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Comparative Study of Biomethane Purification Process using Analytical Hierarchy Process

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ABSTRACT

The selection of purification technology for upgrading biogas to biomethane involves complex considerations, as each technology -such as pressure swing adsorption (PSA), membrane separation (MS), or chemical absorption (CA) - offers distinct advantages and disadvantages. The Analytical Hierarchy Process (AHP), provides a systematic framework to simplify and resolve such complexities. This research aims to apply AHP to critically compare purification technologies for biomethane. AHP method is implemented in four steps which includes determination of AHP structure (goal, criteria, sub-criteria and alternatives), formation of pairwise comparison matrices based on literature study and expert opinion, normalization and consistency calculation, and prioritization of alternatives. The criteria considered in AHP analysis of this study are technology capacity, cost, and environmental impact. Overall, PSA received the highest weight for state of technology. In terms of separation performance, CA achieved the highest scores for methane purity and methane retention. From a cost and environmental impact perspective, MS performed best. However, despite its advantages, MS application is limited by its relatively lower maturity and limited scalability. By evaluating alternatives based on AHP framework, PSA was identified as the top-priority option, with total weight score of 0.426, followed by MS with total weight score of 0.387 and CA with total weight score of 0.181. This study has successfully demonstrate the application of AHP to select purification technologies for converting biogas to biomethane.

Keywords: analytical hierarchy process, biomethane, cost, environmental impact, state of technology.

1. INTRODUCTION

For over a thousand years, human civilization has heavily relied on fossil-based energy sources for various activities. Currently, coal, natural gas, and petroleum collectively supply approximately 80% of global energy demand, with developing countries particularly dependent on these resources [1]. However, fossil fuels are finite resources, and their continuous utilization has raised significant concerns regarding long-term sustainability. Therefore, transitioning toward renewable energy resources is crucial for promoting sustainable development, ensuring energy security, and mitigating the adverse effects of climate change.

Biogas is one of the alternative fuels that mainly consists of CO_2 and CH_4 and is produced through anaerobic digestion of organic waste. In comparison to fossil-based natural gas, biogas outperform since it is renewable, have lower carbon footprint [2] and have higher energy reliability in comparison to other renewable energy sources like solar and wind. Additionally, the application of biogas digestate as natural fertilizer can help reduce reliance on synthetic alternatives, promoting circular economy [3].

Purification of raw biogas, involving removal of impurities including CO_2 (15-60 %vol), N_2 (0-15 %vol), CO (<0.6 %vol), H_2S (0-10000 ppm_v), O_2 (0-3 %vol), ammonia (0-100 ppmv), hydrocarbons (0-200 mg/m^3), water (1-5 %vol) and other particulates [4], increases methane (CH_4) composition to levels typically exceeding 90%, resulting in biomethane [5]. Biomethane offers distinct advantages over raw biogas, since it has higher compatibility with existing natural gas infrastructure,

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higher calorific value, improved energy density and enhanced storage flexibility [6].

The selection of an appropriate purification technology for upgrading biogas to biomethane involves numerous complex considerations, as each technology -such as pressure swing adsorption (PSA), membrane separation, or chemical absorption - offers distinct advantages and disadvantages [5]. These technologies differ significantly in critical aspects including economic feasibility, technical performance, environmental impact, safety consideration, and regulatory compliance.

The Analytical Hierarchy Process (AHP), a widely recognized multiple criteria decision analysis (MCDA) technique, provides a systematic framework to simplify and resolve such complexities. AHP facilitates structured decomposition of intricate problems into manageable hierarchical components, enabling clear comparison and prioritization among alternative solutions. In process engineering applications, specifically biomethane purification, AHP empowers decision-makers to objectively evaluate trade-offs and select the optimal technology, ensuring robust, transparent and justifiable outcomes [7].

Although the AHP has demonstrated effectiveness in diverse engineering decision-making scenarios, its specific application to biogas purification technologies remains limited in existing literature. Particularly, there is a noticeable absence of research employing AHP for selecting optimal technologies tailored to biomethane purification. Therefore, this study aims to systematically evaluate and select the most suitable purification technologies for upgrading biogas into biomethane using the AHP methodology. The research extends the application of AHP to critically compare purification technologies for converting biogas to biomethane, considering multiple criteria including economic viability, technical efficiency and environmental sustainability. Ultimately, this work provides a robust decision-making framework that supports optimized selection of integrated purification for the sustainable and efficient production of biomethane.

2. RESEARCH METHODS

In this paper, the AHP technique was developed and applied to multi-criteria selection of biogas purification processes. AHP method was implemented in four steps which discussed in following sub-section.

2.1. Determination of Goal, Criteria, Sub-Criteria and Alternatives

In the initial step of the Analytical Hierarchy Process, the problem was systematically decomposed into fundamental components, including the goal of the study, the criteria and sub-criteria for evaluation, and the available alternatives. The goal of this study was to determine the best purification technology for biomethane production.

The criteria considered in both of the purification models were technology capacity (TECH), cost (COST), and environmental impact (ENV). The technology capacity criterion was further divided into the sub-criteria of state of technology (ST), methane losses (ML) and methane purity (MP). The cost criterion included investment cost (IC) and operational cost (OC) as its sub-criteria. Similarly, the environmental impact criterion was sub-divided into carbon footprint (CF), land footprint (LF), and water footprint (WF).

Technology alternatives evaluated for biogas purification process included pressure swing adsorption (PSA), membrane separation (MS) and chemical absorption (CA). The AHP decision structure is presented in Figure 1.

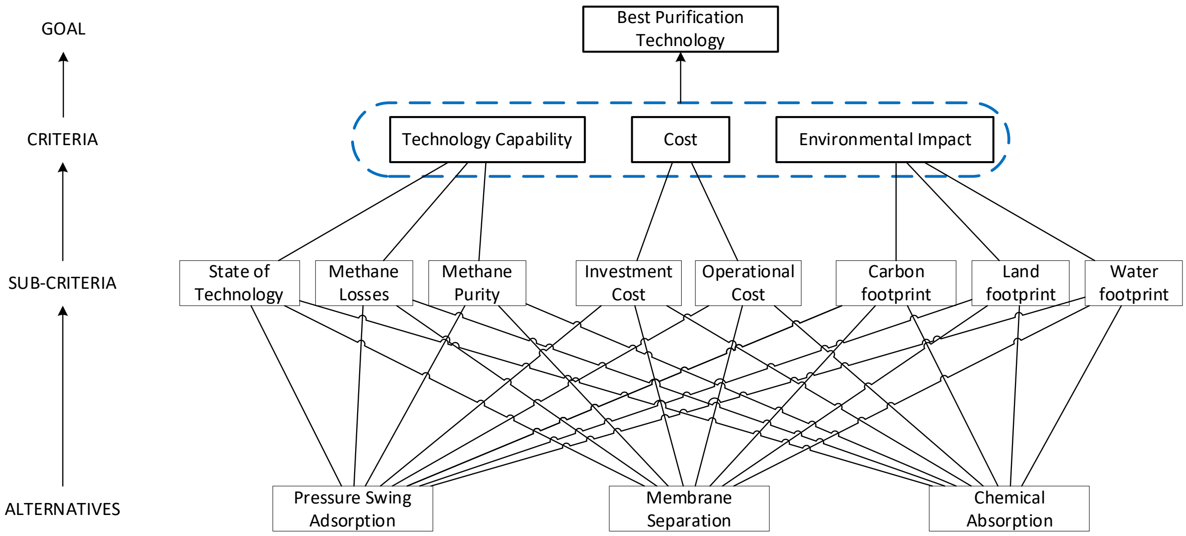

Figure 1. AHP decision structure for purification process.

2.2. Formation of Pairwise Comparison Matrices

Based on literature study, experts'opinions were taken to compare each level in the hierarchy, including: comparison of criteria relative to the goal (e.g. TECH vs COST, TECH vs ENV, COST vs ENV); comparison of sub-criteria within each criterion; comparison of the alternatives for each sub-criterion. In comparing each level in the hierarchy, Saaty's scale were used, which was described in Table 1. The complete comparison of each alternatives based on criterias listed in previous section is shown in Table 2 and 3.

Table 1. 1-9 comparison scale of Saaty [8].

n	RI
1	Equally important/preferred
3	Moderately more important/preferred
5	Strongly more important/preferred
7	Very strongly more important/ preferred
9	Extremely more important/ preferred
2,4,6,8	Intermediate values

Comparison of each level was used to built binary comparison matrices A (Equation 1), in which every elements a_{ij} was an expression that shows how criteria/ sub-criteria/ alternatives i were preferred over criteria/ sub-criteria/ alternatives j.

$$A = \begin{bmatrix} a_{11} & a_{12} & \cdots & a_{1n} \\ a_{21} & a_{22} & \cdots & a_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ a_{n1} & a_{n2} & \cdots & a_{nn} \end{bmatrix} \quad (1)$$

where $a_{ii} = 1$, $a_{ji} = 1/a_{ij}$, $a_{ij} \neq 0$.

2.3. Normalization and Consistency Calculation

Prior to determining the priority vectors, each pairwise comparison matrix was normalized by dividing every element (a_{ij}) by the sum of its respective column sum ($\sum_{i=1}^{n} a_{ij}$). In this way, a normalized matrix was obtained, where the sum of each column vector is 1. Subsequently, relative weight were obtained by averaging the values across each row. These weights represented the importance of each criterion and served as foundation for ranking alternatives within the decision hierarchy.

To ensure the reliability of judgment in the pairwise comparison, consistency ratio (CR) were also calculated. This involved multiplying the unnormalized matrix by the derived weight vector to compute the weighted sum of each row. Each of these sums was then divided by the corresponding criterion weight and the average of these values was taken to obtain λ_{max}. Using this value, consistency index (CI) was then calculated according to Equation 2 [9].

$$CI = \frac{\lambda_{max} - n}{n-1} \quad (2)$$

where n is the size of matrix.

CR was obtained by dividing CI to the random index (RI) which values depend to the matrix size, as shown in Table 2.

Table 2. Random index values according to matrix size [8].

n	1	2	3	4
RI	0.00	0.00	0.58	0.90
n	5	6	7	8
RI	1.12	1.24	1.32	1.41

A CR value below 0.1 indicated acceptable consistency within the matrix. If the CR exceeds 0.1, the matrix was considered inconsistent and should be re-evaluated. After confirming consistency, the main criteria, sub-criteria, and alternatives were ranked in ascending order based on their weight values. The criterion or alternative with the highest weight was identified as the top priority in the AHP decision-making process.

2.4. Prioritization of Alternatives

Once the weights of each criterion and sub-criterion were established and consistency was verified, the weight of each sub-criterion was multiplied by the weight of its corresponding main criterion to obtain the combined weight. Next, the performance score of each alternative under a given sub-criterion was multiplied by this combined weight. The overall score for each alternative was then determined by summing the weighted scores across all sub-criteria. The alternative with the highest total score was identified as the most suitable option for biomethane purification technology [9].

3. RESULTS AND DISCUSSION

To decide the most efficient alternative, both existing literatures and expert knowledge were employed in AHP. In this sub-section, each criterion and sub-criterion will be discussed regarding its meaning, and how each alternatives are compared based on this criteria or sub-criteria.

Technology capability refers to the efficiency of a given alternatives in achieving the primary objective of decision-making process. In selecting the most suitable purification technology, preference is given to alternatives that can produce biomethane with the highest purity within shorter timespan and least amount of methane losses. Hence two of the sub-criteria are including methane losses and methane purity. However, while some technologies are already mature and widely implemented in commercial biomethane production, others may still be in the experimental or laboratory scale and, despite their high efficiency, may lack proven scalability [10]. Therefore, the state of technology is included as an additional sub-criterion to assess the level of technological maturity and practical applicability.

Cost criterion can be further derived as operating cost and investment cost. Operating cost include cost of electricity/power, cost of raw materials, cost of replacement of equipment parts, and labour. Investment cost is the capital cost to set up the process plant [11].

The environmental impact of purification technology for biomethane can be assessed based on several factors: the amount of carbon emission in the form of carbondioxide throughout the process; the volume of water used, consumed or polluted by the process; and the extent of land use required. Considering these aspects will provide a more objective and comprehensive understanding of the environmental footprint associated with each technology [11].

Membrane separation (MS) purifies biomethane by allowing smaller gas molecules such as CO_2, H_2, and H_2S to permeate through a membrane more rapidly than CH_4, based on differences in molecular size and chemical affinity. Common module types include hollow fiber and spiral wound. MS can achieve methane purity above 96% and is favored for its low energy demand, and minimal emissions. However, it has moderate selectivity, making it less economical for bulk separation, and its performance depends heavily on membrane material [12].

Chemical absorption (CA) uses chemical solvents like MDEA to capture CO_2 in an absorption column, followed by solvent regeneration through heating. It is suitable for large-scale applications due to its high removal efficiency and processing capacity. Despite this, CA has high energy requirements and potential corrosion issues [13].

Pressure swing adsorption (PSA) separates gases by selectively adsorbing CO_2 onto solid adsorbents under pressure, releasing CH_4 at purities above 98%. It is a solvent-free method with minimal corrosion risk. However, PSA may result in methane losses during regeneration, slightly lowering overall recovery efficiency and increasing operational costs [14]. The comparison of each alternatives based on criteria and sub-criteria selected in this study is shown in Table 3.

Table 3. Comparison of alternatives based on criteria and sub-criteria.

No	Criteria	Sub-criteria	Alternative 1: PSA	Alternative 2: MS	Alternative 3: CA
1	Technology Capability	State of Technology	• Well-established technology with significant commercial use, particularly in large-scale applications [15] • Carbotech (Germany), Acrona (Switzerland), Gasrec (UK), Xebec (Canada) [16] • Extensive process and require control [10]	• This technology is gaining traction due to its lower energy requirements and operational simplicity [17] • Evonik Industries (Germany); Air Liquide (France); Bright Biomethane (Netherlands) • Easy operation [10]	• Less mature compared to PSA and membrane technologies, often requiring more complex setups and higher operational costs [18] • DMT Environmental Technology (Netherlands); Malmberg Water AB (Sweden); Unisensor GmbH (Germany) • Difficult in operation [10]
2	Technology Capability	Methane Losses	• 1-3.5% losses [10]	• 0.5-20% losses [10]	• 0.04-0.1% losses [10]
3	Technology	Methane	• Capable of	• Generally	• Typically

No	Criteria	Sub-criteria	Alternative 1: PSA	Alternative 2: MS	Alternative 3: CA
	Capability	Purity	achieving high methane purity (up to 99.96%) [15] • >96-98% purity [10]	provides good purity levels (around 95-98%) with lower energy input [17] • 96% purity [10]	achieves high purity but may involve higher operational costs [18] • >98% purity [10]
4	Cost	Investment Cost	• 2300 € per m^3 biogas/hour [17]	• 2200 € per m^3 biogas/hour [17]	• 2600 € per m^3 biogas/hour [17]
5	Cost	Operational Cost	• Consumables including adsorbents and molecular sieve • Highy require pre-cleaning, operational condition 5-30°C, 4-8 bar, no heating requirement; • Maintenance fee 56000 €/ year [10] • Operating cost 505 €/ year per m^3 biogas/hour [17]	• Consumables including membrane of silicone rubbers, cellulose acetate and hollow fibres • Require pre-cleaning, operational condition 25-60°C, 20-36 bar, no heating requirement • Maintenance fee 25000 €/ year [10] • Operating cost 360 €/ year per m^3 biogas/hour [17]	• Consumables including solvents such as amines (MEA, DMEA), alkali solutions, antifouling and drying agents • Require pre-cleaning, operational condition 35-50°C, 1 bar, require heating 120-160°C • Maintenance fee 59000 €/ year [10] • Operating cost 435 €/ year per m^3 biogas/hour [17]
6	Environmental Impact	Carbon Footprint	• 431.1 kg biogenic CO_2 emission per 500 m^3/hour raw biogas • Moderate greenhouse gas emissions since extensive use of energy [17]	• 428.9 kg biogenic CO_2 emission per 500 m^3/hour raw biogas • Lowest carbon footprint, up to 7% reduction in global warming potential compared to others [17]	• 435.5 kg biogenic CO_2 emission per 500 m^3/hour raw biogas • Higher emission due to energy intensive process in solvent regeneration [17]
7	Environmental Impact	Water Footprint	• No water use in the process, primarily for cooling and	• No water use in the process, very low water requirement [17]	• Produce wastewater, and use water (15 kg for 500 m^3 raw

No	Criteria	Sub-criteria	Alternative 1: PSA	Alternative 2: MS	Alternative 3: CA
			maintenance [17]		biogas per hour) for solvent regeneration [17]
8	Environmental Impact	Land Footprint	• Requires moderate land area for installation, primarily due to the need for large equipment and storage facilities [17]	• Generally has a smaller land footprint due to compact equipment design, making it suitable for urban settings [17]	• Typically demands more land for additional infrastructure, including storage for chemicals and larger processing units [17]

Based on the pairwise comparison matrix of the main criteria, technology capability (TP) is rated as moderately more important than cost (COST) and significantly more important than environmental impact (ENV). Between cost and environmental impact, cost is considered moderately more important in this study. An example of how pairwise comparison matrix is built in this study is shown in Table 4.

Table 4. Pairwise comparison matrix for parent criterion.

	TP	COST	ENV
TP	1	3	5
COST	1/3	1	3
ENV	1/5	1/3	1

As previously explained in the Methodology section, initially binary comparisons are made for each pair of options within parent criterion. For diagonal elements of the comparison matrix, comparison of a criterion with itself are always considered equally important. Therefore, the Saaty's scale of prioritization [8] are assigned to a value of one.

Meanwhile, as TP criterion is rated as moderately more important than COST criterion, Saaty's scale value assigned for element a_{12} (TP vs COST) in the comparison matrix become 3 according to Saaty's scale of importance [8]. On the other hand, in element a_{21} (COST vs TP), the reciprocal value is used for the opposite comparison. Hence it become 1/3 which is equivalent to *"moderately less important"* in Saaty's scale to maintain consistency in the matrix.

The same approach is applied in binary comparison of TP and ENV, where the TP criterion is rated *"significantly more important"* than the ENV criterion. The element a_{31} (TP vs ENV) is assigned a value of 5 according to Saaty's scale [8] and the reciprocal value is assigned to the corresponding opposite element a_{31} (ENV vs TP). The value in Table 4 then is normalized as described in Sub-section 2.3.

Emphasizing the state of technology as a key sub-criterion reflects the importance of process safety and technical maturity. Technologies that are widely implemented in existing biomethane plants are generally more reliable and pose lower operational risk. As such, even if these technologies are associated with higher costs, their proven effectiveness can justify the expenditure, reducing the relative importance of the cost criterion. Table 3 highlights that state of technology shows the greatest variation among the evaluated alternatives, unlike sub-criteria such as methane purity and methane losses, where differences between technologies are relatively minor. For this reason, the state of technology was assigned a higher importance score in the comparison matrix within sub-criterion of the TECH criterion.

Although environmental impact is inherently important in sustainable technology selection, achieving zero emissions across available technologies is often challenging. Moreover, environmental burdens can be partially mitigated by incorporating additional units for waste treatment and environmental monitoring. Thus, in this study, environmental impact is weighted lower relative to technology capability and cost. The environmental impact criterion includes three sub-criteria: carbon footprint, water footprint, and land use. Among these, carbon footprint is assigned the highest importance due to its broad implications across atmospheric and biospheric systems. Water use is considered more significant than land use, as improper discharge of large volumes of wastewater can lead to serious ecological harm, whereas land occupation tends to have more localized effects [17].

Within the cost category, operational cost is deemed more important than investment cost. This is because operational expenses including energy, maintenance, and consumables represent recurring costs throughout the lifespan of the technology, whereas investment cost is a one-time expenditure during the initial setup. The weights of sub-criteria and its parent criteria is shown in Table 5. Weights of each criteria have previously validated for its consistency based on consistency index calculation.

Table 5. Aggregated weights for sub-criterion.

Parent Criterion	Weights	Sub-criterion	Weights	Aggregated Weights
Technology Capability	0.63	State of Technology	0.72	0.46
		Methane Losses	0.08	0.05
		Methane Purity	0.19	0.12
Cost	0.26	Investment Cost	0.39	0.10
		Operational Cost	0.61	0.16
Environmental Impact	0.11	Carbon Footprint	0.74	0.08
		Land Footprint	0.08	0.01
		Water Footprint	0.18	0.02

Based on the literature-based evaluation of each alternative with respect to separation performance, cost, and environmental impact, pairwise comparison matrices were constructed to determine their relative weights. The resulting scores of each alternative for every sub-criterion are presented in Figure 2.

Among three alternatives, pressure swing adsorption (PSA) received the highest weight for state of technology or technological maturity. As shown in Table 3, PSA is one of the most widely adopted technologies for biogas upgrading, second only to water scrubbing, which was excluded from this study due to its high water consumption and operational cost. PSA's industrial maturity provides it with a reliability advantage, particularly for large-scale applications [15]. In this study, the value that was assigned in comparison to membrane separation (MS) became 5, which is equivalent to *"significantly more preferred"*, because MS is the least mature technology. In comparison with chemical absorption (CA), as CA has wider commercial adoption than MS, Saaty's preference scale value assigned in this study was the intermediate between *significant* and *moderately preferred,* or value of 4. The comparison of alternatives within sub-criterion state of technology was added for the rest of the matrix, including the corresponding opposite elements. The normalized weights are shown in Figure 2, which reflects the outcome of the pairwise comparisons described above.

In terms of separation performance, CA achieved the highest Saaty's scores of preference for methane purity and methane retention sub-criterion. This technology is capable of delivering methane purities exceeding 98%, which meets the standards for grid injection [19]. Conversely, MS was penalized due to its relatively high methane losses, where 10–25% of methane may be lost to the permeate stream [10]. Therefore, CA is *very significantly more preferred* (Saaty's scale value of 7) than MS and moderately more preferred than PSA. Between, PSA and MS, PSA is *significantly more preferred* than MS.

From a cost perspective, MS performed best, showing the lowest scores for both investment and operational costs. The lower frequency of membrane replacement contributes to reduced consumable costs, unlike CA which requires regular solvent replenishment and PSA which requires adsorbent regeneration. Additionally, CA systems are more energy-intensive due to the heating required for solvent regeneration, resulting in higher carbon emissions [20].

Based on Life Cycle Cost (LCC) analysis conducted by Ardolino et al. [17], within best scenario, specific investment cost for MS can reach up to 2200 €/($m^3_{N\ biogas}$)/h, while PSA and CA can be up to 2300 €/($m^3_{N\ biogas}$)/h and 2600 €/($m^3_{N\ biogas}$)/h, respectively [17]. From investment cost perspectives, MS is *slightly more preferred* than PSA and *very significantly more preferred* than CA.

On the other hand, from operational cost perspectives, MS is *very significantly more preferred than* PSA, as specific operating cost for MS reach up to 360 (€/y)/($m^3_{N\ biogas}$)/h , while PSA is 40% higher than MS [17]. Operating cost for CA is 20% higher than MS, and in this study, the value assigned in comparison matrix was defined as *significantly less preferred* than MS.

In terms of environmental impact, membrane separation again demonstrated favorable results. Its compact design results in lower land use compared to the larger land footprint of PSA and CA systems, which require additional columns for regeneration [17]. Furthermore, while PSA and MS are water-free, CA requires dilution of the solvent with water, leading to a higher water footprint [17]. In comparison matrix, value assigned for MS was *significantly more preferred* for both PSA and CA. Between PSA and CA, higher preference score was assigned to PSA for water and carbon footprint sub-criterion. Meanwhile in land footprint, PSA is *slightly more preferred* than CA because both technologies require vast land use. The normalized weight for each biogas purification technology alternatives across all sub-criterion is shown in Figure 2.

Despite its advantages, MS is limited by its relatively lower maturity and limited scalability for large-scale industrial use [20]. CA, while excellent in separation efficiency and gas retention, is associated with high energy demand, greater emissions, and higher costs. PSA, on the other hand, represents a moderate option across most sub-criteria—but benefits from being a well-established and reliable technology.

The final ranking of the alternative technologies was obtained by multiplying the weight of each alternative by the aggregated weights of the corresponding sub-criteria and summing the results across all sub-criteria. The complete ranking is presented in Table 6.

Table 6. Weights and rankings of alternatives according to AHP.

Alternatives	Total Weight Score	Rank
PSA	0.426	1
MS	0.387	2
CA	0.181	3

Therefore, based on this AHP analysis explored in this study, pressure swing adsorption is regarded as prioritized technology alternatives for biomethane production.

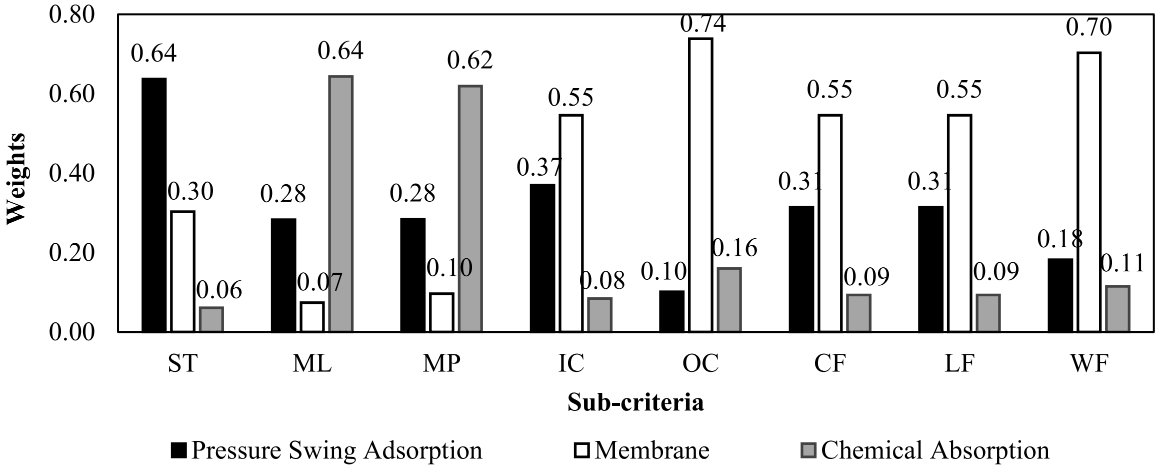

Figure 2. Weights of alternatives for biomethane purification based on each sub-criteria.

4. CONCLUSION AND OUTLOOK

This study has demonstrated the effective application of the Analytical Hierarchy Process (AHP) for technology selection in biomethane purification. By evaluating alternatives based on key criteria—technology capability, cost, and environmental impact—and their associated sub-criteria, Pressure Swing Adsorption (PSA) was identified as the top-priority option with total weight score of 0.426. Although PSA showed moderate performance across most sub-criteria, its strong score in technological maturity, combined with the initial weighting of criteria, significantly influenced its final ranking. MS which is superior in terms of less environmental burden and less investment and operational cost have total weight score of 0.387, which is due to its less implementation in commercial plant. CA has the the lowest total weight score, with value of 0.181, because despite its high methane purity and low methane losses, CA has high operating cost and environmental burden. These findings emphasize the value of structured decision-making tools like AHP in guiding the selection of sustainable and technically viable purification technologies.

For future study, it is suggested to conduct a more comprehensive analysis, such as Life Cycle Assessment (LCA), using software such as GaBi/Sphera to obtain detailed estimation of environmental burden and cost. In addition to this, it is also important to incorporate recent advancements of biogas purification technology to improve the relevance of analysis. For example, incorporation of electrochemically mediated amine regeneration (EMAR) in chemical absorption (CA) should be considered, as it can significantly reduce the energy demand and amine degradation [21], which further impact the decision analysis process. This study, which was limited to conventional PSA, CA and MS has potential to be improved in terms of analysis and technology updates.

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