuzzy Delphi Method was applied to validate evaluation criteria based on expert judgment. Criteria that reached consensus were retained for further analysis, while those that did not meet the threshold were excluded from the decision model.

The validated criteria and shortlisted alternatives were then analyzed using the AHP method. AHP was applied to systematically compare alternatives based on multiple criteria structured in a three-level hierarchy: the main objective of selecting the optimal hydrogen supply alternative, evaluation criteria (financial, reliability, operability, maintainability, and risk), and the available alternatives. Pairwise comparisons were conducted using Saaty's 1–9 scale, and individual judgments were aggregated using the geometric mean. Consistency was assessed using the Consistency Ratio (CR), with values of 0.10 or lower considered acceptable.

The third stage focused on implementation planning for the selected alternative. The highest-ranked option from the AHP results was translated into an implementation plan covering timeline, responsible stakeholders, and risk mitigation measures. This ensured that the selected alternative was not only analytically optimal but also operationally feasible within the context of PT Energi Nasional X.

Primary data were obtained from SMEs and stakeholders involved in hydrogen supply decision-making, including representatives from operations, engineering and maintenance, reliability, planning, finance, procurement, and selected EPC contractors or hydrogen vendors. These respondents were selected purposively based on their direct experience with hydrogen plant operations, polypropylene unit performance, investment evaluation, procurement processes, and refinery reliability management.

Secondary data were collected from internal and external sources to support the analysis. Internal data included project cost estimates, owner estimates, purchase orders, vendor quotations, technical reports, operational logbooks, downtime records, maintenance data, and feasibility studies related to hydrogen supply and plant revitalization. External data included academic literature, industry benchmark reports, hydrogen market information, vendor documentation, and risk management standards. Risk analysis was supported by the risk matrix and guidelines applied at PT Energi Nasional X, referring to ISO 31000 on risk management.

Data analysis integrated SWOT–TOWS, Fuzzy Delphi Method, AHP, and financial-risk assessment. SWOT–TOWS was used to formulate hydrogen supply alternatives, while Fuzzy Delphi was used to validate decision criteria based on expert consensus. AHP was applied to prioritize alternatives by integrating financial indicators (CAPEX, OPEX, Net Present Value), reliability indicators (availability, downtime, MTBF, MTTR), and risk indicators (supply continuity, operational safety, and implementation uncertainty).

The final output of the study was a ranked list of hydrogen supply alternatives based on global priority scores. The highest-ranked alternative was selected as the recommended solution due to its balanced performance across financial feasibility, operational reliability, maintainability, supply security, and risk control. The results also formed the basis for developing an implementation plan to support strategic investment decision-making for hydrogen supply at PT Energi Nasional X.

RESULTS AND DISCUSSION

Strategic Alternative Identification Using SWOT-TOWS Analysis

This section presents the SWOT analysis conducted to identify the internal and external factors relevant to the hydrogen supply decision at PT ENERGI NASIONAL X. The identified factors are subsequently integrated using the TOWS matrix to generate feasible strategic alternatives.

SWOT Factor Identification

Based on interviews with Subject Matter Experts (SMEs) and a review of internal documents, the following SWOT factors were identified:

Table 1. SWOT Analysis of Hydrogen Supply at PT ENERGI NASIONAL X

Code	Strengths (S)	Code	Weaknesses (W)
S1	Available land and infrastructure for hydrogen plant construction within PT ENERGI NASIONAL complex	W1	Hydrogen plant has been non-operational since 2017 (7+ years) due to equipment failure and lack of maintenance
S2	Experienced engineering and maintenance team with 10+ years operating hydrogen plant (until 2017 shutdown)	W2	Current full dependency on external supplier creates vulnerability to supply chain disruptions
S3	Established utility infrastructure (electricity, water, cooling) suitable for electrolyzer operation	W3	Limited in-house expertise on modern electrolyzer technology (alkaline vs PEM selection)
S4	Financial capacity as subsidiary of PT ONE ENERGY with access to corporate funding for strategic investments	W4	High CAPEX requirement for new plant (IDR 15 billion) competing with other investment priorities
S5	Existing hydrogen storage and distribution system to PPU (piping, safety systems)	W5	Uncertainty on future hydrogen demand if PPU production volume decreases
S6	Strong safety culture and HSE management system compliant with ISO 14001 and OHSAS 18001	W6	No dedicated budget allocated for hydrogen plant investment in current 5-year plan
Code	**Opportunities (O)**	**Code**	**Threats (T)**
O1	Declining cost of electrolyzer technology (alkaline and PEM) due to global green hydrogen momentum	T1	Volatility of hydrogen prices from external suppliers (historical range: IDR 1.2-1.6 billion/year)
O2	Government incentives for industrial energy efficiency and emission reduction under NDC commitments	T2	Risk of supply interruption due to supplier operational issues or logistics constraints
O3	Availability of proven electrolyzer vendors with local representatives in Indonesia	T3	Rising electricity tariffs for industrial users affecting electrolyzer OPEX economics
O4	Growing industrial hydrogen demand in Indonesia creating economies of scale for suppliers	T4	Stringent and evolving safety regulations for hydrogen production and storage facilities
O5	Potential for selling excess hydrogen capacity to nearby industrial users in X area	T5	Competition for investment budget with other critical refinery projects (catalytic reformer, utilities)
O6	Technology advancements improving electrolyzer efficiency and reducing OPEX (electricity consumption)	T6	Limited availability of skilled personnel in Indonesia for electrolyzer operation and maintenance

TOWS Matrix and Strategic Alternative Generation

The TOWS matrix systematically matches internal and external factors to generate actionable strategic alternatives. Table 2 presents the TOWS matrix results.

Table 2. TOWS Matrix for Hydrogen Supply Alternatives

TOWS	Strengths (S)	Weaknesses (W)
Opportunities (O)	**SO STRATEGIES** (Leverage strengths to capitalize on opportunities) **SO1: Build New Hydrogen Plant** - Utilize available land (S1), infrastructure (S3, S5), experienced team (S2), and financial capacity (S4) to capitalize on declining electrolyzer costs (O1) and government incentives (O2). New plant provides long-term supply security and potential revenue from excess capacity (O5). **SO2: Establish Strategic Partnership** - Leverage existing infrastructure (S3, S5) and strong HSE culture (S6) to attract technology partners (O3) for joint investment in advanced electrolyzer technology (O6), reducing CAPEX burden while accessing cutting-edge technology.	**WO STRATEGIES** (Overcome weaknesses by exploiting opportunities) **WO1: Revitalize Existing Plant with Modern Technology -** Address non-operational status (W1) and technology gap (W3) by leveraging available vendors (O3) and declining costs (O1) to upgrade existing plant with modern electrolyzer technology. Lower CAPEX than new plant addresses budget constraints (W4, W6). **WO2: Phased Development Approach** - Overcome budget limitation (W4, W6) by starting with smaller capacity leveraging technology advancement (O6) and government incentives (O2), then expanding based on validated demand (W5) and growing market (O4).
Threats (T)	**ST STRATEGIES** (Use strengths to avoid or mitigate threats) **ST1: In-house Production for Supply Security** - Leverage existing infrastructure (S1, S3, S5), team capability (S2), and financial resources (S4) to eliminate dependency on external supplier (W2), mitigating price volatility (T1) and supply interruption risks (T2). Strong HSE system (S6) addresses regulatory compliance (T4). **ST2: Develop Internal Expertise -** Utilize experienced team (S2) and strong safety culture (S6) to build in-house electrolyzer expertise through vendor training programs, reducing vulnerability to skilled personnel shortage (T6) while ensuring safe operation (T4).	**WT STRATEGIES** (Minimize weaknesses and avoid threats) **WT1: Continue External Procurement with Improved Terms -** Given current dependency (W2), budget constraints (W4, W6), and investment competition (T5), negotiate long-term supply contract with price cap to mitigate volatility (T1) and dual-supplier arrangement to reduce interruption risk (T2). Minimal investment avoids electricity tariff exposure (T3). **WT2: Outsourced Operation Model -** Address technology gap (W3), expertise shortage (T6), and budget limitation (W4) by engaging third-party operator for hydrogen plant management. PT ENERGI NASIONAL provides infrastructure (reducing W1) while avoiding regulatory compliance burden (T4) and investment competition (T5).

Summary of Identified Alternatives

Based on the TOWS matrix analysis and subsequent Focus Group Discussion (FGD) with Subject Matter Experts, the following hydrogen supply alternatives are identified as shown at Table 3 for further evaluation. Three primary strategic alternatives identified are : Build New Hydrogen Plant; Revitalize Existing Plant; and Continue External Procurement.

Table 3. Identified Hydrogen Supply Alternatives

Alternative	TOWS Quadrant	Strategic Rationale
A1: Build New Hydrogen Plant (32 Nm³/hr, IDR 15 billion CAPEX)	SO Strategy (SO1)	Maximize long-term value by leveraging internal strengths and external opportunities. Provides complete operational independence and potential for additional revenue streams.
A2: Revitalize Existing Plant (28-30 Nm³/hr, IDR 6 billion CAPEX)	WO Strategy (WO1)	Overcome current weaknesses while capitalizing on technology improvements. Balances investment constraint with supply security objective.
A3: Continue External Procurement (IDR 1.4 billion/year OPEX)	WT Strategy (WT1)	Defensive approach minimizing investment and operational risk. Suitable if budget constraints and other priorities dominate decision.

These three alternatives were carried forward for quantitative evaluation using FDM and AHP.

Validation of Decision Criteria Using Fuzzy Delphi Method (FDM)

This section presents the application of the Fuzzy Delphi Method to validate the relevance of evaluation criteria through expert consensus. The FDM process ensures that only criteria with sufficient agreement among experts are retained for the AHP evaluation.

Expert Panel Profile

The decision-making process in this study involved the participation of nine Subject Matter Experts (SMEs) representing multiple functions related to hydrogen supply, refinery operation, reliability, engineering, maintenance, planning, and business evaluation at PT ENERGI NASIONAL X. The SMEs consisted of managers, section heads, senior engineers, and technical specialists with professional experience ranging from 11 to 18 years in refinery and petrochemical operations.

The same group of SMEs participated in both the Fuzzy Delphi Method (FDM) and Analytic Hierarchy Process (AHP) stages to ensure consistency and continuity throughout the research process. During the FDM stage, the SMEs evaluated and validated the relevance of the proposed decision criteria using linguistic assessments. The validated criteria were subsequently used as the basis for the AHP evaluation model. Table 4 summarizes the expert profiles.

Table 4. Expert Panel Profile for FDM Survey

No.	Position/Role	Department	Experience	Expertise Area
1	Manager Reliability	Reliability	17 years	Stationary & Rotating Equipment Maintenance
2	Manager Maintenance Planning & Support	MPS	18 years	Electrical & Instrument Equipment Maintenance
3	Section Head Equipment Reliability	Reliability	15 years	Equipment Reliability
4	Section Head Plant Reliability	Reliability	13 years	Engineering & Planning
5	Section Head Planning & Scheduling	MPS	16 years	Planning & Scheduling, Budgeting
6	Section Head Performance Business & Evaluation	RBO	14 years	Process Engineer, Polypropylene Plant
7	Sr Group Leader Process Engineer	Engineering & Development	13 years	Process Engineering, H2 Plant
8	Sr Group Leader Rotating Equipment	MPS	11 years	Rotating Equipment Maintenance
9	Sr Engineer Overhaul	Reliability Corporate	13 years	Stationary & Rotating Equipment Reliability & Maintenance

Proposed Evaluation Criteria

Based on the literature review and preliminary expert interviews, the following evaluation criteria were proposed for validation through FDM. These criteria span three dimensions: Financial, Reliability, and Risk as shown at Table 5. During the FDM stage, the SMEs evaluated and validated the relevance of the proposed decision criteria using linguistic assessments. The validated criteria were subsequently used as the basis for the AHP evaluation model.

Table 5. Proposed Evaluation Criteria for FDM Validation

Code	Criteria	Dimension	Unit/Proxy	Description
C1	Capital Expenditure (CAPEX)	Financial	IDR	Total initial investment required for plant construction, equipment procurement, and installation.
C2	Operating Expenditure (OPEX)	Financial	IDR/year	Annual operating & maintenance cost
C3	Net Present Value (NPV)	Financial	IDR	Present value of future cash flows minus the initial investment over the project lifetime (20 years).
C4	Equipment Reliability	Reliability	Qualitative	Expected operational reliability of the hydrogen supply system

Code	Criteria	Dimension	Unit/Proxy	Description
				measured by MTBF, availability, and unplanned downtime risk.
C5	Operability & Maintainability	Reliability	Qualitative	The ease of operating the system by existing operators, including monitoring, control, startup, shutdown, and troubleshooting activities.
C6	Supply Continuity	Risk	Qualitative	Risk of hydrogen supply interruption due to supplier issues, logistics, or equipment failure.
C7	H_2 Quality/Purity Assurance	Risk	Qualitative	Consistency and reliability of hydrogen purity meeting PPU process requirements (minimum 99.95%).
C8	Implementation Risk	Risk	Qualitative	Risk of project delays, cost overruns, or technical failures during construction or revitalization.

FDM Linguistic Scale and Triangular Fuzzy Numbers

Experts assessed each criterion using a 5-point linguistic scale. Each linguistic variable is converted into a Triangular Fuzzy Number (TFN) as shown in Table 6.

Table 6. Linguistic Variables and Corresponding Triangular Fuzzy Numbers

Linguistic Variable	l (lower)	m (middle)	u (upper)
Very Unimportant	0.0	0.0	0.2
Unimportant	0.0	0.2	0.4
Moderately Important	0.2	0.4	0.6
Important	0.4	0.6	0.8
Very Important	0.6	0.8	1.0

FDM Aggregation and Defuzzification Results

The expert responses were aggregated using the fuzzy averaging method. For each criterion, the aggregated TFN (l, m, u) was computed, followed by defuzzification using the centroid method: Defuzzified Value = (l + m + u) / 3. Criteria with a defuzzified value equal to or above the consensus threshold of 0.60 are retained.

Table 7. FDM Aggregation and Defuzzification Results

Code	Criterion	l (avg)	m (avg)	u (avg)	Defuzzified	Status
C1	Capital Expenditure (CAPEX)	0.533	0.733	0.933	0.733	Accepted
C2	Operating Expenditure (OPEX)	0.533	0.733	0.933	0.733	Accepted
C3	Net Present Value (NPV)	0.578	0.778	0.978	0.778	Accepted
C4	Equipment Reliability	0.511	0.711	0.911	0.711	Accepted
C5	Operability & Maintainability	0.533	0.733	0.933	0.733	Accepted
C6	Supply Continuity	0.511	0.711	0.911	0.711	Accepted
C7	H_2 Quality/Purity Assurance	0.556	0.756	0.956	0.756	Accepted
C8	Implementation Risk	0.533	0.733	0.933	0.733	Accepted

Based on the above FDM results, all the criteria (C1-C8) met the consensus threshold of 0.60 and are retained for the AHP evaluation.

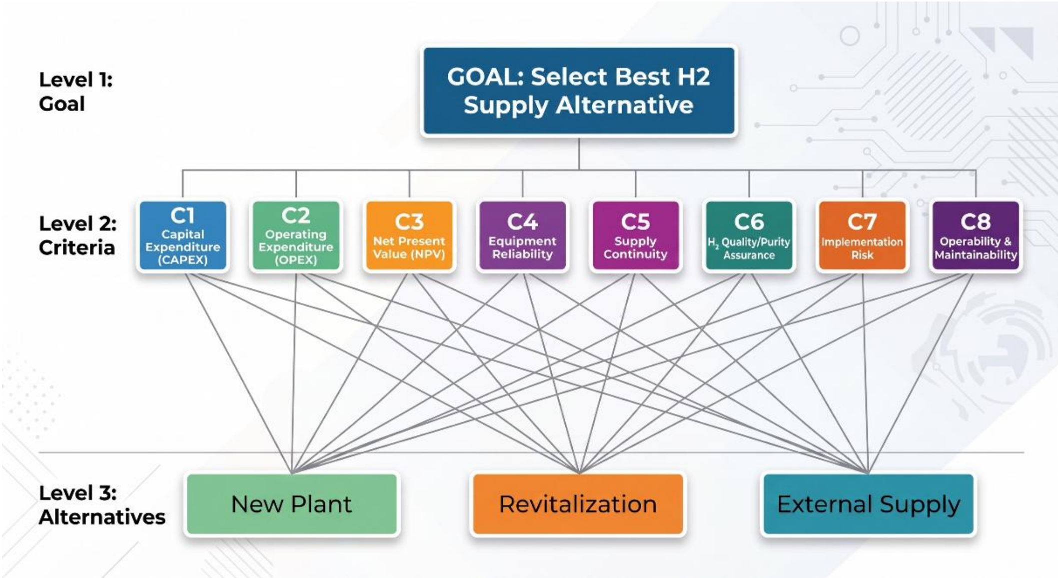
Multi-Criteria Prioritization Using Analytic Hierarchy Process (AHP)

This section presents the application of AHP to prioritize the three hydrogen supply alternatives based on the validated criteria from the FDM stage. In the AHP stage, the SMEs completed pairwise comparison questionnaires to assess the relative importance among evaluation criteria and the relative performance of each hydrogen supply alternative under each criterion.

The individual judgments from all SMEs were then aggregated using the geometric mean method to produce a group decision matrix. This approach was selected to minimize individual bias and generate a collective expert judgment that better represents the operational and strategic perspective of PT ENERGI NASIONAL X. The AHP model structures the decision into a hierarchy of Goal, Criteria, and Alternatives.

AHP Hierarchical Structure

Figure 1. illustrates the AHP hierarchical structure for the hydrogen supply decision



Picture 1. AHP Hierarchy Diagram

Pairwise Comparison of Criteria

Expert judgments were collected using Saaty's 1-9 scale for pairwise comparison of criteria. Individual judgments were aggregated using the geometric mean method. Table 8 presents the aggregated pairwise comparison matrix for criteria.

Table 8. Aggregated Pairwise Comparison Matrix for Criteria

	C1	C2	C3	C4	C5	C6	C7	C8
C1	1.000	1.000	0.702	0.643	2.273	0.701	0.933	1.773
C2	1.000	1.000	0.395	0.516	1.714	0.699	0.956	1.229
C3	1.423	2.535	1.000	0.481	3.429	1.227	2.047	2.633
C4	1.556	1.937	2.077	1.000	2.992	1.379	2.385	1.723
C5	0.440	0.583	0.292	0.334	1.000	1.139	2.006	3.045
C6	1.427	1.430	0.815	0.725	0.878	1.000	1.489	1.466
C7	1.072	1.046	0.489	0.419	0.499	0.672	1.000	2.849
C8	0.564	0.814	0.380	0.580	0.328	0.682	0.351	1.000

λ max = 8.528, CI = 0.075, CR = 0.054

The AHP results show that the consistency ratio (CR) is 0.054, which is below the acceptable threshold of 0.10, indicating that the judgments of the experts are consistent.

Criteria Priority Weights

The priority weights (eigenvector) derived from the pairwise comparison matrix are presented in Table 9.

Table 9. Criteria Priority Weights

Code	Criterion	Weight	Rank
C1	CAPEX	0.116	4
C2	OPEX	0.097	7
C3	NPV	0.182	2
C4	Equipment Reliability	0.207	1
C5	Operability & Maintainability	0.104	5
C6	Supply Continuity	0.128	3
C7	H_2 Quality/Purity	0.099	6
C8	Implementation Risk	0.068	8
	Total	1.000	

The priority weights reveal that Equipment Reliability is the most critical criterion (0.207), followed by NPV (0.182) and supply continuity (0.128). This indicates that decision-making is primarily driven by long-term value and operational reliability rather than cost considerations.

Pairwise Comparison of Alternatives Under Each Criterion

For each validated criterion, pairwise comparisons of the three hydrogen supply alternatives were conducted. The aggregated comparison matrices and local priority scores are presented below.

Pairwise Comparison Under Criterion C1 (CAPEX)

Table 10. Pairwise Comparison of Alternatives Under C1

C1	New Plant	Revitalization	External Supply
New Plant	1.000	0.280	0.124
Revitalization	3.578	1.000	0.224
External Supply	8.077	4.455	1.000

Local Priority - New Plant: 0.072, Revitalization: 0.204, External Supply: 0.725| CR = 0.044 (consistent)

Pairwise Comparison Under Criterion C2 (OPEX)

Table 11. Pairwise Comparison of Alternatives Under C2

C1	New Plant	Revitalization	External Supply
New Plant	1.000	2.794	0.135
Revitalization	0.358	1.000	0.111
External Supply	7.428	9.000	1.000

Local Priority - New Plant: 0.141, Revitalization: 0.067, External Supply: 0.792 | CR = 0.067 (consistent)

Pairwise Comparison Under Criterion C3 (NPV)

Table 12. Pairwise Comparison of Alternatives Under C3

C1	New Plant	Revitalization	External Supply
New Plant	1.000	0.152	0.114
Revitalization	6.587	1.000	0.317
External Supply	8.767	3.156	1.000

Local Priority - New Plant: 0.057, Revitalization: 0.280, External Supply: 0.663 | CR = 0.072 (consistent)

Pairwise Comparison Under Criterion C4 (Equipment Reliability)

Table 13. Pairwise Comparison of Alternatives Under C4

C1	New Plant	Revitalization	External Supply
New Plant	1.000	6.501	8.541
Revitalization	0.154	1.000	3.115
External Supply	0.117	0.321	1.000

Local Priority - New Plant: 0.783, Revitalization: 0.159, External Supply: 0.068 | CR = 0.072 (consistent)

Pairwise Comparison Under Criterion C5 (Supply Continuity)

Table 14. Pairwise Comparison of Alternatives Under C5

C1	New Plant	Revitalization	External Supply
New Plant	1.000	4.737	8.883
Revitalization	0.211	1.000	4.042
External Supply	0.113	0.247	1.000

Pairwise Comparison Under Criterion C6 (H_2 Quality/Purity)

Table 15. Pairwise Comparison of Alternatives Under C6

C1	New Plant	Revitalization	External Supply
New Plant	1.000	2.884	6.245
Revitalization	0.347	1.000	4.366
External Supply	0.160	0.229	1.000

Local Priority - New Plant: 0.639, Revitalization: 0.280, External Supply: 0.081 | CR = 0.047 (consistent)

Pairwise Comparison Under Criterion C7 (Implementation Risk)

Table 16. Pairwise Comparison of Alternatives Under C7

C1	New Plant	Revitalization	External Supply
New Plant	1.000	0.294	0.164
Revitalization	3.399	1.000	0.237
External Supply	6.112	4.228	1.000

Local Priority - New Plant: 0.086, Revitalization: 0.219, External Supply: 0.696 | CR = 0.070 (consistent)

Pairwise Comparison Under Criterion C8 (Operability & Maintainability)

Table 17. Pairwise Comparison of Alternatives Under C8

C1	New Plant	Revitalization	External Supply
New Plant	1.000	7.539	8.653
Revitalization	0.133	1.000	2.922
External Supply	0.116	0.342	1.000

Local Priority - New Plant: 0.790, Revitalization: 0.143, External Supply: 0.067 | CR = 0.084 (consistent)

Global Priority Scores and Final Ranking

The global priority score for each alternative is calculated by multiplying the local priority under each criterion by the corresponding criteria weight, then summing across all criteria. Table 18 presents the synthesis of results.

Table 18 Global Priority Scores and Final Ranking

Alter.	C1	C2	C3	C4	C5	C6	C7	C8	Global Score
New Plant	0.008	0.014	0.010	0.160	0.082	0.094	0.063	0.006	**0.437**
Revitalization	0.024	0.006	0.051	0.033	0.015	0.026	0.028	0.015	0.197
External Supply	0.084	0.077	0.121	0.014	0.007	0.008	0.008	0.047	0.366

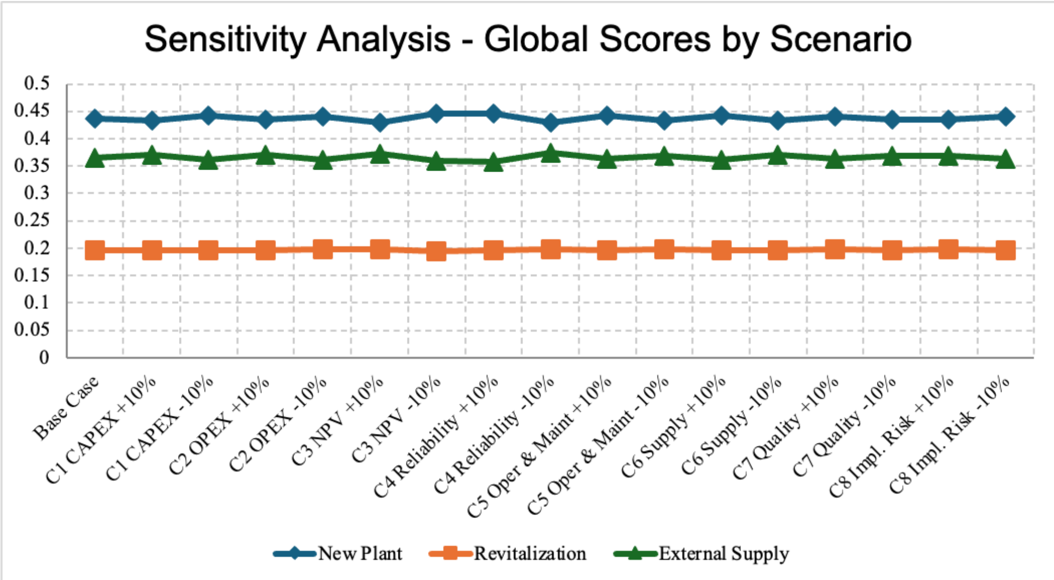
Based on the AHP results, the New Plant alternative obtained the highest global priority score of 0.437, followed by External Supply with a score of 0.366, and Revitalization with a score of 0.197. Therefore, the New Plant alternative is recommended as the best option for hydrogen supply at the Polypropylene Unit of PT ENERGI NASIONAL X.

Sensitivity Analysis

A sensitivity analysis was conducted to evaluate the robustness of the AHP ranking under different weight scenarios. The analysis tests how the final ranking changes when the weight of each criterion is varied. In this case, the author examined the impact of increasing and decreasing the weight of each criterion by ±10% while maintaining the proportional adjustment of the remaining criteria. Table 19 and Figure 2 shows sensitivity analysis result.

Table 19. Sensitivity Analysis Results

Scenario	Changed Criterion	Delta	C1	C2	C3	C4	C5	C6	C7	C8	Total Weight	New Plant	Revitalization	External Supply	Best Alternative	Rank Stability
Base Case	Base	0	0.116	0.097	0.182	0.207	0.104	0.128	0.099	0.068	1.000	0.437	0.197	0.366	New Plant	Stable
C1 CAPEX +10%	C1	0.1	0.128	0.096	0.179	0.204	0.102	0.126	0.098	0.067	1.000	0.432	0.197	0.371	New Plant	Stable
C1 CAPEX -10%	C1	-0.1	0.104	0.098	0.184	0.210	0.105	0.129	0.101	0.069	1.000	0.442	0.197	0.361	New Plant	Stable
C2 OPEX +10%	C2	0.1	0.115	0.107	0.180	0.205	0.102	0.126	0.098	0.067	1.000	0.434	0.196	0.370	New Plant	Stable
C2 OPEX -10%	C2	-0.1	0.117	0.087	0.184	0.209	0.105	0.129	0.100	0.068	1.000	0.440	0.198	0.361	New Plant	Stable
C3 NPV +10%	C3	0.1	0.114	0.095	0.200	0.202	0.101	0.125	0.097	0.066	1.000	0.429	0.199	0.372	New Plant	Stable
C3 NPV -10%	C3	-0.1	0.119	0.099	0.164	0.212	0.106	0.130	0.102	0.069	1.000	0.446	0.195	0.359	New Plant	Stable
C4 Reliability +10%	C4	0.1	0.113	0.095	0.177	0.228	0.101	0.124	0.097	0.066	1.000	0.446	0.196	0.358	New Plant	Stable
C4 Reliability -10%	C4	-0.1	0.119	0.100	0.186	0.186	0.106	0.131	0.102	0.069	1.000	0.429	0.198	0.374	New Plant	Stable
C5 Oper & Maint +10%	C5	0.1	0.115	0.096	0.180	0.205	0.114	0.126	0.098	0.067	1.000	0.441	0.196	0.362	New Plant	Stable
C5 Oper & Maint -10%	C5	-0.1	0.117	0.098	0.184	0.209	0.093	0.129	0.100	0.068	1.000	0.433	0.198	0.369	New Plant	Stable
C6 Supply +10%	C6	0.1	0.114	0.096	0.179	0.204	0.102	0.140	0.098	0.067	1.000	0.442	0.197	0.361	New Plant	Stable
C6 Supply -10%	C6	-0.1	0.118	0.098	0.184	0.210	0.105	0.115	0.101	0.069	1.000	0.433	0.197	0.370	New Plant	Stable
C7 Quality +10%	C7	0.1	0.115	0.096	0.180	0.205	0.102	0.126	0.109	0.067	1.000	0.440	0.198	0.363	New Plant	Stable
C7 Quality -10%	C7	-0.1	0.117	0.098	0.184	0.209	0.105	0.129	0.089	0.068	1.000	0.435	0.196	0.369	New Plant	Stable
C8 Impl. Risk +10%	C8	0.1	0.115	0.096	0.180	0.206	0.103	0.127	0.099	0.074	1.000	0.435	0.197	0.368	New Plant	Stable
C8 Impl. Risk -10%	C8	-0.1	0.117	0.098	0.183	0.209	0.104	0.128	0.100	0.061	1.000	0.440	0.197	0.363	New Plant	Stable



Picture 2. Sensitivity Analysis Chart

The above results show that the New Plant alternative consistently remains the best option in all scenarios tested. Although there are slight changes in the global priority scores, the overall ranking does not change. This indicates that the decision model is stable and not sensitive to moderate changes in criteria weighting.

The analysis also shows that criteria related to reliability and supply continuity slightly strengthen the position of the New Plant alternative, while financial and risk-related criteria only cause minor changes in the final scores.

Overall, the sensitivity analysis confirms that the selection of the New Plant alternative is robust and reliable as the preferred hydrogen supply strategy for PT ENERGI NASIONAL X.

Business Solution

To achieve strategic decision concerning the optimal hydrogen supply alternative for the refinery, after conducting analysis using the SWOT-TOWS framework, this research identified three feasible hydrogen supply alternatives, namely New Plant, Revitalization, and External Supply.

Furthermore, through the subsequent analyses using the integration of SWOT-TOWS, Fuzzy Delphi Method (FDM), and Analytic Hierarchy Process (AHP), the development of a

New Hydrogen Plant was determined to be the most appropriate business solution for supporting the Polypropylene Unit operation. The selected alternative achieved the highest overall evaluation based on financial, operational reliability, and risk-related considerations.

The analysis results indicate that the New Plant alternative achieved the highest global priority score compared to the Revitalization and External Supply alternatives. Although the New Plant option requires the largest capital investment, it provides superior long-term benefits in terms of Net Present Value (NPV), operational reliability, and supply continuity. The solution also reduces dependency on external hydrogen suppliers, which is considered critical for maintaining stable polypropylene production.

From a strategic perspective, the proposed solution aligns with the company's objective of improving operational resilience and ensuring long-term sustainability of high-margin petrochemical products. The establishment of a dedicated hydrogen plant is expected to improve process stability, reduce supply interruption risks, and enhance production efficiency.

In addition, the proposed solution supports better control over hydrogen quality and availability, which are essential for maintaining product specification consistency in polypropylene production. The implementation of an internal hydrogen supply system also provides operational flexibility and reduces exposure to external market volatility and supply chain uncertainty.

Overall, the New Plant alternative is considered the most balanced and sustainable solution, as it offers the optimal integration of financial feasibility, operational performance, reliability improvement, and long-term strategic value for PT ENERGI NASIONAL X. This conclusion is supported by the results of the AHP global priority analysis, where the New Plant alternative achieved the highest global priority score of 0.437.

CONCLUSION

Based on the results of the analysis, the conclusions are structured according to the research questions as follows:

1. Feasible Hydrogen Supply Alternatives

Based on the SWOT–TOWS analysis and validation through Focus Group Discussions (FGDs) with subject matter experts (SMEs), three feasible hydrogen supply alternatives were identified: (1) a new hydrogen plant, (2) revitalization of the existing hydrogen plant, and (3) external hydrogen supply. In addition, the Fuzzy Delphi Method (FDM) confirmed that the selected evaluation criteria (including financial, reliability, and risk aspects) were relevant for decision-making.

2. Best Strategic Alternative

The AHP analysis indicated that decision-making was primarily driven by equipment reliability, long-term economic value (net present value/NPV), and supply continuity, rather than short-term cost considerations. Based on the global priority results, the new hydrogen plant achieved the highest score among all alternatives, making it the most appropriate strategic investment option for PT Energi Nasional X due to its superior long-term operational and strategic benefits.

3. Implementation Plan

A structured implementation plan was developed for the selected alternative, covering people, processes, and project monitoring tools, with an estimated implementation duration of approximately two years, subject to management approval. This demonstrates that the selected solution is not only strategically preferable but also practically feasible for execution.

STATEMENT OF AUTHOR CONTRIBUTION

Amar Ma'ruf: As the principal researcher and graduate student at the School of Business and Management, Institut Teknologi Bandung (SBM ITB) was responsible for the overall execution of the study, including research conceptualization, study design, data collection, analysis, interpretation of findings, and manuscript preparation.

Pri Hermawan: As the academic supervisor, provided research supervision, methodological guidance, critical review of the research framework and findings, and constructive feedback to ensure the study maintained academic rigor and that the research objectives were systematically achieved.

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