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Evaluation Criteria for Carbon Storage through Gas Hydrate Formation

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ABSTRACT

Carbon dioxide (CO_2) sequestration using gas hydrate formation in marine sediments is emerging as a promising strategy for mitigating climate change. To identify and evaluate suitable storage before injection into sites is crucial. In this study, we established a structured framework of assessment criteria tailored to the unique characteristics of gas hydrate-based storage systems. We adopt the Analytic Hierarchy Process (AHP) to quantitatively assign weights to nine key geological and environmental criteria. The AHP method enables consistent, expert-informed pairwise comparisons and ensures logical consistency through metrics such as the Consistency Ratio (CR), which was within acceptable limits in this study. The resulting weighted criteria are then used in a multi-criteria decision-making framework to score and rank potential CO_2 storage basins in South Korea.

1. INTRODUCTION

Assigning appropriate weights to criteria is a crucial aspect of most multi-criteria decision-making (MCDM) frameworks. This process is essential because it helps define the decision-maker's preferences numerically in several meaningful ways:
(i) it quantifies the importance of each objective using specific numerical values,
(ii) it allows for accurate comparison between objectives by expressing their relative significance as ratios, and
(iii) it ensures a normalized system where all weights sum to one, reflecting a balanced distribution of importance among the criteria (Saaty, 1980; Hwang & Yoon, 1981).

Numerous techniques have been developed for assigning these weights, generally falling into two categories: subjective and objective (Tzeng et al., 1998).

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Subjective methods rely on expert judgment and decision-maker preferences, incorporating their experience and insights into the weight allocation. In contrast, objective methods derive weights using mathematical calculations based on the decision matrix's data, ensuring minimal human bias. Among the subjective approaches, popular methods include: (1) point-allocation, (2) direct rating, (3) pairwise comparisons via the Analytic Hierarchy Process, (4) ranking and ratio ranking, (5) swing weighting, (6) nominal group technique, and (7) the simple multi-attribute rating technique (SMART).

2. ANALYTICAL HIERARCHY PROCESS (AHP) METHOD

The Analytic Hierarchy Process (AHP), introduced by Saaty in 1980, is a systematic approach for decision-making that determines the relative importance of criteria through pairwise comparisons.

Step 1: Creating the pairwise comparison matrix

In the initial phase, each criterion is compared with every other criterion using a numerical scale known as the Saaty scale. This scale ranges from 1 (equal importance) to 9 (extreme importance), including intermediate values like 2, 4, 6, and 8. The matrix is structured such that the diagonal entries are always 1, and the values below the diagonal are the reciprocals of the values above, forming a reciprocal matrix.

Step 2: Determining criteria weights

There are two main methods to calculate the priority weights:

- Method 1: Normalized method
  First, total each column of the comparison matrix. Then, divide each element by its column total to normalize the matrix. Finally, compute the average of each row to determine the weights.
- Method 2: Geometric mean method
  Multiply the elements in each row, take the nth root of the product (where n is the number of criteria), and normalize the resulting values to obtain the weights.

Step 3: Consistency check

Because human judgments can be inconsistent, AHP includes a mechanism to test for consistency. Begin by multiplying the original matrix by the priority vector to produce a new vector. Divide each value in this new vector by the corresponding priority weight. The average of these values gives an estimate of the maximum eigenvalue, denoted as λ_{max}.
Using this, the consistency Index (CI) and the consistency Ratio (CR) are calculated as follows:

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

$$\mathrm{CR} = \frac{\mathrm{CI}}{\mathrm{RI}} \tag{2}$$

When n is the number of criteria and RI is the Random Consistency Index. If CR < 0.1, the level of consistency is acceptable. A CR>0.1 suggests inconsistency in the judgments, and it may be necessary to revise the pairwise comparisons.

Table 1. AHP scale of importance

Intensity of importance	Definition
1	Equal importance
3	Moderate importance
5	Strong importance
7	Very strong importance
9	Extreme importance
2, 4, 6, 8	Can be used to express intermediate value

(Source: Saaty, 1980)

Table 2. Random index

Order	1	2	3	4	5	6	7	8	9	10
RI	0.00	0.00	0.58	0.90	1.12	1.24	1.32	1.41	1.45	1.49

(Source: Saaty, 1980)

To evaluate the relative significance of key geological and environmental factors in identifying optimal sites for CO_2 storage via gas hydrate formation, we employed the Analytic Hierarchy Process. The assessment focused on nine criteria: permeability, pore volume, hydrogeology, pore-water chemistry, seal thickness, fault distribution, seismic activity, water depth, and distance from the source.

Using the column-sum normalization method, we constructed a pairwise comparison matrix and computed the priority weights for each criterion. Each matrix entry was divided by the total of its corresponding column, and the average of each row was then calculated to determine the final weight.

The analysis revealed that pore volume (0.391) and water depth (0.173) had the highest influence on CO_2 storage site suitability. Permeability (0.125) and seal thickness (0.070) also showed moderate importance. On the other hand, distance from the source (0.042) and seismic activity (0.044) were assigned the lowest weights, indicating they played a comparatively minor role in the evaluation.

Table 3. Assigning weight to criteria using the AHP method

No.	Criteria	Weight
1	Permeability	0.125
2	Pore volume	0.391
3	Hydrogeology	0.063
4	Pore-water chemistry	0.045

5	Thickness of seal	0.070
6	Fault distribution	0.048
7	Seismic activity	0.044
8	Water depth	0.173
9	Distance from source	0.042

To verify the consistency of the pairwise comparison judgments, we calculated both the Consistency Index (CI) and the Consistency Ratio (CR). The results, CI = 0.143 and CR = 0.098, fell within the acceptable limit of 0.10, confirming that the assessments were sufficiently consistent and the resulting weights are dependable for further decision-making.

3. CONCLUSIONS

This study developed a structured, quantitative framework for assessing the suitability of CO_2 storage sites utilizing gas hydrate formation in marine sediments. By employing the Analytic Hierarchy Process (AHP), we systematically evaluated the relative importance of nine geological and environmental criteria relevant to gas hydrate-based storage systems. The analysis identified pore volume and water depth as the most critical factors influencing storage potential, while permeability and seal thickness also played a moderately significant role. In contrast, criteria such as seismic activity and distance from the CO_2 source were found to have relatively lower influence. We conducted expert-informed pairwise comparisons and validated consistency through the Consistency Index (CI = 0.143) and Consistency Ratio (CR = 0.098). These measures ensured that the assigned weights were both logical and reliable. Since the CR remains within the acceptable threshold of 0.10, the results of the weight assignment can be confidently utilized in further multi-criteria decision-making processes to identify and rank prospective CO_2 storage basins in South Korea. This methodology promotes transparent, consistent, and scientifically grounded decision-making for advancing carbon sequestration strategies in marine environments.

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