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Multi-Criteria Evaluation of Large-Scale Hydrogen Storage Technologies in Oman using the Analytic Hierarchy Process

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The hydrogen supply chain must be optimised to ensure the sustainability of the hydrogen economy that has been highly promoted lately. Hydrogen production, transportation and storage are the critical elements in the supply chain. Large-scale hydrogen storage can be done through various technologies and includes more than one determining factor to decide best. Therefore, this is considered one of the significant challenges in the hydrogen supply chain for promoting the hydrogen economy. This research evaluates the best options for large-scale hydrogen storage applications using the Analytic Hierarchy Process (AHP) concerning four main criteria: economics, technical, environmental and infrastructure. The storage systems evaluated include compressed hydrogen gas, liquefied hydrogen and ammonia. The case study was developed for evaluating the most suitable technology for hydrogen storage, which is connected to a green hydrogen production plant in Duqm, Sultanate of Oman. According to this research results, compressed hydrogen gas was the most suitable option for large-scale hydrogen storage in Oman, followed by ammonia and liquefied hydrogen. In addition, sensitivity analysis is carried out in this work to examine the effects of different criteria.

1. Introduction

Over the past years, hydrogen has been identified as one of the most promising energy carriers to address the challenge of energy storage and transportation, which are the significant challenges related to renewable energy industry. Hydrogen storage technologies have become a core player to be an effective solution to solve the renewable energy intermittency and address other environmental issues.

The need for clean energy is growing rapidly, and it seems that hydrogen may supply such demand solely when produced and stored in big numbers. The industries are also projected to fuel switching from fossil-based fuel to renewable hydrogen fuel (Mah et al., 2019). Although it is the lightest element, hydrogen nevertheless boasts the highest energy content per weight (Gim and Kim, 2014). In comparison to other liquid fuels like gasoline, hydrogen poses a barrier for storage and transportation due to its low volume energy density (Rivard et al., 2019). To realize the hydrogen economy, it will be difficult to design hydrogen storage technologies that can hold large scale quantities of hydrogen.

Saaty (1980) developed the Analytic Hierarchy Process (AHP), which has proven to be a potent decision analysis technique for multi-criteria decision-making situations. To reduce and divide complicated problems into manageable pieces, the selected method uses hierarchical approach to break down the challenge. To check the importance of relative criteria and alternatives at each hierarchy level, pairwise comparison judgments are utilized (i.e. storage options) (Pilavachi et al., 2009). Numerous research on the emission from power plants and technologies for producing hydrogen have applied the methodology (Recently, Xu et al. (2022) developed a new AHP model for evaluating hydrogen safety, while Kokkinos et al. (2022) used AHP methodology for selecting hydrogen storage station location for freight transportation.

So, although there have been many research on hydrogen storage evaluation, such as Rivard et al. (2019), they have focused on concerns with hydrogen storage for transportation rather than large-scale hydrogen storage systems for industrial use. Using the AHP technique, this study evaluates three of the most popular hydrogen storage methods for large-scale applications based on four key criteria that take into account economic,

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environmental, and technical factors. In order to choose the best choice based on the chosen location and appropriate criteria comparison, this research would be crucial and beneficial for policymakers.

2. Selection of criteria

After an extensive literature review, the three storage technologies were evaluated based on four main criteria: Economics, technical, environmental and infrastructure. The environmental criterion was selected as it assesses the GHG emissions and safety of the storage system and the amount with which the system is safeguarded against risk factors such as toxicity, explosion, or leaking. Infrastructure refers to the current existence of the infrastructure for the storage systems accessible in the given location; in this research, Duqm region in Oman (Gim and Kim, 2014). Moreover, the rest of the main criteria were split into sub-criteria to better evaluate the technologies. For the technical criterion, both energy density and efficiency were selected as reported by the US DOE (US DoE, 2011). the hydrogen storage system's energy intake divided by its net energy output. For economics, both system cost (CAPEX) and, operation and maintenance (O&M) costs were selected to evaluate the technologies. The CAPEX criterion refers to mostly the cost of equipment and unit constructions while O&M costs involve expenses related to equipment maintenance (Gim and Kim, 2014). All these criteria are implemented to evaluate the most suitable large-scale storage option using the AHP approach.

3. Methodology

The AHP technique, which was used in this research study, logically divides the challenging decision problem into a number of levels of hierarchy. In order to select the ideal choice, it can break down the probel to help decision makers to conduct pairwise comparisons to identify the relative relevance of the variable at each level of the hierarchy and to analyze the alternatives (i.e., storage systems) at the lowest level of the hierarchy. The primary purpose of this study-prioritizing large-scale hydrogen storage technologies in a place and outlining the factors that would affect it-was first defined via the AHP methodology. The complex problem's aim, criteria, sub-criteria, and alternatives are then divided into several tiers by the building of a hierarchy structure, as shown in Figure 1.

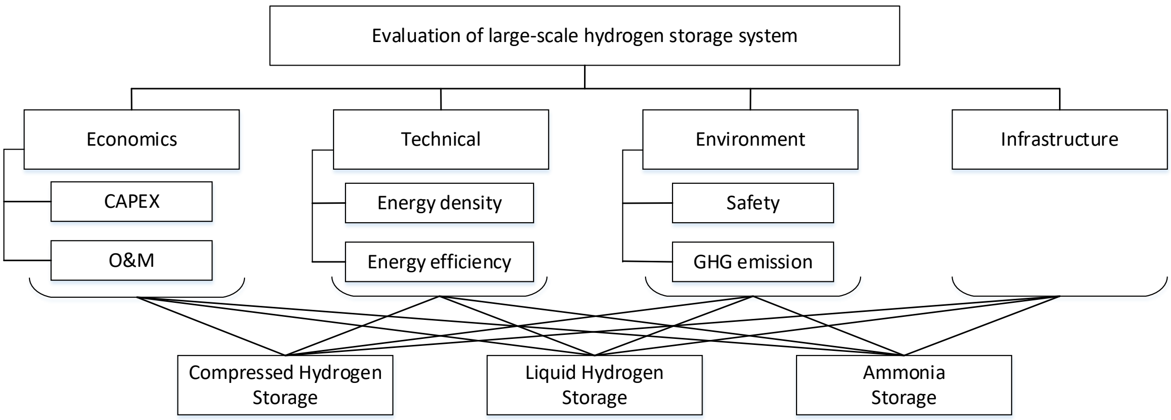

Figure 1: Hierarchy structure for evaluating hydrogen storage technologies using AHP

After creating the hierarchy, pairwise comparisons were done between criteria about the identified aim, between each sub-criteria and the relative options, and between alternatives that are available concerning all sub-criteria. This eventually led to the construction of judgemental matrices. Firstly, the main criteria's judgmental matrix was arranged by allocating a numerical rating to compare each element from the nine-point scale that was proposed by Saaty’s (i.e. scoring system from 1 to 9) as shown in Table 1. Next, the judgments in the pairwise comparison matrix were obtained from the results gathered from the extensive literature review. Subsequently, the weights for the matrix judgements were created by calculating the average of each matrix row and normalising them.

The following evaluation involved comparing the effects of sub-criteria on the main criteria. The sub-factor of CAPEX and O&M were compared concerning the main criterion economics, energy density and efficiency were compared with the technical criterion, and consequently, safety and GHG emissions were compared with the environmental criterion. Hence, this comparison formed three judgmental matrices for sub-criteria evaluation. Afterwards, the matrices are normalised following the same steps performed for the main criteria to calculate the weight for each sub-factor.

Table 1: Scale used for pairwise comparison (Saaty, 1980)

Numerical rating	Verbal judgments of preferences between *i* and alternatives *j*
1	*i* is equally important to *j*
3	*i* is slightly more important than *j*
5	*i* is strongly more important than *j*
7	*i* is very strongly more important than *j*
9	*i* is extremely more important than *j*
2, 4, 6, 8	Intermediate values
If *i* is less important the reciprocal is used	

To confirm that the pairwise comparison judgments are adequately consistent, a consistency check was carried out by initially computing the principal eigenvalue (λ_{max}). the first step, is to calculate the weighted sum value of all criteria and divide it with the given weight of each criteria. After that, the average ratio of all these weights is denoted by (λ_{max}) , which will be used then to calculate the consistency index (CI) as seen in Eq(1).

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

Finally, the consistency ratio (CR) was computed by dividing the CI by a random index (RI) as seen in Eq(2).

$$CR = \frac{CI}{RI} \quad (2)$$

The RI value varied for different matrix sizes (n) and was selected to be 0.9 for a four-sized matrix based on Satty's scale shown in Table 2. The resultant CR value needs to be lower than 0.1 for the judgments to be consistent and satisfactory (Saaty, 1980).
The evaluation of the comparison of hydrogen storage technology options based on the many sub-criteria and primary criteria comprised the last stage. Seven matrices were created using pairwise comparisons of the data and evaluated similarly to those above to produce the weights. The rating of each alternative was first multiplied by the weights of the sub-criteria, which were then aggregated to give the local weight of alternatives to each criterion where the main criterion has sub-criteria. The overall (or final) weight for each storage choice was then calculated by multiplying the obtained local weights by the weight of each primary criterion.

Table 2: Random index (RI) values for different matrix sizes (Saaty, 1980)

Matrix size (n)	1	2	3	4	5	6	7	8	9	10
Random index	0	0	0.58	0.9	1.12	1.24	1.32	1.41	1.45	1.49

4. Results and discussion

A case study is done to study the feasibility of large-scale hydrogen storage technologies implementation in Oman using the AHP methodology. The judgement of each criterion and alternative in Oman are shown in Tables 3 and 4 for constructing the pairwise comparison matrix based on an extensive literature search.

Table 3: Data used in pairwise comparison

Criteria	Compressed gas	Liquid hydrogen	Ammonia	References
Energy Density	4.9 MJ/L	6.4 MJ/L	11.5 MJ/L	Rivard et al. (2019)
Energy Efficiency	49 – 51 %	30 – 33 %	34 – 37 %	Aziz et al. (2019); Gardiner (2009)
Safety	High-pressure risk, Leakage	Hydrogen losses from liquid boil-off, Leakage	Toxic, Leakage	Gim et al. (2014); Ni (2006)
GHG Emissions*	0.1 kg CO_2, eq/kg H_2	3.8 kg CO_2, eq/kg H_2	5.27 kg CO_2, eq/ kgH_2	Awoe (2022); Al-Breiki and Bicer, (2021)
Infrastructure	Mostly available at the selected location	Less infrastructure is available	Already exists in the selected location	

**Values are converted to kg CO_2, eq/kg H_2*

Table 5 shows the priorities for weight factors on hydrogen storage for the case study. The synthesised judgment matrices for the main and sub-criteria were consistent with a CR value of -0.03 and zero. Hence, following the identified AHP steps, the results (Figure 2) showed that the most suitable hydrogen storage technology for large-scale applications in Oman appears to be compressed hydrogen gas with a final weight of (41.03 %) followed by ammonia (35.17 %) and lastly liquid hydrogen (24.98 %). The results also indicated that the environmental criterion significantly influenced selecting a storage technology, followed by economics and infrastructure. In contrast, the technical criterion had the most negligible influence.

Table 4: Cost data used in pairwise comparison

Cost Breakdown			References
Compressed gas	Pressurised vessel cost	667 USD/kg H_2	Amos (1998)
	Compressor cost	80 – 380 USD/kW of H_2	Ni (2006)
	O&M	0.01 – 0.05 % CAPEX	Ni (2006)
	Energy consumption	2.2 kWh/kg H_2	Ni 2006
Liquid hydrogen	System cost	17.07 USD/(kgH_2/d)	Amos (1998)
	O&M	4 % CAPEX	Ni (2006)
	Energy consumption	11.9 kWh/ kg H_2	Al Ghafri et al. (2022)
Ammonia	System cost	1,393,98 USD/(ton$_{NH3}$/y)	IEA GHG (2017)
	O&M	7 % CAPEX	Youngkyun and Han (2021)
	Regeneration Energy	7.9 kWh/kg	Patonia and Poudineh (2020)

Table 5: Summary of priorities for weight factors on hydrogen storage options

	Economics	Technical	Environment	Infrastructure
Compressed gas	0.414	0.463	0.467	0.334
Liquid hydrogen	0.297	0.187	0.408	0.142
Ammonia	0.289	0.350	0.125	0.525

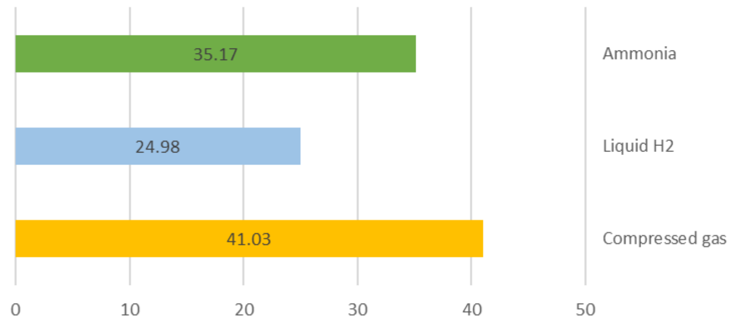

Figure 2: Overall evaluation of hydrogen storage technologies for Case 1

4.1 Sensitivity analysis

Sensitivity analysis is required to be done for validating the AHP model. Five additional cases were developed alongside the base case to examine the effects of different criteria. The five cases are (a) equally distributed criteria (Case Equal Weights), (b) 100 % economic (Case EcC), (c) 100 % technical (Case TC), (d) 100 % Environmental (Case EnC), and (e) 100 % infrastructure (Case IC).

In Case Equal Weights (equally distributed criteria), the weight was distributed equally among all the four main criteria; Economics: 25 %, Technical: 25 %, Environmental: 25 %, and Infrastructure: 25 %. Therefore, as seen in Figure 3, which represents the ranking of the hydrogen storage systems, ammonia and compressed are similar options to some extent, indicating that both options are comparable if all criteria were equivalent. In contrast, the liquid hydrogen option remained competitive with a minimum increment.

In Case EcC, the evaluation has been carried out emphasising the economic criterion, while the other three were ignored. As can be seen in Figure 4(a), compressed gas and ammonia had the same score, while liquid hydrogen scores increased by 4 %, which means the economic factor can be a critical factor for this option since the cost of this technology is the highest among the others. In Case TC, the evaluation has been carried out emphasising the technical criterion in (Figure 4(b)), while the other three were ignored. The best option was found to be ammonia technology, given its high energy density and the maturation of this technology. At the same time, compressed gas dropped lower by 2 %, demonstrating the level of adaptation can be lower in some cases, if technical criteria were involved only compared to ammonia.

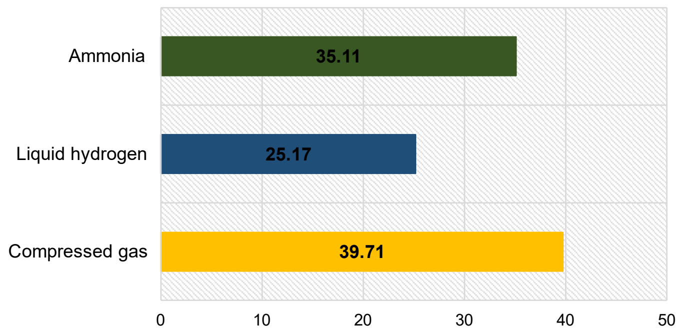

Figure 3: Overall evaluation of hydrogen storage technologies for Case 2

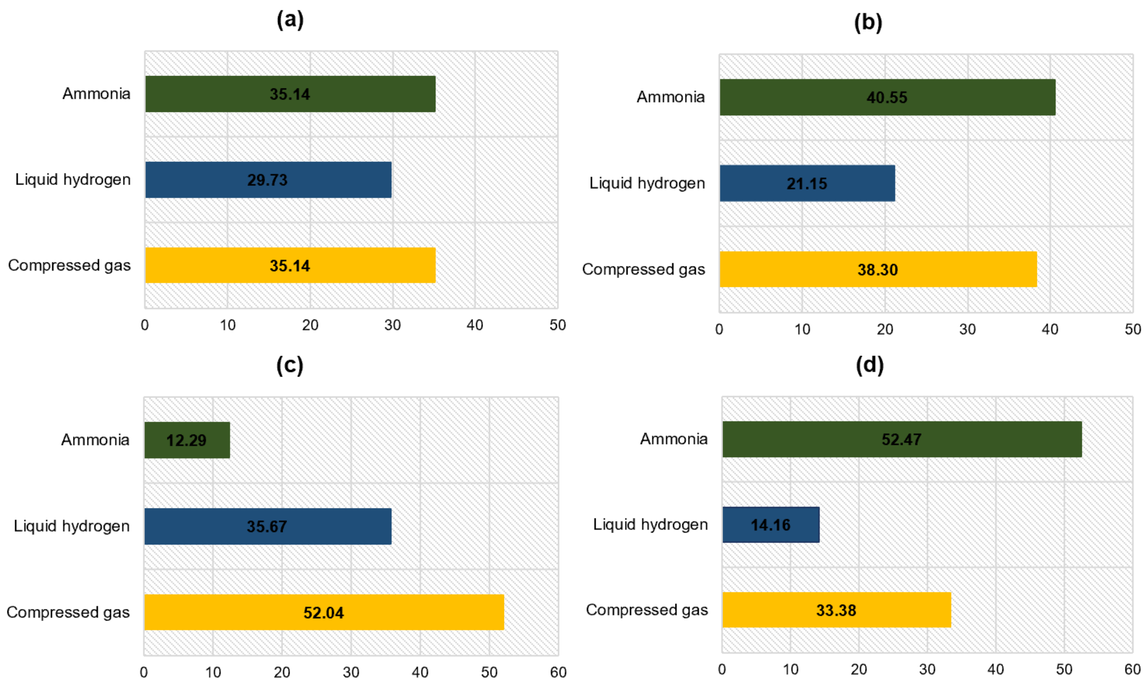

Figure 4: Overall evaluation of hydrogen storage technologies for (a) Case Ecc, (b) Case TC, (c) Case EnC, (d) Case IC.

The environmental criterion was 100 % weight in Case EnC, while the other three were ignored, as seen in Figure 4(c). The best option was compressed gas, while ammonia ranked the last given its high CO_2 emissions and toxicity if there were no safety measures. Meanwhile, when the only infrastructure has been focused in Case IC, the evaluation ignored the other three criteria. As a result, the best option was ammonia, given its available infrastructure in Duqm, as can be seen in Figure 4(d). At the same time, liquid hydrogen ranked last due to the infrastructure requirements to build a new facility for liquefaction.

5. Conclusions

This study uses the Analytic Hierarchy Process approach to evaluate hydrogen storage technologies for large-scale applications in Oman, including compressed hydrogen gas, liquefied hydrogen, and ammonia. According to the evaluation for the base case, compressed hydrogen gas received the highest score, followed by ammonia and liquefied hydrogen. Ammonia and liquid hydrogen received similar evaluation scores with only a 0.3 % weight difference. If the infrastructure for liquid hydrogen was well established in Oman, the option's rank may improve and can secure a higher rank. It is worth mentioning that the rank of the storage technologies can be reformed according to any technological development. This work will hopefully contribute to accelerating the green hydrogen economy growth as it studies the available large-scale hydrogen technologies, thus having a direct positive impact on the country's clean energy transition. The research could be further improved by obtaining a more up-to-date financial data, which would improve the judgement during the rating step.

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