

# Determination of Sustainable Supply Chain Strategy in Natural Gas Transition as a Substitute for Subsidized Household LPG using FAHP and TOPSIS Method

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## Abstract

The high dependency on subsidized LPG imports and the increasing demand for cleaner energy encourage the utilization of natural gas as an alternative household energy source in Indonesia. This study aims to determine the most appropriate sustainable supply chain strategy in supporting the transition of natural gas as a substitute for subsidized household LPG at Company XYZ. The research applies a Multi-Criteria Decision Making approach using Fuzzy Analytical Hierarchy Process (FAHP) and Technique for Order Preference by Similarity to Ideal Solution (TOPSIS). FAHP is used to determine the weight of criteria based on economic, environmental, and social aspects, while TOPSIS is applied to rank the alternative strategies. The results indicate that the strategy of infrastructure integration and gas distribution efficiency achieved the highest preference value of 0.9712, making it the most recommended strategy. The selected strategy is considered capable of improving distribution efficiency, expanding household gas network utilization, and reducing dependency on subsidized LPG. Therefore, the implementation of sustainable supply chain management in the gas sector can support energy transition and improve the effectiveness of household gas distribution systems.

*Keywords:* FAHP; natural gas; sustainable supply chain; TOPSIS

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## 1. Introduction

Global energy demand continues to increase along with population growth and economic activities. The energy sector contributes more than 70% of global carbon dioxide emissions, encouraging many countries to implement energy transition policies toward low-carbon systems [1]. However, global energy consumption is still dominated by fossil fuels such as oil, coal, and natural gas. This condition indicates that dependence on fossil-based energy remains relatively high and continues to create environmental challenges related to carbon emissions and climate change.

Indonesia has established a national target to achieve Net Zero Emission by 2060. Nevertheless, the national energy mix is still dominated by fossil energy, while the contribution of renewable energy remains below the national target [2], [3]. In the household sector, subsidized Liquefied Petroleum Gas (LPG) cylinders continue to become the primary energy source for cooking activities. The increasing demand for LPG and the high dependency on imports create challenges related to energy security and

supply stability. The Ministry of Energy and Mineral Resources reported that most domestic LPG demand is fulfilled through imports, indicating that domestic production capacity remains insufficient to support national consumption. This condition increases the vulnerability of national energy systems to fluctuations in international energy markets. In addition, the high utilization of subsidized LPG contributes to increasing government subsidy expenditure.

As part of the national energy transition program, the government has encouraged the utilization of gas through household gas networks as an alternative energy source. Compared to LPG cylinders, gas distributed through pipeline systems provides several advantages, including continuous supply availability, operational efficiency, and lower carbon emissions [2], [4], [5]. Wibowo and Windarta [2] explained that natural gas is considered a transition energy source because it has lower emission intensity compared to conventional fossil fuels.

The implementation of household gas networks requires effective coordination between procurement, transmission, distribution, and customer service systems. Chopra and Meindl [6] explained that supply chain integration plays an important role in improving operational effectiveness and distribution reliability.

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Therefore, the effectiveness of gas utilization programs is not only influenced by infrastructure development but also by the performance of sustainable supply chain management systems.

Table 1. Natural gas supply chain management system

SCM Stage	Main Activities	Related Units/Processes	Issues and Challenges
Gas Procurement (Upstream Interface)	Gas supply contracts with producers [PT Pertamina EP Cepu, Husky-CNOOC Madura Limited, PT Medco Energi Internasional Tbk], ensuring gas volume and quality	Gas producers, gas sales contracts	Supply dependency, volume fluctuations, long-term uncertainty risks
	Distribution of high-pressure gas through transmission pipelines	Transmission pipeline infrastructure, pressure control systems	Technical risks, high maintenance costs, safety aspects
Gas Distribution	Distribution of gas to consumer areas through distribution pipelines	Distribution pipeline network, city gas system	Limited coverage, infrastructure investment
Household Connection	Installation of household connections (SR), conversion from LPG to natural gas Network	Field technical team, installation contractors	Delays in installation, household readiness
Operations and Maintenance	monitoring, handling leakage and operational disturbances	O&M, network monitoring systems	Supply reliability, customer safety
Customer Service (Downstream)	Complaint services, billing, gas usage education	Customer service, customer information systems	Customer satisfaction, complaint response, public acceptance

Table 1 shows that the implementation of household gas distribution systems involves several interconnected supply chain activities, starting from gas procurement, transmission, distribution, household connections, operational maintenance, and customer services. Each stage has different operational challenges that may affect the effectiveness of gas distribution systems.

The upstream process mainly focuses on gas procurement and transmission activities. At this stage, supply reliability, transmission infrastructure, and operational safety become important factors in maintaining distribution continuity. Meanwhile, the downstream process involves customer services, household installations, and operational maintenance, which directly influence customer satisfaction and public acceptance.

The table also indicates that infrastructure limitations, high operational costs, technical risks, and public acceptance remain major challenges in supporting gas transition programs. Therefore, sustainable supply chain

strategies are required to improve operational effectiveness and support long-term energy sustainability.

Sustainable Supply Chain Management (SSCM) has become an important approach in improving organizational performance while maintaining environmental and social sustainability. SSCM integrates economic, environmental, and social dimensions into supply chain activities to support long-term sustainability performance [7]–[9]. According to Bui et al. [7], sustainable supply chain implementation can improve operational effectiveness while strengthening environmental responsibility and organizational competitiveness. The sustainability concept applied in this study refers to the Triple Bottom Line approach consisting of economic, environmental, and social dimensions. Elkington [10] explained that organizational sustainability should not only focus on economic performance but also consider environmental and social responsibilities simultaneously.

Several previous studies have implemented Multi-Criteria Decision Making (MCDM) approaches in sustainability-related decision-making problems. Wimalasena et al. [11] applied the FAHP–TOPSIS approach for green supplier selection, while other studies discussed the implementation of sustainable supply chain evaluation systems using multi-criteria approaches [12], [13]. However, limited studies specifically discuss sustainable supply chain strategies within household gas distribution systems as a substitute for subsidized LPG.

The determination of sustainable supply chain strategies involves multiple criteria simultaneously, including operational efficiency, environmental sustainability, and public acceptance. Decision-making methods capable of accommodating uncertainty and multiple evaluation criteria are required in determining sustainable supply chain strategies. Nguyen [14] explained that the Fuzzy Analytical Hierarchy Process method can effectively determine criteria importance weights in complex decision-making processes. Meanwhile, Singh et al. [15] stated that the TOPSIS method can determine alternative priorities based on their closeness to the ideal solution. Similar findings were also discussed by Wang et al. [8] and Mardani et al. [11] regarding the application of MCDM methods in sustainable energy decision-making.

Based on these conditions, this study aims to determine the most appropriate sustainable supply chain strategy for supporting gas transition as a substitute for subsidized household LPG at Company XYZ using the Fuzzy Analytical Hierarchy Process (FAHP) and Technique for Order Preference by Similarity to Ideal Solution (TOPSIS) methods. The results of this study are expected to provide strategic recommendations for improving household gas distribution systems while supporting sustainable energy transition programs in Indonesia.

## 2. Research Method

This research was conducted at Company XYZ, which operates in the household gas distribution sector. The study applies a quantitative approach using Multi-Criteria

Decision Making (MCDM) methods, namely Fuzzy Analytical Hierarchy Process (FAHP) and Technique for Order Preference by Similarity to Ideal Solution (TOPSIS). The integration of these methods was used to determine the most appropriate sustainable supply chain strategy in supporting gas transition as a substitute for subsidized household LPG.

The research variables were developed based on the Triple Bottom Line concept consisting of economic, environmental, and social aspects. The criteria and sub-criteria were identified through literature studies, preliminary observations, interviews, and discussions with experts involved in household gas distribution management.

The data used in this study were obtained through questionnaires and interviews conducted with internal respondents who have expertise and experience in gas distribution systems and operational management. The respondents consisted of professionals involved in the management and development of household gas networks. The selection of respondents was carried out purposively to ensure that the assessments represented practical and managerial considerations related to sustainable supply chain implementation.

Data collection was conducted in three stages. The first stage aimed to identify relevant criteria and sub-criteria using the Cut Off Point method. The second stage involved pairwise comparison questionnaires to determine criteria importance weights using the FAHP method. The third stage focused on evaluating alternative strategies using the TOPSIS method.

Table 2. Criteria and sub-criteria

Aspect	Criteria	Number of Sub-Criteria
Economic	Energy Cost	5
Economic	Operational Cost	5
Economic	Efficiency	5
Economic	Investment	5
Economic	Sustainability	5
Economic	Energy Price	5
Economic	Stability	5
Economic	Distribution Cost	5
Economic	Efficiency	5
Environmental	Energy Efficiency	5
Environmental	Reduction of Greenhouse Gas Emissions	5
Environmental	Reduction of Environmental Pollution	5
Environmental	Utilization of Cleaner Energy	5
Environmental	Compliance with Environmental Regulations	5
Social	Safety of Use	5
Social	User Convenience	5
Social	Public Acceptance	5
Social	Service Availability	5
Social	Long-Term Social Impact	5

The criteria and sub-criteria used in this study were developed based on the Triple Bottom Line concept consisting of economic, environmental, and social aspects. The term “aspect” in this study refers to the main sustainability dimensions based on the Triple Bottom Line

concept, namely economic, environmental, and social aspects. Each aspect consists of several criteria representing major evaluation factors in sustainable supply chain management. Furthermore, each criterion is divided into several sub-criteria that represent more specific operational indicators used in the FAHP and TOPSIS evaluation process. The use of this hierarchical structure aims to simplify the decision-making process while ensuring that all sustainability considerations are evaluated systematically [16], [17].

Table 2 presents the criteria and sub-criteria used in evaluating sustainable supply chain strategies for household gas transition. The criteria were grouped into economic, environmental, and social aspects based on the Triple Bottom Line approach. Each criterion contains several sub-criteria representing operational, environmental, and social considerations related to household gas distribution systems.

The determination of criteria weights was carried out using the FAHP method. Pairwise comparison values obtained from respondents were converted into triangular fuzzy numbers consisting of lower (l), middle (m), and upper (u) values. The FAHP method was selected because it can accommodate uncertainty and subjectivity in respondents’ judgments during the decision-making process [16].

Before conducting fuzzy calculations, consistency testing was performed using the Analytical Hierarchy Process (AHP) approach. The consistency ratio (CR) value was used to evaluate the reliability of respondents’ judgments. A CR value below 0.1 indicates that the pairwise comparison results are acceptable and consistent [12].

After obtaining the criteria weights, the TOPSIS method was applied to rank the alternative strategies. TOPSIS evaluates each alternative based on its distance from the positive ideal solution and the negative ideal solution. The alternative with the highest preference value is considered the best strategy because it has the closest distance to the ideal solution [18].

The stages of TOPSIS analysis conducted in this study consist of:

- Constructing the decision matrix.
- Normalizing the decision matrix.
- Calculating the weighted normalized matrix.
- Determining the positive and negative ideal solutions.
- Calculating the separation distance values.
- Determining the preference value and ranking the alternative strategies.

The integration of FAHP and TOPSIS methods in this study was expected to support decision-making processes involving multiple sustainability criteria simultaneously. Through this approach, the selected strategy can provide operational effectiveness while maintaining environmental and social sustainability within the household gas distribution system.

Fig. 1 presents the hierarchical structure of the decision-making model used in this study. The first level represents the main objective, namely determining the most appropriate sustainable supply chain strategy for supporting gas transition as a substitute for subsidized

household LPG. The second level consists of three main aspects based on the Triple Bottom Line concept, namely economic, environmental, and social aspects. The third level contains the criteria and sub-criteria used in the

evaluation process, while the final level represents the alternative strategies evaluated using the FAHP and TOPSIS methods.

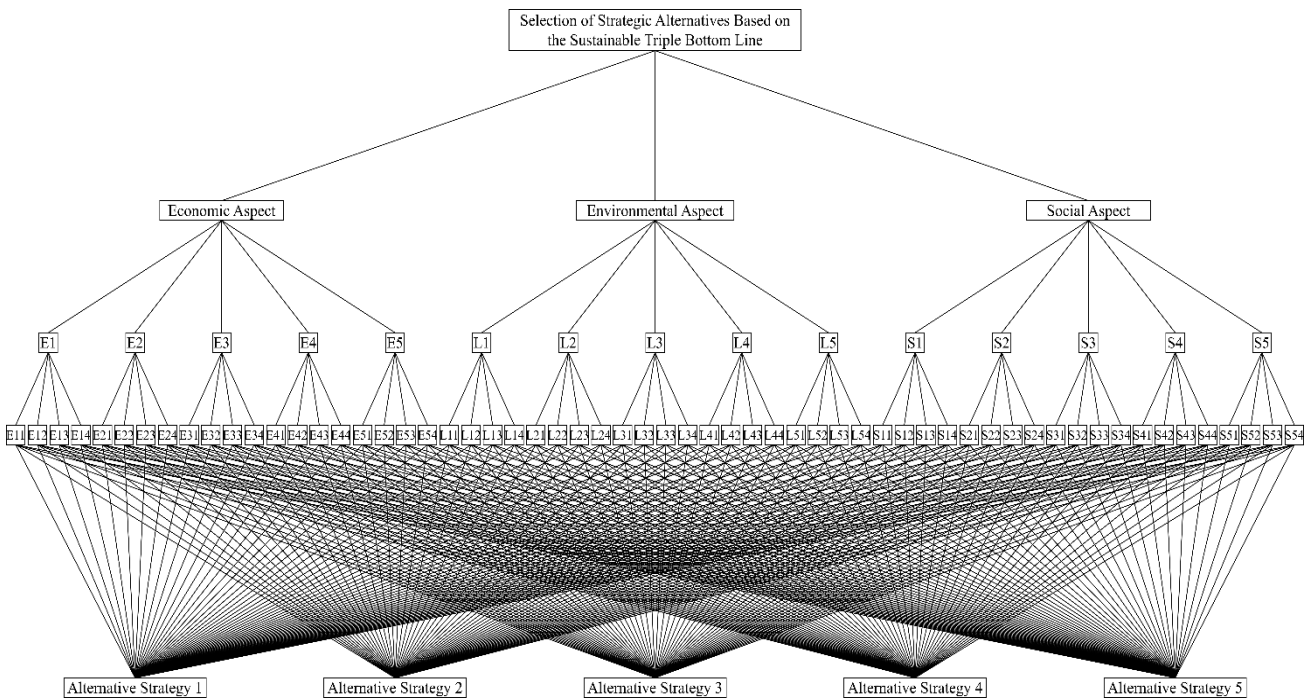


Figure 1. Hierarchical structure of sustainable supply chain strategy selection

### 3. Results and Discussion

#### 3.1. Criteria and sub-criteria weight analysis using FAHP

The determination of criteria and sub-criteria weights was carried out using the Fuzzy Analytical Hierarchy Process (FAHP) method. The weighting process involved pairwise comparison assessments conducted by respondents who have expertise in household gas distribution systems and sustainable supply chain management. The FAHP method was applied to accommodate uncertainty and subjectivity in respondents' judgments through the use of triangular fuzzy numbers.

Before conducting the fuzzy weighting process, consistency testing was performed using the Analytical Hierarchy Process (AHP) approach. The results showed that all pairwise comparison matrices obtained consistency ratio (CR) values below 0.1, indicating that the respondents' judgments were consistent and acceptable for further analysis [12].

The weighting results indicate that economic aspects have the greatest influence in determining sustainable supply chain strategies for household gas distribution systems. This condition demonstrates that operational efficiency, affordability, and distribution effectiveness remain the primary considerations in supporting the implementation of gas transition programs.

Environmental aspects also contribute significantly to the decision-making process. The reduction of greenhouse gas emissions and cleaner energy utilization indicate that sustainability considerations are increasingly important in supporting national energy transition programs.

According to Wibowo and Windarta [2], natural gas is considered a transition energy source because it has lower carbon emissions compared to conventional fossil fuels such as LPG.

In addition, social aspects such as service availability, safety, and public acceptance also influence the effectiveness of household gas implementation. Public trust and user convenience become important factors affecting the sustainability of household gas utilization programs. Bui et al. [7] stated that sustainable supply chain implementation not only improves operational performance but also strengthens environmental and social sustainability performance.

Table 3. Final criteria weight results

Code	Criteria	M <sub>i</sub>
E1	Energy Cost	0.3880
E2	Operational Cost Efficiency	0.1847
E3	Investment Sustainability	0.1549
E4	Energy Price Stability	0.0688
E5	Distribution Cost Efficiency	0.1250
L1	Energy Efficiency	0.0279
L2	Reduction of Greenhouse Gas Emissions	0.0006
L3	Reduction of Environmental Pollution	0.0010
L4	Utilization of Cleaner Energy	0.0020
L5	Compliance with Environmental Regulations	0.0030
S1	Safety of Use	0.0002
S2	User Convenience	0.0066
S3	Public Acceptance	0.0120
S4	Service Availability	0.0051
S5	Long-Term Social Impact	0.0204

The criteria codes used in this study represent the sustainability aspects evaluated in the FAHP and TOPSIS analysis process. The code "E" refers to economic criteria,

“L” refers to environmental criteria, and “S” refers to social criteria. Each code represents a specific criterion used in evaluating sustainable supply chain strategies for household gas transition programs.

The weighting results indicate that the energy cost criterion (E1) obtained the highest weight value of 0.3880, indicating that economic considerations remain the primary concern in determining sustainable supply chain strategies for household gas distribution systems. This condition reflects the current dependency of households on subsidized LPG, where affordability and operational efficiency become important factors influencing energy transition decisions. In addition, stable and affordable household energy costs are considered capable of increasing public interest in utilizing household gas networks in the long term.

The Operational Cost Efficiency criterion (E2) also obtained a relatively high weight value. This finding indicates that operational effectiveness and distribution efficiency have an important role in supporting the continuity of gas distribution systems. Efficient operational systems are considered capable of reducing transportation and distribution costs while improving supply reliability and network performance [8].

From the environmental aspect, criteria related to greenhouse gas emission reduction and cleaner energy utilization also contribute to the overall sustainability assessment. This finding demonstrates that environmental sustainability considerations are increasingly important in supporting national energy transition programs. Natural gas is considered to have lower carbon emissions compared to subsidized LPG, making it more suitable as a transition energy source [2].

Meanwhile, social criteria such as public acceptance, service availability, and user convenience also influence the effectiveness of household gas implementation. Reliable services and positive public perceptions are considered important in supporting long-term sustainability within household gas distribution systems [7].

### 3.2. Global sub-criteria weight analysis

The global sub-criteria weighting results indicate that household energy cost savings obtained the highest global weight value among all sub-criteria evaluated in this study. This condition demonstrates that reducing household energy expenditure remains the primary consideration influencing the implementation of gas transition programs. The result reflects the current dependency of households on subsidized LPG, where affordability becomes one of the most important factors affecting public willingness to switch to natural gas utilization systems.

From the environmental aspect, Carbon Emission Reduction and Low-Carbon Energy also obtained relatively high global weight values. These findings indicate that environmental sustainability considerations increasingly influence strategic decision-making within household gas distribution systems. The lower carbon emission intensity of natural gas compared to LPG strengthens its role as a transition energy source that supports cleaner household energy utilization [2].

Meanwhile, from the social aspect, Availability of Customer Service and Public Acceptance obtained relatively high weight values. This finding indicates that service reliability, responsiveness to complaints, and positive public perception become important factors supporting the sustainability of household gas programs. Good service quality is considered capable of increasing public trust and improving the effectiveness of long-term gas utilization programs [12].

Overall, the global weighting results demonstrate that economic, environmental, and social considerations contribute simultaneously to the determination of sustainable supply chain strategies. Therefore, the selected strategy should not only focus on operational effectiveness but also support environmental sustainability and long-term public acceptance [10].

Table 4. Global sub-criteria weight results

Criteria	Sub-Criteria	Global Weight
Energy cost	Energy Affordability	0.1357
	Household Energy Cost Savings	0.1421
	Energy Use Efficiency	0.1184
	Cost Comparison with LPG	0.1096
	Energy Cost Stability	0.0975
Operational cost efficiency	Distribution Operational Cost Efficiency	0.1215
	Reduction in Energy Transportation Costs	0.1132
	Reduction in Energy Storage Costs	0.1018
	Energy Distribution Process Efficiency	0.1094
	Effectiveness of Gas Network Operational Systems	0.0956
Investment sustainability	Long-Term Investment Benefits	0.0863
	Infrastructure Reliability	0.0824
	Gas Network Development	0.0795
	Investment Efficiency	0.0738
	Support for Energy Systems	0.0684
Energy price stability	Price Consistency	0.0672
	Resistance to Fluctuations	0.0635
	Energy Cost Certainty	0.0618
	Supply Stability	0.0586
	Energy Price Reliability	0.0552
Distribution cost efficiency	Logistics Cost Efficiency	0.0744
	Transportation Cost Efficiency	0.0715
	Distribution System Efficiency	0.0698
	Reduction in Distribution Costs	0.0664
	Distribution Network Optimization	0.0627
Energy efficiency	Optimal Energy Utilization	0.0582
	Reduction in Energy Waste	0.0564
	Effectiveness of Energy Use	0.0538
	More Efficient Energy Use	0.0512
	Energy Consumption Management	0.0495
Reduction of greenhouse gas emissions	Carbon Emission Reduction	0.0987
	Reduction of Greenhouse Gas Emissions	0.0941
	Low-Carbon Energy	0.0894
	Energy Emission Control	0.0825
	Environmental Impact of Energy Use	0.0781
Reduction of environmental pollution	Reduction of Air Pollution	0.0725
	Reduction of Environmental Impact	0.0698
	Better Environmental Quality	0.0652

	Reduction of Pollution from Energy Use	0.0624
	More Environmentally Friendly Energy	0.0597
	Clean Energy	0.0864
	Low-Emission Energy	0.0816
Utilization of cleaner energy	Environmentally Friendly Energy	0.0774
	Clean Energy Transition	0.0748
	Sustainable Energy Use	0.0715
	Compliance with Energy Policies	0.0588
	Compliance with Environmental Regulations	0.0557
Compliance with environmental regulations	Support for National Energy Programs	0.0535
	Implementation of Clean Energy Policies	0.0516
	Alignment with Government Regulations	0.0484
	Energy Use Safety	0.0526
	Risk of Energy Accidents	0.0497
Safety of use	Gas Network Security Systems	0.0468
	Energy Safety Standards	0.0442
	User Protection	0.0415
	Ease of Use	0.0578
	Practicality of Energy Use	0.0551
User convenience	Ease of Energy Access	0.0524
	Availability of Energy Supply	0.0495
	Ease of Operation	0.0467
	Level of Public Acceptance	0.0618
	Public Support for Gas Network Programs	0.0586
Public acceptance	Public Trust in Natural Gas	0.0564
	Public Interest in Using Natural Gas	0.0538
	Public Perception of Gas Energy	0.0507
	Availability of Customer Service	0.0742
Service availability	Response to Disruption Handling	0.0718
	Gas Network Technical Support	0.0685
	Gas Network Maintenance	0.0654
	Access to Energy Services	0.0628
	Improvement of Quality of Life	0.0594
Long-term social impact	Social Benefits of Energy Use	0.0568
	Improvement of Community Welfare	0.0541
	Ease of Household Activities	0.0517
	Long-Term Social Impact	0.0486

Based on Table 4, the sub-criterion household energy cost savings obtained the highest global weight value, indicating that reducing household energy expenditure becomes the primary consideration in determining sustainable supply chain strategies. This finding demonstrates that affordability and operational efficiency remain important factors influencing household gas transition programs.

From the environmental aspect, Carbon Emission Reduction and Low-Carbon Energy also obtained relatively high global weight values. These findings indicate that environmental sustainability considerations have an important role in supporting cleaner and lower-emission household energy systems. According to Wibowo and Windarta [2], natural gas has lower carbon emission intensity compared to LPG, making it suitable as a transition energy source.

Meanwhile, from the social aspect, Availability of Customer Service and Level of Public Acceptance obtained relatively high weight values. This condition indicates that customer trust, service reliability, and public acceptance remain important factors affecting the effectiveness of household gas implementation programs.

Overall, the global weighting results demonstrate that economic, environmental, and social considerations contribute simultaneously to the determination of sustainable supply chain strategies. Therefore, the selected strategy should not only focus on operational effectiveness but also support environmental sustainability and social acceptance in the long term.

### 3.3 Alternative strategy ranking using TOPSIS

The TOPSIS method was applied to determine the priority ranking of alternative sustainable supply chain strategies. TOPSIS evaluates each alternative based on its distance from the positive ideal solution and the negative ideal solution. Singh et al. [15] stated that TOPSIS is widely applied in multi-criteria decision-making problems because it can identify the most optimal alternative through systematic ranking procedures.

Five alternative strategies were evaluated in this study. Each alternative was assessed based on economic, environmental, and social criteria obtained from the FAHP weighting process.

Table 5. TOPSIS preference value results

Code	Alternative Strategy	Preference Value (Vi)
A1	Infrastructure integration and gas distribution efficiency	0.9712
A2	Development of household gas network systems	0.7873
A3	Improvement of operational and maintenance systems	0.5099
A4	Optimization of customer service systems	0.3736
A5	Development of sustainable energy support programs	0.1721

The TOPSIS analysis results indicate that alternative strategy A1 obtained the highest preference value of 0.9712, indicating that the strategy has the closest distance to the positive ideal solution compared to other alternatives. The selected strategy focuses on infrastructure integration and gas distribution efficiency, which are considered important in improving the effectiveness of household gas distribution systems.

The high preference value obtained by A1 demonstrates that infrastructure integration can improve coordination between transmission systems, distribution networks, and household gas installations. Better integration between operational processes is considered capable of reducing distribution inefficiencies, improving supply continuity, and minimizing operational disruptions within household gas systems [6].

In addition, distribution efficiency also contributes to reducing transportation and operational costs while expanding the coverage of household gas networks. This condition supports the sustainability of household gas utilization programs because more households can access cleaner and more stable energy systems.

Alternative strategy A3 obtained the second-highest preference value of 0.7873, indicating that the strategy

also has relatively good sustainability performance. However, its contribution to operational integration and distribution efficiency remains lower compared to A1. Meanwhile, alternative strategy A4 obtained the lowest preference value, indicating that the strategy has the farthest distance from the positive ideal solution and provides lower overall sustainability performance.

Overall, the TOPSIS results demonstrate that strategies focusing on infrastructure integration, operational effectiveness, and distribution efficiency provide greater contributions to supporting sustainable household gas transition programs.

#### 4. Conclusion

Based on the results of the study, the integration of the Fuzzy Analytical Hierarchy Process (FAHP) and Technique for Order Preference by Similarity to Ideal Solution (TOPSIS) methods was successfully applied to determine the most appropriate sustainable supply chain strategy for supporting gas transition as a substitute for subsidized household LPG at Company XYZ. The evaluation process involved economic, environmental, and social aspects based on the Triple Bottom Line concept.

The FAHP analysis results indicate that economic criteria have the greatest influence on sustainable supply chain strategy determination. Energy cost obtained the highest criteria weight value, indicating that affordability, operational efficiency, and distribution effectiveness remain the primary considerations in supporting household gas distribution systems. Environmental and social aspects also contribute significantly to the decision-making process, particularly in relation to greenhouse gas emission reduction, cleaner energy utilization, service availability, and public acceptance.

The TOPSIS analysis results show that alternative strategy A1 achieved the highest preference value of 0.9712, indicating that the strategy has the closest distance to the positive ideal solution. The selected strategy focuses on infrastructure integration and gas distribution efficiency. This strategy is considered capable of improving operational performance, expanding household gas network utilization, reducing distribution costs, and reducing dependency on subsidized LPG imports.

Overall, the findings demonstrate that the implementation of sustainable supply chain strategies can support operational effectiveness while maintaining environmental sustainability and social acceptance within household gas distribution systems. Therefore, the integration of FAHP and TOPSIS methods can provide effective support for strategic decision-making processes involving multiple sustainability criteria simultaneously.

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## APPENDIXES

### Appendix A. Pairwise Comparison Scale

Appendix A. TOPSIS preference value results

Scale	Definition
1	Equal importance
3	Moderate importance
5	Strong importance
7	Very strong importance
9	Extreme importance
2,4,6,8	Intermediate values

The pairwise comparison scale was used to evaluate the relative importance between criteria and sub-criteria in the AHP and FAHP analysis process.

### Appendix B. Triangular Fuzzy Number Scale

Appendix B. Triangular fuzzy number scale

AHP Scale	Fuzzy Scale (l,m,u)
1	(1,1,1)
2	(1,2,3)
3	(2,3,4)
4	(3,4,5)
5	(4,5,6)
6	(5,6,7)
7	(6,7,8)
8	(7,8,9)
9	(9,9,9)

Triangular fuzzy numbers were used to transform pairwise comparison values into fuzzy scales consisting of lower (l), middle (m), and upper (u) values.

### Appendix C. Consistency Ratio Result

Appendix C. Consistency ratio result

Matrix	$\lambda_{max}$	CI	CR	Result
Criteria	15.842	0.060	0.038	Consistent
Economic Aspect	5.274	0.068	0.061	Consistent
Environmental Aspect	5.318	0.079	0.071	Consistent
Social Aspect	5.226	0.056	0.050	Consistent

All pairwise comparison matrices obtained consistency ratio values below 0.1, indicating that the respondents' judgments were acceptable and consistent.

### Appendix D. Sample FAHP and TOPSIS Calculation

#### D.1. Normalization process

The normalization process was conducted to convert the decision matrix into comparable values using the following equation:

$$r_{ij} = \frac{a_{ij}}{\sum X_{ij}}$$

$$r_{11} = \frac{1}{6.405} = 0.156$$

where,

$X_{ij}$  = comparison value  
 $\sum X_{ij}$  = total column value  
 $r_{ij}$  = normalized value

The calculation result indicates that the normalized value for the first comparison matrix is equal to 0.156.

#### D.2. Defuzzification process

The defuzzification process was performed to convert triangular fuzzy numbers into crisp values using the following equation:

$$M_i = \frac{l+m+u}{3}$$

Example calculation:

$$M_i = \frac{0.125+0.156+0.188}{3} = 0.156$$

where,

$l$  = lower value  
 $m$  = middle value  
 $u$  = upper value  
 $M_i$  = defuzzification value

The calculation result shows that the defuzzified value obtained from the triangular fuzzy number is equal to 0.156.

#### D.3. Consistency ratio calculation

The consistency ratio was calculated to evaluate the reliability of respondents' judgments using the following equation:

$$CI = \frac{\lambda_{max} - n}{n - 1}$$

Example calculation:

$$CI = \frac{15.842 - 15}{15 - 1} = 0.060$$

The consistency ratio value was then calculated using:

$$CR = \frac{CI}{RI}$$

Example calculation:

$$CR = \frac{0.060}{1.59} = 0.038$$

The calculation result indicates that the consistency ratio value is below 0.1, meaning that the pairwise comparison matrix is consistent and acceptable for further analysis.

#### D.4. Preference value calculation using TOPSIS

The preference value was calculated using the following equation:

$$V_i = \frac{D_i^-}{D_i^- + D_i^+}$$

Example calculation:

$$V_i = \frac{0.842}{0.025 + 0.842} = 0.9712$$

where,

$D_i^+$  = distance from positive ideal solution

$D_i^-$  = distance from negative ideal solution

$V_i$  = preference value

The calculation result shows that alternative strategy A1 obtained a preference value of 0.9712, indicating that the strategy has the closest distance to the positive ideal solution and becomes the most recommended strategy for implementation.

#### Appendix E. Alternative Strategy Codes

Appendix E. Alternative strategy codes

Code	Alternative Strategy
A1	Infrastructure integration and gas distribution efficiency
A2	Development of household gas network systems
A3	Improvement of operational and maintenance systems
A4	Optimization of customer service systems
A5	Development of sustainable energy support programs